Measurement Systems and Sensors

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Waldemar Nawrocki

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Chapter 1

Computer-Based Measurement Systems

One of the tendencies in measurement technology development is the development of measurement systems. By the measurement systems, we refer to a set of material and organizational resources, as well as programs for information processing, aggregated in order to obtain, transmit, and process measuring data, and to display and store them. The measurement system is equipped with a PC computer or a microprocessor chip; its task is to control information flow in the system, to process measuring data, and sometimes to store them. The computer or the microprocessor chip is a system controller, that is to say, a device managing the system. The measurement systems described in this book are exclusively digital systems. Measurement systems with the personal computer (PC), named computer-based measurement systems, are of great importance. Considering the widespread use of PCs in both industrial and research measuring laboratories, the building of a computer measurement system usually does not imply the purchase of a separate computer, but allows the utilization of the existing ones. This is especially important and economically effective in the case of building up computer measurement systems for the realization of temporary measuring tasks. Separate classes of computer measurement systems are the simplest two-component systems, composed of one measuring instrument plus one computer as the system controller. It is self-evident that the possibility of applying an existing computer for setting up the simplest measurement system decreases construction expenses of such a system considerably.

1.1 CONFIGURATION AND STRUCTURE OF MEASUREMENT SYSTEMS

An important problem in designing and operating the measurement system is the organization of information flow in the system. Two criteria are essential for this organization:

- The kind of transmission in the system: serial, bit-by-bit, or parallel, where the information is transmitted in the form of multibit words. According to this criterion, there are systems with serial interfaces and parallel interfaces.
- The mode of information exchange between system devices with regard to the connection configuration of instruments: linear (bus), star, or daisy chain (arranged in rows).

Measurement systems in the linear, star, or daisy chain configurations are shown in Figure 1.1. The linear configuration is used most often; in this configuration, the exchange of instructions passed between system devices is realized exclusively by the data bus of the system. The linear configuration is elastic, because it makes change of the system structure readily possible by adding or disconnecting devices or by changing the placement of instruments in relation to other devices.

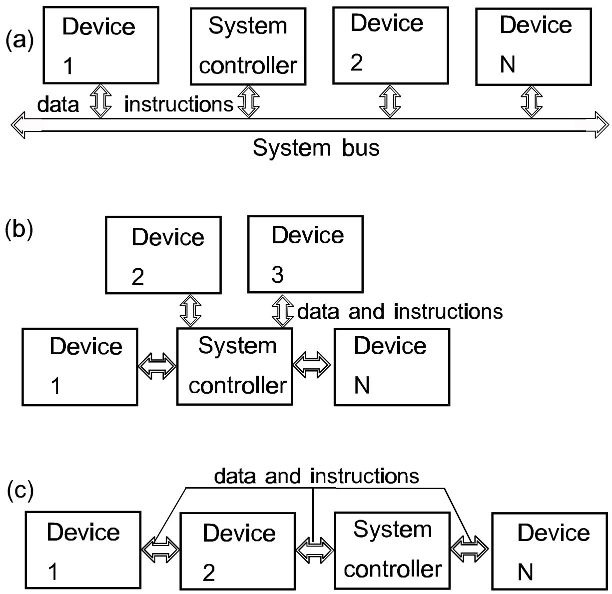


Figure 1.1 Configuration of measurement system: (a) linear, (b) star, and (c) daisy chain.

The star configuration requires the number of multibit computer inputs equal to the number of devices in the system (except for the computer). An advantage of this configuration is the fact that it does not address the bus devices because they are connected to determined computer inputs. Alteration of the structure of such a system is difficult, and sometimes impossible, since the measurement system contains a greater number of instruments. Even less elastic is the daisy chain configuration, in which the exchange is possible only between neighboring instruments. Such configuration is sometimes used in the case of simple measurement systems with the finally definite way of information flow. In discussing measurement system configurations, it must be remembered that a lot of measurement systems consist of two components only: the controller and the measurement instrument. The problem of system configuration thus does not appear.

The measurement system designed for measuring various physical quantities in the object consists of the following functional components:

- A sensor or a set of sensors of physical quantities. The sensor causes changes of a definite electric parameter in the function of the value of a measured quantity (e.g., the resistance alteration in the function of temperature),
- Measurement transducers, in which the electric parameter of the sensor is transformed into the voltage direct or the direct current (e.g., the electric voltage at the output of the Wheatstone bridge with the bridge branch as resistance sensor).
- Conditioners or circuits standardizing the level of signal from the measurement transducer to the range of the input voltage of the analog-to-digital converter.
- Analog-to-digital converters (ADCs) or digital measuring instruments containing such a converter; the task of ADCs is to convert analog into digital signals.
- Devices for visual display of measurement results in the form of the display field of a digital measurement instrument, the screen of a digital instrument (e.g., the digital oscilloscope or the frequency analyzer), or a computer monitor.
- A computer with its software and memory resources;
- Actuators or generators of test signals.
- Power supplies of the object, operating autonomously or under control (optional).

The flow-process diagram in a measurement system is shown in Figure 1.2. It is worth mentioning that the measurement system is often—particularly in industry—part of a control-measurement system. Measuring data are is for controlling objects measured, for diagnosing the objects, and monitoring their state.

More complicated measurement systems can be constructed in the hierarchical structure. On the lowest level, there are measurement subsystems arranged to collect data from the object. Subsystems are situated on a separate area (e.g., in the manufacturing room or the laboratory). Data from such subsystems are sent to the main controller of the measurement system (see Figure 1.3). The main controller of the system not only receives initially processed measuring data, but it can also send commands relating to the execution of a measuring procedure or a set of commands for measurement instruments to subsystems. The main controller of the measurement system can also take advantage of memory resources, data display, and data storage devices.

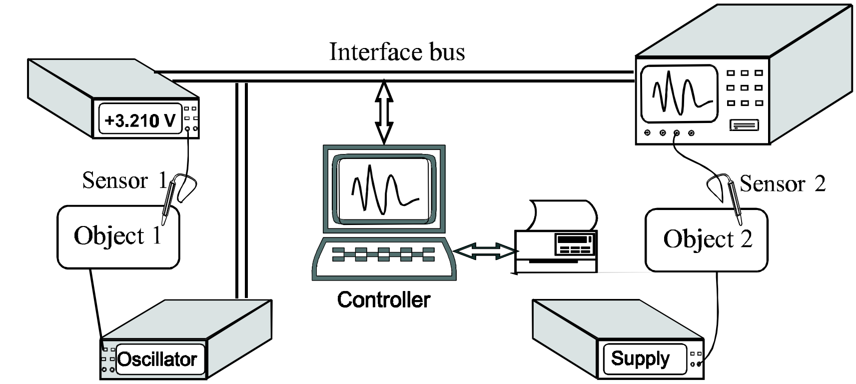


Figure 1.2 The flow-process diagram in a measurement system.

These devices would not be effectively used in subsystems. The SUN, PC, Mac, or similar class computer—as the main controller of the measurement system—can be programmed for a synthesis of collected measuring data and for advanced processing, as well as for data presentation. Interface systems on different levels of the hierarchical measurement system can belong to different interface standards.

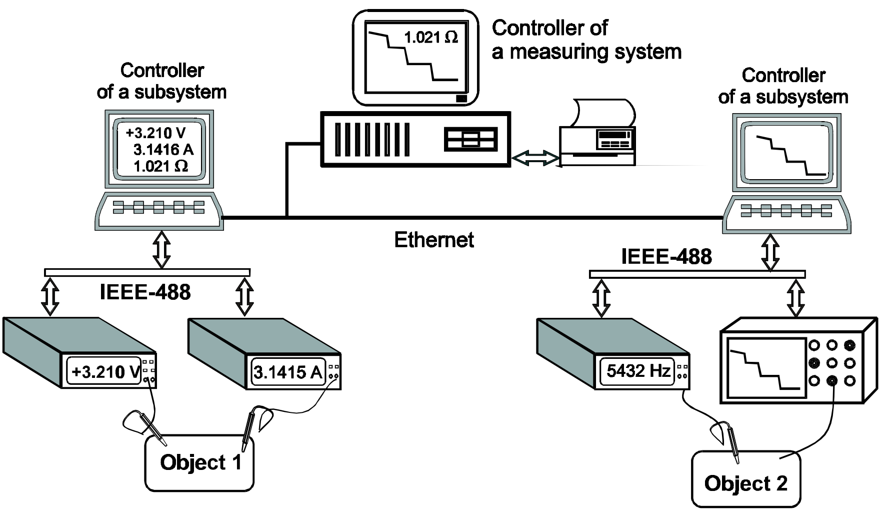


Figure 1.3 The hierarchical structure of the measurement system.

In the example shown in Figure 1.3, each subsystem is composed in the standard of the IEEE-488 parallel interface. All subsystems are united into the system by means of the Local Area Network (LAN) computer network, the Ethernet type with serial transmission. For the implementation of such a configuration, the computer in a subsystem must be equipped with the IEEE-488 interface board and the Ethernet network board. Some interface standards (e.g., Profibus or VXI) make it possible to build up hierarchical systems in the frame of one interface system.

1.2 INTERFACE SYSTEM

A generally applied criterion of the division of measurement systems is a kind of transmission of digital announcements in the system (e.g., data, addresses, and commands); in other words, serial transmission or parallel transmission. The interface system assures equipment and programmatic adjustment of devices attached to the bus. According to the criterion mentioned, measurement systems are divided into the following categories:

- Measurement systems with serial interface;
- Measurement systems with parallel interface.

The interface systems used most often in computer-based measurement systems are the following: the RS-232 serial interface and the IEEE-488 parallel interface (also named IEC-625, HPIB, or GPIB).

1.2.1 Interface System Meaning

There is a notion of interface system, as well as a notion of interface only, which have a wider and narrower sense, respectively. They are defined in standards. According to the standard, “interface is the coupling between a system considered and another system, or between devices of a system, through which information passes.” Interface in the narrower sense is only a matching-up circuit (e.g., matching-up signals of the TTL circuits to signals of the CMOS circuits), or adapting binary signals coded with voltage levels (e.g., logical 0 is 0V; logical 1 is 4.5V) for of binary signals coded with impulse frequency (e.g., logical 0 means 2,200 Hz; logical 1 means 1,200 Hz). The wider sense is given to the interface system, which according to the standard means, “the gathering of device-independent components—mechanical, electrical, and functional—necessary in the process of information exchange between devices.” Such gathering requires “cables, junctions, signal transmitters and signal receivers, interface functions with their logical description, the line signal, time relations as well as control rules.” Transmission protocols and control programs concerning system operation also belong to the interface system. In the common parlance, the notion of interface is often relevantly used instead of the notion of interface system. In this book, we will also take advantage of this abbreviation. It should be once again emphasized that the interface system describes (defines) the processing of only those signals that are transferred through an interface bus. Other signals in the measurement system, including very essential input measuring signals, both analog and digital, are neither defined nor standardized by the interface standard.

1.2.2 Interface Bus

Signals transmitted through an interface bus bear the general name of interface messages. Interface messages are divided into data and instructions. The data transmitted is not only the result of measurement (measuring data), but also sets of instruments: measurement ranges, limit values for alarms, sets of power supply, sets of oscillators, the mode and the level of triggering oscilloscopes, and others. Instructions in the interface system are divided into commands and addresses.

Certainly, the organization of the interface bus depends on the kind of interface. Parallel interface buses are more complex. The lines of the parallel interface bus are divided into groups that are also called buses. A separate bus of the parallel interface is always the *data bus*. The data bus contains 4 lines (Centronics) to 64 lines (PXI). The *synchronization bus* contains lines assuring time coordination between the sending and the accepting of data. The *control bus* (or *interface management bus*) contains lines destined for transmission of control signals. Control signals in a measurement system are: the signal of resetting, interrupt request signals, commands of measurement execution, commands of generating a set of signals (for a generator in the system), and others. The appropriation of the *address bus* is defined by its name. Binary addresses are transmitted across this bus. The addresses are sent to these devices, which ought to execute commands; related commands are available on the control bus. Quicker addressing takes place when the number of lines in the address bus is equal to the number of instruments included in the system. In such a case, addressing is performed with the "1 from n" method. In cassette (crate) systems with the parallel interface, a bus for clock pulses is set up. Sometimes, one part of the bus is the local rail, the line of which connects only neighboring modules in the cassette; and thus, as opposed to other lines in the interface bus, they are not led to all devices in the system. For particular systems of the parallel interface, the organization of the interface bus may differ considerably from the organization described above. For example, in the CAMAC system there are two separate data buses, each with 24 lines. One CAMAC data bus is provided for recorded data, the other for read-out data. However, in the IEEE-488 system, the data bus serves not only for data transmission, but for addresses transmission as well.

The bus of the serial interface can number two or more lines. The messages transmitted are organized according to careful rules and standards named communication protocols. The interface message frame contains both the receiver address and the data field; it also contains the field of control bits, as well as redundant CRC bits for transmission validity check. The CAN and MicroLAN measuring-control systems have a similar data bus. In spite of a trivial opinion evaluating the number of lines of each serial interface to two, this bus can have up to 35 lines, as in the RS-449 interface. They are mostly control lines, but some of them also may be data lines (for received data, for transmitted data, or for the secondary channel). The full bus of the most popular RS-232C serial interface contains 22 lines. Only the elimination of some control and synchronization functions enables a decrease in the number of lines used in this interface to five (including the line of the ground), and, in the simplest version, even to two.

1.2.3 Interface Functions

The following are interface functions used in linear configuration measurement systems.

- Matching functions. Functions of adjusting consist of the processing of signals sent to the interface buses or received by the buses with a device, into a standard form in the interface system. One can state that circuits acting in the interface system are interfaces in the narrower sense.
- Synchronization functions. Synchronization is understood as the coordination of data transmission in the function of time, realized in order to match the transmission speed of data to its reception speed. The kind of transmission used most often in measurement systems is the asynchronous transmission with an acknowledgment of receipt, in the so-called handshake mode. Another kind of transmission is the synchronous transmission.
- Functions of buffering and error corrections. The correctness of the data transfer process in the system is checked. The fault detection of data received in a file often causes a requirement for the resending of the file or its fragment (frames), according to the procedure of the automatic repeating transmission of the determined data file, known as Automatic Repeat reQuest (ARQ). It requires previous data storage in the buffer register. The buffering is also necessary when slight differences in the speed of data reception in relation to their transmission appear. In the case of unsynchronized transmission, the received data can be buffered in the receiver, and only after that read out.
- Management functions. Functions of management consist of the control process of measurement and data processing, according to previously recorded programs and procedures. In particular, this function regulates the access to data transmitted by transmitters to the bus. It decides the sequence of events in confrontational events, and brings system devices to the initial state (the resetting).

Devices included in the measurement system must have separate electronic circuits, enabling the realization of interface functions. Such devices are more complex than those which are not adapted for working in the system. This also pertains to computers working as controllers in measurement systems.

1.3 COMPUTER IN MEASUREMENT SYSTEMS

1.3.1 Computer Architecture

The increasing significance of computer-based measurement systems results from a widespread use of computers and software. The PC in standard configuration may operate as a controller of simple measurement systems. Such possibilities of controlling a measurement system is given by junctions and drivers of the RS-232 interface, as well as of the Centronics interface, installed conventionally. The controlling of the measurement system with interfaces other than these two requires the addition of an additional board or controller module to the computer. The functions of the PC in the measurement system are as follows:

- Functions of controlling the system (the controller of the measurement system);
- Functions of data processing in wide range, using computer programs such as Matlab or Excel;
- Functions of servicing peripheral devices, such as monitors and keyboards;
- Data storage;
- The possibility of controlling data transmission outside the measurement (e.g., via the Internet).

In the case of the measurement system without a computer (e.g., the system with a microprocessor), a majority of the functions mentioned must be also fulfilled in the system, sometimes only in the narrower range. In particular, the installation of peripheral devices such as a keyboard and a monitor, as well as data storage, are essential in every measurement system, and data processing is usually very advisable.

The point of joining the interface board to the computer is very important with regard to the data processing rate. The further from the processor (in the computer architecture) the interface board will be, the slower the communication with this board will be, and the slower the operation of the board itself will be. The modular structure of modern PCs makes it possible to connect additional circuits (e.g., boards, memory circuits), as well as peripheral devices to various points of computer buses. In Figure 1.4, a simplified block diagram of the PC motherboard and the distribution of buses in the computer are shown, along with the arrangement of junctions provided by constructors for joining additional or external devices. In Figure 1.4, neither buses nor nonessential ports for the measurement system are shown, nor are the E-IDE bus (for hard disks and CD), the SCSI bus, PS2 junctions for a keyboard or a mouse, or junctions for a floppy disk. Additional computer boards are joined to sockets inside the computer in the space provided for this purpose, in the so-called slots. External devices are joined to junctions (sockets or connectors, according to the kind of interface) mounted into the computer casing.

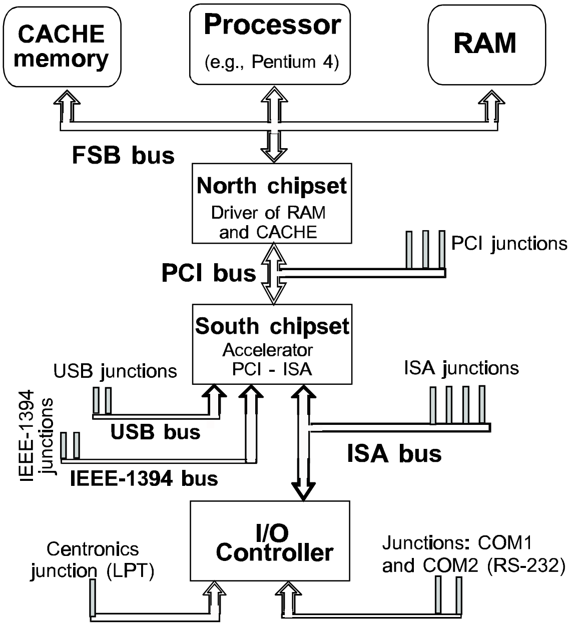


Figure 1.4 Buses and their junctions in a PC.

1.3.2 Buses and Parallel Rails in the Computer

The most essential integrated circuit of the computer, the processor, is connected to the remaining part of the computer with a Front Side Bus (FSB). The fastest microprocessor for the PC in current use at the time of this writing, the Pentium 4, manufactured by Intel, has a clock frequency of 3.2 GHz. Connected to the FSB rail, the integrated circuit Chipset 1 is the controller of the random access memory (RAM) and cache memory. Chipset 1 is the interconnector between the FSB bus and a basic bus of the computer, the PCI bus. Cache is a very fast memory of the processor, which serves to store the most often used instructions and data, applied in order to accelerate the information processing. The Chipset 2 integrated circuit on the motherboard of the computer goes between the PC bus and the ISA bus—the second most important bus in the computer PC. A very important circuit in the computer structure is the input/output controller. The circuit of the input/output controller contains drivers of these interface systems, the junctions of which are placed on the computer casing: the RS-232 interface serial and the IEEE-284 parallel interface (Centronics). The Peripheral Component Interconnect (PCI) bus is equipped with a 32-bit data bus, controlled by a clock signal with a frequency of 33 MHz (in the PCI 2.1 version, a frequency of 66 MHz), which provides the data rate of 132 MBps (megabytes per second), and in the case of the 66-MHz clock, the rate of 264 MBps.

Table 1.1

Buses in a PC and in a Laptop

Bus	*Clock Frequency*	*Number of Clock Cycles for Transmission*	*Number of Bits*	*Transmission Rate (Maximum)*	*Notes*
ISA	8 MHz	2 to 8	16	8 MBps	Low cost, low rate
PCI	33 MHz	1	32 64	132 MBps 264 MBps	High rate
PCMCIA (Card Bus)	33 MHz	1	32	132 MBps	For laptops
USB 2.0	480 MHz	1	1	480 Mbps	For peripherals
IEEE-1394b	800 MHz	1	1	800 Mbps	For peripherals
IEEE-1284	1 MHz	1	8	1 MBps	For a printer

Bps: bytes per second, bps: bits per second.

However, high rates can be obtained only in serial mode of transmission (burst mode), which assumes that a single addressing of the data receiver is followed by the transmission of a data block with any volume. The recording of the full word (32 bits), the so-called single write, which requires at least two clock cycles, or the reading of the full word (that is to say “single read”), is slower: it requires three clock cycles. The transmission of full words goes on with the top rate of 44 or 66 MBps. The data bus of the PCI bus can be extended to 64 bits. Basic parameters of the buses discussed are introduced in Table 1.1.

In the computer architecture, the PCI bus is located nearest to the processor, and, therefore, the transmission rate on this bus is higher. In this estimation, the FSB bus is omitted, to which no additional devices are joined, except for additional RAM memory circuits. Three to six slots for PCI devices are set up onto the motherboard of the computer. A motherboard of a PC with slots for PCI devices and slots for ISA devices is shown in Figure 1.5. Computer boards serving devices of high operation speed are connected to the PCI bus, including an interface board, measuring boards, and I/O boards.

For example, in measurement tasks it is possible to join the following types of computer boards manufactured by National Instruments to the PCI bus:

- LAN board, (mostly Ethernet board);
- PCI-GPIB board of the parallel IEEE-488 interface controller;
- PCI-485 controller board of the RS-485 serial interface with two to eight ports;

- PCI-CAN controller board of the measurement system with the CAN serial bus;
- NI 5911 board of the analog-to-digital converter (I/O board);
- PCI-DIO-24 Data AcQuistion Board (DAQ), the multichannel I/O board;
- Oscilloscope board, serving to set up the virtual oscilloscope;
- PCI-1422 board, 16-bit board of the ADC for visual signals.

Figure 1.5 A motherboard of a PC with slots for PCI boards (five white connectors), and for ISA boards (two black connectors).

Computer boards of other measuring devices manufacturers, like Keithley, are also designed to be connected to the PCI bus. Novelties in the measuring technology are modular measurement systems, PCI eXtensions for Instrumentation (PXI) with PCI bus as an interface bus. The PCI bus is installed in both PCs and Power-PCs (e.g., manufactured by Apple), as well as in workstations. Thus, the interface board or the PCI measuring board can be composed into a computer measurement system with computers of these classes.

The Industry Standard Architecture (ISA) bus has a 16-bit data bus (in older versions an 8-bit bus), controlled by the clock with a frequency of 8 MHz. Because the data transfer on the ISA bus requires at least two clock cycles (and in many cases even eight cycles), the top rate of data transmission with the ISA bus amounts to 8 MBps, or, in other words, it is 32 times lower than the transmission rate on the PCI bus, carried on in the serial mode (burst). So the top speed operation of measurement systems using the ISA bus is lower than systems with the PCI bus.

Various types of computer boards designed for measurement systems can be connected to the ISA bus:

- AT-GPIB (by NI) or KPC-488 (by Keithley), the IEEE-488 interface controller board;

- AT-485 (by NI), the RS-485 interface controller with 2 to 8 ports;
- AT-232 (by NI), the RS-232 interface controller with 2 to 16 additional ports (the PC computer conventionally has two RS-232 ports installed);
- AT-CAN (by NI), the controller board of the measurement system with the CAN bus with 1 or 2 ports;
- The I/O boards contain an analog-to-digital converter and a digital-to-analog converter [e.g., NI 5102 (by NI)].

The Chipset 2 circuit controls the Universal Serial Bus (USB), with a transmission rate up to 480 Mbps (USB 2.0). In these computer measurement systems, in which a laptop is the system controller, parameters of the Personal Computer Memory Card International Association (PCMCIA) bus are essential.

The PCMCIA bus is set up in computers of this class and a similar PCI bus in PCs. The PCMCIA ports were introduced in 1989 in order to connect additional memory boards to the portable computer. Instead of the last Version 2.0 of the PCMCIA standard, the Card Bus standard was introduced in 1994, with parameters similar to the PCI bus. Essential differences between the PCMCIA Version 2.0 and the Card Bus consist of the extension of data wordlengths from 16 bits (PCMCIA) to 32 bits, and in increasing clock frequency of the bus up to 33 MHz. In the new standard (Card Bus), the dimension of the PCMCIA boards and 68-pin junctions to the bus are retained. The PCMCIA name is still applied, for both the bus and junctions, and for computer boards fulfilling the conditions of the Card Bus standard. The power supply voltage of PCMCIA boards is 3.3V. At present, the PCMCIA junction still serves to join additional memory cards or additional hard disks to the laptop. Moreover, for such junctions, one can connect the following measuring devices in the form of the PCMCIA boards: the interface board (IEEE-488, RS-232C, CAN), the DAQ (measuring board) with ADCs and DACs, the modem board of the PSTN telephony, and the modem of the GSM cellular telephony. The PCMCIA boards have the following standard dimensions: a length of 85.6 mm, a width of 54 mm, and a thickness d different for three card types: the PCMCIA type I—the thickness d = 3.3 mm; the PCMCIA type II—d = 5 mm; and the PCMCIA type III—d = 10.5 mm.

Laptops often have slots for two PCMCIA boards of type II. A thinner PCMCIA board can be inserted into the slots of a thicker board.

1.3.3 Universal Serial Bus

Measurement systems are usually very simple systems, composed of one digital instrument and one computer (see Chapter 6). For construction of such a system, one can use the RS-232C serial interface installed in each PC. An essential limitation of the system with this interface is a transmission rate not higher than 20 kbps for transmission lines with a length of 15m, and not higher than 115 kbps for systems with a short transmission line of 1.5m. Data transmission in the computer system and in the computer-based measurement system can be realized with a rate considerably higher than in the RS-232C interface.

The USB and the IEEE-1394 (FireWire) create a new method of attaching and accessing peripheral devices, which simplifies the attachment and configuration from the end-user point of view. The USB universal serial bus allows a transmission rate up to 480 Mbps (USB 2.0). The USB belongs to the PC structure or to the laptop structure. Still higher transmission rates, up to 800 Mbps, can be obtained by using the IEEE-1394 serial bus. For several years, the IEEE-1394 bus has been installed in computers, both in the physical layer and in the form of bus drivers in the Windows 2000 operating system. As far as the usage in the measurement system is concerned, there is a qualitative difference between the RS-232C serial interface and the IEEE-1394 serial bus, or the USB serial bus. The difference consists in the fact that the RS-232C interface system is more complex, as regards electric and mechanical parameters, organizational rules, and transmission protocols. The USB serial bus or the IEEE-1394 serial bus, then, are intended mostly for unidirectional digital data transmission (and bidirectional transmission of commands) into the computer for short distances, ranging from one-half to several meters. Accordingly, the USB bus can be used for measuring data transmission; there is, however, no software for the measurement system with USB provided in standard resources of computer operating systems. The proprieties of the IEEE-1394 bus are more multipurpose, and, therefore, it is better fitted to the measurement system construction. The junctions of the USB and the IEEE-1394 buses are used in measurement systems to connect the following instruments:

- An interface board, which, along with the computer, sets up the interface controller. The board of GPIB-USB or GPIB-1394 type (manufactured by National Instruments) may be an example of such a board. It can fulfill the controller functions of the IEEE-488 system.
- A DAQ board, which contains an analog-to-digital converter, and often a digital-to-analog converter. The DAQ board with a PC and a program creates a virtual measurement instrument.

When all junctions of the main bus are installed inside the PC casing, the socket of the USB or of the IEEE-1394 is able to connect other devices to the computer, including the DAQ board.

The USB bus is present in the structure of each PC or laptop. The desktop computer is equipped with two or more USB junctions, placed onto its casing, and the laptop is equipped with one or two junctions. The USB is designed to connect a variety of peripheral devices to the computer. The USB assures a standardization of cabling connecting these devices with the computer and serves for communication with them, giving a low number of interruptions and input/output addresses. In its equipment part, the USB consists of host controller/root hub, USB concentrators, and USB devices, as shown in Figure 1.6. Both peripheral devices and hubs can be connected to the USB junction in the computer. The sending or receiving of data by a concrete USB device cannot take place on the initiative of this device, but only in consequence of periodic polling of all devices by the main controller. The USB concentrator is also a distributor and a signal amplifier. For example, hub 4 in Figure 1.6 fulfills only functions of the amplifier. The following four kinds of data transfer are possible in the USB:

- Control transfers, applied after connecting a new USB device to the USB bus in order to configure the device;
- Interrupts, related to periodical polling of slow "devices" (e.g., keyboards);
- Bulk data transfers, applied in the case of devices with irregular communication, but with a high rate (e.g., printers or digital cameras);
- Isochronous transfers, referring to devices working in real time (e.g., CD recorders and readers); it transmits data in the asynchronous mode; however, breaks between particular signs must be integral to the multiplicity of the bit cycle T_b. It requires good synchronization of the transmitter and of the receiver; in the asynchronous transmission, character spacings are arbitrarily long.

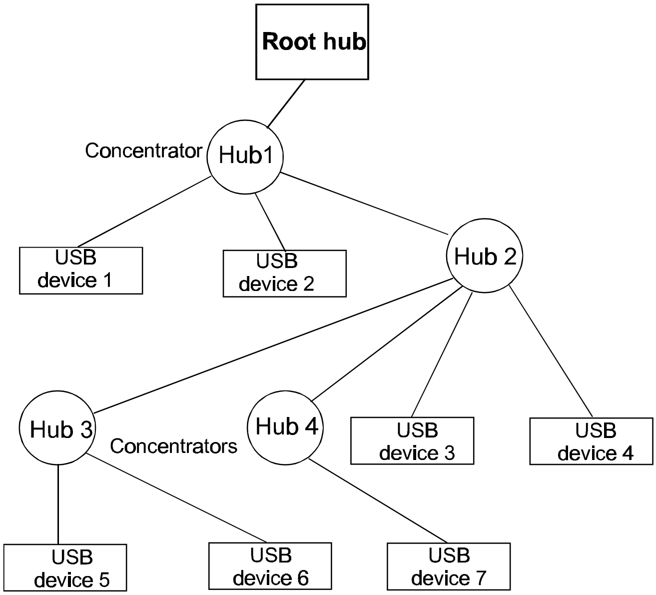


Figure 1.6 The tree structure of USB devices in the computer system.

The features of the USB are as follows:

- One type of interruptions and one USB address space;
- The possibility of joining up to 127 devices;

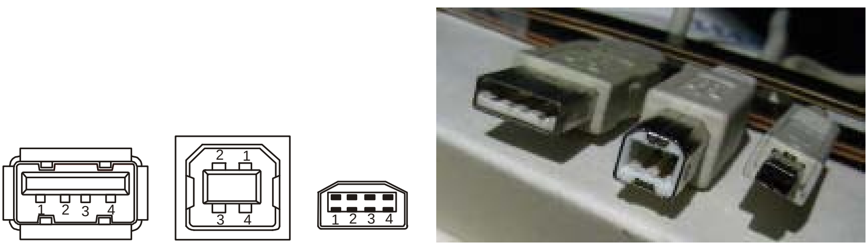
- One type of junction and cable for USB devices—the USB cable is a four-wire cable: two signal lines (for the differential transmission of a single signal) and two power supply wires; the maximum cable length amounts to 5m;
- Low transmission rate less than 1.5 Mbps (the standard USB 1.0), the average rate less than 12 Mbps (the standard USB 1.1), or high rate less than 480 Mbps (the high speed is provided by the USB 2.0 standard introduced in April 2000);
- The installation in "plug and play" mode;
- The possibility of providing power to peripheral USB devices from the computer through the bus. The USB port in the computer contains the power supply voltage of 5V, with a load-carrying capacity of 0.5A for external devices.

A comfortable "plug and play" feature results in computer insensibility for joining and disconnecting USB devices on the bus. After such change of the system configuration the computer need not be restarted. The start of servicing (the initialization) of the USB bus by the computer follows automatically. Under the initialization of the computer or the main controller, the USB system (root hub) gives a 7-bit wise address to a USB device and receives data concerning, among others, transmission mode and rates. Binary signals in the USB bus are transferred with a pair of wires appointed by D+ and D–. The potential difference between the bus wires means:

- Logical 1 for V(D+) – V(D–) > 200 mV;
- Logical 0 for V(D+) – V(D–) < 200 mV.

In steady logical state, the voltage on the D+ or D– line must be higher than 0.8V. During the transmission of coded signs or numbers, bits are transferred beginning from the least significant bit (LSB).

Three types of USB junctions are shown in Figure 1.7. The line description in USB junctions is presented in Table 1.2.



(a) (b)

Figure 1.7 Three types of USB junctions: (a) plug-in sockets (from left: a socket of a type A, a socket of a type B, and a miniature-type socket; and (b) plugs: A, B, and miniature.

Table 1.2

Line Description in USB Junctions

Pin Number	Line Description
1	Power, +V
2	D–
3	D+
4	GND

The standard USB 1.1 is not in use as an interface bus of the measurement systems due to slightly higher transmission rates (12 Mbps), as compared with the system of the RS-485 serial interface (10 Mbps). Other signal parameters of the USB 1.1 are even worse than signals in the RS-485 system. The USB junction can serve for connecting the interface board to the computer (e.g., the IEEE-488 interface board), as shown in Figure 1.8.

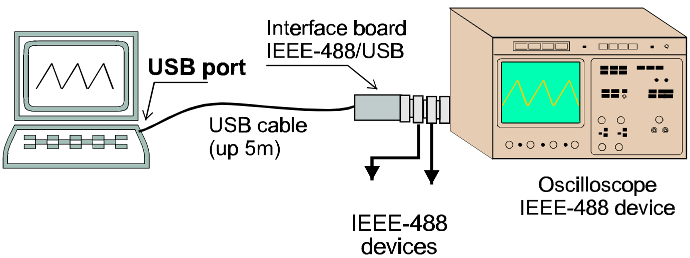


Figure 1.8 Connecting of the measurement system with the IEEE-488 parallel interface to the computer using the USB serial bus.

As the result of connecting such a board, the computer becomes an interface controller of the IEEE-488. Particular devices attached to the USB system can exchange data in pairs, with different transmission rates for every pair. High speed of data transmission through the USB serial bus can be obtained only when both devices communicating with one another are prepared for such a transmission rate. The highest transmission rate in USB, amounting to 480 Mbps, is presently used for data exchange between memory disks, or for reading DVD disk recordings. The USB 2.0 can be used as a measurement system bus with good dynamics, as shown in Figure 1.9. USB 2.0 ports are equipped with:

- Oscilloscopes TDS 6000 and TDS 7000 series (Tektronix);
- Oscilloscopes WaveSurfer series 400 and WaveRunner series 6000 (LeCroy);
- Many types of spectrum analyzers manufactured by Rohde & Schwarz (e.g., R&S FS300);
- Oscilloscopes Infiniium 54800, and arbitrary generators 33220A manufactured by Agilent Technologies.

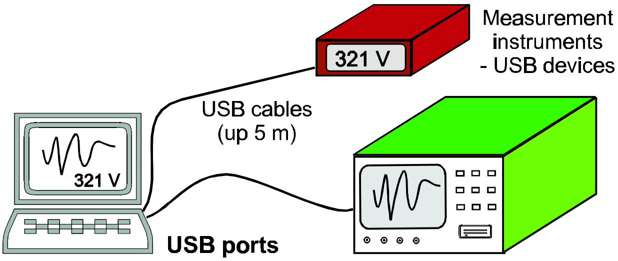


Figure 1.9 The measurement system with the USB 2.0 serial bus.

The computer-based measurement system with the USB bus can contain more instruments than the USB sockets installed in the computer, because it is possible to include hubs in any point of the USB network. One can expect that the development of the USB equipment will be followed by the development of software for measurement systems with the USB bus. Most types of printers manufactured can be controlled from the computer by the USB bus (the USB 1.1 standard) installed in the printer next to or instead of the Centronics interface.

1.3.4 IEEE-1394 Serial Bus

The serial bus with high transmission speed was developed in 1986 by Apple Computer under the name of FireWire; this name is still in use with the Apple company. In 1995, this bus was given the status of a standard, with the name IEEE-1394 (other names of this bus are iLink or Digital Link). The IEEE-1394 bus fulfills a function similar to the function of the USB bus. It is intended, however, for devices requiring higher transmission rates, like digital cameras, DVD readers, measurement instruments, and navigational or medical instruments. The IEEE-1394 and USB standards are complementary, but not interexchangeable. More recent computers are equipped with ports of both buses. Drivers servicing them are contained in the Windows 2000 operating system.

The IEEE-1394 bus assures the highest transmission rate of all the serial interface standards.

- 400 Mbps in a basic IEEE-1394a version;
- 800 Mbps in the IEEE-1394b version (accepted in 2003).

Work continues to improve the IEEE-1394b version, in order to increase the transmission rate up to 3.2 Gbps. For such a high transmission rate, optical fiber lines will be required. The bus is intended for both modules installed in the PC casing and devices connected to the PC by means of a cable.

Three types of IEEE-1394 junctions are used: nine-pin, six-pin, and four-pin junctions. Plug-in sockets of six-pin and four-pin junctions are shown in Figure 1.10. The descriptions of lines in the IEEE-1394 junctions are given in Table 1.3.

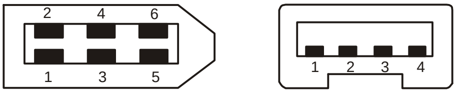


Figure 1.10 Two types of IEEE-1394 junctions (six-pin and four-pin plug-in socket).

Table 1.3

Line Description in IEEE-1394 (FireWire) Junctions

Junction A			Color of a Wire	Junction B		
Four-pin	Six-pin	Line description		Line description	Six-pin	Four-pin
-	1	Power, +V	white	Power, +V	1	-
-	2	GND	black	GND	2	-
1	3	TPB–	red	TPA–	5	3
2	4	TPB+	green	TPA+	6	4
3	5	TPA–	orange	TPB–	3	1
4	6	TPA+	blue	TPB+	4	2

The features of the IEEE-1394 serial bus are as follows:

- One type of interruption and one address space;
- The possibility of joining up to 63 devices;
- High speed of transmission less than 800 Mbps;
- The installation “plug and play”;
- One (from three) chosen type of junction and cable for IEEE-1394 devices; the cable is usually a six-wire cable: four signal lines and two wires of power. A junction provides amounts of power on the IEEE-1394 bus up to 45W, with a maximum of 1.5A and 30V. Only nine-pin and six-pin junctions can carry power, four-pin junctions cannot.

The general structure of the IEEE-1394 network (up to 64 devices) is a tree structure. The maximum length of a single section of the cable amounts to 4.5m. Up to 16 IEEE-1394 devices can be connected in chain mode, which gives the length of the bus equal to 67m for each chain, assuming the maximum length of each section of the cable.

The transmission protocol in an IEEE-1394 system is organized on three layers: a transaction layer, a link layer, and a physical layer, as shown in Figure 1.11. In the IEEE-1394 bus, two kinds of transmission are possible:

- Asynchronous;
- Isochronal.

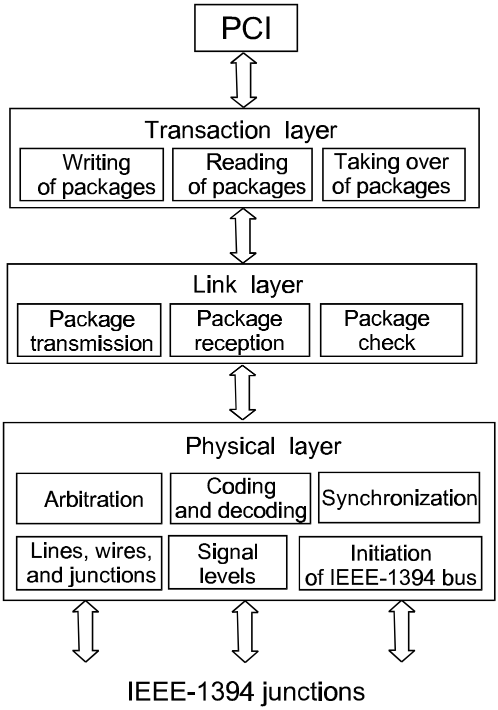


Figure 1.11 Three layers for IEEE-1394 protocol.

The "plug and play" installation in the IEEE-1394 system does not demand computer restarting after the connection of another device to the IEEE-1394 bus, or after disconnecting the device. During the initialization of the IEEE-1394 system, its self-acting configuration takes place. In this operation, devices obtain their identification numbers and ID addresses. In the heading of a data file transmitted, the following items are included: the number of the data receiver (destination ID), and the number of the data sender (source ID).

As opposed to the USB system, where the management function is realized by the main controller of the USB bus (root hub), the IEEE-1394 system has no superior devices. All IEEE-1394 devices have the same rights in the access to the bus and in data exchange. This does not exclude, of course, the programming of one of the devices, for example the computer, to obtain more frequent data requests than other devices. Some measurement instruments manufacturers (e.g., National Instruments or Tektronix) already provide higher class instruments equipped with the IEEE-1394 bus driver and junction. The IEEE-1394 bus also can be used as the system bus of a measuring device, consisting of modules situated in one casing.

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Chapter 2

Temperature Sensors

This chapter describes sensors and electrical circuits for temperature measurements. The International Temperature Scale of 1990 (ITS-90) is described first. It forms a standard for temperature measurements. Resistive sensors, thermocouples, and semiconductor devices are presented next.

2.1 INTERNATIONAL TEMPERATURE SCALE (ITS-90)

The temperature scale fulfills the same function in thermometry as standards of other physical quantities (e.g., the standard of electric voltage) in electric metrology. At present, ITS-90 is obligatory. This scale was established in the same way as every previous international temperature scale, beginning with the International Temperature Scale of 1927:

- A certain number of defining fixed points for temperature values assigned to them were determined; each fixed point is a well-reproducible equilibrium state of an element (or water).
- Interpolative thermometers, calibrated in defining fixed points, were determined.
- Equations were formulated to enable the interpolation of readings of interpolative instruments in temperature measurements between the defining fixed points.

ITS-90 takes over the range from 0.65K to the highest measurable temperature by means of the monochromatic pyrometer. The 17 Defining Fixed Points, listed in Table 2.1, were determined for ITS-90. The fixed points given in the table were defined at the pressure p_a = 101,325 Pa, if different data was not given in the description of the equilibrium state. In the upper range of ITS-90, three equivalent defining fixed points were determined: the freezing point of silver (961.78°C), the freezing point of gold (1,064.18°C), and the freezing point of copper (1,084.62°C).

Table 2.1

The Defining Fixed Points of the ITS-90 Scale

	Equilibrium state	*T* [K]	*T* [°C]
1	Vapor-pressure point of helium ^4He	3 to 5	–270 to –268
2	Triple point of equilibrium hydrogen ^2H	13.8033	–259.3467
3	Boiling point of hydrogen at a pressure 33330.6 Pa	17	–256
4	Boiling point of equilibrium hydrogen	20.3	–252.85
5	Triple point of neon	24.5561	–248.5939
6	Triple point of oxygen	54.3584	–218.7916
7	Triple point of argon	83.8058	–189.3442
8	Triple point of mercury	234.156	–38.8344
9	Triple point of water	273.16	0.01
10	Melting point of gallium	302.9146	29.7646
11	Freezing point of indium	429.7485	156.5985
12	Freezing point of tin	505.078	231.928
13	Freezing point of zinc	692.677	419.527
14	Freezing point of aluminium	933.473	660.323
15	Freezing point of silver	1,234.93	961.78
16	Freezing point of gold	1,337.33	1,064.18
17	Freezing point of copper	1,357.77	1,084.62

The interpolative instruments of ITS-90 are the following:

- Within the range 0.65K to 24K: helium gas thermometers (the constant volume type) or vapor pressure thermometers of He;
- In the range 13.8033K to 1,234.93K: platinum resistance thermometers;
- Above 1,234.93K: optical pyrometers of the monochromatic radiation with the use of Planck’s law of radiation.

Apart from defining fixed points, other fixed points of the ITS-90 scale, the so-called secondary reference points, are used for the calibration of thermometers. Among them are the boiling point of water and the melting point of ice 0°C (instead of the triple point of water 0.01°C). According to the ITS-90, the boiling point of water amounts to 99.975°C at normal atmospheric pressure, p_a = 101,325 Pa. The boiling point of water in the open pot within the range from 99.5°C to 100.5°C is a function of atmospheric pressure, according to (2.1). From (2.1), one can also determine an approximate alteration of the boiling point of water ΔT at a change of atmospheric pressure Δp; it amounts to 0.028°C at a change of pressure by 1 hPa.

$$T\,[°\mathrm{C}] = T_{90} + 28\left(\frac{p}{p_a} - 1\right) - 12\left(\frac{p}{p_a} - 1\right)^2 \tag{2.1}$$

where T is the boiling point of water in the function of atmospheric pressure, T_{90} is the boiling point of water according to the ITS-90 scale at normal atmospheric pressure p_a = 101,325 Pa, T_{90} = 99.975°C, and p is the atmospheric pressure.

For the calibration of sensors in the temperature range 0°C to 100°C, other definitional points of the ITS-90 scale are used. One should mention here that calibration is an expensive process. For example, the calibration of a single sensor in a single point of the temperature scale costs approximately 30 Euro in an accredited European laboratory.

2.2 RESISTANCE SENSORS

2.2.1 Platinum Sensors

Industrial measurements usually exploit resistance sensors, resistance thermometer detectors (RTDs), or thermocouples. Resistance sensors are fabricated of pure metals (platinum, nickel, and copper), of carbon, germanium, silicon, or other semiconductor materials. Metals used for temperature sensors are characterized by large temperature coefficients of resistance, with high melting temperature, and steadiness of the thermometric characteristic. In accurate temperature measurements, platinum sensors are used, usually the Pt100 type; their nominal resistance at a temperature of 0°C amounts to 100Ω. Platinum sensors are manufactured of the sunken platinum wire in the cover of ceramic material in the rod shape. Geometrical sizes of Pt100 sensors are different: they are 25 to 150 mm in length, and from 2.5 to 8 mm in diameter (for the rod shaped sensors) [1, 2]. One respected manufacturer of sensors is the KFAP company in Cracow, Poland. Pt100 sensors in the form of elastic platinum foil, which is 5 mm thick, are also manufactured by JP Technologies. The resistance values of the Pt100 sensor in the function of temperature within the range of the sensor application −200°C to 850°C is defined by the international standard IEC 751 (International Electrotechnical Commission), as shown in Table 2.2. In Figure 2.1, the thermometric characteristics of the platinum sensor Pt100, nickel Ni100, and copper Cu100 are shown in the full temperature range of Cu100 (i.e., –50°C to +175°C), in accordance with the standard.

In a narrow temperature range (tens of degrees Celsius) the thermometric characteristic R_T (T) of the Pt sensor is a nearly linear function. However, in a wider temperature range, the nonlinearity error might be considerable. The replacement of the real thermometric characteristic with a linear function in an exemplary range of temperature 0°C to 300°C is related with the nonlinearity error equal to 3.5°C, and in the interval 0°C to 600°C, with the error of 15°C. For industrial measurements, sufficient accuracy of the reproduction of the real thermometric characteristic of the Pt sensor is assured by (2.2)

Table 2.2
Thermometric Characteristics of the Pt100 Sensor

T [°C]	*R* [Ω]	*T* [°C]	*R* [Ω]	*T* [°C]	*R* [Ω]	*T* [°C]	*R* [Ω]
–200	18.52	50	119.40	250	194.10	600	313.71
–100	60.26	100	138.51	300	212.05	700	345.28
–50	80.31	150	157.33	400	247.09	800	375.70
0	100.00	200	175.86	500	280.98	850	390.48

$$R_T = R_0(1 + aT + bT^2) \tag{2.2}$$

where R_T is the resistance of the Pt100 sensor in the function of temperature T, R_0 is the resistance of the Pt100 sensor at the temperature of 0°C, T is the temperature in degrees Celsius, and a and b are temperature-resistance coefficients of the platinum sensor.

The values of temperature coefficients of (2.2) for platinum in the temperature range 0°C to 600°C amount to $a = 3.91\times10^{-3}$ [1/°C] and $b = 5.8\times10^{-7}$ [$(1/°C)^2$]. For calibration with extreme accuracy (i.e., to the reproduction of the ITS-90 scale in ranges between definitional fixed points), the thermometric characteristic of the platinum sensor is described with the polynomial of the 15th order.

For industrial measurements, almost exclusively platinum sensors are used, although standards were also established for sensors made of nickel Ni100 and copper Cu100, as shown in Figure 2.1. This situation is a result of the great advantage of platinum over nickel and copper. Platinum is a metal characterized by low chemical activity and a high melting temperature. The low chemical activity of platinum assures long usage of the platinum sensor without significant alterations of its parameters, even under hard operation conditions at high temperatures, which contribute strongly to the metal oxidation. The high melting temperature of platinum assures higher acceptable operation temperature of the platinum sensor, in comparison with the nickel or copper sensor.

Temperature sensors are placed in industrial sheaths mounted on the measuring object, as shown in Figure 2.2. Good linearity of the thermometric characteristic makes the cooperation of the platinum sensor with ADCs easier.

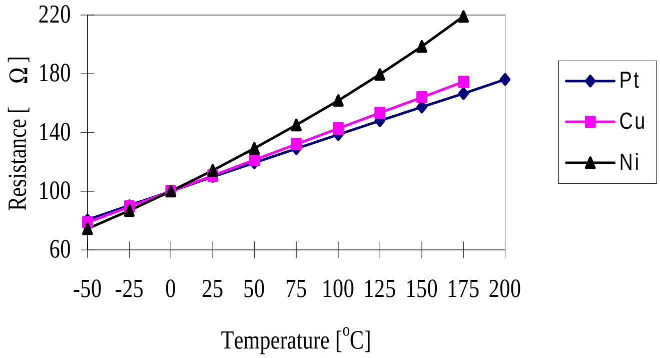

Figure 2.1 Resistance of the metallic sensors: Pt100, Ni100, and Cu100, in the function of temperature.

Taking into account the more expensive material of the platinum sensor, and the still higher costs of replacement and calibration of the sensor in the case of its consumption (oxidation) or overheating, the majority of constructors choose platinum sensors, even in the situation when the measuring range makes it possible to apply cheaper sensors (e.g., nickel or copper ones).

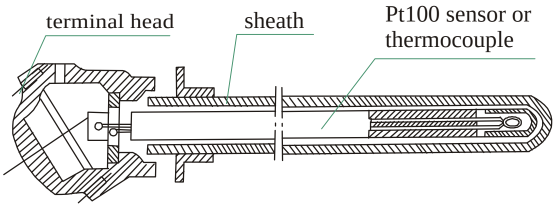

Figure 2.2 Temperature sensor in an industrial sheath.

In industrial systems, resistance sensors for the measuring range $\Delta T = T_H - T_L$ (T_H—upper limit, T_L—lower limit), but not wider than ΔT = 300°C, are usually applied. In systems with wider measuring range, thermocouples are used much more often. A typical measuring circuit for metallic resistance sensors is the Wheatstone bridge, as shown in Figure 2.3, in which a resistor $R(T)$ (e.g., of the Pt100 type) is the temperature sensor.

For a given temperature T_0, the bridge is in the balance state when the following condition for the bridge resistances is fulfilled: $R_1/R(T_0) = R_2/R_3$. For the balance state of the bridge, the output voltage V_{out} equals 0. With an alteration of the sensor temperature by $\Delta T = T - T_0$, voltage V_{out}, proportional to temperature change ΔT (proportional within a nonlinearity error), appears at the bridge output. V_{out} corresponds to the sensor resistance alteration $\Delta R = R(T) - R(T_0)$.

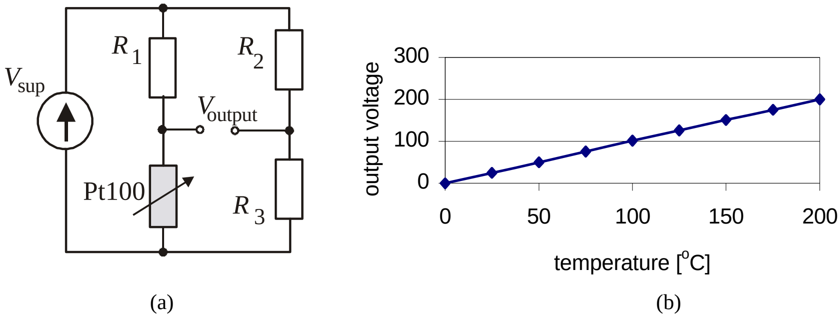

Figure 2.3 The thermometer with the Pt100 sensor: (a) the measuring circuit with the Wheatstone bridge; and (b) V_{output} voltage of a thermometer with the range 0°C to 200°C for the parameters $R_1 = R_2 = 1$ kΩ, $R_3 = 100\Omega$, $V_{sup} = 3.41$V.

For the thermometer shown in Figure 2.3, the nonlinearity error of the V_{out} value amounts to 1% if the measured temperature T changes from $T_0 = 0$°C in the range from –75°C to +80°C.

2.2.2 Thermistors

A thermistor is a temperature-dependent resistor made of a semiconductor material. Thermistors are intended to temperature measurement with large resolution in a narrow range of temperatures. The thermistor resistance in the function of the absolute temperature (Kelvin scale) is determined by an exponential function (2.3), and is presented in Figure 2.4.

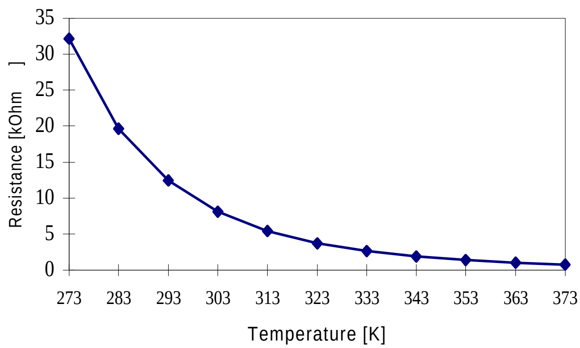

Figure 2.4 Thermistor resistance in the function of temperature.

$$R_t(T) = R_{298} \exp\left[B\left(\frac{1}{T} - \frac{1}{298}\right)\right] \tag{2.3}$$

where $R_t(T)$ is the thermistor resistance in the function of temperature, R_{298} is the thermistor resistance at the reference temperature of 25°C ≅ 298K, T is the temperature in the Kelvin scale, and B is the material constant of the thermistor (typical B value is included within the range 2,500K to 4,500K). The catalog parameter of the thermistor is a resistance at a reference temperature equal to 25°C ≅ 298K. The temperature-resistance coefficient a of the thermistor may be calculated on the basis of (2.4)

$$\acute{a} = \frac{dR_t}{dT} \times \frac{1}{R_t} = -\frac{B}{T^2} \tag{2.4}$$

where a is the temperature-resistance coefficient of the thermistor. It should be noted that the value of coefficient a is temperature-dependent.

An exemplary value of coefficient a of the thermistor with the constant B = 3,800K at a temperature of 20°C = 293K amounts to –0.044 1/K. As compared to the Pt100 sensor, the value of coefficient a of the thermistor is approximately 10 times greater, which implies 10 times greater sensitivity. Disadvantage of the thermistor are the strongly nonlinear character of its thermometric characteristic, the large dispersion of parameters of the thermistors manufactured (the tolerance of B constant amounts to ±5% or ±10%), as well as the narrow range of the operation temperature. The upper limit of the temperature range amounts to 150°C to 250°C [1].

In all resistance sensors conducting the electrical current, the so-called self-heating effect appears. It consists of a temperature rise of the sensor above the temperature of the ambience, caused by a heat loss on a resistance of the sensor due to the flow of measuring current through the sensor. In consideration of the compact design of the sensor, especially its thermosensitive part, the semiconductor “bead,” the self-heating effect, and the thermometry error can have a significant impact on the thermistor. This effect can be estimated, given the self-heating coefficient k_s, the value of which for exemplarily selected thermistors NTC210 (manufactured by CEMI, Poland) equals 1 mW/K. Thus, as the current I flows across the sensor with the resistance $R(T)$, the electric power P causes a temperature rise ΔT in the sensor

$$\Delta T = \frac{P}{k_s} = \frac{R(T)I^2}{k_s} \tag{2.5}$$

where ΔT is the thermometry error caused by self-heating, and k_s is the self-heating coefficient of the sensor.

If we take a thermistor with resistance R = 10 kΩ, k_s = 1 mW/K, and assume a measurement current through a thermistor I = 100 µA, we obtain the self-heating error ΔT = 0.1K.

The Wheatstone bridge and the series circuit are temperature measurement systems with thermistors. A thermistor connected into the Wheatstone bridge forms a thermometer with high sensitivity and zero-indication in the initial point of the scale (for the balance state of the bridge). A simple thermistor thermometer with good sensitivity, but with a nonlinear scale, may be obtained after the connecting of the sensor into the electrical serial circuit, as shown in Figure 2.5.

Thermistor thermometers in the form of an electric oscillator with temperature-dependent frequency are also used. The circuit of a transistor oscillator, shown in Figure 2.6, can fulfill the function of a thermometer if the thermistor is connected into the circuit of the base of one of the transistors. The frequency *f* of the oscillation is a function of the parameters $R(T)$, R_3, and C.

$$f = \frac{1}{\ln 2 \times [R(T) + R_3]C} \tag{2.6}$$

Within the temperature range of tens of degrees Celsius the function of conversion $T \to f$ has a small deviation from the linear course. A thermistor thermometer with the Wheatstone bridge usually has a narrow measuring range several or tens of degrees Celsius. Such an instrument is applied in medicine and in chemical and alimentary industry.

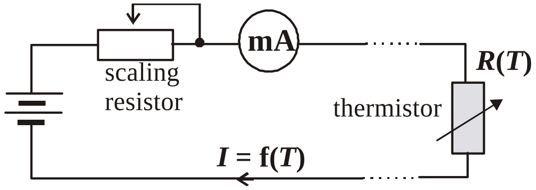

Figure 2.5 Series connected thermistor thermometer.

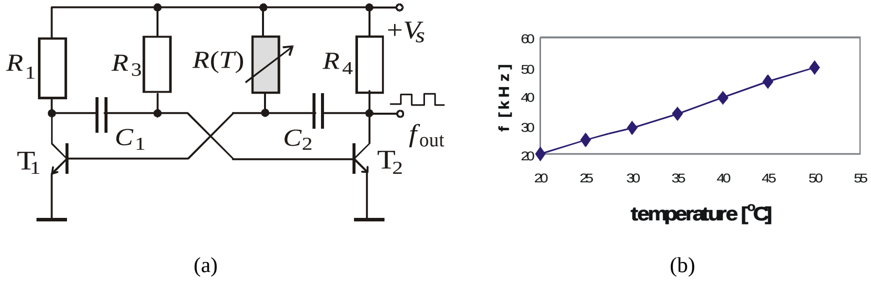

Figure 2.6 Thermistor thermometer with temperature-frequency conversion: (a) the scheme of an oscillator thermometer with temperature-dependent frequency *f*; and (b) an exemplary characteristic of the transformation for the scheme with the thermistor with parameters R_{298} = 10 kΩ and B = 3,800K.

2.3 THERMOCOUPLES

Thermocouples are applied for the thermometry above 300°C. The thermocouple is created by a couple of metallic wires connected at the ends by welding, soldering, or twisting. At the point of junction of wires created from two dissimilar metals or metal alloys, a contact potential difference E_{12} arises, as shown in Figure 2.7 and (2.7).

$$E_{12} = \frac{A_2 - A_1}{e} + \frac{k_B T}{e} \ln\left(\frac{N_1}{N_2}\right) \tag{2.7}$$

where e is the electron charge ($e = 1.6 \times 10^{-19}$ C), k_B is the Boltzmann constant ($k_B = 1.38 \times 10^{-23}$ J/K), N_1 and N_2 are the concentration of free electrons in metal 1 and metal 2 (the number of electrons in 1 cm^3), and A_1 and A_2 [eV] are the electron workfunction from the metal, weakly dependent on T.

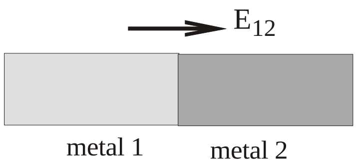

Figure 2.7 The contact potential difference at the point of junction of two metals.

The contact potential difference depends on temperature T of the joint point, on the concentration of free electrons N in metals, as well as on the electron workfunction from the metal A. Both the concentration of free electrons N and the electron workfunction, from the metal A are weakly dependent on the temperature (the alteration of value N or A by a few percent within the temperature range of several hundred of degrees Celsius). In a circuit composed of two wires connected at both ends, with different temperatures at these contact points, T_x and T_R, there is a thermoelectric ElectroMotive Force (EMF) equal to the difference of $E_{12}(T_x)$ and $E_{12}(T_R)$, as shown in Figure 2.8(a), and (2.8) [1, 2].

$$\text{EMF} = E_{\text{EMF}} = E_{12}(T_x) - E_{12}(T_R) = \frac{k_B}{e}(T_x - T_R) \times \ln(N_1/N_2) \tag{2.8}$$

$$\text{EMF} = E_{\text{EMF}} = k_T (T_x - T_R) \tag{2.9}$$

where k_T is the thermoelectric coefficient.

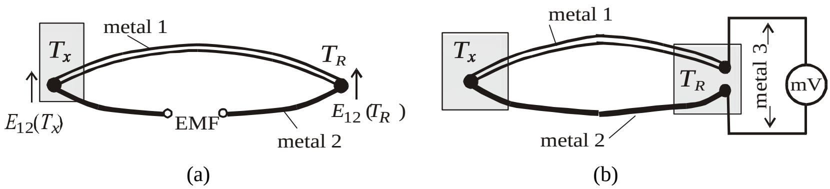

Figure 2.8 The origination of thermoelectric force (EMF) in the thermocouple: (a) in a two-metal system; (b) in a three-metal system.

$$E_{\mathrm{EMF}} = k_T(T_x - T_R) = k_T T_x, \quad \text{at } T_R = 0°\text{C} = \text{const} \tag{2.10}$$

The thermoelectric EMF in such a circuit is proportional to the difference of the temperature between point *X*, called the measuring junction, and point *R*, called the reference junction. For a fixed temperature of the reference junction T_R = 0°C, the thermoelectric force in the circuit is proportional to the temperature T_x in the measuring point *X*.

Table 2.3

Parameters of Industrial Thermocouples

Type	*Metal* (+)	*Metal* (–)	k_T [μV/°C]	*Temperature Range* [°C]	*Tolerance* ΔT at 750°C	*Properties*
K	Chromel Ni-Cr	Nickel	40.5	–270 to +1,370	Class 1: ±3.0°C; class 2: ±5.6°C	Good linearity
S	Platinum	Pt-Rh10 90%Pt+10%Rh	6.4	–50 to +1,760	Class 1: ±1°C; class 2: ±1.9°C	Good accuracy
J	Iron	Copper–nickel	51.7	–210 to +1,200	Class 1: ±3°C; class 2: ±5.6°C	Not expensive, good sensitivity
T	Copper	Copper–nickel	49	–200 to +400	Class 1: ±1.4°C; class 2: ±2.6°C	Not expensive, good sensitivity
W3	W-Re3 97%W+3%R	W-Re25: 75%W+25%Re	18	0 to +2,320	No class 1; class 2: ±10°C	High operation temperature

Note: The tolerance for the thermocouple T is standardized only in the temperature range from –40°C to +350°C; the value of ΔT for it is given for T = +350°C.

In relation to a serial electric circuit made of two metal sections, the law of the third metal is effective, according to which the thermoelectric force in the circuit will not change after the inclusion of the third metal into the circuit, only if both contact points of the third metal have equal temperature. The law is also in force in the situation when the junction of metal 1 with metal 2 in the point *R* becomes open, and, in this place, the third metal is connected to the ends of metal 1 and metal 2, in the form of metallic wire (e.g., copper), connecting a thermocouple with an electric measure [see Figure 2.8(b)]. The circuit shown in Figure 2.8(b) is an electric thermometer extensively used in the practice of industrial thermometry within the temperature range 200°C to approximately 1,000°C. This thermometer does not require any power source if a separate power supply is also not required by the measure (e.g., a magnetoelectric microampermeter).

In Table 2.3, practical data of various types of thermocouples with distinguished proprieties applied in industry are compared. The diagrams of thermometric characteristics of these thermocouples, according to the international standard IEC 584, are presented in Figure 2.9.

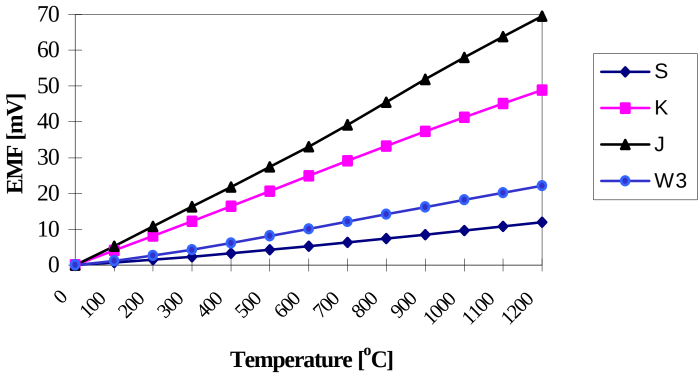

Figure 2.9 Thermometric characteristics of thermocouples of type S (Pt, Pt-Rh10), K (Ni-Cr, Ni), J (Fe,Cu-Ni), and W3 (W-Re3, W-Re25) within the temperature range 0°C to 1,200°C for a reference temperature of 0°C.

The electrodes of thermocouples are usually made in the form of wire with a normalized diameter, which amounts to 0.2 to 5 mm in the case of electrodes not containing noble metals, and 0.1, 0.35, and 0.5 mm in the case of electrodes made of platinum or alloys with the content of Pt. There are also electrodes made in the form of metal tape. Greater diameter of the cross section of the electrode assures its greater durability and smaller resistance; however, it causes greater thermal inertia of the thermocouple.

A typical circuit used for temperature measurements realized by means of thermocouples is shown in Figure 2.10.

A relevant problem in temperature measurement realized by means of thermocouples is the influence of the temperature of the reference joint on the accuracy of the measurement. It is necessary to take into account two factors in such measurements:

1. The measuring line connecting the thermocouple to the instrument with the reference temperature and to the measure;

2. The stabilization of reference temperature.

Figure 2.10 The circuit for thermometry realized by means of the thermocouple.

The measuring line should be made of materials which, when connected to the thermocouple, give the thermoelectric force with the least possible value. Such wires are called compensating leads (lines). In the case of a thermocouple composed of inexpensive materials, the measuring line is created with wires (or twisted lines) of smaller diameter, but made of the same materials as the thermocouple electrodes.

For thermocouples made of expensive metals, compensating lines are produced with cheaper materials, which ensures low EMF in the contact with the thermocouple electrodes. Thus, in connecting compensating leads with thermocouples, the essential elements are the material of the line, well-matched to the type of thermocouple, and the polarity of contacts (i.e., connecting proper wires to proper electrodes). Colored codes distinguishing particular types of compensating leads are, unfortunately, not normalized on an international scale, and may cause errors in the composing of systems from components manufactured in different countries. A short characterization of the thermocouples used most often is given next.

The thermocouple K is used to thermometry below 700°C, due to its good sensitivity, linear thermometric characteristic, and low cost of materials. The positive electrode [the (+) electrode] of the thermocouple K is the pure nickel or the chromel alloy with the composition 90% Ni and 10% Cr, while the negative electrode [the (–) electrode] is the alumel alloy with the composition 94% Ni, 2% Mn, 2% Al, and 1% Si. The chemical composition of electrodes is not normalized, but the thermocouple parameters must fulfill the standard terms. Compensating leads to the thermocouple K should be made of the same materials as the electrodes, so, respectively, the measuring line is made of nickel wire for the (+) wire, and of alumel for the (–) wire. It is also possible to use some wire made of Cu and Cu-Ni when the resistance of the line should be decreased. The values of the thermoelectric coefficient k_T amounts to 39.5 μV/°C for 0°C, 42.7 μV/°C for 500°C, and 39.0 μV/°C for 1,000°C, which implies a characteristic with little nonlinearity. Continuous working of the thermocouple in temperatures above 700°C is not recommended due to fast consumption of the electrodes.

The thermocouple J keeps still greater sensitivity than the thermocouple *K*, and is made of still cheaper materials. The (+) electrode is made of pure iron, while the (–) electrode is made of a copper alloy and nickel, with an average composition of 50% Cu and 50% Ni, with a 10% tolerance of each metal content. The thermocouple J is also known under the name of iron-constantan. Its compensating leads are made of the same materials as the electrodes. With regard to the chemical activity of electrodes, which increases with a temperature rise, the recommended temperature for continuous working is lower than 600°C. The value of the coefficient k_T amounts to 50.4 μV/°C at 0°C, 55.9 μV/°C at 500°C, and 59.2 μV/°C at 1,000°C, so it changes by 18% in the temperature range considered.

The thermocouple T, known also under the name of copper-constantan, has the (+) electrode made of pure copper, while the (–) electrode made of a copper alloy and nickel with the composition of approximately 50% Cu and 50% Ni, with the tolerance of 10% of the content of each metal. Its compensating leads are made of the same wires as the electrodes. For constant operation, a temperature up to 400°C is recommended. Polish standard defines the thermometric characteristic of the thermocouple T within the range –270°C to +400°C. The value of coefficient k_T in this temperature range amounts to 2.6 μV/°C at –270°C, 38.7 μV/°C at 0°C, and 61.7 μV/°C at +400°C. The sensitivity of the thermocouple T is therefore very low in the bottom measuring range and very high in the upper range.

The thermocouple S is most often applied to measurements of high temperatures (above 500°C), as well as to standard measurements. The (+) electrode is made of pure platinum, and the (–) electrode is made of an alloy 90% Pt and 10% Rh. The basic material for electrodes of the thermocouple S (i.e., platinum), is characterized by a very weak chemical activity and a high melting point. The weak chemical activity ensures the invariability of chemical composition of electrodes and strong resistance to the thermocouple oxidation. Platinum is a very expensive material (as of this writing, its price was $860/ounce, in relation to the gold price of $440/ounce), and therefore the thermocouple S electrodes are made of wire with the diameter smaller than the diameter of the electrodes of the thermocouple K, J, or T. The compensating leads are copper wire used for the (+) electrode, and wire made of alloy 99.4% Cu and 0.6% Ni, used for the (–) electrode. The value of coefficient k_T amounts to 5.4 μV/°C at 0°C, 9.9 μV/°C at 500°C, and 11.2 μV/°C for 1,000°C, thus the sensitivity of the thermocouple S is more or less five times lower than the sensitivity of the previously mentioned thermocouples, but above 500°C, the value of the coefficient k_T remains on the level of approximately 10 μV/°C.

In industrial measurements the thermocouple K is usually used within a temperature range up to approximately 500°C, and the thermocouple S is used for measurements of higher temperatures or with higher accuracy. It is worth mentioning that thermometry above 1,000°C is accompanied by problems concerning the choice of material for both the sensor sheath and the measuring line, due to thermal resistance of materials.

From (2.9), the value of thermoelectric force is proportional to the difference of the temperature between a measuring junction and a reference junction. In measuring circuits, the temperature of the reference point is stabilized, or the EMF is corrected at the change of reference temperature. The reference temperature is stabilized by means of placing the reference junction in the thermos with a mixture of water and ice (at a temperature of 0°C with an error of ±0.01°C), or by placing the reference junction in ground conditions in a measuring well dug 2m deep in the earth, where a stable temperature of +12°C, with deviation ±2°C, is set up throughout the year.

2.4 SEMICONDUCTOR TEMPERATURE SENSORS

The operation of semiconductor temperature sensors is based on the dependence of voltage in the p-n junction on the temperature. The p-n junction of the diode or the transistor biased with the current of the junction (the diode current or the emitter current) is a function of voltage-biased V_{BE} and temperature T (2.11) [3].

$$I_E = I_0(T)\exp\left[\frac{e}{k_B T}(V_{BE} - V_G)\right] \tag{2.11}$$

where I_E is the current flowing through the junction (e.g., the emitter current), $I_0(T)$ is the reverse saturation current, T is the temperature in the absolute scale, V_{BE} is the voltage on the p-n junction (e.g., the base-emitter voltage), and V_G is the material constant, a potential difference resulting from the energy gap of a semiconductor (for Si, V_G = 1.205V).

Equation (2.11) is used in thermometry, converted into the form (2.12), describing the voltage on the junction in the function of temperature, for a constant value of current junction (see Figure 2.11).

$$V_{BE} = V_G + \frac{k_B T}{e}\ln\left[I_E / I_0(T)\right] \tag{2.12}$$

The voltage V_{BE} on the p-n junction of the transistor (or diode) made of silicon increases together with its temperature decrease from 0.6V at a temperature of 350K to 1.3V at a temperature of 50K. The sensitivity of the device is therefore equal to −2.3 mV/K. Below the temperature of 50K, the voltage-temperature characteristic of the junction becomes strongly nonlinear, and in this temperature range, the p-n junction is not useful for thermometry. The scattering of values of the reverse saturation current, $I_0(T)$, observed for several thermosensors, causes the characteristics V_{BE} = f(T) of particular sensors to differ from one another with both V_{BE} values and the characteristic slope.

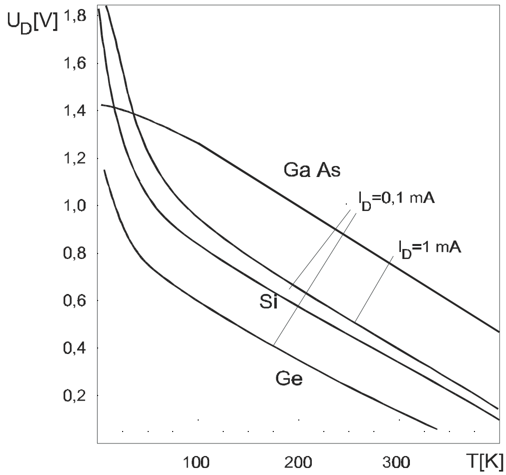

Figure 2.11 Voltage characteristics in the function of temperature for the silicon diode, the germanium diode, and the GaAs diode.

A single p-n junction may be used as a temperature sensor after individual calibration, which is not always possible, but is always expensive. An integrated semiconductor sensor contains two p-n junctions, usually base-emitter junctions of two transistors, made of one block (piece) of semiconductor. Therefore, the scattering of parameters for a pair of integrated transistors is much smaller than for a pair of separate transistors. The voltage difference V_{BE} for two integrated transistors conducting the emitter currents I_{E1} and I_{E2} is expressed with the following formula.

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{k_B T}{e}\ln\left[I_{E1}/I_0(T)\right] - \frac{k_B T}{e}\ln\left[I_{E2}/I_0(T)\right] = \left[\frac{k_B}{e}\ln\left(\frac{I_{E1}}{I_{E2}}\right)\right]\times T \tag{2.13}$$

For a constant value of the rate of currents I_{E1}/I_{E2} (e.g., equal to 10), the voltage difference ΔV_{BE} is a linear function of temperature within a range of 50K to 420K.

$$\Delta V_{BE} = 200\left[\frac{\text{ìV}}{\text{K}}\right]\times T$$

Integrated thermosensors contain in one structure a couple of transistor-sensors as well as amplifier circuits converting the signal ΔV_{BE} to the required level of voltage V_{out} = f(T) or output current I_{out} = f(T). Due to a very considerable decrease in the amplification of internal amplifiers within a temperature range below 200K, the measuring range of integrated sensors has the lower temperature limit of –50°C (≈220K) [1, 3]. Exemplary parameters of selected integrated semiconductor sensors are given next.

The AD592 device (manufactured by Analog Devices) has an output signal in the form of current I_{out} = f(T) = 1 [μA/K]×T [K], and the measuring range –25°C to 105°C. A typical measurement error of the AD592AN version amounts to ±1.8°C (the maximal error ±3.5°C), and of the AD592CN version amounts to ±0.4°C [4]. The nonlinearity error of the sensor is included in the interval 0.1°C to 0.4°C (depending on the version), and the power supply voltage may be selected from a wide range of values included between 4V and 30V. The mode of connecting the sensor into the measuring circuit and current characteristic of the AD592 sensor is shown in Figure 2.12.

The LM35 device (manufactured by National Semiconductor) has an output signal in the form of the voltage V_{out} = f(T) = 10 [mV/°C] × T_x [°C]; therefore, for an exemplary temperature of 25°C the output voltage amounts to 250 mV. The measuring range of this sensor is included in the interval 0°C to +125°C, the measurement error ±2°C to ±3°C, and the supply voltage 2.7V to 5.5V [4].

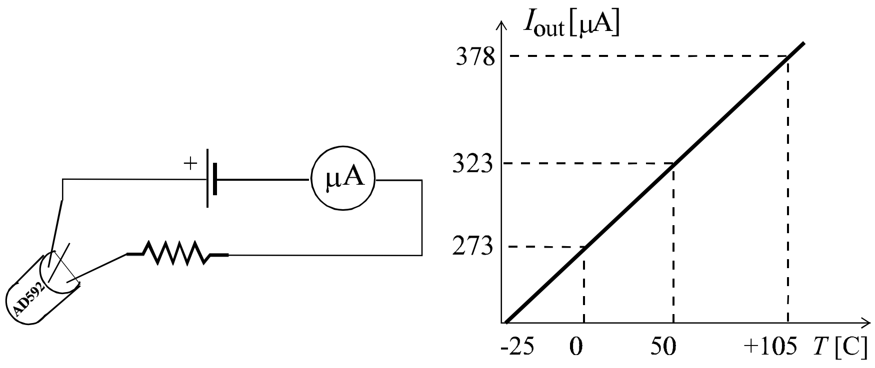

Figure 2.12 The measuring circuit with the AD592 integrated sensor, and the characteristic of I_{out} = f(T) of this sensor.

The TMP01 sensor (manufactured by Analog Devices) is a complex integrated circuit containing the sensor that produces a voltage output (the VPAT pin) proportional to the temperature measured, and the analog comparator that sends a control signal with a temperature above (the OVER pin) or below (the UNDER pin) the settled range [4]. The block diagram of the TMP01 system is shown in Figure 2.13. The measuring range of the TMP01 system is a temperature range of –55°C to +125°C. The voltage at the analog output of the system is described by the formula: V_{out} = 5 [mV/K] × T_x [K], which for temperature T_x = 25°C = 298K determines the nominal value of output voltage for 1.490V. The error of the sensor depends on a subrange of the temperature as well as on the conditions of system loading, and is included in the range ±0.5°C to ±2.5°C. The reference voltage $V_{REF,}$ generated inside the devices, amounts to +2.5V. Signals programming the upper temperature T_H and the lower temperature T_L for the window comparator are fixed by means of the resistors R_1, R_2, and R_3, attached from outside to the circuit, as shown in Figure 2.13.

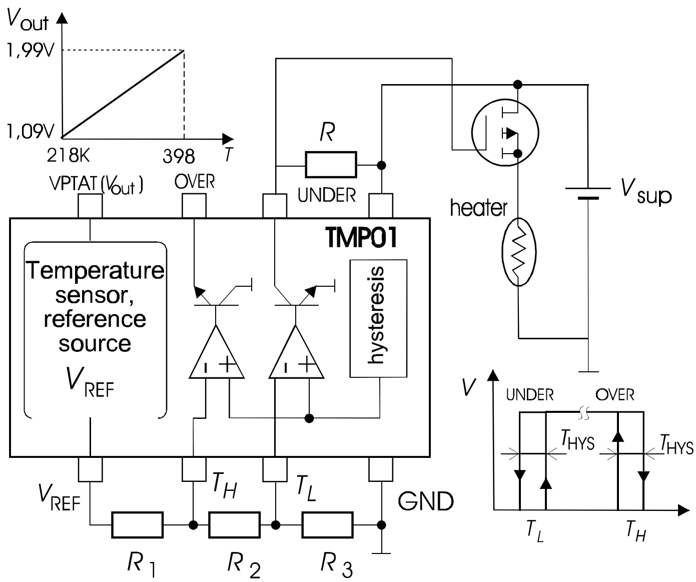

Figure 2.13 The TMP01 device in the two-stage temperature controller system.

The resistor values are calculated for required thresholds T_H and T_L and for an assumed comparator hysteresis T_{HIS} [4].

$$I_{HIS} = 5\ [\text{ìA}\ \ /\ \text{K}] \times T_{HIS} + 7\ \text{ìA}$$

$$R_1 = \frac{V_{REF} - 5[\text{mV/K}] \times T_H}{I_{HIS}} = \frac{2500\ \text{mV} - 5[\text{mV/K}] \times T_H}{I_{HIS}}$$

$$R_2 = \frac{5\ [\text{mV/K}] \times (T_H - T_L)}{I_{HIS}} \quad \text{and} \quad R_3 = \frac{5\ [\text{mV/K}] \times T_L}{I_{HIS}}.$$

For example, for control thresholds T_H = 303K and T_L = 293K, and for the widths of hysteresis T_{HIS} loop equal to 1K, the calculated values of resistors amounts to R_1 = 82 kΩ, R_2 = 4.2 kΩ, and R_3 = 122 kΩ. The TMP01 device has eight pins, and is manufactured in plastic dual-in-line package (DIP), in metal package TO-99, or in miniature package SOIC. It appears sometimes in catalogs under the name of programmable temperature controller. Apart from integrated temperature sensors with analog output signal (V_{out} or I_{out}), sensors with digital output signal are also manufactured. An integrated circuit of such a sensor is formed of the following elements—a couple of transistors, the voltage of which (ΔV_{BE}) is a measuring signal, amplifiers, the analog-to-digital transducer, and the digital interface. Usually integrated digital sensors are connected to various types of digital interface systems. Sensors with a complex structure and digital output are sometimes called "smart sensors" [5]. Integrated digital sensors are offered by such manufacturers as National Semiconductor, Analog Devices, or Siemens [4]. A review of digital sensors is shown in Table 2.4.

Table 2.4

Selected Digital Temperature Sensors (Devices) Manufactured by Analog Devices (AD), National Semiconductor (LM), Maxim (MAX), and Dallas Semiconductor (DS)

Type	*Temperature Range*	*Output Signal*	*Error*	*Resolution*
AD7416	–55°C to +125°C	10-bit serial, I^2C/SMBus	±2°C	±0.25°C
AD7817	–55°C to +125°C	10-bit serial, I^2C/SPI	±1°C	±0.25°C
MAX6635	–55°C to +150°C	2-wire, SMB	±1°C	±0.0625°C
MAX6662	–55°C to +150°C	3-wire, SPI	±1°C	±0.0625°C
LM74	–55°C to +150°C	12-bit serial + 1-bit sign, SPI	±0.5°C	±0.0625°C
LM92	–55°C to +150°C	12-bit serial + 1-bit sign, SPI	±0.5°C	±0.0625°C
DS1624	–55°C to +125°C	12-bit serial + 1 bit sign, 2-wire, SMB	±0.5°C	±0.03125°C
DS18B20	–55°C to +125°C	9- to 12-bit serial, 1-wire, SPI	±0.5°C	±0.0625°C

An example of integrated digital thermosensors is the AD7814 device (manufactured by Analog Devices) with 10-bit output, the measuring range –55°C to +125°C, a measurement resolution of 0.25°C, and a measurement accuracy of ±2°C. The sensor may be connected with a microprocessor system according to the following protocols of serial interface I^2C—SPI (Motorola standard), MICROWIRE (National Semiconductor standard), and obligatory standards for signal processors. The manner of coupling the AD7814 integrated sensor with a microprocessor of the MC68HC11 type is shown in Figure 2.14.

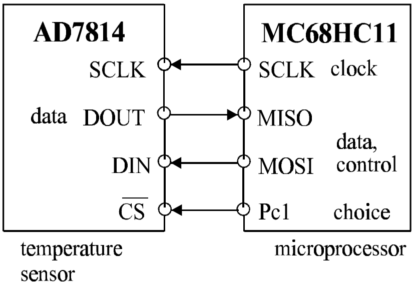

Figure 2.14 The connection of the integrated digital device AD7814 with a microprocessor.

The AD7814 integrated circuit in the miniature package of the SOT23 type (sizes $3.1 \times 3.0 \times 1.45$ mm^3) has six pins. Two pins are destined to connect the power supply, while four pins serve to connect signal lines. The AD7814 sensor requires the minimum number of two pins to be connected with a measuring system. The pins are DOUT (date output) and SCLK (serial clock input). At the DOUT pin, bits of the word output (10 bits) with coded value of the measured temperature are available serially. These bits are given according to the impulses of clock signal connected to the SCLK pin. Two remaining pins of the AD7814 device are CS (chip select) and DIN (date input). The CS pin function is to select the definite sensor when several sensors have been connected to the interface bus. Data may be put in a control register monitoring the system serially by the DIN pin [4].

Semiconductor temperature sensors—both analog and digital—are characterized with big converting (measurement) error, usually not less than ±1°C (without calibration), and with a relatively narrow measurements range, at best included between –55°C and +150°C (according to catalog data). However, our investigations show that the lower temperature limit of digital sensors can be much better. In our measurements at the Poznan University of Technology, all five investigated sensors of the LM74 type were able to operate at a temperature as low as –196°C (temperature of liquid nitrogen). Unfortunately, an error at the temperature of –196°C was approximately 15°C. It means the measurement error was unacceptably big.

For sensors of the LM7416 type, the lower limit of a measurements range was –128°C. The typical error of the LM7416 was of ±1.5°C. Figure 2.15 shows an exemplary diagram of the difference between the temperature measurement using the AD7416 sensor and the Pt100 thermometer in the temperature function for four measuring cycles.

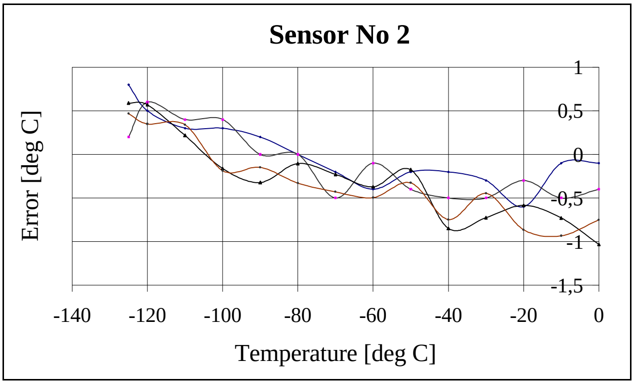

Figure 2.15 The error ΔT for temperature measurement with AD7416 digital sensor No. 2 (four measuring cycles).

The area of applications of digital temperature sensors comprises watchdogs and monitoring systems, as well as temperature indicators; they are rarely applied to industrial control systems [6].

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Chapter 3

Stress and Pressure Sensors

The measurements of mechanical stress and pressure are among the most frequently performed measurements. The force per unit area is called the pressure of a fluid if the fluid is in contact with a boundary. The stress in a solid body is usually considered to be caused by a force applied in a certain direction and with a defined sense (e.g., tensile/negative stresses, compressive/positive stresses, torsional stresses). Mechanical stress in a solid body is the relation of force applied to the body in a specified direction to the cross-sectional area of the solid body in this direction. The measurements of mechanical stress or pressure may also be indirect measurements performed in order to determine a force or a mass. The unit of mechanical stress and pressure in the SI system is the pascal: 1 Pa = 1 N/m^2. There is another pressure unit used frequently in American or British technical literature: pounds per square inch (psi): 1 psi = 6,895 Pa. The value of atmospheric pressure is also measured in other units such as standard atmosphere [atm], technical atmosphere [at], bar [bar], millimeter of mercury [mmHg], and inch of mercury [inHg]. There are numerical relations between these units: 1 bar = 10^5 Pa, 1 atm = 101,325 Pa, 1 at = 98,066.5 Pa, 1 mmHg = 133.3224 Pa, and 1 inHg = 3,386.389 Pa.

3.1 MECHANICAL STRESSES AND PRESSURE

Electronic measuring circuits or systems designed to measure stress and pressure utilize the phenomenon of the change in dimensions of the object measured, caused by those physical quantities. Change in dimensions (e.g., longitudinal extension or strain) is converted into an electric signal by means of a resistance strain gauge or capacitive strain gauge. Let us consider a beam with cross-section area A, subjected to tensile stresses caused by force F, as shown in Figure 3.1. The mechanical stress in the beam is

$$\acute{o} = \frac{F}{A} \tag{3.1}$$

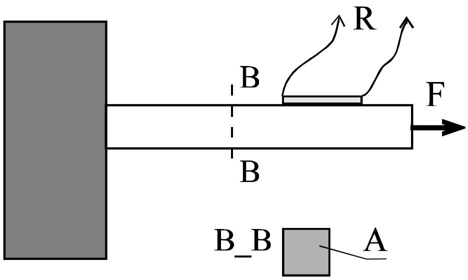

Figure 3.1 A beam with a resistance strain gauge, subjected to tensile stresses.

The force stretching the beam causes its longitudinal extension by the absolute length Δl. The extension may be expressed by a fractional change in length, $\Delta l/l$ = *e*. According to Hooke's law, in the range of elastic strains, the fractional change in length *e* is directly proportional to the tensile stress *s*, and inversely proportional to Young`s modulus of elasticity *E*:

$$å = \frac{\Delta l}{l} = \frac{ó}{E} \tag{3.2}$$

A resistance strain gauge, usually in the form of a wire, with the initial resistance *R*, is attached to the measurement object, in this case on a beam. The gauge resistance is determined by its geometrical dimensions and by the resistivity *r* of the gauge material [1].

$$R = \frac{ñ l_t}{A_t} \tag{3.3}$$

where R = initial resistance of the gauge (without stress)
l_t = length of the gauge wire
A_t = cross-sectional area of the gauge wire
r = resistivity of the gauge material

Electric pressure sensors are used to measure differential pressure or absolute pressure of gases and fluids in the range from subatmospheric pressure ($p \geq 0.05$ bar in automatic washing machines), to high pressure ($p \geq 500$ bars in industrial hydraulic systems).

3.2 RESISTANCE STRAIN GAUGES

A resistance strain gauge is a wire-wound resistor that is designed to measure mechanical stress. The gauge is subjected to the same stresses *s* as the object on which it is located. Tensile stresses cause an increase in gauge resistance from R to $(R + \Delta R)$. This effect results from a change in the value of each factor in (3.3), caused by the stresses. The resistivity and the length of the gauge wire increase, while the wire cross-sectional area decreases.

$$R + \Delta R = \frac{(\tilde{n} + \Delta\tilde{n})(l_t + \Delta l_t)}{A_t - \Delta A_t} \tag{3.4}$$

$$\frac{dR}{R} = \frac{d\tilde{n}}{\tilde{n}} + \frac{dl_t}{l_t} - \frac{dA_t}{A_t}$$

The gauge factor

$$k_t = \frac{\frac{dR}{R}}{\frac{dl_t}{l_t}} = 1 + \frac{\frac{d\tilde{n}}{\tilde{n}}}{\mathring{a}} - \frac{\frac{dA_t}{A_t}}{\mathring{a}} \tag{3.5}$$

The change of resistance is proportional to mechanical stress

$$\Delta R = k_t R\mathring{a} = k_t R\frac{\acute{o}}{E} \tag{3.6}$$

Resistance gauges are produced from a metallic wire or a semiconductor [1, 2]. The fractional change of resistance, $\Delta R/R$, of a metallic gauge is quite slight. The maximal resistance change, according to (3.6), results from the value of gauge constant k_t, and from the fractional change in length e in the range of elastic strains. The gauge factor k_t of metallic gauges is approximately equal to 2, and the value $e_{\max}$ equals 2×10^{-3} for steel, the material generally used for mechanical construction. An exemplary value of maximal resistance change is

$$\Delta R/R = k_t\, e = 2 \times 2 \times 10^{-3} = 4 \times 10^{-3}$$

A similar value of fractional change of resistance $\Delta R/R = 4 \times 10^{-3}$ is shown by such metals as copper or nickel, at a minimum temperature change of 1°C. The numerical examples given above indicate that a very important factor in selecting the gauge material is a small value of temperature coefficient of resistance changes a_T of the material. Frequently used materials for gauge wires are copper-nickel alloys, along with other metals such as constantan, manganin, nichrome, and chromel of 10 to 30 μm in thickness. In Table 3.1, the parameters of metallic alloys used for gauge wires and, for a comparison, the nickel parameters are also given.

Table 3.1

Materials Used for Resistance Strain Gauges

Material	*Alloy*	*Gauge Factor* k_t	*T. c.* a_T [1/K]	*TEF to Cu* [μV/K]	*Modulus E* [N/mm^2]
Constantan	40% Ni, 60% Cu	2	-3×10^{-6} to $+1 \times 10^{-6}$	—	148,000
Manganin	84% Cu, 4% Ni, 12% Mn	0.5	-3×10^{-5} to $+2 \times 10^{-5}$	2	126,000
Nichrome	80% Ni, 20% Cr	1.9 to 2.4	$+1.2 \times 10^{-4}$	22	200,000
Chromel C	65% Ni, 12% Cr, 23% Fe	2.5	2×10^{-5}	17	200,000
Elinwar	56% Fe, 36% Ni, 8% Cr	3.6	2×10^{-5}	4	—
Platinum-tungsten	—	4.6	$+10^{-4}$	5 to 10	—
Silicon	100% Si	20 to 100	-1.4×10^{-3}	—	—
Nickel	100% Ni	−12 to +2	$+5 \times 10^{-3}$	23	220,000

Apart from the values of temperature coefficient a_T, Table 3.1 also indicates the values of EMF thermoelectric force of the joint of a given material with copper, used for conductors.

Metallic gauges are manufactured as low-resistance gauges, with a typical initial resistance (without stresses) in a range of 100Ω to 350Ω, and as high-resistance gauges with rest resistance of 500Ω, 1 kΩ, 2 kΩ, and 5 kΩ. Typical values of gauges` resistances are 120Ω and 350Ω. It is possible to compute that the full-range resistance change of a gauge with a rest resistance of 500Ω and constant $k_t = 2$ is equal to merely 2Ω (for $e = 2\times10^{-3}$). The sensitive element of the gauge—the resistance wire—is produced in the form of a grid from 0.1 to 10 mm in length, and from 1 mm to 5 mm in width, or in the form of helix or rosette from 5 to 25 mm in diameter, depending on the purpose of the gauge.

In Table 3.2, the parameters of industrial metallic resistance gauges are indicated—high-resistance gauges manufactured by JP Technologies and gauges produced by Hottinger Baldwin Messtechnik. In Figure 3.2, different forms of gauge resistance wires are shown.

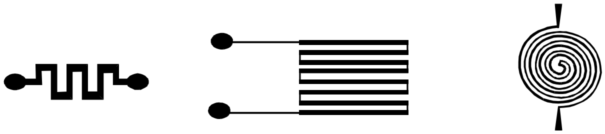

Figure 3.2 Metallic resistance gauges (metallic resistors are fused in flexible insulating foil).

Table 3.2

Parameters of Industrial Metallic Resistance Gauges (Examples of Types Manufactured by JP Technologies Inc. and HBM—Hottinger Baldwin Messtechnik)

Type	*Material*	*Gauge Resistance*	*Dimensions* [mm]	*Temperature Range*	*Producer*
JKxx-125AG-5000	Nichrome	5,000Ω	6.35 × 6.35	–265°C to +600°C	JP
JAxx-125BA-1000	Constantan	1,000Ω	3.18 × 1.57	–200°C to +205°C	JP
JAxx-060CC-500	Constantan	500Ω	1.52 × 4.57	–200°C to +205°C	JP
LY41 6/350	Constantan	350Ω	6 × 3.4	–200°C to +200°C	HBM
LC11 10/120	Nichrome	120Ω	10 × 3.5	–200°C to +250°C	HBM

Manufacturers offer at least several hundred types of resistance strain gauges, which first of all differ in geometrical dimensions and in the kind of insulating foil, with the resistance wire of the gauge fused in the foil. The insulating foil should be flexible. The kind of foil is adjusted to the longitudinal extension factor of the material under test (which is usually steel, aluminium, or wood), as well as to the working temperature range of the gauge.

The measuring circuit suitable for processing small changes in resistance of the strain gauge into output current or output voltage is the Wheatstone bridge, as shown in Figure 3.3.

In order to limit the influence of temperature on the gauge and the bridge indications, apart from the active gauge, a compensating gauge is also applied in the circuit. The compensating gauge should be located close to the active gauge, in order to retain the same temperature. The compensating gauge cannot be subjected to the stresses measured.

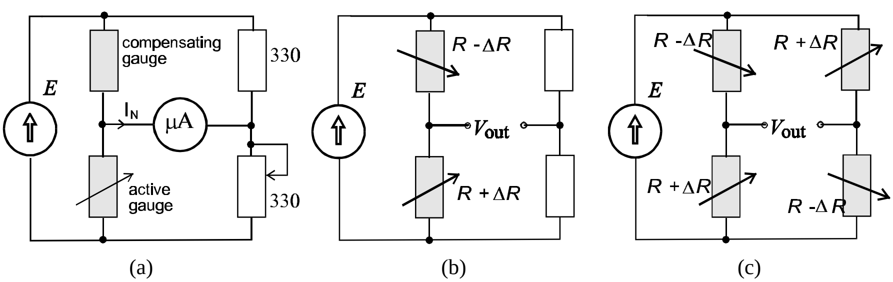

Figure 3.3 Measuring circuits with resistance strain gauge: (a) quarter-bridge (Wheatstone bridge with one active gauge) and compensating gauge to compensate temperature changes; (b) half-bridge (Wheatstone bridge with two active gauges) and the compensation of temperature changes; and (c) full-bridge (Wheatstone bridge with four active gauges).

A better solution is to use two active gauges in the circuit, subjected to the stresses with an inverse sense—placed respectively on the stretched plane (the upper surface) and the compressed plane (the lower surface) of the bent beam. The connection of both active gauges in the Wheatstone bridge, as in Figure 3.3(b), also ensures the compensation of the temperature influence on the output voltage of the circuit. The analog output signal of the measurement bridge may be subjected to A/D conversion, and in the form of digital signal is transmitted to the measurement system bus.

Integrated circuit AD7791 is designed to amplify the signal of a full-bridge with gauge sensors, as shown in Figure 3.4 [3]. At the output of the AD7791 circuit is a digital signal with the pressure and tension information. The digital signal can be processed using a digital system (e.g., microprocessor system). Compact and modular signal conditioners for gauge sensors are presented in Chapter 4.

A type of a measurement bridge is the Wheatstone bridge with a switched additional resistor, as shown in Figure 3.5.

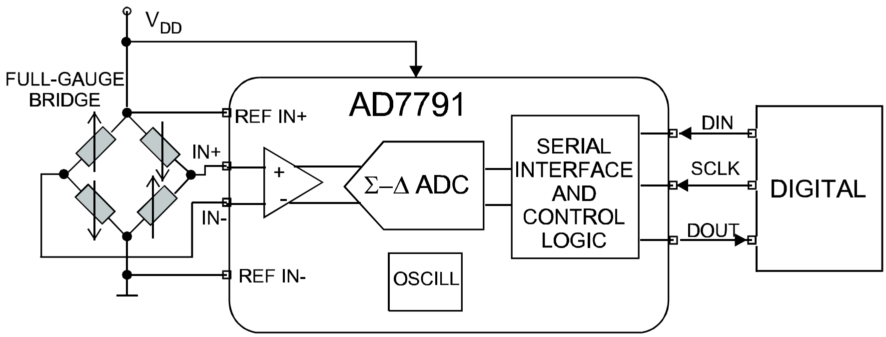

Figure 3.4 A digital measurement system with resistance gauges.

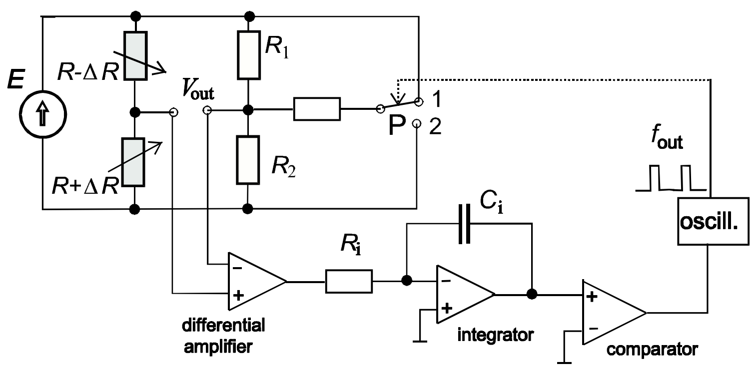

Figure 3.5 Measuring converter $\Delta R/\Delta f$ with gauges.

The system tends to determine dynamical equilibrium automatically (by means of a feedback)—working conditions in which the average value of the bridge output voltage is zero. After the bridge is balanced by the strain gauges, the bridge dynamical equilibrium may be established through a variable time of connecting the additional resistor in position 1 of switch P, and a constant time of connection in position 2. The variable time results in a variable frequency f of keying the switch. The frequency change Δf in the circuit is proportional to the change in gauge resistance ΔR and, consequently, to the value of stress s [1]. In a measuring system manufactured at the Poznan University of Technology (Division of Electronic Measurement Systems), the sensitivity of processing the described circuit equals 2.5 kHz/Ω for basic frequency of 10 kHz. The nonlinearity error of the system concerned was less than 1% in the range of change in gauge resistance, $R_t = 120\Omega \pm 0.2\Omega$.

A much greater value of the gauge factor and, consequently, much greater resistance changes, may be obtained for semiconductor gauges [4]. A value of gauge factor k_t in semiconductor gauges, in a range of 20 to 100, is accompanied, however, by an unsuitable increase of temperature coefficient a_T. The upper temperature of working range for semiconductor gauges is equal to approximately 100°C and is lower than that for metallic gauges, which can work even in a temperature range up to 600°C. The thermal properties of semiconductor gauges are explicitly worse than those of metallic gauges.

3.3 CAPACITIVE GAUGES

Capacitive gauges are also used for pressure measurements. The capacity between the condensator plates is a function of the plates distance x and, indirectly, a function of pressure or stress, as shown in Figure 3.6 and (3.7).

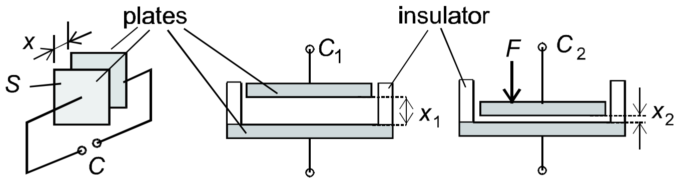

Figure 3.6 A capacitive gauge.

$$C = \frac{e_x S}{x} = \frac{k_1}{p} \tag{3.7}$$

where e_x = permittivity
S = surface of condensator plates
x = distance between the plates

p = pressure
k_1 = processing coefficient of capacitive gauge

An example of applying the capacitive gauge is the pressure transducer of type SMAR-LD301 (manufactured by Introl), with a chosen measuring range from p_1 = 125 Pa to p_2 = 40 MPa, and a standardized output signal from 4 to 20 mA.

3.4 PIEZOELECTRIC SENSORS

In piezoelectric stress sensors, a piezoelectric effect is applied. This effect occurs when an electric charge Q is established in the dielectric crystal, or when a mechanical force (e.g., stress, pressure) is applied to the crystal. Such stress causes a mechanical deformation of the crystal. The electric voltage V_x is proportional to the charge: $V_x = Q/C_s$, where C_s is the electrical capacity of the sensor with metallic plates, and the dielectric crystal is an insulator between them, as shown in Figure 3.7(a). The sensor is an electric condensator with capacity C_s [5, 6]. A piezoelectric sensor can be modeled as a voltage generator with high internal resistance. Amplification of voltages from this sensor requires an amplifier with very high input resistance, for example amplifiers with MOSFET transistors at their input. Another option is the use of a charge amplifier: an operational amplifier with a capacitor in the feedback path, as shown in Figure 3.7(b). The advantage of this approach is a transfer that is independent of cable impedance and input impedance of the amplifier. An electronic circuit with a piezoelectric gauge and a CMOS operational amplifier is shown in Figure 3.7(b).

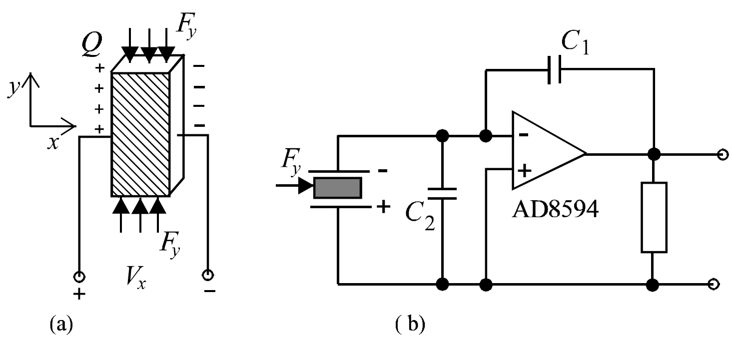

Figure 3.7 A piezoelectric gauge: (a) force into voltage conversion; (b) electric signal amplifier.

Quartz, Rochelle salt, and certain ceramic materials are used as dielectric crystals in piezoelectric gauges. Piezoelectric gauges are used only for dynamic measurements of pressure. Piezoelectric microphones are a similar application. Because of resistance leakage between two terminals of a piezoelectric gauge, measurements of static pressure are not carried out. The electric condensator C_s (sensor) is discharged by the leakage resistance, so the voltage caused by static pressure is not static itself. The upper limit of measurement by piezoelectric gauges is 30 MPa. The frequency range is from 1 Hz to approximately 50 kHz.

Piezoelectric sensors are also applied to measure acceleration a. In an accelerometer sensor, a known mass m is attached to a piezoelectric crystal. As the sensor moves, the mass creates a force ($F_y = m$ ´ a) acting on the piezoelectric crystal, as shown in Figure 3.8. The force F_y generates an electrical charge Q and voltage V_a, proportional to the acceleration value a. Of course, to measure the voltage V_a, we need a charge amplifier with a very high input impedance.

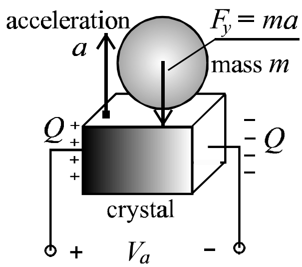

Figure 3.8 A piezoelectric accelerometer sensor.

There are passive and active accelerometer sensors. Passive accelerometers generate a small electrical voltage that must be amplified by a charge amplifier. An active accelerometer is more complicated. It is composed of an accelerator sensor, a charge amplifier, a source of an excitation constant current, and a lowpass filter. In fact, the active accelerator is a signal conditioner with an accelerator sensor (see Section 4.4).

The well-known inverse piezoelectric effect consists of mechanically deforming (e.g., to the extension) the piezoelectric crystal, on which is applied the electric voltage. For example, the piezoelectric actuator manufactured by Physik Instrumente becomes 2 µm longer with the applied voltage of 1,500V.

3.5 SEMICONDUCTOR PRESSURE SENSORS

Electric pressure sensors use the same phenomena as the mechanical stress sensors —a change in longitudinal extension is processed into a change in resistance or electric capacity of the sensor. Sensors with membrane construction are usually used to pressure measurements, as shown in Figure 3.9.

The electric signal of the sensor is a selected electric parameter of the membrane itself, or of the strain gauge attached to the membrane. Semiconductor pressure sensors are generally used, in the form of integrated devices. The voltage at the output of the integrated pressure sensor is proportional to the measured value p. The material used for semiconductor sensors is p-type silicon, and sometimes germanium. The pressure sensors are designed to measure absolute pressure or differential pressure. In the case of absolute pressure measurement, one side of the sensor membrane is subjected to a strong subpressure, and in the ideal case, to vacuum pressure. Pressure sensors may be otherwise divided up according to the criterion of measuring range.

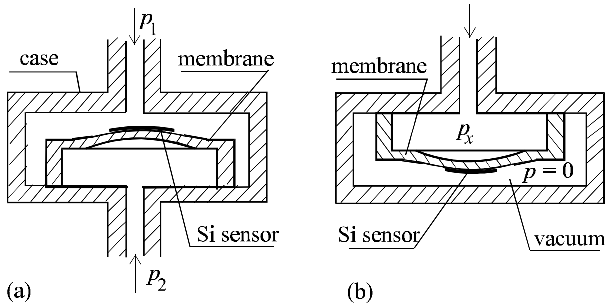

Figure 3.9 Semiconductor pressure sensors: (a) for differential pressure measurements; and (b) for absolute pressure measurements.

There are subpressure sensors ($p < 1$ bar), standard pressure sensors (p close to 1 bar), and high-pressure sensors ($p > 2$ bar). Semiconductor pressure sensors, like semiconductor strain gauges, demonstrate a strong dependence of their processing characteristic on temperature. For silicon pressure sensors, the change in strain gauge factor k_t is estimated to be 10% for $\Delta T = 1°C$. In a measuring circuit with semiconductor pressure sensors, the compensation of temperature influence should *always* be taken into consideration.

Table 3.3

Semiconductor Pressure Sensors: A Survey of Types and Parameters

Sensor Type	*Measuring Range*	*Processing Coefficient*	*Remarks*	*Producer*
KPY32	0 bar to 0.06 bar	10 mV/bar	—	Siemens
KPY69	0 bar to 400 bar	10 mV/bar	—	Siemens
MPX10	0 bar to 1 bar	60 mV/bar	Calibrated, nonlinearity error ±0.25%	Motorola
MPX5100	0.15 bar to 1.15 bar	4.5 V/bar	Calibrated, total error ±0.2%	Motorola
XCX150AN	0 bar to10 bar (0 to 150 psi)	9 mV/bar	Noncalibrated, response time 1 ms	NS Data Instruments
XCX01DNC	0 bar to 70 mbar (0 to 1 psi)	250 mV/bar	Calibrated, supply voltage 12V	NS Data Instruments

Some types of integrated semiconductor strain gauges, designed to measure stress or pressure, contain a strain gauge and a thermosensitive device in one structure. The purpose of the thermosensitive device is internal compensation of temperature effect in the integrated pressure sensor. The second variant for a temperature compensation is to establish pins on the pressure sensor package in order to connect the thermosensitive device. The latter solution allows construction of a measuring circuit with additional compensation of temperature influence. A pressure sensor with internal thermal compensation indicates the dependence of output voltage on temperature, determined by a coefficient value of approximately 0.2% per degree Celsius. A considerable number of semiconductor pressure sensors are calibrated by the manufacturer and sold together with a certificate of parameters, or even with an individual sensor characteristic. Certainly, this makes the price of the sensor higher.

Table 3.3 indicates the parameters of exemplary pressure sensors, selected from extensive company lists or catalogs [7]. For example, the catalog of a series of pressure sensors manufactured by NeXt Sensors-Data Instruments numbers 127 types of semiconductor integrated sensors. Some manufacturers of semiconductor pressure sensors (e.g., Data Instruments, Honeywell) plan to introduce digital sensors to the market. The output voltage of integrated pressure sensors is usually on the order of millivolts, and it is symmetric to the ground. The recommended measuring circuit for such sensors is the differential amplifier, as shown in Figure 3.10. The amplifier shown in Figure 3.10 is a differential amplifier. It amplifies the voltage difference correctly if $R_3/R_1 = R_4/R_2$. The ratio of resistance values is the coefficient of voltage gain of the differential amplifier—$R_3/R_1 = k_u$.

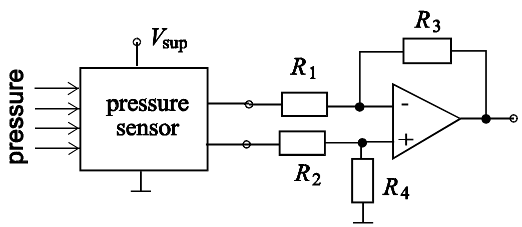

Figure 3.10 Measuring circuit with an integrated pressure sensor and a differential amplifier.

Integrated converters indicate a high offset voltage, comparable to the utilization signal. The voltage must be compensated in the measurement circuit. Semiconductor sensors are characterized by a great value of the overload factor. For the XCX01DNC sensor, the nondestructive test overload factor p_{test}/p_{range} equals 5, and the destructive load factor equals 20.

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Chapter 4

Signal Conditioners

A slotted line in a computer measurement system requires a circuit amplifying the signal power and matching the signal level with the operating range of an ADC. Analog circuits performing such functions are conditioners, manufactured in two groups. The first group consists of analog-to-analog converters—current-to-voltage, voltage-to-voltage, and voltage-to-current, with different ranges of input signal. The other group contains circuits cooperating with sensors of physical quantities with defined parameters and measuring range [1]. Circuits cooperating with thermocouples and Pt100 resistance temperature sensors constitute the most numerous group among them. For sensors such as thermocouples and strain gauges, signal conditioning is very important.

In industrial computer-based measurement systems, conditioners are placed between sensors and a plug-in DAQ board, or between sensors and a digital instrument. The signal flow in such systems is shown in Figure 4.1.

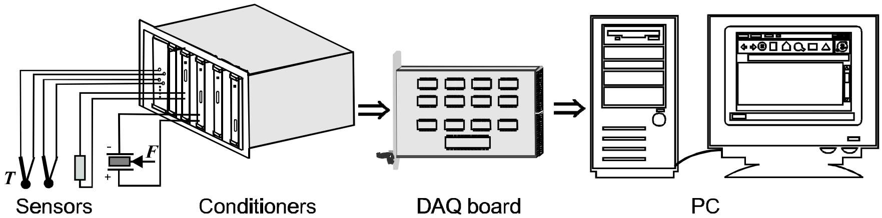

Figure 4.1 The signal flow in a computer-based measurement system.

Apart from conditioners in the form of integrated circuits, there are also conditioners in the form of modules, on which terminals for connecting sensors are placed. These devices may also be equipped with an amplifier. The most important component of such a conditioner is an integrated circuit. Examples of such conditioners are devices made by Analog Devices. There are conditioners for RTD sensors, thermocouples, and strain gauges. Voltage conditioners, both single-ended amplifiers and differential amplifiers, may also be included in the group of signal conditioners. National Instruments has developed two modular signal conditioning platforms—the compact conditioning system SCC and the high-performance multichannel system SCXI. There are conditioners for temperature sensors (e.g., thermocouples, RTDs, and thermistors), strain gauges, piezoelectric sensors, voltage-to-voltage converters, voltage-to-current converters, lowpass filters, frequency input modules, and optically isolated digital input/output modules in both conditioning systems. Keithley, IOtech, and many other manufacturers also offer modular signal conditioners.

4.1 VOLTAGE AND CURRENT AMPLIFIERS

Operational amplifiers for constructing single-ended voltage amplifiers are commonly used in measurement circuits and systems, as shown in Figure 4.2. Voltage amplification (gain) for the circuit in Figure 4.2(a) (an inverting amplifier) is described as follows:

$$k_V = V_{out}/V_{in} = -R_2/R_1, \tag{4.1}$$

and for the circuit in Figure 4.2(b) as

$$k_V = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_2} + \frac{R_3}{R_4}\right) \tag{4.2}$$

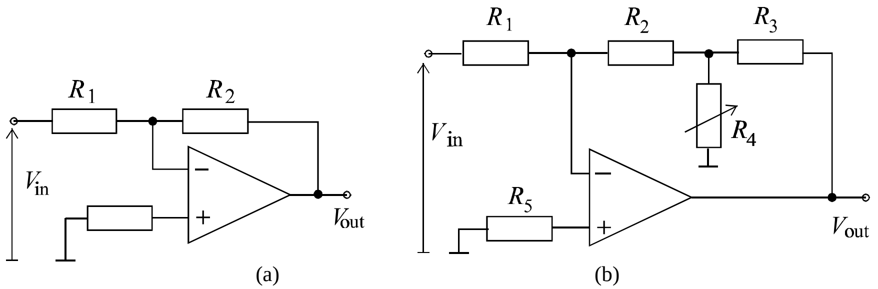

Figure 4.2 Single-ended voltage amplifiers: (a) a simple amplifier and (b) an amplifier with an amplification controlled by R_4.

An amplifier feature required in a measurement system is a possibility of controlling the voltage gain. In the amplifiers in Figure 4.2(a), the change of the gain is possible by the alteration of the values of resistors in the feedback loop. Resistors R_1 or R_3 are connected directly to the inverting input of the operational amplifier, that is to the point of the greatest sensitivity in the circuit. The resistor exchange for the purpose of gain controlling needs to perform the connection between a resistor (R_1 or R_3) and a switch. In the connecting leads, interferences induce themselves (i.e., leads are an antenna for interferences). The interferences are amplified by the operational amplifier with the great open-loop gain G. G varies from 10^5 to 10^6 V/V for operational amplifiers [2]. The amplification change in the amplifier in Figure 4.2(b) is possible by the exchange R_4 resistor, which is not directly connected to the operational amplifier input. So the interferences immunity of this circuit is considerably greater than that of the circuit in Figure 4.2(a).

Amplifiers with high voltage sensitivity, characterized with low input offset voltage V_{os}, small temperature drift of this voltage dV_{os}/dT, and low noise voltage V_{noise}, in particular the noise of type $1/f$, are of major importance. Operational amplifiers, with commuting auto-zero (CAZ) and chopper amplifiers, have the lowest offset voltage [3]. Table 4.1 shows examples of operational amplifier types, satisfying those conditions.

Table 4.1
Operational Amplifiers with Low Input Offset Voltage

Type	V_{os} (Typical)	dV_{os}/dT (Typical)	V_{noise} (for Δf = 1 Hz)	*Producer*
MAX4238	0.1 μV	10 nV/°C	25 nV	Maxim
LTC2050	0.5 μV	10 nV/°C	1.5 μV_{pp} 0.01 Hz to 10 Hz	Linear Technology
AD8628	1 μV	2 nV/°C	22 nV	Analog Devices
LT1028	10 μV	200 nV/°C	0.85 nV	Linear Technology
TLE2027AC	10 μV	200 nV/°C	2.5 nV	Texas Instruments
OPA277	20 μV	100 nV/°C	8 nV	Burr-Brown
AD797	25 μV	200 nV/°C	0.9 nV	Analog Devices
MAX4475	70 μV	300 nV/°C	4.5 nV	Maxim

Differential amplifiers are very frequently used to amplify the measuring signal. The task of the differential amplifier is to amplify the potential difference of voltage on two amplifier inputs ($V_1 - V_2$)—the differential voltage $V_d = (V_1 - V_2)$. The differential amplifier amplifies the input signal from the measurement Wheatstone bridge. The ideal differential amplifier has the amplification factor k_d controlled in a certain range, and the amplification k_{com} of common signal $V_{com} = 0.5(V_1 + V_2)$ with zero value (i.e., $k_{com} = 0$). A diagram of the differential amplifier is shown in Figure 4.3.

The circuit presented in Figure 4.3 is the differential amplifier if the values of resistors in the circuit satisfy the relation (4.3).

$$R_3/R_1 = R_4/R_2 \tag{4.3}$$

The gain k_d of differential voltage is equal to:

$$k_d = R_3/R_1 = R_4/R_2 \tag{4.4}$$

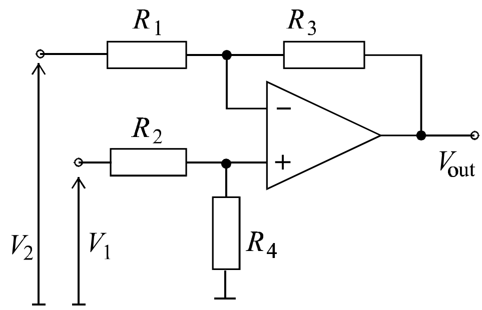

Figure 4.3 Differential voltage amplifier.

Voltage V_{out} on the output of a real (nonideal) differential amplifier is a function of differential voltage V_d and common voltage $V_{com} = 0.5(V_1 + V_2)$ on the amplifier input.

$$V_{out} = k_d V_d + k_{com} V_{com} \tag{4.5}$$

Nonzero value of amplification factor k_{com} results from two reasons:

- An operational amplifier itself has a finite common mode rejection ratio (CMRR). This means that a common mode voltage V_{com} (same voltage applied to both inputs simultaneously) is not completely rejected.
- Equation (4.3), satisfied for nominal resistance values of resistors in the circuit, is usually not satisfied for real (nonnominal) values of their resistance. The real values of each resistor may differ from the nominal value in a tolerance limit *äR*.

The control of amplification factor k_d in the circuit in Figure 4.3 is possible only by simultaneously changing the values of two resistors in the circuit, which is inconvenient. Equation (4.3) must still be satisfied.

The instrumentation amplifier shown in Figure 4.4 is characterized by better parameters and an easier method of amplification control [2]. The gain of the instrumentation amplifier is expressed by (4.6).

$$V_{out} = \frac{R_3}{R_1} \times \frac{R_5 + R_6 + R_7}{R_5} (V_1 - V_2) \tag{4.6}$$

Control of the instrumentation amplifier is realized by changing the values of resistor R_5. This resistor can be connected as an external resistor, or it can be included in the internal structure of the integrated device. The instrumentation amplifiers are manufactured in the form of integrated circuits. A list of parameters of such amplifiers is included in Table 4.2.

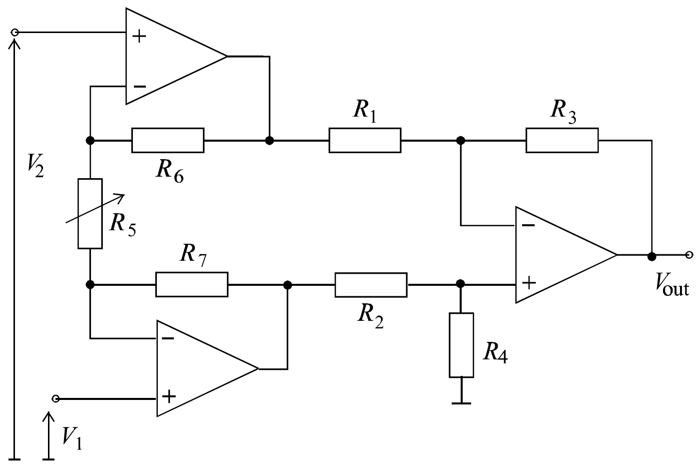

Figure 4.4 Instrumentation amplifier.

Table 4.2

Instrumentation Amplifiers

Type	I_{BIAS} (Maximum)	V_{os} (Maximum)	dV_{os}/dT (Maximum)	*CMRR* (Minimum)	*Producer*
INA115	25 fA	2000 µV	5 µV/°C	86 dB	Burr-Brown
INA111	20 pA	500 µV	5 µV/°C	106 dB	Burr-Brown
LTC1100	65 pA	10 µV	100 nV/°C	90 dB	Linear Technology
MAX4462	100 pA	500 µV	—	120 dB	Maxim
AD8221BR	400 pA	25 µV	0.3 µV/°C	90 dB	Analog Devices
AD8225	1.2 nA	150 µV	2 µV/°C	86 dB	Analog Devices
LTC2053	10 nA	10 µV	50 nV/°C	105 dB	Linear Technology

Amplifiers of high current sensitivity are also used in measurement circuits and systems. In measurement circuits, they have the function of current-to-voltage converters, as shown in Figure 4.5. The conversion of current value to voltage in the converter is realized according to the following (4.7).

$$V_{out} = R_1 I_{in} \tag{4.7}$$

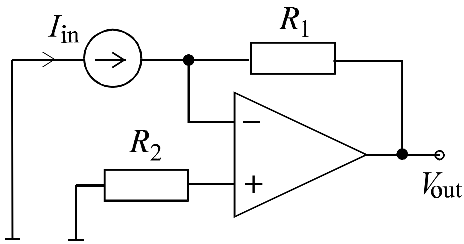

Figure 4.5 Current-to-voltage converter.

Table 4.3

Operational Amplifiers with Small Input Bias Current

Type	I_{BIAS} (Maximum)	I_{noise} Δf = 1 Hz	V_{os}	*Slew Rate*	*Producer*
OPA129	0.1 pA	0.4 fA	2 mV	2.5V/μs	Burr-Brown
OPA602	1 pA	0.6 fA	250 μV	35V/μs	Burr-Brown
AD8605	1 pA	10 fA	300 μV	5V/μs	Analog Devices
AD8627	1 pA	0.4 fA	500 μV	5V/μs	Analog Devices
LT1464A	2 pA	0.4 fA	800 μV	0.4V/μs	Linear Technology
LMC6001	2 pA (typical 25 fA)	0.13 fA	350 μV	1.5V/μs	National Semiconductor
LMC6062	4 pA	0.4 fA	350 μV	35 mV/μs	National Semiconductor
LT1793A	10 pA	0.8 fA	800 μV	2.1V/μs	Linear Technology

Operational amplifiers in converters should also have a small input bias current I_{BIAS}. For that reason, operational amplifiers manufactured in the bi-FET or CMOS technologies are the best devices. In Table 4.3, several operational amplifiers with a small input bias current are compared. The least input bias currents characterize the operational amplifiers manufactured in the bi-FET and CMOS technologies. Dynamic properties of an operational amplifier are, among others, the bandwidth and the slew rate. The slew rate is defined as the maximum voltage rate at the output of the amplifier. Table 4.3 shows for slew rate values for operational amplifiers.

4.2 VOLTAGE CONDITIONERS

An analog circuit matching the signal with the operational range of an ADC is called a conditioner, or a signal standardizing circuit. Conditioners are manufactured in two groups. Typical ranges of output signals in conditioners are from 0V to +5V, from –5V to +5V, from 0 to 20 mA, and from 4 to 20 mA. Conditioners, which are analog converters of common use, usually have their ranges of input voltage (optionally) and output current ranges defined. An example of such a conditioner is the monolithic integrated circuit AD694 [4]. Its block diagram is shown in Figure 4.6.

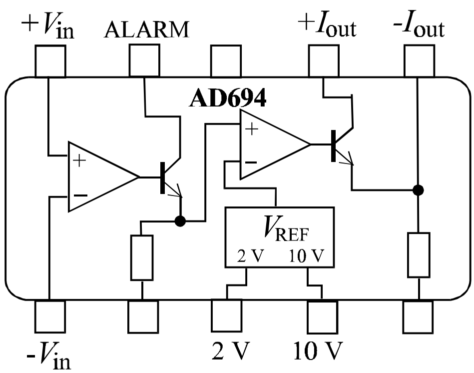

Figure 4.6 Signal conditioner: integrated circuit AD694.

The AD694 conditioner (made by Analog Devices) has two ranges of input voltage—0V to 2V and 0V to 10V—selected through keying two control terminals. It is possible to determine other values of the input voltage range through connecting external resistors. The conditioner output signal is an output current in a range of 4 to 20 mA. The conditioner is equipped with circuits useful to the manufacturer and to the user of the measurement system. These are:

- Break signaling on the output circuit;
- Possibility of connecting an external transistor in order to diminish the power and temperature of the conditioner integrated circuit;
- Source of reference voltage 2.000V or 10.000V;
- Switching of the lower limit of the output current range from 4 to 0 mA with the TTL signal; it may be noticed that the circuit with output current I_{out} in a range of 0 mA to 20 mA ensures a unique interpretation of current I_{out} = 0 mA; the value I_{out} = 0 mA may denote both the state of value measured at the start measuring range (e.g., for T = 0°C) and the break of output circuit due to a failure. Therefore, the range of output current of 4 to 20 mA is used more frequently; the state of break in the circuit and the lower limit of measuring range may be clearly differentiated.

The AD693 conditioner is a much more universal circuit [4]. The AD693 integrated circuit is adapted to cooperate with:

- Signal source of low voltage: 0 to 30 mV or 0 to 60 mV;
- Resistance temperature sensor (Pt100 or Ni100) in bridge;
- Thermocouple.

The AD693 circuit contains three functional elements: an instrumentation amplifier of great amplification factor (gain) and great input resistance, a voltage-current converter with current I_{out} up to 20 mA, and a standard voltage source 6.2V with resistance divider, as shown in Figure 4.3. The input signal for the AD693 circuit is current I_{out}, with a value of 0 to 20 mA, 4 to 20 mA, or 12 ± 8 mA. It denotes a current of 0 to 20 mA (or 4 to 20 mA, or 12 ± 8 mA) in the measuring range of a certain value measured (e.g., for input voltage 0 to 30 mV), or for temperature measured in a range between 0°C and 100°C. The AD693 conditioner is a precise circuit. Typical values of its errors in signal processing are—the value of current I_{out} in the lower limit of the range: 4,000 ± 25 µA, 8,000 ± 35µA, 12,000 ± 40 µA; nonlinearity error d_n = 0.01% for V_{in} = 0 to 30 mV, and d_n = 0.02% for V_{in} = 0 to 60 mV; and input voltage offset ΔV_{in} = ±40 µV.

Table 4.4

Voltage Conditioners: A Survey of Types

Type	*Input Signal*	*Output Signal*	*Remarks*	*Producer*
AD693	0 to 30 mV, 0 to 60 mV, output of resistance bridge	4 to 20 mA, 0 to 20 mA, (12 ± 8) mA	A variety of cooperating sensor types: Pt100, thermocouples	Analog Devices
AD694	0V to 2V, 0V to 10V	4 to 20 mA, 0 to 20 mA	Voltage conditioner	Analog Devices
XTR112	0 to 50 mV	4 to 20 mA	$I_{out} = V_{in} \times 40/R_G$ + 4 mA, R_G – source resistance	Burr-Brown
XTR114	V_{in}, voltage from measuring bridge	4 to 20 mA	High accuracy	Burr-Brown
MAX1459	1 mV to 40 mV/V, voltage from measurement bridge	4 to 20 mA	Digital control of a gain, CMRR > 90 dB, for piezoresistive sensors	Maxim

On the pins of the AD693 integrated circuit, there is a reference voltage accessible V_{ref} = 6.200V with a tolerance of ±3 mV (typical) and defined temperature drift ±20 µV/K. Similar to the AD693, excellent conditioners of type XTR112, XTR114, and MAX1459 are designed to cooperate with resistance sensors in the bridge circuit. Their parameters are listed in Table 4.4 [4].

4.3 CONDITIONERS FOR TEMPERATURE SENSORS

There are signal standardizing circuits in the form of monolithic integrated circuits, designed to cooperate with thermocouples generating the EMF thermoelectric force (TEF) of small value (TEF from 5 to 50 μV/°C). The Analog Devices company designed monolithic integrated circuits to cooperate with thermocouples of type J (AD594 and AD596 circuits), with thermocouple of type K (AD595 and AD597), and resistance sensor Pt100 (AD693 and ADT70) [4].

The AD594 and AD595 circuits have identical functions and pin topology (dual-in-line package DIP with 14 pins). The conversion coefficient temperature/voltage of thermocouples is amplified by these circuits (and by AD596 and AD597) up to the value of 10 mV/°C. In the case of applying the AD594 circuit with a type J thermocouple (see Figure 4.7), it means that instead of the TEF of type J thermocouple from –7.89 mV (for –200°C) to +42.283 mV (for +750°C), the output voltage of the circuit ranges between –1.523V (for –200°C) and +8.181V (for +750°C).

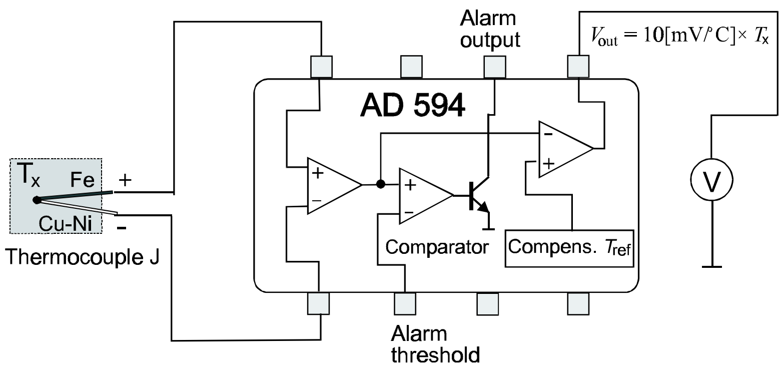

Figure 4.7 Electric thermometer with a *J*-type thermocouple and a conditioner—the AD594 integrated circuit.

For a type K thermocouple, corresponding values of voltage in the measuring range amount to: EMF (electromotive force) from –5.891 mV (at –200°C) to +50.633 mV (at +1,250°C), and for the AD595 circuit with a type K thermocouple the output voltage ranges between –1.454V (at –200 °C) to +12.524V (at +1,250°C). The calibration error does not exceed ±1°C for AD594C and AD595C, and ±3°C for AD594A and AD595A. The AD594 and AD595 integrated circuits may be supplied with voltage of one polarity from +5V to +15V, or with voltage symmetric in relation to zero, from ±5V to ±15 V; at the same time, the conversion of a thermoelectric force in temperature measurements $T < 0°C$ requires a supply with bipolar voltage ±*V*.

Table 4.5 compares the parameters of conditioners for thermocouples. All the integrated circuits in conditioners from this table contain in their structure circuits compensating changes of temperature in the reference junction. Since no thermocouple is connected to the AD596 or AD597 conditioner circuit, and the circuit input is shorted, the circuit generates a voltage proportional to the conditioner temperature. For example, for the conditioner circuit at a temperature of 20°C, its output voltage V_{out} = 200 mV. All the conditioners from Table 4.5 also have a failure alarm—a circuit signaling failures of a thermocouple or a measuring line (i.e., a signaling of a break in the input circuit). A signal indicating a failure is available on the conditioner voltage output V_{out}. Apart from the break alarm, conditioners also have an alarm circuit that signals the exceeding of given temperature values by the sensor. The value threshold temperature is programmed with the voltage in the “alarm threshold” input.

Table 4.5
Integrated Circuits of Conditioners for Thermocouples (by Analog Devices)

Type	*Thermocouple Type*	*Thermocouple Measuring Range*	*Conversion Coefficient*	*Circuit Error*
AD594C	J	from –200°C to +750°C	193.4 V/K	±1°C
AD595C	K	from –200°C to +1,250°C	247.3 V/V	±1°C
AD596AH	J	from –200°C to +750°C	180.6 V/V	±4°C
AD597AH	K	from –200°C to +1,250°C	245.5 V/V	±4°C

As mentioned in the previous section, the AD693 conditioner may cooperate directly with temperature sensors, including the resistance sensor Pt100. A thermometer built of a combination of a Pt100 sensor with an AD693 circuit may have one of six temperature ranges, and one of two output current ranges: 0 to 20 mA, or 4 to 20 mA (see Figure 4.8).

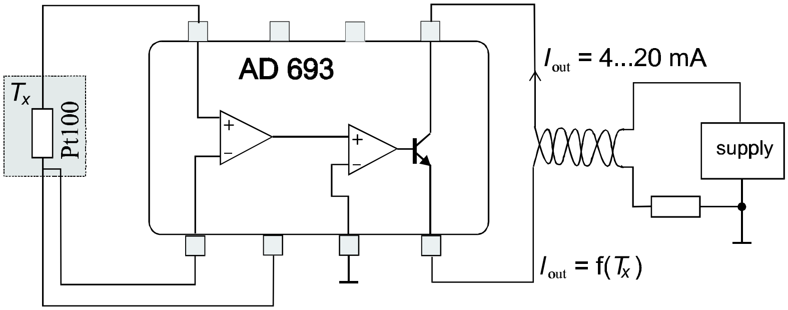

Figure 4.8 Electric thermometer with a Pt100 sensor and an AD693 integrated circuit. A three-wire measuring line connects the sensor with the measurement circuit.

The temperature measuring range is determined by connecting control signals to the pins of the AD693 circuit (pins 1 to 6, and 17 to 20).

The ADT70 circuit is designed to cooperate exclusively with resistance sensors of type Pt100 and Pt1000. The circuit contains two current sources, a reference voltage source 2.5V, an instrumentation amplifier, and an independent operational amplifier. The circuit manufacturer (Analog Devices) particularly recommends it for measuring low temperatures (down to −200°C) by means of the Pt1000 sensor. The output voltage of the ADT70 circuit results from the amplification factor of the internal instrumentation amplifier, and is equal to 5 mV/°C. For the ADT70 circuit, it is possible to determine a unipolar (0V, +5V) or bipolar (from −5V to +5V) supply voltage.

An example of a modular signal conditioner for Pt100 sensors is a 5B34-04 module manufactured by Analog Devices [4], as shown in Figure 4.9.

Figure 4.9 Three signal conditioners from the Analog Devices 5B series on an interface board (the 5B34-04 module for a Pt100 sensor is in front on the picture).

The 5B34-04 is intended for temperature measurements in the range 0°C to 600°C. The voltage output signal is from 5V to +5V.

4.4 CONDITIONERS FOR STRAIN GAUGES AND PIEZOELECTRIC SENSORS

Because signals from strain and pressure gauges are very small, the conditioning for those signals is essential. As it is described in Chapter 3, resistive strain gauges operate in Wheatstone bridge in three configuration modes: quarter-bridge (with one active gauge), half-bridge (with two active gauges), and full-bridge (with four active gauges). The basic structure of a signal conditioner for strain gauges is shown in Figure 4.10.

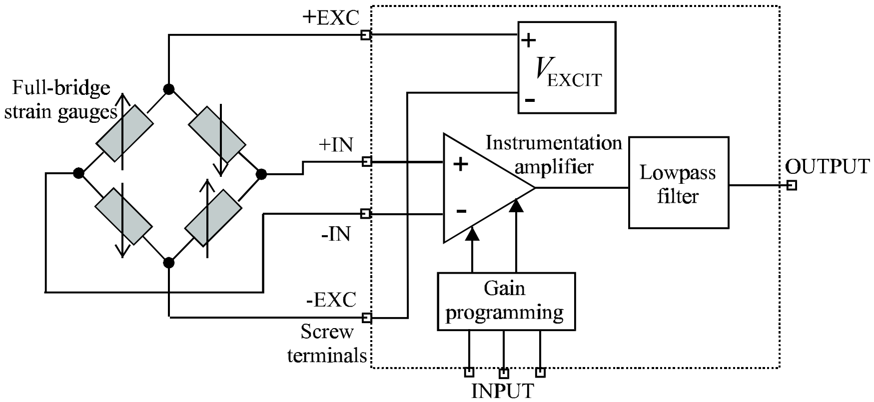

Figure 4.10 Structure of a signal conditioner for strain gauges.

Different conditioner devices manufactured by National Instruments are intended to operate in a different gauge configuration mode. The SCC-SG01 and the SCC-SG02 dual-channel modules, from the NI compact signal conditioning platform SCC, are intended for a quarter-bridge strain gauge [4]. Both conditioner types include an excitation source (dc voltage 2.5V), an instrumentation amplifier, a 1.6-kHz lowpass filter, and a potentiometer for bridge-offset nulling. The SCC-SG01 module is for a 120Ω strain gauge, and the SCC-SG02 is for a 350Ω strain gauge. The SCC-SG03 module is developed for half-bridge strain gauges, and the SCC-SH-04 for full-bridge gauges. The voltage gain (bridge output voltage to conditioner output voltage) of all NI signal conditioners for strain gauges is 100 V/V.

Keithley manufactures modular signal conditioners for strain gauges operating in half-bridge (MB38-04) and full-bridge configuration (MB38-02, MB38-05, and MB38-07) [4]. The resistance range of strain gauges is 300Ω to 10 kΩ for all MB38 modules. The modules need the excitation voltage of 10V, and they have the output voltage –5V to +5V.

IOtech offers modular the eight-channel signal conditioner of the WBK16 type for strain gauges [4]. The device belongs to the WaveBook modular family from IOtech. The WBK16 conditioner is a flexible device. It can cooperate with strain sensors in all three configuration modes—quarter-bridge, half-bridge, and full-bridge. The resistance range of strain gauges can be from 60Ω to 1,000Ω. The WBK16 conditioner has a programmable excitation voltage source (from 0.5V to 10V), a programmable gain amplifier (from 1 to 20,000), and a separate lowpass filter for each channel.

Piezoelectric sensors need a current excitation. Their output signal is an alternating voltage. A signal conditioner for a piezoelectric sensor includes an amplifier, a dc excitation source (typically 1 to 10 mA), a lowpass filter with the upper limit frequency up to 20 kHz, as well as a highpass filter. The latter, with the low limit frequency from 0.1 to 1 Hz, filters a dc voltage and low-frequency components in the signal spectrum. Multichannel conditioners also have Sample and Hold (S&H) circuits. A signal conditioner for a piezoelectric accelerometer is shown in Figure 4.11.

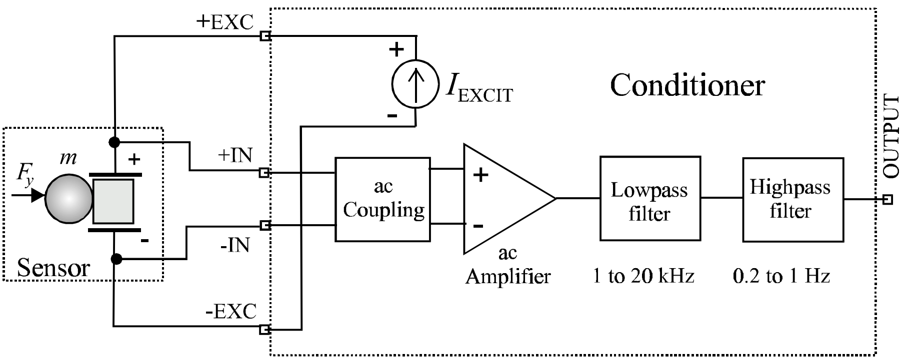

Figure 4.11 Signal conditioner for piezoelectric accelerometer.

For piezoelectric sensors, National Instruments developed signal conditioners in SCC and SCXI modular families. The SCC-ACC01 is a single-channel conditioner for a piezoelectric accelerometer. The module is equipped with a 4-mA current excitation source, an amplifier with gain of 2, a 19-kHz lowpass filter, and a 0.8-Hz highpass filter. The SCXI-1530 and SCXI-1531 multichannel conditioners have four and eight channels, respectively. Each channel in both modules has a current excitation source, a programmable amplifier, a programmable lowpass filter (one can select from four values for the lowpass limit: 2.5, 5, 10, or 20 kHz), and a 0.2-Hz highpass filter. Signals from all channels can be held in S&H circuits. It is possible to provide a calibration in modules and to store calibration results in an onboard EPROM.

4.5 CONDITIONERS FOR LINEAR POSITION SENSORS

The AD598 and AD698 integrated circuits (by Analog Devices) are conditioners of alternating voltage signal, generated by a linear variable differential transformer (LVDT) of linear position, and converted into constant output voltage [4, 5]. Thus, together with the linear position transformer, the conditioner circuit constitutes a linear position converter Δx to constant voltage.

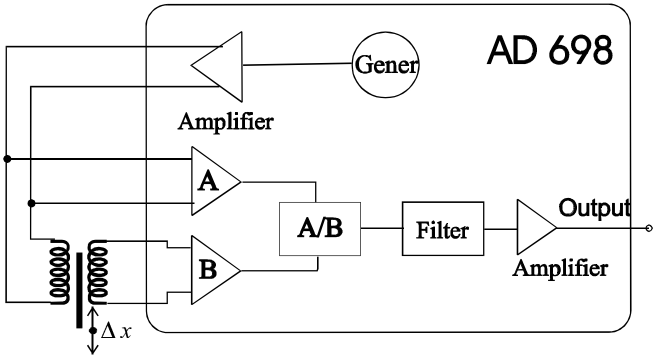

Figure 4.12 The circuit for measuring linear position Δ*x* with the AD698 integrated circuit.

Both circuits (AD598 and AD698) have similar internal structures, but differ in output circuits and conversion function. A block diagram of the AD698 circuit is shown in Figure 4.12. The AD698 integrated circuit contains the following functional elements: a sinusoidal voltage generator, alternating voltage amplifiers, an A/B phase detector, a lowpass filter, and a constant voltage amplifier. The generator ensures a constant value of the amplitude of ac voltage supplying the transformer. The internal generator frequency (from 20 Hz to 20 kHz) and the amplitude of the voltage generated (from 1.8V to 30V) is defined by means of external elements *R* and *C* connected to the integrated circuit. The voltage on the secondary winding of the transformer depends on the position of magnetic core that is mechanically connected to the object measured. The conditioner output signal is a voltage constant in a range of −11V to +11V, and a load current value of $I < 50$ mA. The input impedance of input channels A and B amounts to 200 kΩ. In order to ensure high accuracy of conversion (i.e., typical error value $d = \pm 0.4\%$ of full range), the ratio of input voltages should be in the following range: $0.1 < V_B/V_A < 0.9$.

The AD2S80A, AD2S83, and AD2S90 conditioners (by Analog Devices) are designed to convert an analog signal of the object angular position to a digital signal, available as a serial word 10 to 16 bits long. The analog input signal is sinusoidal voltage, the actual value of which is dependent on the angular position of the object measured. The conditioners are designed to control servomechanisms, or record precisely a nonintegral number of rotations. Angular position conditioners are complex ADCs, manufactured in multipin packages (e.g., the AD2S83 circuit has a package of type PLCC with 44 pins). The conversion accuracy of those conditioners is defined with an error of ±8 minutes, plus one LSB for the AD2S83 circuit, and with an error of ±10.6 minutes plus one LSB for the AD2S90 circuit. The LM1815 circuit (by National Semiconductor) also has a similar function. It generates only one impulse for one rotation of a measured object.

Modular SCXI-1540 type eight-channel conditioners for LVDT linear position sensors are manufactured by National Instruments [4]. The SCXI-1540 module has programmable input range of 50 mV_{rms} to 6 V_{rms}, programmable excitation per channel of 1 to 3 V_{rms} signal at 2.5 to 10 kHz frequency, programmable gain of 0.8 to 25 (V_{dc} output to V_{rms} input), and autocalibration, which is optional.

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Chapter 5

Digital-to-Analog and Analog-to-Digital Converters

The measurement signal appearing at the output of a measurement converter is an analog quantity, described by a continuous function $x(y)$, usually a time-dependent variable $x(t)$. In order to process measurement signals in computer systems, analog signals must be converted into digital signals, which are recorded as binary words. This conversion is performed by analog-to-digital converters (ADCs). The reverse operation, that is the digital-to-analog (D/A) conversion, is very often necessary as well. This operation is performed by digital-to-analog converters (DACs).

5.1 SAMPLING AND QUANTIZING

5.1.1 Sampling

Analog-to-digital (A/D) conversion of a variable signal $x(t)$ involves two processes:

- *Sampling*: the drawing of samples of the signal at specific time moments,
- *Quantizing*: assigning to every sample a value X from a finite set of N values, into which the conversion (measurement) range is divided.

After sampling the analog signal becomes a discrete signal, and after quantizing, it becomes a digital signal. In the sampling process the sampling period T_s, which is the time between drawing successive samples, is usually constant. This kind of sampling is called uniform sampling. In advanced measurement systems, a variable sampling period is sometimes used. The period is then dependent on the dynamics of the measured quantity $x(t)$. Henceforth, only conversion with uniform sampling will be considered.

The reverse of the sampling period is the sampling frequency, $f_s = 1/T_s$. Sampling consists of digitizing the argument of a function. Therefore, after sampling, $x(t)$ is represented by a set of values $\{x(kT_s)\}$, drawn at time periods T_s, as shown in Figure 5.1(a, b). The conversion efficiency requires sampling to be performed as rarely as possible; that is, it requires the lowest possible sampling frequency.

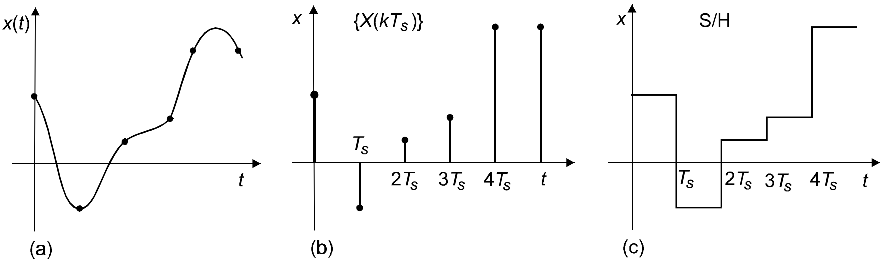

Figure 5.1 Signal sampling and holding: (a) analog signal with sampling points; (b) discrete samples; and (c) holded samples.

However, sampling frequency should be high enough to provide a number of samples sufficient to reproduce the signal in the analog form. The Shannon's theorem about sampling determines the sampling frequency for a strictly lowpass signal with upper frequency f_u; that is, the signal with the spectrum limited to frequency f_u: $X(f > f_u) = 0$. According to this theorem, the sampling frequency f_s should not be lower than twice the upper frequency f_u of the sampled signal spectrum.

$$f_s > 2f_u \tag{5.1}$$

The frequency f_s defined by the sampling theorem is called the Nyquist frequency. The spectrum characteristics of real signals are often the same as the characteristics of a lowpass filter with upper frequency f_u. If we consider the signal components whose frequency is slightly higher than f_u, (5.1) must obtain the form.

$$f_s > 2.5f_u \tag{5.2}$$

Sometimes, neither (5.1) nor (5.2) is fulfilled. Therefore, the reproduction of the discrete signal recorded in such conditions yields a distorted analog signal. The phenomenon of producing distortions caused by too low of a sampling frequency is called *aliasing*. An example of aliasing is a filmed sequence of the rotation of wagon wheels in a Western movie. The filming of the movement, in other words the sampling, takes place at a standard frequency of 24 frames per second. The wheels that are moving at the exact rotational speed of 24 turns per second appear to be *still* on the screen (i.e., the stroboscope phenomenon occurs). When the wheels rotate a little slower than 24 turns per second (e.g., 23.9 turns per second), they appear on the screen to rotate slowly in the opposite direction. The rotation of the wheels on the screen and in reality are in agreement with each other only if the velocity of the wheels is not higher than 12 turns per second. In order to eliminate aliasing, some DAQ cards have a lowpass input filter, or an antialiasing filter. The function of the antialiasing filter is to limit the frequency band of the sampled signal to the range from 0 to $0.4f_s$.

The ideal sampling process would require sampling impulses of zero time (zero pulse width). Real sampling impulses are longer, that is, $T_i > 0$. In the signal theory approach, the sampling of a signal $x(t)$ with the spectrum from 0 to f_u, with sampling impulses of frequency f_s, time T_i, and amplitude A, is equal to amplitude modulation, where the sequence of sampling impulses is the modulated carrier wave, and $x(t)$ is the modulating signal. The result of this operation is the signal spectrum after sampling, as shown in Figure 5.2.

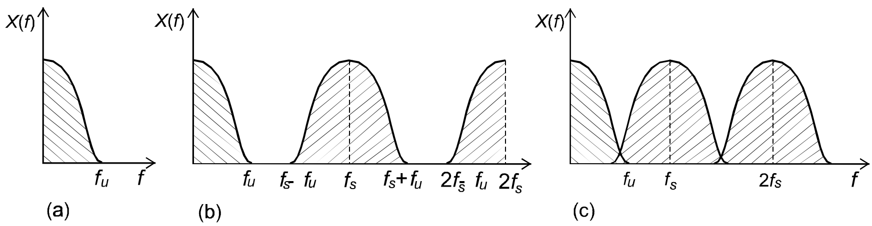

Figure 5.2 Sampling and aliasing effect: (a) signal spectrum; (b) signal spectrum after sampling with the frequency $f_s > 2f_u$; and (c) signal spectrum after sampling with the frequency $f_s < 2f_u$ (aliasing effect occurs).

Figure 5.2(b) shows the signal spectrum after sampling with frequency f_s, which fulfills the sampling theorem conditions. Figure 5.2(c) shows the spectrum of the signal sampled with too low a frequency, which causes aliasing.

While converting fast signals, it is useful to hold the sample until the next sample is drawn. This task is performed by an S&H circuit. The held analog signal is quantized, and the quantization time is usually much longer than the time necessary to draw the sample. Therefore, the use of the S&H circuits allows us to reduce the dynamic errors that occur during A/D conversion of fast signals. The S&H circuit may be a separate analog integrated circuit embedded in the measurement system or a part of an integrated ADC. The functional scheme of the S&H circuit is shown in Figure 5.3.

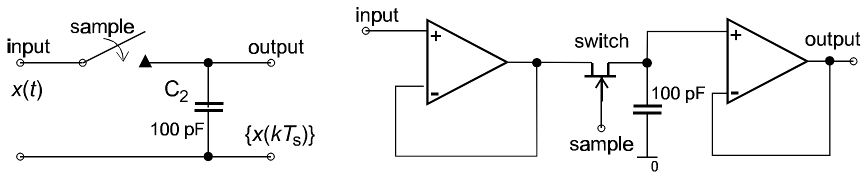

Figure 5.3 S&H circuit.

The sampled voltage (input signal) is connected through the switch to the hold device, which is a low leakage capacitor. In the S&H circuit, operational amplifiers function as separators. The operation cycle of the S&H circuit consists of the sampling phase T_i, which is the acquisition time of the sampling signal, and the hold phase T_h, which is the time when the sampled input voltage is held by the capacitor and appears at the S&H output.

The main parameters of the S&H circuit are:

- Acquisition time, which is the time from the beginning of the sampling impulse to the setting of the value of output voltage (equal to the input voltage) with acceptable error. The acceptable acquisition error is usually in the range of 0.005% to 0.2%, and it is defined for a specific value of input voltage (e.g., 10V).
- Hold mode droop, which results from the discharge of the capacitor in the hold phase, expressed in volts per second.

The typical parameters of an example AD781 S&H integrated circuit are acquisition time 600 ns (for input voltage 10V and acquisition error 0.01%), hold mode droop 0.01 nV/ns, input impedance 50 MΩ, and input capacity 2 pF.

5.1.2 Quantizing

Quantizing consists of assigning to every sample a value X from a finite set of N values into which the conversion (measurement) range is divided. The range from 0 to $X_{\max}$ is divided into N intervals of the width

$$\Delta X = \frac{X_{\max} - X_{\min}}{N} = q \tag{5.3}$$

called quantization interval q. The value X assigned to every sample is represented by a certain code. Most often, the quantization result is given as a digital word, usually a binary number written in the natural binary code:

$$a_{n-1}2^{n-1} + a_{n-2}2^{n-2} + ... + a_1 2^1 + a_0 2^0$$

where n is the number of bits of the digital word (word length), and a may assume the values 0 or 1.

In a digital word, a_{n-1} is the most significant bit (MSB), and a_0 is the least significant bit (LSB). Figure 5.4 shows two ways of determining quantization intervals. Figure 5.4(a) shows the quantizing of voltage in the range from $V_{\min}$ = 0V to $V_{\max}$ = 8V into an n-bit digital signal. This quantizing operation yields a

3-bit digital word. Therefore the number of quanta is $2^n = 8$, and all the quantizing intervals have the same width equal to quantum q:

$$q = \frac{V_{\max} - V_{\min}}{2^n} = \frac{8-0}{2^3} = 1\text{V} \tag{5.4}$$

It seems that this method of determining intervals is the most appropriate. However, it is not true if we consider the quantization error (also called digitizing error), which is an inevitable result of the quantizing process.

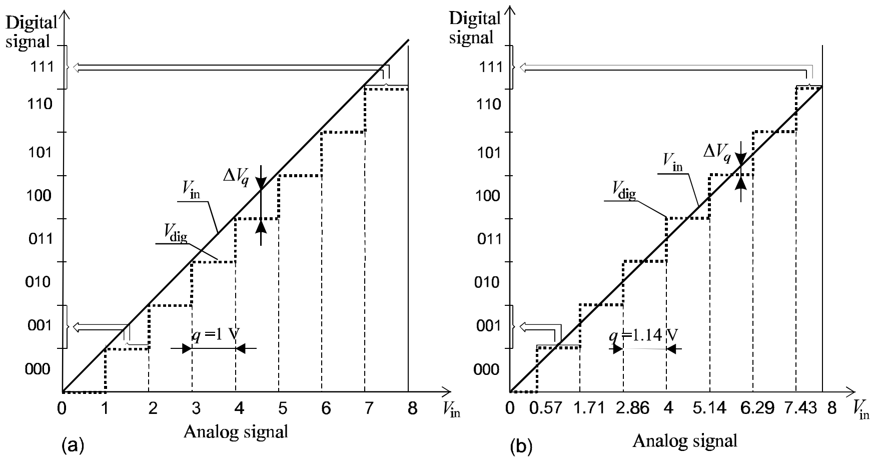

Figure 5.4 Quantization and two methods of dividing the conversion range: (a) with all quantization intervals equal to quantum q and the maximal quantization error $\Delta V_{q\ \max} = -q$; (b) with different quantization intervals (q and $q/2$) and the maximal quantization error $\Delta V_{q\,\max} = \pm q/2$.

The quantization error ΔV_q is the difference between the analog value V_{dig} of the digital representation (the quantization result) and the analog value of the measured quantity V_{in}, as shown in Figure 5.4. ΔV_q is given by (5.5).

$$\Delta V_q = V_{dig} - V_{analog} = V_{dig} - V_{in} \tag{5.5}$$

In Figure 5.4(a) quantum q = 1V. In the input voltage range V_{in} from 1V to 2V, the value of quantization error changes from $\Delta V_q = 0$ for V_{in} = 1V to $\Delta V_q = -q$ for V_{in}, which s close to the quantum threshold 2V. In the whole conversion range, the quantization error changes periodically from 0 to $-q$ with the period q.

Another method of dividing the conversion range into quantization intervals is shown in Figure 5.4(b). Here, the number of quantization intervals is also 2^n, but the interval widths are not equal. The quantum value is calculated from the dependence:

$$q = \frac{V_{\max} - V_{\min}}{2^n - 1} = \frac{8-0}{2^3 - 1} = 1.14\text{V}$$

The first and the last quantization intervals are equal to $q/2$, and the remaining intervals are equal to q. Using (5.5), it is easy to calculate that in the whole A/D conversion range, the quantization error changes periodically from –q/2 to $+q/2$, with the period q. The quantization error obtained is two times smaller than the error obtained previously. Therefore, the latter way of determining the quantization error and the quantization threshold, as shown in Figure 5.4(b), is used in ADCs.

5.2 DIGITAL-TO-ANALOG CONVERTERS

5.2.1 Parameters of Digital-to-Analog Converters

DACs are used to convert the input digital signal $\langle a_{n-1}a_{n-2}....a_2a_1a_0\rangle$ into the output analog signal V, whose value is determined by the value of the digital signal.

$$V = k_x\left(a_{n-1} \times 2^{n-1} + a_{n-2} \times 2^{n-2} + ...a_2 \times 2^2 + a_1 \times 2^1 + a_0 \times 2^0\right) \times \left(V_{\max} - V_{\min}\right) \quad (5.6)$$

where a_k is the input word bit, a_{n-1} is the MSB, a_0 is the LSB, $V_{\min}$ and $V_{\max}$ are the lower and upper values of the output voltage range, respectively, and k_x is the conversion coefficient.

DACs are applied in industrial equipment and household appliances, in particular audiovisual devices, for the measurement of equipment indicators and digitally controlled industrial devices. The main metrological parameters of DACs are:

1. *Conversion resolution*, defined as the number of the states N of the input digital word, equal to the number of analog values of the output signal. The number N is determined by the number of bits n of the input word: $N = 2^n$. However, we usually say that the converter has a *resolution of n bits*, and not N states. In practice, n is 4 to 24 bits. The absolute resolution of the converter results from the number of states N and the output signal range. Therefore, the absolute resolution ΔV_{res} is equal to quantum q for a converter with the output voltage range from $V_{\min}$ to $V_{\max}$ and the n-bit resolution.

$$\text{Ä}V_{\text{res}} = \frac{V_{\max} - V_{\min}}{N} = \frac{V_{\max} - V_{\min}}{2^n} = q \quad (5.7)$$

For example, a 16-bit DAC with the output voltage range from 0V to 5V has an absolute resolution of $q = \Delta V_{\text{res}} = 5\text{V}/2^{16} = 5\text{V}/65536 = 76.3\ \mu\text{V}$.

2. *Converter accuracy*, defined by the absolute or relative error. Absolute error ΔV_e is the difference between the real value V_{real} of the *output analog signal* and the expected (ideal) value V_{ideal} of the signal, $\Delta V_e = V_{\text{real}} - V_{\text{ideal}}$. The absolute error is often given as the number of LSBs. The relative error ***d*** of the converter is calculated as the ratio of absolute error and the input signal range:

$$d = \frac{\text{Ä}V_e}{V_{\max} - V_{\min}} \tag{5.8}$$

The converter accuracy is always worse than its resolution:

$$\Delta V_e > q = \Delta V_{\text{res}} \tag{5.9}$$

The converter accuracy results from the linear error (also called integral nonlinearity), the differential nonlinearity (see Figure 5.5), the gain error, and the offset error (i.e., the constant deviation of the DAC output signal from the ideal characteristic).

The resolution of a DAC may be better than its accuracy by several bits. However, such high resolution is often useless, since the function of the converter is to produce an analog signal whose value is accurately determined by the input digital signal.

3. *Settling time* is the time interval from the moment of change of the input signal to the setting of the output analog signal, with accuracy equal to one-half the quantum +0.5q. The maximum change of the digital signal should cause maximum change of the analog signal—the change from ⟨000...00⟩ to ⟨111...11⟩ or from ⟨111...11⟩ to ⟨000...00⟩.

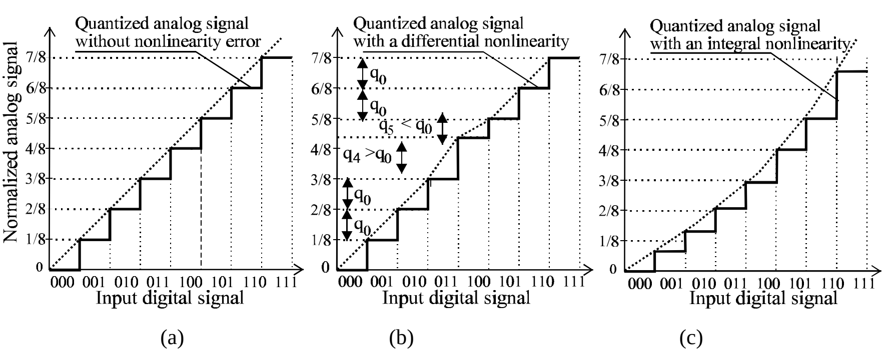

Figure 5.5 Differential and integral nonlinearity effect in DACs: (a) the conversion without nonlinearity error; (b) the conversion with a differential nonlinearity (fourth and fifth steps are not equal to q_0); and (c) the conversion with an integral nonlinearity.

In high resolution DACs (16 bits and more), the settling time is defined as the time from the moment of change of the input digital signal to the setting of the output analog signal, with the accuracy of ±0.01%, ±0.001%. The settling time is given in nanoseconds or microseconds.

4. *D/A conversion rate*, defined as the number of conversion periods per second, assuming that the conversion conditions are fulfilled. D/A conversion rate is given in samples per second (SPS).

From the point of view of construction**,** there are converters with a resistance divider (voltage divider or current divider) and converters with pulse duration modulation (PDM).

5.2.2 DACs with Resistor Dividers

Figure 5.6 shows the block diagram of a DAC with a resistance divider. A DAC consists of a reference voltage source V_{ref}, a set of *n* analog switches, a network of resistors linked to the voltage source V_{ref} by the analog switches, and the input buffer where the *n*-bit input digital word (signal) is recorded. The DAC output signal is the output current I_{out} or output voltage V_{out}. The current-to-voltage converter, I_{out} into V_{out}, is frequently included in a DAC. However, it is not always necessary. The resistor network works as a voltage or current divider. The division coefficient is set by the analog switches. The analog switches used in the converter are usually electronic switches, as the setting time of electronic switches is several orders shorter than that of electromechanical switches. Electromechanical keys, on the other hand, have a very small closed switch resistance R_{on} (of the order of milliohms), and a very large open switch resistance R_{off} (of the order of 10^{12} ¿, depending on the contact size). Therefore, they are used in very precise DACs which have the acceptable conversion time of the order of milliseconds.

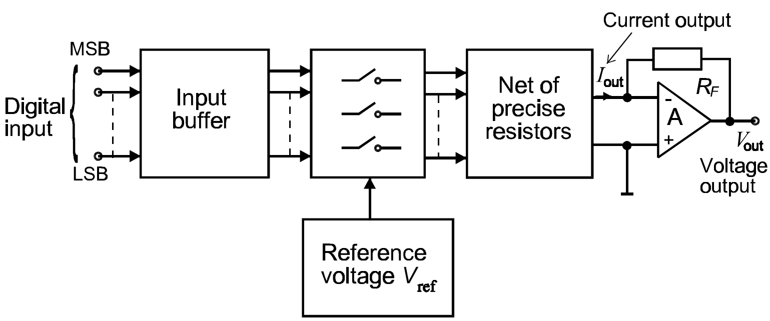

Figure 5.6 Structure of a DAC.

The resistances R_{on} and R_{off} of the electronic switch strongly depend on temperature, input voltage, and supply voltage of the circuit. For example, the typical value of resistance R_{on} is 100Ω for a CMOS 4066 electronic switch, and

5Ω for the Analog Devices ADG 451 switch. In both cases, the approximate value of R_{off} is of the order of 10^{10}Ω. The catalog parameter defined for a switch with an open contact is the input current as a function of input voltage, supply voltage, and temperature.

Figure 5.7 shows the diagram of a DAC with a weighted resistor network, where the weights are equal to 2^n. The input buffer is not included in the diagram. The system converts an 8-bit digital word $\langle a_7a_6a_5a_4a_3a_2a_1a_0\rangle$ into output voltage V_{out}, where a_7 is the MSB. The logic state of every bit a_k of the input word is represented by one of two possible resistor connections. The connection of the resistor to the reference voltage source, realized by the analog switch, represents the logic 1, while the resistor-ground potential represents the logic 0. The current flow through the weighted resistor at the kth position is equal to $V_{ref}/2^kR$ (kth weighted resistor). The sum of the currents from onset resistors is an analog current I_{out} proportional to the input digital signal.

$$I_{out} = V_{ref}\left(a_7\frac{1}{R} + a_6\frac{1}{2^1R} + a_5\frac{1}{2^2R} + a_4\frac{1}{2^3R} + a_3\frac{1}{2^4R} + a_2\frac{1}{2^5R} + a_1\frac{1}{2^6R} + a_0\frac{1}{2^7R}\right) \tag{5.10}$$

where a_k is the logic value of the kth bit. The value of a_k can be 1 or 0. Voltage V_{out} at the output of the operational amplifier that functions as a current-to-voltage converter is proportional to current I_{out}, and therefore to the input digital word $\langle a_7a_6a_5a_4a_3a_2a_1a_0\rangle$.

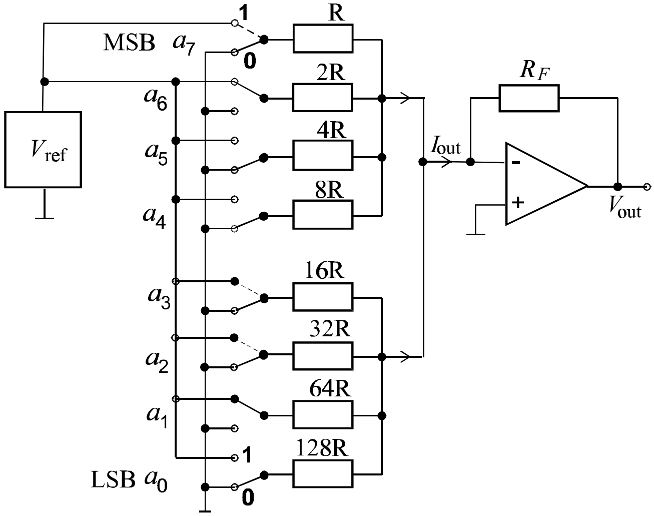

Figure 5.7 Weighted resistor DAC.

$$V_{out} = -R_F I_{out} \tag{5.11}$$

Although the structure and operation (control) of the converter circuit from Figure 5.7 is simple, this converter is rarely used because of the difficulty of obtaining good parameters. It is obvious that the converter accuracy also depends on the accuracy of weighted resistors. In high resolution converters, the ratio $R_{n\text{-}1}/R_0$ of extreme resistors of the resistor ladder is very large. For example, for 16-bit resolution, it is 2^{15}, or 32,768, and for 20-bit resolution, it is approximately 5×10^5. The technological process of production of a resistor network of such a large range of values (for example, $R_0 = 1$ kΩ and $R_{19} = 500$ MΩ) and such high accuracy (the error is 0.1% or less) would be expensive and difficult. The resistance of the electronic switch contact is comparable to R_0 for closed switch resistance R_{on}, and open switch resistance R_{off} is comparable to $R_{n\text{-}1}$. Considering the fact that the values of R_{on} and R_{off} are not very well determined, and that they depend on temperature and on circuit parameters, it must be stated that the accuracy of a DAC with weighted resistors is limited by the parameters of analog switches.

The value range of precision resistors in a DAC is much smaller in a circuit with weighted resistors and a current divider, as shown in Figure 5.8. Weighted resistors in the current divider are divided into groups of four, and the values of resistors in each group are R, $2R$, $4R$, and $8R$, respectively. In an 8-bit DAC with a current divider, the output current I_1 from the first group of resistors flows into the main circuit node and only one-sixteenth of I_2 flows into the node, due to the operation of the current divider $R_d/15R_d$. For a converter with a larger number of bits, for example, $n = 16$, there are four 4-resistor groups, whose weighted output currents are added in a main node of the circuit, creating output current I_{out}.

$$I_{out} = I_1 + \frac{1}{16} I_2 + \frac{1}{256} I_3 + \frac{1}{4{,}096} I_4$$

The accuracy of weighted resistors in a DAC with a current divider depends both on the weighted resistors accuracy and on the accuracy of R_d in the current divider. The maximum value resistor to minimum value resistor ratio $8R/R$ equals 8, independent of the number of bits n of the converter, equal to the number of resistors n. This low ratio, equal to 8, simplifies the technical problems of production, which are so severe in the converter in Figure 5.7.

The basic DAC circuit with a resistor network is a converter with an R-$2R$ ladder network, as shown in Figure 5.9. The resistance ladder output voltage of the converter shown in Figure 5.9 is $V_{out} = 0.5V_{ref}$ for a digital input word ⟨1000⟩ with MBS = 1, $V_{out} = 0.25V_{ref}$ for ⟨0100⟩, and $V_{out} = 0.0625V_{ref}$ for ⟨0001⟩. The resistance ladder circuit is a linear circuit. Therefore, the superposition principle applies. A digital input word with a higher number of logic ones (1) causes an output voltage whose value is the sum of values typical for combinations given above.

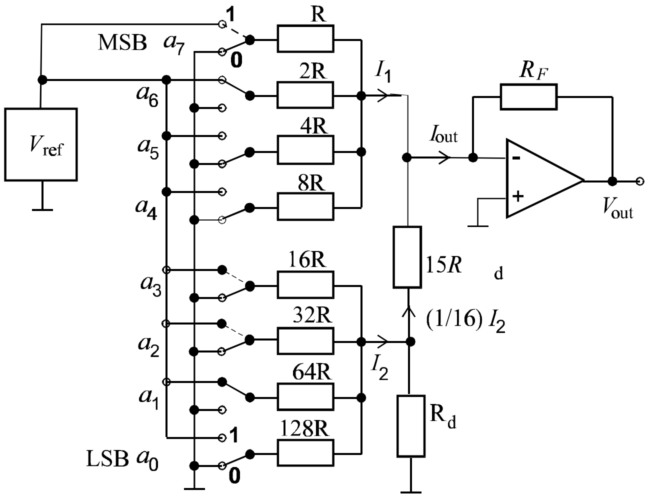

Figure 5.8 Weighted resistor DAC with a current divider.

For example, for the ⟨0011⟩ input word, the output voltage $V_{out} = 0.1875V_{ref}$, and for ⟨1111⟩, the output voltage $V_{out} = 0.9375V_{ref}$. Therefore, the analog output voltage of a 4-bit DAC may have 16 values from 0V to 0.9375V, with the quantum $q = 0.0625$V.

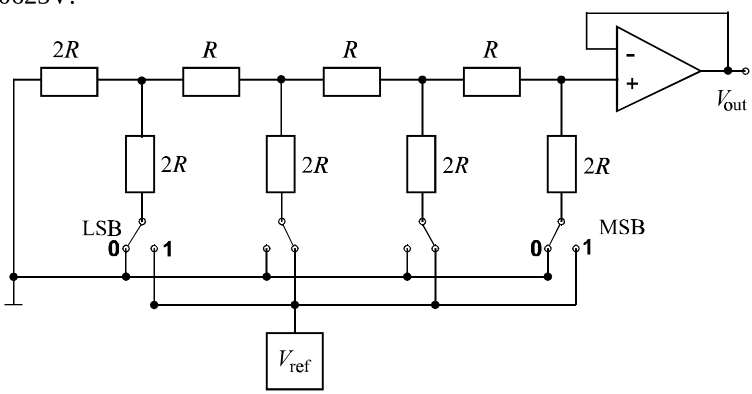

Figure 5.9 DAC with an *R*-2*R* ladder network.

There are very large differences between resistor values in the circuit with the *R*-2*R* ladder and the circuit with weighted resistors. The *R*-2*R* ladder network consists of resistors of only two values, *R* and 2*R*, which simplifies the resistor production process. In practice, all necessary resistors have the same value *R*.

The resistance 2*R* is obtained by a series connection of two resistors *R*. With respect to a ladder of arbitrary length, used to build a multibit DAC, the same structure is used, and the resistor ratio in the circuit is equal to 2. The characteristic feature of the *R*-2*R* ladder is its constant resistance equal to 2*R* in every direction of every inner node of the circuit. Therefore, current *I*, which flows into every node, is divided into two circuit branches in equal values of *I*/2.

The DAC with an *R*-2*R* ladder network is so important that several modifications of this converter have been developed. The first variety is the multiplying DAC with a reversed *R*-2*R* ladder network, shown in Figure 5.10. In this circuit, the output voltage V_{out} is proportional to the product of an input voltage V_{in} and a digital word $\langle a_7a_6a_5a_4a_3a_2a_1a_0\rangle$. The load of the input voltage source V_{in} is constant and equal to *R*. Therefore, the input voltage V_{in} does not change according to the digital input word and to the current state of switches in the circuit. It is an important factor for a high accuracy DAC.

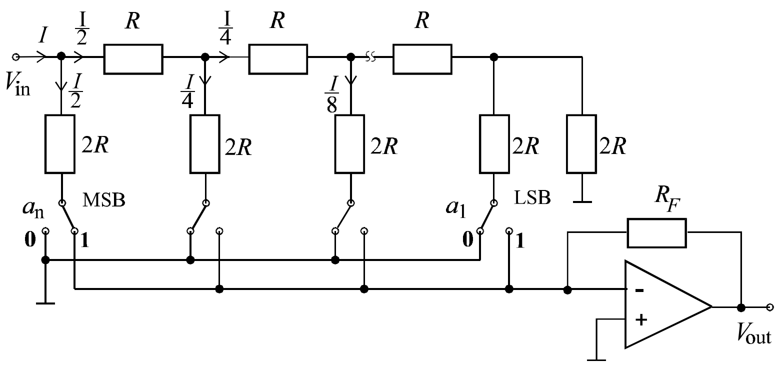

Figure 5.10 DAC with a reversed *R*-2*R* ladder network.

Another modification of the converter is a circuit with an *R*-2*R* ladder, closed at the side of MSB, with an additional resistor 2*R*, as shown in Figure 5.11. Constant resistance, equal to 3*R* in the direction of each switch, is characteristic of this resistance ladder. An analysis of such a circuit is rather simple.

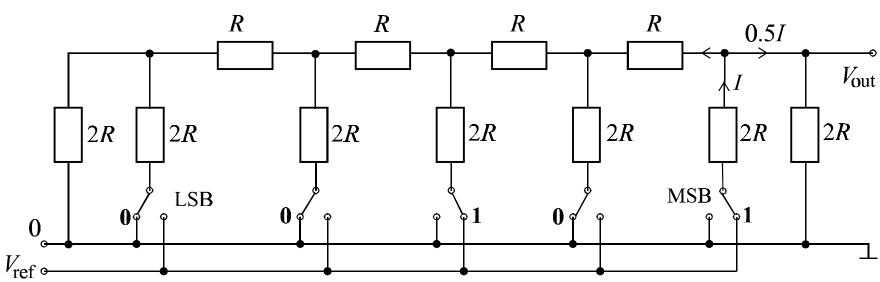

Figure 5.11 DAC with an *R*-2*R* ladder network.

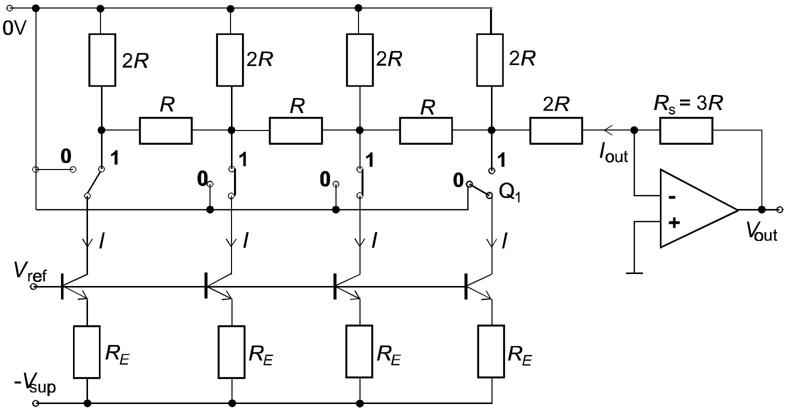

Figure 5.12 DAC with an *R*-2*R* ladder network and transistor switches.

In order to shorten the setting time of a DAC, a circuit with current switches and an *R*-2*R* ladder network is used, as shown in Figure 5.12 [1]. In a converter with current switches, the value of the current flowing through each key (transistor switch) is constant, and equal to *I* for both logic positions of a switch (1 or 0).

The current sources form bipolar transistors driven by the reference voltage V_{ref}. Due to the fact that the currents in the key circuits are independent of the position of keys (0 or 1), the delay in circuit operation is avoided. The delay would otherwise be caused by the recharging of capacitance *C* by different current values for 0 and 1 in the above circuits.

5.2.3 DACs with PDM

DACs with PDM are easier to produce as integrated circuits rather than converters with a precision resistor network. In a DAC with PDM, the pulse duty factor depends on the input digital word. Figure 5.13 shows the block diagram of such a converter. The converter shown in Figure 5.13 consists of an 8-bit input buffer, a digital comparator, an *n*-bit binary counter, a reference voltage source V_{ref}, a lowpass filter, and a clock. The digital comparator compares the input word A: $\langle a_n...a_3a_2a_1\rangle$ with the binary counter output word B: $\langle b_n...b_3b_2b_1\rangle$ (here, we consider *n*-bit word with the a_n MSB and the a_1 LSB, instead of a_{n-1} for MSB and a_0 for LSB). The comparator logic output is 1 for the case when A is greater than B. It is logic 0 for A equal to or less than B. The voltage level representing logic 1 must be accurately defined. It is equal to reference voltage V_{ref}. The digital output of the binary counter assumes the logical values from the range $\langle 0...000\rangle$ to $\langle 1...111\rangle$. In full period T_P, which is determined by the clock frequency and the capacity 2^n of the binary counter, the comparator produces an impulse of time T_x, proportional to the input digital word $\langle a_n...a_3a_2a_1\rangle$.

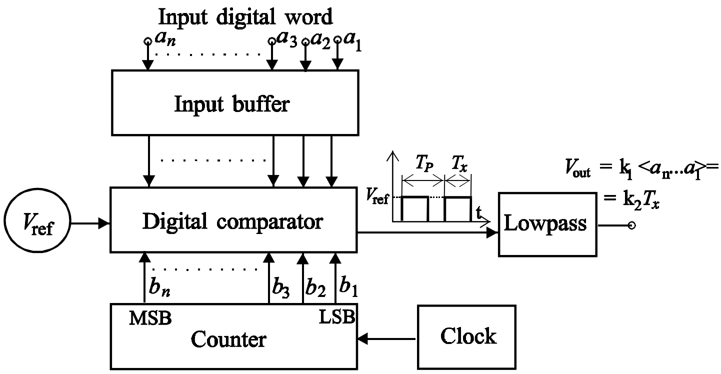

Figure 5.13 DAC with PDM with a binary counter.

The lowpass filter produces the DAC output analog signal that results from averaging the pulse train T_x. The conversion function is defined by

$$V_{\text{out}} = k_1 \langle a_n a_{n-1} \ldots a_2 a_1 \rangle = k_2 \frac{T_x}{T_P} V_{\text{ref}} \tag{5.12}$$

Notice that the function of the lowpass filter is to eliminate the alternating components of the impulse signal. The first (basic) harmonic frequency is $f_s = 1/T_P$. The DAC dynamics depend on the time constant of the lowpass filter. In turn, the higher the upper limit frequency f_u of the lowpass filter, the lower its time constant. The DAC may have better dynamics if the comparator output signal frequency is higher than $f_s = 1/T_P$.

This effect may be obtained if the binary counter in the converter circuit is replaced by a pseudorandom number generator (PNG), as shown in Figure 5.14.

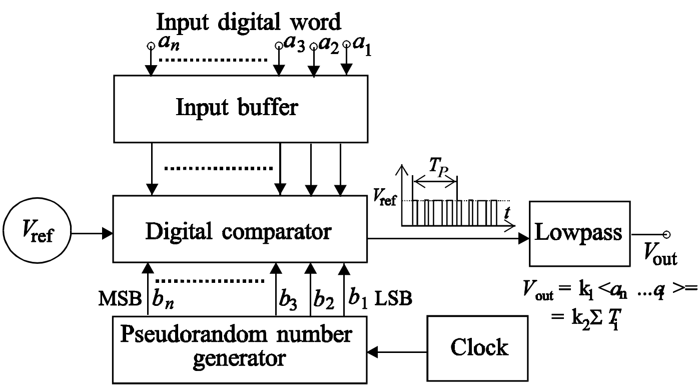

Figure 5.14 DAC with PDM with a pseudorandom number generator.

The block diagram of the DAC shown in Figure 5.14 is similar to the DAC shown in Figure 5.13, with the exception of the PNG block. The PNG produces a digital signal series with period T_P, with the condition that within one period every possible digital word is generated only once, as in the binary counter. However, the order of words is pseudorandom. Instead of binary coded numbers: B = 2, 3, 4, 5, 6, ..., which successively appear at the binary counter as digital words, the PNG produces words like B = 1, 22, 5, 2, 17, 8, ... For the input digital word A, which is a binary representation of a numerical value 5, and for the binary counter output B, which is a binary representation of numerical values 0, 1, 2, 3, or 4, the digital comparator produces a logic 1. For subsequent counter output values, it shows a logic 0. For the same input word A = 5 and the generator output B = 1, 22, 5, 2, 17, 8, the digital comparator produces a logic 1 for B = 1, a logic 0 for B = 22 and for B = 5, then a logic 1 for B = 2, and a logic 0 for B = 17 and for B = 8. Instead of one long pulse, the digital comparator produced two short pulses.

The analysis of the DAC with a PNG shows that, in the circuit with a PNG the output pulse, width ΣT_i is equal to the pulse width T_x in the DAC with a binary counter. However, the fundamental signal frequency in the DAC with a PPG is higher, and the dynamics of the lowpass filter and of the whole converter from Figure 5.13 may be greater. The conversion function of the DAC with a PNG is given by

$$V_{\text{out}} = k_1 \langle a_n a_{n-1} \ldots a_2 a_1 \rangle = k_2 \frac{\Sigma T_i}{T_P} V_{\text{ref}} \tag{5.13}$$

5.2.4 Integrated DACs

DACs are produced as integrated circuits in a large range of parameters. From the point of view of parameter values, they can be divided into high-speed DACs and precision (high resolution) DACs. Usually, high resolution DACs (up to 24 bits) are also very accurate. As far as construction is concerned, we have DACs with an inner reference voltage source V_{ref}, and DACs in which the voltage source V_{ref} is a separate device. From the point of view of the output signal form, we have DACs with voltage output and current output, and DACs with unipolar and bipolar output.

Most DACs are produced by Analog Devices, Maxim, Burr-Brown, and Plessey [2]. More sophisticated circuits provide additional functions, such as the presentation of the analog output voltage as a function of time, interpolation of the output voltage, and synthesis of the output analog voltage. Digitally controlled current sources are separate types of DACs. Table 5.1 shows the parameters of selected high-speed DACs. The digital control signal is connected to the DAC in a parallel or series way. In a system with a large number of slow DACs, control signals may be sent by a two-wire or three-wire serial bus.

Table 5.1

Integrated High-Speed Digital-to-Analog Converters

Type	*Sampling Rate*	*Settling Time*	*Resolution*	*Power*	*Output Type*	*Producer*
AD9726	600 MSPS	No data	16 bits	479 mW	Current	Analog Devices
AD9786	500 MSPS	No data	16 bits	1.25 W	Current	Analog Devices
MAX5888	500 MSPS	11 ns	16 bits	130 mW	Current	Maxim
MAX5858	300 MSPS	11 ns	10 bits	504 mW	Current	Maxim
DAC908	200 MSPS	30 ns	8 bits	170 mW	Current	Burr-Brown
AD9777	160 MSPS	11 ns	16 bits	1.2 W	Current	Analog Devices
SP98608	No data	2 ns	8 bits	No data	Current	Plessey

Figure 5.15 shows DACs controlled with such buses. Notice that the term of the bus (two-wire bus and three-wire bus) does not include the ground wire. The two-wire bus also carries the DAC address. In the three-wire bus, the DAC is selected by the chip select (CS) line. Table 5.2 shows examples of precision (high resolution) DACs. Their conversion rate is 1,000 times lower than the frequency of fast DACs shown in Table 5.1.

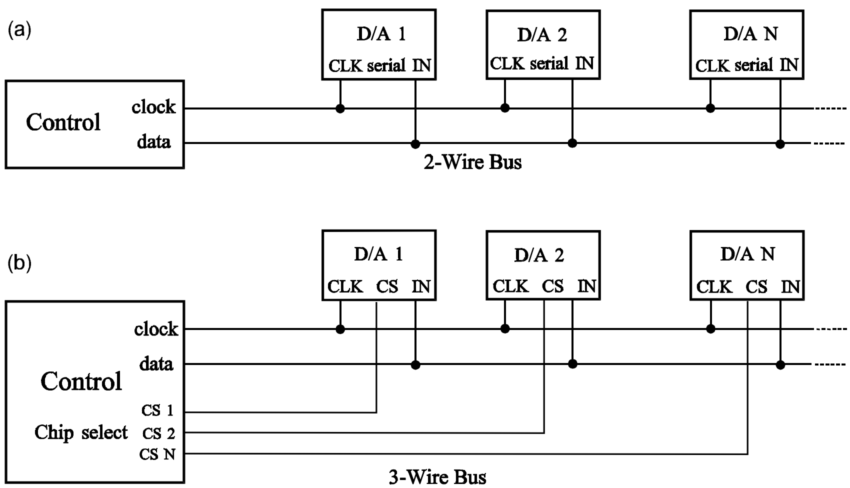

Figure 5.15 Control of several DACs: (a) system with a two-wire bus; and (b) system with a three-wire bus.

Digital potentiometers constitute another group of DACs. Digital potentiometers are integrated circuits, which include a resistance divider, electronic switches, and a control circuit.

Table 5.2

Integrated Precision Digital-to-Analog Converters

Type	*Resolution*	*Settling Time*	*Power*	*Output*	*Producer*
AD7846	16	6 μs	100 mW	Voltage	Analog Devices
AD760	18	6 μs	725 mW	Voltage	Analog Devices
AD5570	16	12 μs	150 mW	Voltage	Analog Devices
AD1139	18	40 μs	750 mW	Voltage	Analog Devices
MAX5200	16	25 μs	4 mW	Voltage	Maxim
DAC1220	20	10 ms (Δ-Σ modulator)	2.5 mW	Voltage	Burr-Brown

A digital input signal controls the switches, and a requested number of resistors can be switched on inside the digital potentiometer. When mechanical potentiometers are replaced with digital potentiometers (which are contactless parts), the reliability of the electronic device increases. Table 5.3 shows integrated digital potentiometers offered by Analog Devices. Some types of integrated digital potentiometers include a programmable nonvolatile memory with the capacity of 11 bytes (AD5233) to 30 bytes (AD5231). Many types of integrated digital potentiometer circuits include more than one DAC. Examples of integrated circuits produced by Maxim include two DACs (MAX51222), three DACs (MAX512), four DACs (MAX536), or even eight DACs (MAX7228) in one integrated circuit.

Table 5.3

Integrated Digital Potentiometers by Analog Devices

Type	*Number of States*	*Digital Input*	*Memory*	*Notices*
AD5231	1,024	10 bits, serial bus I/O	30 bytes, nonvolatile memory	SPI interface
AD5241	256	8 bits, two-wire serial bus I^2C	No memory	Thermal coefficient $a < 30$ ppm/°C
AD5200	256	8 bits, serial	No memory	SOIC case
AD5235	1,024	10 bits, serial	30 bytes, nonvolatile memory	Thermal coefficient $a < 35$ ppm/°C

Not only resistance can be controlled by a digital signal. Maxim offers a programmable capacitor—an integrated circuit MAX1474. It is a type of a DAC. In the MAX1474, the capacitance can be set up in the range from 6.4 to 13.3 pF, with the step (quantum) of 0.22 pF and with the accuracy of 15%. The circuit is controlled by a series of input pulses (up to 32 pulses).

5.3 ANALOG-TO-DIGITAL CONVERTERS

5.3.1 A/D Conversion Methods

ADCs are used to convert the analog value of a physical quantity into a digital form. This physical quantity is most often voltage. From the point of view of the method of conversion, ADCs are divided into:

- Integrating converters (dual slope and converters with V/f conversion);
- Successive approximation converters;
- Direct converters (better known as “flash converters”);
- Delta-sigma converters;
- Stochastic converters, converters with a V-device, pulse-width converters, and others.

An A/D voltage converter may also combine two conversion methods in its operation. The most important ADCs are integrating ADCs because of good attenuation of interferences (induced in the measuring circuit or measurement line) during the integration process. It is estimated that integrating ADCs constitute about 70% of all converters in use. The remaining types of converters are used for specific purposes and have specific applications. Successive approximation converters are characterized by a very small conversion error. Consequently, they are used in metrological laboratories. Flash converters are characterized by the shortest conversion time, and are used in video signal conversion and in conversion of other fast signals. Delta-sigma conversion provides very high resolution, especially in converting continuous signals. Delta-sigma converters are used to encode acoustic signals for the purpose of CD recording. Pulse-width converters are characterized by a simple conversion method, and are able to produce a nonlinear digital scale. Therefore, they may be used to measure the amplitude of an acoustic signal in a decibel scale. The remaining conversion methods are of little practical value and will not be described here. The most important parameters of ADCs are:

- *Resolution* or *bit number* in output signal;
- *Conversion time* (in seconds) or *conversion rate* (in sample numbers per second);
- *Conversion error*;

- *Analog voltage input range*. It is the peak-to-peak input voltage that must be applied to the converter to produce a full-scale response.

For the fastest converters, the conversion time is replaced by the number of samples per second (SPS). It must be stressed that there is a significant difference between conversion error in DACs and in ADCs. In an ideal case, the conversion error of a DAC is equal to zero, while A/D conversion *always* involves a quantization error.

5.3.2 Dual Slope Converters

Conversion of voltage into a digital signal by way of double integration method is called dual slope conversion. The block diagram of a dual slope converter is shown in Figure 5.16. The conversion cycle in this circuit consists of two phases. Before actual conversion, a switch SW3 is briefly closed, and the capacitor *C* is discharged.

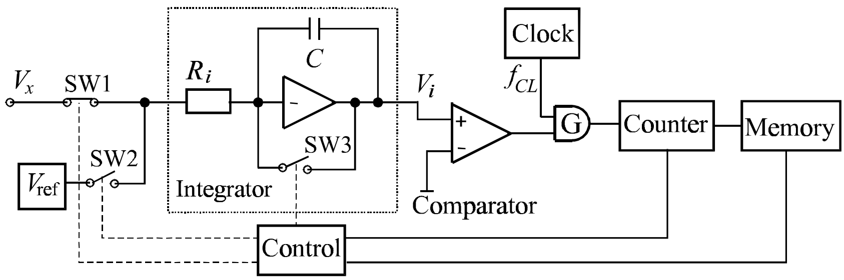

Figure 5.16 Dual slope ADC.

In the first phase of conversion, a constant voltage to be measured $V_x < 0$, is applied at the converter input (switch SW1 is on, and switches SW2 and SW3 are off). As a result of the integration of the input voltage, the integrator yields output voltage V_i, which linearly increases as a function of time, as shown in Figure 5.17. Positive voltage V_i fed to the comparator K yields a logical 1 at its output. Gate G is open, and the counter counts the pulses f_{CL} from the clock. After counting N_{max} pulses, the counter is full and it is set to the zero state. The information that the counter is full is given to the control circuit at time T_1. The control circuit sets switch SW1 off and disconnects voltage V_x. At the same time, it sets switch SW2 on and connects the reference voltage V_{ref} to the integrator input. Voltage V_{ref} has a different polarity than V_x, for example V_{ref} = +10V. The signals in the converter circuit are shown in Figure 5.17.

Time moment T_1 determines the start of the second phase of the cycle. In this phase, the voltage at the output of the integrator decreases, but is still positive. Under these conditions, the comparator output is still in logic state 1, and the gate G is open. At time T_2, capacitor *C* in the integrator is discharged, and voltage V_i

becomes negative (lower than 0V). At this moment, the comparator output changes from logic 1 to logic 0 and gate G becomes closed. In the time interval from T_1 to T_2, the counter counts N_x pulses. The number of pulses N_x is the result of converting the input voltage V_x into a digital form.

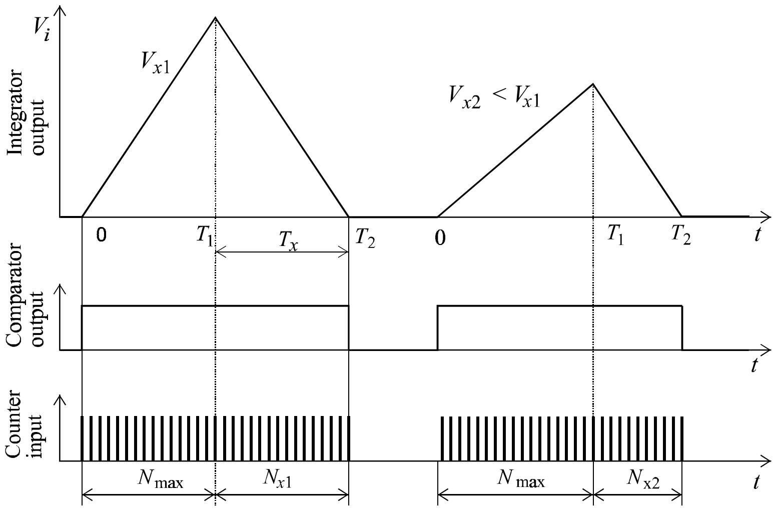

Figure 5.17 Signals in a dual slope ADC.

The term “dual slope converter” is connected with dual integration of voltage in one conversion cycle. The input voltage V_x is integrated in the interval from 0 to T_1, and the reference voltage V_{ref} is integrated in the interval from T_1 to T_2. Equation (5.14) describes voltage V_{i1} at the integrator output in the first phase of the conversion cycle:

$$V_{i1} = (1/R_iC)\int_0^{T_1} V_x\,dt = \frac{V_x T_1}{R_iC} \tag{5.14}$$

During integration of reference voltage V_{ref}, the integrator output voltage V_{i1} decreases from V_{ik} to 0:

$$V_{i2} = (1/R_iC)\int_{T_1}^{T_2} V_{ref}\,dt = \frac{V_{ref}}{R_iC}(T_2 - T_1),\;\; T_x = T_2 - T_1 \tag{5.15}$$

$$V_{i1} - V_{i2} = \frac{1}{R_iC}V_x T_1 - \frac{1}{R_iC}V_{ref}T_x = 0$$

$$T_x = T_1 \frac{V_x}{V_{\text{ref}}} \tag{5.16}$$

The integration time T_1 of the input voltage V_{x1} is determined by the full count N_{max} of the binary counter, and by the clock frequency f_{CL}.

$$T_1 = \frac{N_{\text{max}}}{f_{CL}} \tag{5.17}$$

The integration time T_x of the reference voltage V_{ref} depends on the output voltage of the integrator V_{i1} after the first conversion phase, and it is equal to:

$$T_x = \frac{N_{\text{max}}}{f_{CL}} \tag{5.18}$$

After substituting (5.17) and (5.18) for (5.16), we obtain the final conversion equation of the dual slope converter.

$$N_{x1} = \frac{N_{\text{max}}}{V_{\text{ref}}} V_x \tag{5.19}$$

From (5.19), it follows that dual slope conversion accuracy is affected neither by the long-time stability of clock frequency f_{CL}, nor by the integrator parameters R_i and C. Conversion accuracy is affected by the accuracy of reference voltage V_{ref}, as well as by parameters that do not appear in (5.19): the integrator gain and the offset voltage of the integrator amplifier.

Dual slope converters are widely used in industrial and laboratory devices. Compared to other ADCs, they have very high interference immunity. They are immune to interferences of periods equal to integration period T_1 (or its sub-multiple T_1/n, $n = 1, 2, 3, ...$), which interfere with the measured voltage V_x. The greatest problem in voltage measurements, especially in industrial measurements, is caused by power network interferences of frequency $f_n = 50$ Hz ($T_n = 20$ ms). The interference immunity of dual slope ADCs results from averaging (in the process of integration) of the interference signal. The integer of sinusoidal voltage of period 20 ms is equal to zero on integration time $T_1 = 20$ ms. That is why the integration time T_1 in dual slope converters equals 20 ms, or a multiple of this value. In the United States, the frequency of power network is equal to 60 Hz. Therefore, the integration time T_1 of converters manufactured for the interference U.S. market is 16.67 ms. Figure 5.18 shows examples of averaging interferences during integration of V_x for $T_1 = T_n$, $T_1 > T_n$, and $T_1 < T_n$. Infinite attenuation in the integration process is only possible for interference of the period $T_1 = T_n$ or $T_n = T_1/n$, where n is 1, 2, 3, … The attenuation factor sharply decreases if there is at least a small difference between T_1 and T_n. The frequency of power network fluctuates all the time. For example, in 1993 in the Polish power network, the highest frequency was noted in July, equal to 50.302 Hz, while the lowest frequency was in December, equal to 49.567 Hz. To ensure high attenuation of power network interferences, and to eliminate the influence of network frequency fluctuations, the integration time T_1 must take into consideration the current (actual) power network frequency f_n. This can be achieved by synchronizing the clock frequency f_{CL} and f_n: $f_{CL} = k\, f_n$. In this way, we obtain the adjustment of integration time T_1 and the actual power network frequency.

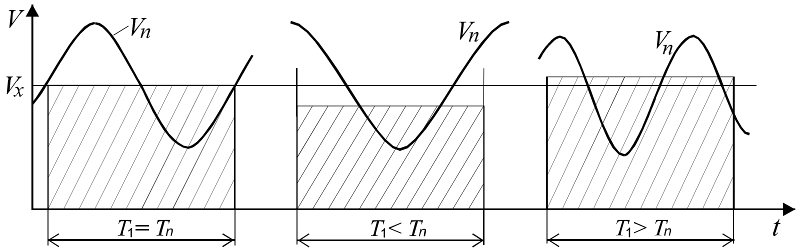

Figure 5.18 Averaging interferences during integration of V_x for $T_1 = T_n$, $T_1 > T_n$, and $T_1 < T_n$.

$$T_1 = \frac{N_{\max}}{f_{CL}} = \frac{N_{\max}}{kf_n} \tag{5.20}$$

The dual slope ADC needs a long conversion time (T_1+T_x), which is a great disadvantage. T_1 is constant, T_1 = 20 ms, and T_x is variable from 0 to 20 ms. The maximum value of conversion time (T_1+T_x) is 40 ms while converters for the U.S. market have the maximum conversion time, T_1+T_x = 33.34 ms.

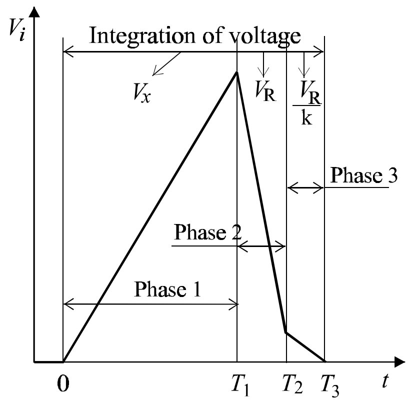

Figure 5.19 Integration in an ADC with three slopes.

The A/D conversion time may be reduced by introducing a third integration phase. This method is a variation of the dual slope method. The measuring cycle consists now of three phases, as shown in Figure 5.19. The first phase consists of the integration of V_x. In the second phase, the reference voltage V_{ref} is integrated until the integrator output voltage obtains a sufficiently small value. This is the so-called rough integration of the reference voltage. The third phase is fine integration of V_{ref} / k, which lasts as long as $V_i = 0$. The inaccuracy of dual slope converters or ADCs with three integration cycles is included in the interval from 0.005% to 0.5%. Its resolution is also high, and it amounts to 1 μV. The disadvantage of dual slope ADCs is their long conversion time, which is in practice at least 40 ms (or 33.34 ms in the United States).

The ICL7106 and ICL7107 Intersil dual slope ADCs are the two most popular integrated ADCs. They have a resolution of 13 bits, a voltage measurement range of 200 mV or 2V (optionally), and a ±0.2% conversion error. The ICL7106 and ICL7107 converters are integrated circuits with 40 pins. The ICL7106 converter can work with an LCD display, and can be used to build a battery-powered digital measurement device, as shown in Figure 5.20.

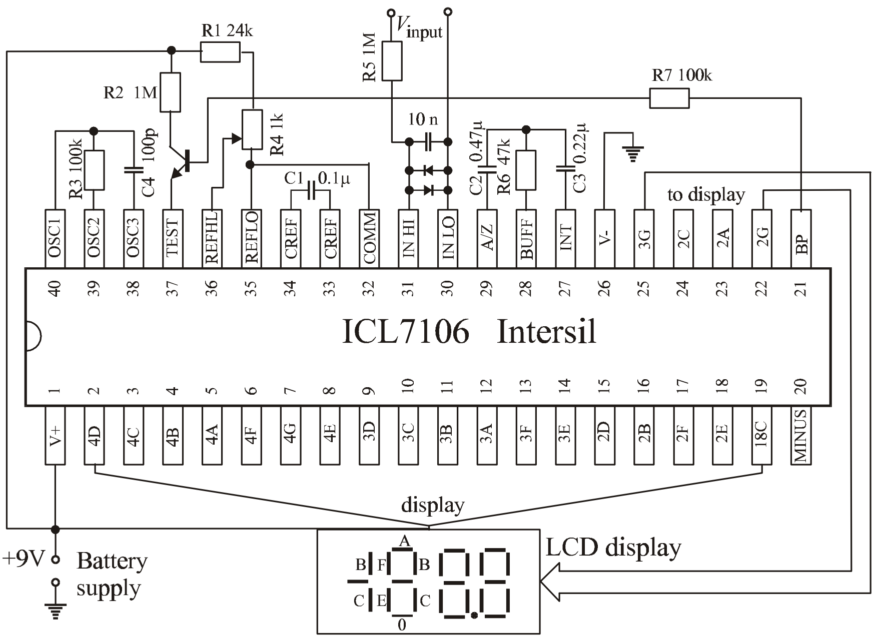

Figure 5.20 A simple voltmeter with a dual slope ADC ICL7106.

The ICL7107 converter works with an LED display. Both converters can control a display with 3.5 digits. This means a display of three positions that can show the digit from 0 to 9, and one position that can show the value 0 or 1.

Intersil also produces dual slope converters with higher accuracy, which can work with 4.5 digit display. The ICL7135 works with an LED display, and the ICL7128 works with an LCD display.

5.3.3 Converters with Voltage-to-Frequency Conversion

An integrating ADC with voltage-to-frequency *V/f* conversion is also called the ADC with charge balancing. This kind of ADC consists of two independent parts: a *V/f* converter and a circuit for digital measurement of frequency. Figure 5.21 shows the principle of this A/D conversion. The measured voltage V_x is connected to the integrator, which is a part of the *V/f* converter. As a result of applying V_x, the capacitor C_i is charged, causing a voltage change at the output of the integrator. When the integrator output voltage becomes equal to a level of a reference voltage V_{ref}, the comparator K output changes from logic 0 to logic 1. The comparator triggers a monostable multivibrator (MM), which generates an impulse of time length T_d. This impulse causes the discharge of capacitor C_i in the integrator circuit. After discharging, the capacitor C_i is charged again to V_{ref}, activating the comparator. Thus, the voltage-to-frequency conversion cycle is repeated.

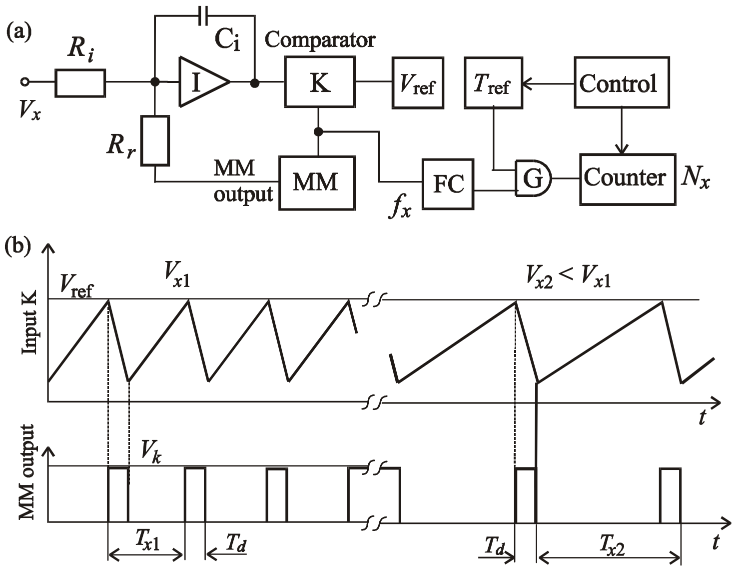

Figure 5.21 ADC with voltage-to-frequency conversion: (a) system diagram; and (b) signals in the system.

The charging rate of capacitor C_i depends on the value of V_x; therefore, for V_{x1} the charge-discharge cycle takes place at a higher rate than for $|V_{x2}| < |V_{x1}|$. The comparator output signal is applied to the forming circuit (FC), and then passed to the classic digital measuring circuit for frequency measurement. In this circuit frequency, f_x is measured during count reference time T_{ref}. The number N_x of impulses counted by the counter is the digital result of the measurement of f_x. This is also the final result of A/D conversion. In the mathematical description of this conversion method, we must use the charge balance obtained in the conversion process. In one conversion cycle, the electrical charge Q_{ch} applied to the capacitor C_i in the integrating circuit is equal to the outflowing charge Q_d:

$$Q_{ch} = Q_d, \quad Q_{ch} = \int_0^{T_x} i_x dt, \quad Q_d = \int_0^{T_d} i_r dt \tag{5.21}$$

The amplitude V_k of discharge impulses is constant. Moreover, it is assumed that V_x = constant during one measurement cycle:

$$\frac{1}{R_i} V_x T_x = \frac{1}{R_r} V_k T_d \tag{5.22}$$

where: T_x = the conversion cycle
$f_x = 1/T_x$ = the conversion frequency (conversion rate)
T_d = the discharged impulse length

$$\frac{T_x}{R_i} V_x = \frac{T_d}{R_r} V_k$$

$$f_x = \frac{R_r}{R_i T_d V_k} V_x \tag{5.23}$$

$$N_x = T_{\text{ref}}\, f_x$$

$$N_x = \frac{T_{\text{ref}}\, R_r}{T_d\, R_i\, V_k} V_x \tag{5.24}$$

It follows from (5.24) that the accuracy of A/D conversion in the converter depends on the constant value of charge Q_d, discharging the capacitor C_i. The value of Q_d is determined by V_k, T_d, and R_r. The reference interval T_{ref} and the discharging pulse duration T_d can be obtained by dividing the clock frequency. Then the ratio T_{ref} / T_d is a constant value k_1 ($k_1 = T_{\text{ref}} / T_d$), and the (5.24) becomes

$$N_x = k_1 \frac{R_r}{R_1 V_k} V_x \tag{5.25}$$

In (5.25), there are only three parameters influencing the conversion accuracy, while in (5.24), there are five.

The converter *V/f*, shown in Figure 5.22 as a solution, won considerable popularity because of construction and inexpensive components. Nevertheless, this converter has good metrological parameters. The low-cost converter is constructed from three main parts: the type 741 op-amp, the type 74121 TTL monostable multivibrator, and the p-n-p transistor (e.g., BC178). The 74121 monostable multivibrator performs the functions of the comparator and of the generator of the single pulse. The transistor serves as the analog switch. The negative input voltage V_x fed to the converter input causes the loading of the integrator capacitor and the voltage increase at the amplifier output. The amplifier output is connected to the pin 5 of the multivibrator, that is the trigger input with amplitude discrimination. When the op-amp output voltage achieves the threshold value of approximately 1.5V, the multivibrator generates an impulse with the length $T_i = R_p C_m \ln 2$. ADCs with *V/f* conversion enable the measurement of voltage with the error from 0.1% to 0.01%, and with the resolution from 1 to 10 mV.

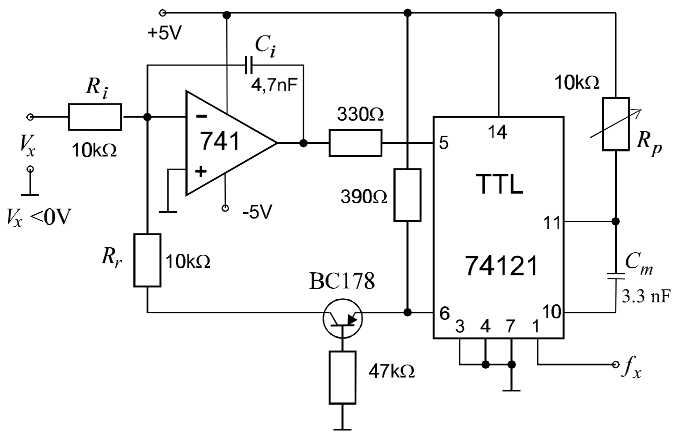

Figure 5.22 Low-cost *V/f* converter.

Discussing converters with *V/f* conversion, it is proper to mention the Josephson junction (cryoelectronic device), which is a *V/f* converter with a coefficient $V/f = 2e/h \approx 484 \times 10^{12}$ Hz/V (*h* is Planck's constant, and *e* is the electron charge). Operating condition of the Josephson junction is the superconductive state. The superconductivity demands the cooling down of the Josephson junction of niobium to the temperature of 4.2K (the temperature of liquid helium); or using the Josephson junction made of a high-temperature superconductor and cooling it down to 77K. *V/f* converters with Josephson junctions are used for converting extremely low signals, for example in noise thermometry applications in standard laboratories [3].

5.3.4 ADCs with SAR

Two different ways of comparing converting voltage V_x with quantized reference voltage (the compensating voltage) led to the development of two kinds of ADCs. They are:

- Successive approximation converters, or ADCs with successive approximation register (SAR),
- Direct ADCs (better known as flash converters).

The block diagram of an ADC with SAR is shown in Figure 5.23(a). The comparison of the measured voltage V_x with the compensating voltage V_0 is a step-by-step procedure, serial in time. The measurement using this conversion method is explained in Figure 5.23(b). A source of the compensating voltage V_0 is the DAC. A digital input signal for a DAC is the binary state of the counter included in control block, as shown in Figure 5.23(a). A binary counter state (current content of the counter) is transferred to the buffer.

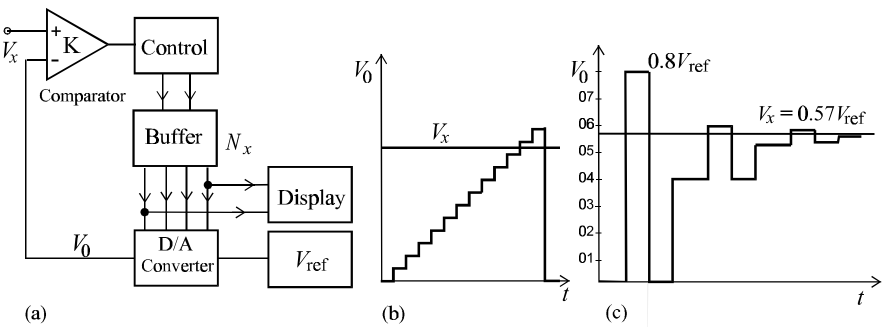

Figure 5.23 ADC with SAR: (a) block diagram; (b) conversion in BCD code with a stepwise compensating voltage; and (c) conversion with a weighted regulated voltage.

According to the counter state, the DAC generates stepwise the voltage V_0, with the step of a quantum $q = D\,V_0$. The voltage V_0 increases from the start, up to the moment of equalizing voltages, $V_0 = V_x$. After the comparator signals the equalizing moment, the counter is stopped. The state N_x of the counter is a digital measure of converted voltage V_x (5.26).

$$V_0 = N_x \times \Delta V_0 = N_x \times q, \ \text{for} \ V_0 = V_x$$

$$N_x = \frac{V_x}{q} \tag{5.26}$$

A main disadvantage of the successive approximation converter with stepwise compensating voltage is the changing conversion time, which depends on the value of the measured voltage V_x. The full conversion time is contained in the interval from T_k to $T = N_{max} \times T_k$, where T_k is the duration of one approximation step. The constant and shorter conversion time may be achieved if the compensating voltage V_0 is generated in portions equal to $1/2^n$ part of the conversion range, as shown in Figure 5.23(c). The conversion takes place by way of weighted compensation. The number of conversion steps is constant, and equal to the number of bits, n, in the output word. When the ADC is used in a digital voltmeter, the converter output word is presented in binary coded decimal (BCD) code, instead of the natural binary code. For example, for a voltmeter with a three-digit display, the number of steps is $3 \times 4 = 12$, because one decade of the result proceeds from a 4-bit record that demands four approximation steps.

Figure 5.23(c) shows the compensating voltage during the first four steps of conversion (in BCD code), which yields the first four in the decade output voltage V_x. In the first step, the regulated voltage $V_0 = 0.8V_{ref}$ is produced. The comparator sends information to the control circuit that $V_0 > V_x$. The control circuit causes the zeroing of voltage V_0. In the second step of conversion, the compensating voltage is equal to $0.4V_{ref}$. Since the comparator shows that $V_0 < V_x$, voltage $V_0 = 0.4V_{ref}$ remains. In the third step, the compensating voltage is incremented by $0.2V_{ref}$, but this increment is later zeroed. Finally, in the fourth conversion step, the compensating voltage is incremented by $0.1V_{ref}$, and this increment is not zeroed after comparison. On the basis of information about switching on and zeroing the increments of V_0 in the first four conversion steps, the first decimal digit of the conversion result 0101 is binary coded:

$$0 \times 0.8V_{ref} + 1 \times 0.4V_{ref} + 0 \times 0.2V_{ref} + 1 \times 0.1V_{ref}$$

In the next four steps, voltage V_0 is successively incremented by $0.08V_{ref}$, $0.04V_{ref}$, $0.02V_{ref}$, and $0.01V_{ref}$. As a result, we obtain the second binary coded decimal digit of the measurement result. The successive conversion steps consist of incrementing V_0 by thousandths, ten thousandths, and so on; parts of reference V_{ref}, which yields the third, fourth, and so on; decimal digit of the measurement result.

Successive approximation converters are used in the most accurate digital voltmeters. The measurement error of these voltmeters is in the range from 0.05% to 0.001%, excluding the digitizing error. The conversion resolution is of the order of 1 μV and better. This ADC can perform more than 10^6 measurements per second (1 MSPS). In other words, the conversion rate is at least 10^4 times higher than in an integrating converter.

5.3.5 Flash Converters

Converters with direct coding (called flash converters) have an even higher conversion rate, over 10^9 SPS. In some technical sources, flash converters are not considered to be converters with compensation, but constitute a separate group. Figure 5.24 shows the block diagram of a flash converter. The measured voltage V_x is applied to noninverting inputs (+ inputs) of analog comparators. Quantized reference voltage is applied to inverting inputs, that is, (–) inputs, in the following way. V_1 equal to $1q$ is applied to the (–) input of K1 comparator. V_2 equal to $2q$ is applied to the (–) input of K2 comparator. The voltage applied to (–) inputs of successive comparators is incremented by successive multiples of q. Reference voltage V_{ref} equal to $V_N = N \times q$ is applied to the (–) input of KN comparator. The logical values of comparator outputs depend on the actual value of V_x. The comparator output signals are decoded in the decoder and sent to the buffer, with the time step determined by the control circuit.

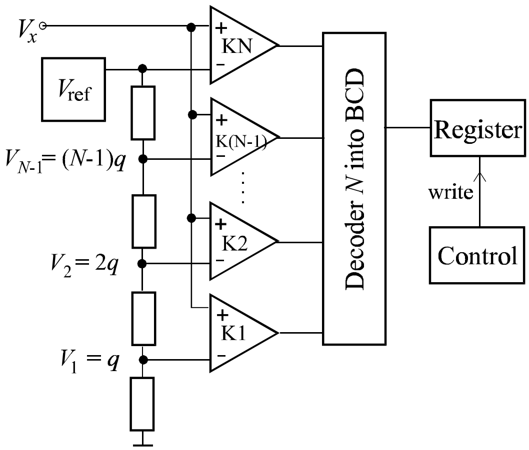

Figure 5.24 ADC flash (direct) converter.

The conversion rate in this circuit is limited by the operation of comparators. The time rate of the fastest comparators is less than 1 ns. The resolution of a flash converter depends on the number of comparators in the converter circuit. Converting voltage into n-bit words requires N comparators, and ensures 2^n digitizing levels of V_x.

$$N = 2^n - 1 \tag{5.27}$$

The output word of the flash converter is usually six to eight bits, not longer than 10 bits. A 10-bit word requires $2^{10} - 1 = 1{,}023$ analog comparators. Therefore, neither the converter resolution nor the comparator accuracy is high, and the measurement error is on the order of a few percent.

If we compare the metrological parameters of successive approximation converters and flash converters, we see that the former have the highest accuracy, and the latter are the fastest. The combination of two methods of conversion with compensation allows the development a half-flash converter—that is a converter with series-parallel compensation. The half-flash converter has a high resolution, and is only three times slower than the flash converter. However, these advantages are set off by the high complexity of the converter circuit.

5.3.6 Delta-Sigma ADCs

The delta-sigma ADC has gained considerable importance. Figure 5.25 shows the block diagram of this converter. The term delta-sigma comes from the subtraction (delta) of signals and the addition (sigma) of a series of subtraction results.

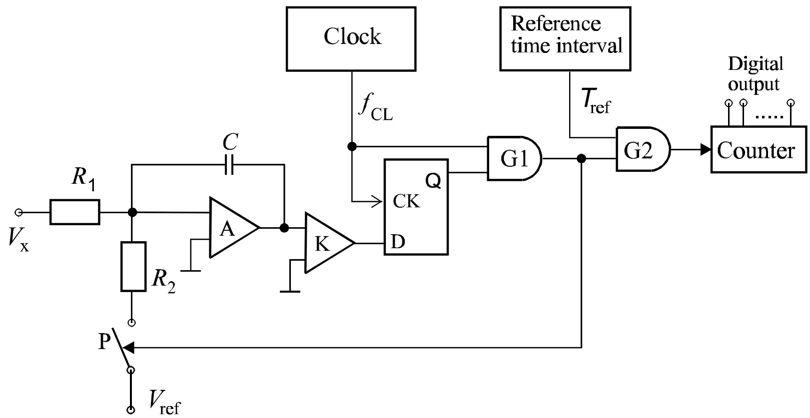

Figure 5.25 Delta-sigma ADC.

The converter is based on the principle of compensation of electrical charge in capacitor *C*. Assume that a positive voltage V_x equal to 1V is applied to the converter input, and that switch P is open. Capacitor *C* is charged, the integrator A yields a negative voltage, and a logic 1 appears at the output of comparator K. This logic value appears at the output Q of flip-flop D (Q = 1). The clock impulses of frequency f_{CL} pass through logic gate G1 and are counted in the counter. Each clock impulse closes the switch P for time T_i. The switch P connects negative reference voltage V_{ref} (for example, 10V) to the integrator input. Under the influence of a series of negative voltage pulses, the capacitor is discharged, and the integrator output yields positive voltage. This positive voltage causes the comparator to yield logic 0, which appears at the output of the flip-flop and closes gate G1 for clock impulses. In a steady state, a higher input voltage V_x results in a greater charge in the capacitor and a higher number of discharging impulses. The counter counts these impulses in a fixed interval of reference time T_{ref}. As a result, we obtain the value N_z, which is proportional to the measured voltage V_x. The comparator may work continuously or with strobe frequency. This is unimportant, however, because the logic state of the comparator is copied to the flip-flop D synchronously with frequency f_{CL}. The process of comparing signals by the comparator is called 1-bit quantizing. A value of clock frequency f_{CL} is an important parameter of the delta-sigma comparator. The value of f_{CL} should be at least 100 times higher than the Nyquist frequency f_s, which follows from Shannon's theorem (5.1).

$$f_{CL} > 100 f_s \tag{5.28}$$

We say that delta-sigma conversion is performed with oversampling, because, 1-bit quantizing frequency is much higher than Nyquist frequency. In delta-sigma converters, it is easy to increase conversion resolution. In order to achieve this, it is sufficient to increase the reference time interval T_{ref}. In integrated delta-sigma converters, resolution can be as high as 24 bits (for example, in the AD2210 converter).

Table 5.4

Integrated ADCs

Type	*Resolution*	*Sampling Frequency*	*Conversion Method*	*Producer*
AD7710	24 bits	1,000 SPS	Delta-sigma	Analog Devices
AD1175K	22 bits	20 SPS	Multi-integrating	Analog Devices
ADS7805	16 bits	100 kSPS	SAR	Burr-Brown
AD7621	16 bits	3 MSPS	SAR	Analog Devices
AD9410	10 bits	210 MSPS	Flash	Analog Devices
ADC08200	8 bits	200 MSPS	Flash	National Semiconductor
MAX108	8 bits	1,500 MSPS	Flash	Maxim

Table 5.4 presents an overview of parameters of integrated ADCs [2]. The frequency of converting is given as the number of samples per second (SPS).

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Chapter 6

Measurement Systems with Serial Interface

6.1 MEASUREMENT SERIAL INTERFACES: AN OVERVIEW

Two possible methods of transmitting digital measuring data, and, generally speaking, digital data, are serial transmission and parallel transmission. Serial transmission consists of transmitting a sequence of bits, bit-by-bit, according to the timing signals of a system clock synchronizing the transmission. Parallel transmission, on the other hand, consists of transmitting a sequence of words, usually 8-bit words (as in the IEEE-488 interface system), word-by-word, according to the timing (synchronization) signals. The mode of data transmission, serial or parallel, is the basic criterion of classifying computer measurement systems into measurement systems with serial interface or measurement systems with parallel interface. Computer measurement systems with serial interface are used to set up a simple measurement system, or to create a distributed measurement system. A distributed measurement system may be composed of measuring devices set up in a system by means of modems and a wire transmission network (telephone network) or a wireless network.

Chapter 6 is devoted to wired measurement systems with a serial interface. The structure and organization of an RS-232 system are described in Section 6.2. Section 6.3 is devoted to programming of measurement systems with RS-232. Two examples of software are presented and discussed in this section. Distributed measurement systems with RS-232 interface and a modem are presented in Section 6.4. Other recommended standards of serial interface (e.g., RS-422A, RS-423A, or RS-485) are introduced in Section 6.5. PROFIBUS and CAN systems, both very important for industry applications, are presented in Section 6.6. In Section 6.7, the use of power line communication for measurements is discussed briefly. Interface systems with wireless transmission are reviewed in Chapter 7.

Every PC has a driver and the RS-232C serial interface connectors as standard equipment. One of the RS-232C connectors may be used to connect a measuring device. A majority of currently produced digital measurement devices (e.g., multimeters, oscilloscopes, or frequency meters) are also equipped with drivers and connectors of the RS-232C interface, which enables both serial transmission of measuring data from a device to a computer, as well as transmission of measurement control instructions from a computer to a device. Connecting a computer and a digital measuring device to the RS-232C interface cable allows the setup of a simple measurement system composed of two parts. In such a system, the measuring device carries measuring data, and the computer is used to process and record data; it may also be used to control the measurements. It is better to build extended measurement systems using the serial interface system dedicated to measurement tasks (e.g., RS-485 or RS-423A), instead of using a "nonmeasurement interface" (i.e., the interface not developed for measurement tasks). Instead of the system with RS-232C, a system based on the RS-530 and RS-485 standards may be set up; those two standards replace the settlements included in the RS-232C standard (see Section 6.5). The RS-530 standard (or its older and wider version, RS-449) describes the functional and mechanical properties of the serial interface, including the function of lines in the interface bus. The RS-485 standard describes the electrical parameters of the interface, including the voltage levels for signals, the RLC parameters of transmission line, and the number of devices in the system. The computer measurement system with the RS-485 interface requires, however, a special driver system in the form of "an interface board" to the computer; the drivers of this interface must also be installed in the measuring devices connected in a system. Serial buses of high and very high transmission rate installed in computers (e.g., USB and IEEE-1394 bus), are discussed in Chapter 1. The Inter Integrated Circuits bus (I^2C), well-known to the designers of electronic systems, is not discussed here. The I^2C interface is used to set up integrated devices in a microprocessor system (in a device or on a computer board); it is not used, however, in computer measurement systems.

Measurement systems with a great number of sensors may be built up using specialized sensor interfaces. It is particularly simple to set up the so-called smart sensors in a system which includes a sensor, an ADC, and an interface in one case. An example of a smart sensor is the digital temperature sensor AD7814, discussed in Chapter 2. An example of an interface system with smart sensors is MicroLAN produced by Dallas Semiconductor, which can include digital temperature sensors and 8-bit ADCs.

6.2 RS-232C SERIAL INTERFACE SYSTEM

6.2.1 General Description

The Recommended Standard system (RS-232) was elaborated in 1962 at the request of the American Electronic Industries Association, in order to standardize the signal parameters and the construction of devices capable of exchanging digital data through a telephone network. In the RS-232 interface system, a mode of establishing and realizing communication between two terminals was defined; the terminals were named Data Terminal Equipment (DTE). Each of two DTE items is connected to a telephone line through a modem, marked with a Data Communication Equipment (DCE) symbol. This interface system was internationally recognized, and, after slight changes made in 1969, it was given the RS-232C name and the status of a U.S. standard. The RS-232C system is currently the standard of serial interface, applied to exchange digital data (information) between DTE devices, also without modems. It is more important that the RS-232C interface has become the standard for series line to connect a personal computer to peripheral devices (e.g., to a mouse or a modem); only then has it become widely known to myriads of computer users. The RS-232C system is a basis for international standards V.24 (functions, lines, cabling, connectors) and V.28 (electrical parameters of circuits defined in V.24) accepted for serial interface system by the International Consulting Committee for Telephony and Telegraphy (CCITT). The parameters of the RS-232C interface system were also standardized by national standardization institutions in many countries.

A block diagram for a digital system exchanging data between DTE terminals by means of the RS-232C interface was shown in Figure 6.1. The figure shows two terminals: DTE1 and DTE2, each of them linked with its DCE modem. Both modems are linked with each other by a transmission channel—a telephone line, a radio channel, or an optical channel. The recommendations and requirements for the RS-232C interface system refer first of all to a connection between DTE and DCE, although the final effect is information (data) exchange between DTE1 and DTE2.

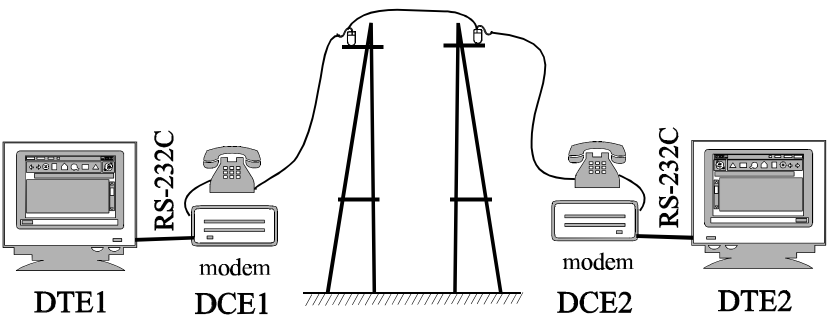


Figure 6.1 Diagram of digital data exchange by means of the RS-232C serial interface.

Considering the system in Figure 6.1 as a distributed measurement system, one can notice that the DTE terminal may not only be a computer (a typical DTE device), but may also be a digital measuring device. However, a measuring device has rarely any function in a measurement system with modems. Since it is necessary to control the modem and to monitor its work, it is also more useful to use a computer as a terminal in this system, and to connect a measuring device to the computer by means of a separate port.

In recent years, the modem module is usually a printed circuit, the so-called modem card, installed inside PCs. In this case, all connections between DTE and DCE are made inside the computer case, without pins and cables.

6.2.2 Transmission in the RS-232C Interface System

The following are the modes of transmission, as far as the direction of data flow between terminals DTE1 and DTE2 is concerned (the participation of DCE modems in transmission is not necessary):

- Simplex, unidirectional transmission, which consists of only DTE1 transmitting data to DTE2 (DTE1→DTE2), or only DTE2 transmitting data to DTE1 (DTE2→DTE1);
- Semiduplex, bidirectional asynchronous nonsimultaneous transmission, which enables tandem (serial) data transmission in both directions (e.g., first DTE1→DTE2, and then DTE2→DTE1);
- Duplex, bidirectional simultaneous, which enables simultaneous data transmission in both directions (i.e., DTE1→DTE2 and DTE2→DTE1).

The simplex mode of data transmission may be sufficient when one device is exclusively the data transmitter but not a receiver, and the other device exclusively receives, records, and processes data. Such a relation occurs when the measuring data is sent by a digital measuring device with constant settings, and is received by a computer.

Data transmission in the RS-232C interface system consists in tandem (serial) transmission of successive bits. There are two modes of transmission—asynchronous and synchronous.

Asynchronous Transmission

The asynchronous transmission mode consists of transmitting successive characters (e.g., alphanumeric, printing, and control); at the same time, each data character includes from five to eight bits, is preceded by the START bit, and is finished with a check bit (even parity bit) and STOP bits. The data field most frequently includes seven bits representing an ASCII code character. Data bits, together with a check bit and synchronization bits (START and STOP), form a serial data unit (SDU). The SDU format is shown in Figure 6.2. Data bits are sent in the order from the LSB D1 to the MSB D7. The existence of a check bit (even parity bit or odd parity bit) is not necessary, and the number of STOP bits is equal to one or two.

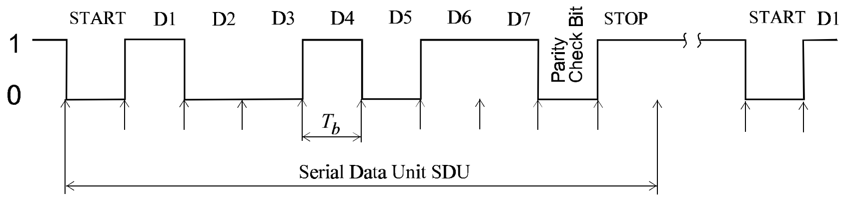


Figure 6.2 SDU in asynchronous transmission in the RS-232C system. An example of SDU format includes seven data bits, one even bit, one start bit, and one stop bit.

The even bit has a logical value equal to the sum of modulo 2 of all data bits. Then, the logical value of the even bit is equal to 1 for an odd number of data bits with logical value 1; the logical value of the even bit is equal to 0 for an even number of data bits with logical value 1, as shown in Figure 6.2. The number of bits included in an SDU is not strictly determined, and it is usually between 8 and 12. The duration of one bit is denoted by T_b, and the inverse value determines the transmission rate f_t in bits per second (bps)

$$f_t = \frac{1}{T_b} \tag{6.1}$$

In simple modulation methods, 1 bps = 1 baud. Typical values of f_t in measurement systems are: 300, 600, 1,200, 2,400, 4,800, 9,600, and 19,200 bps. The rate of asynchronous transmission is the basic parameter determined when configuring a system with serial interface. It is necessary to set up an identical values rate in transmitter and receiver. During asynchronous character transmission, seven data bits are (typically) accompanied by synchronization and check bits (usually three to five bits), which are ineffective for data processing. Characters are sometimes grouped in messages (frames) including additional message identification bits and additional check bits. The asynchronous character transmission is also called start-stop transmission. The asynchronous transmission mode results from transmitting successive characters which is not time-synchronized. The interval between STOP of the *n*th data character and START bit of the (n + 1)-character is not defined.

Synchronous Transmission

Synchronous transmission consists of transmitting characters grouped in blocks called frames, with a content up to 2 KB. The characteristics of synchronous transmission are the following:

- The same timing signal frequency in the transmitter and the receiver;
- Data transmission in units called frames, with a variable frame volume, with the frame start and end distinguished;

- Detection (and, if necessary, correction) of transmission errors;
- Automatic retransmission of a data sequence with errors (ARQ).

It is necessary to emphasize that synchronous transmission in the RS-232C interface system usually *does not* consist of transmitting data according to clock (synchronization) pulses of the system clock in both the transmitter and the receiver. Transmission in the system of synchronization pulses in parallel to information bits, although possible, would require a separate synchronization transmission line between DCE1 and DCE2, which considerably increases the costs of building and maintaining the system. There are separate clocks in the receiver and the transmitter for the synchronous transmission, as in the asynchronous character transmission. In the synchronous transmission, the frequency of the receiver clock is obtained from the carrier of the received signal in the system of element synchronization. The requirements concerning the synchronization of frequency of the clock controlling receiving bits with transmitting bits are much higher in the synchronous transmission than in the asynchronous character transmission.

An information frame consists of the frame header, a segment of data grouped in characters, and the final (end-of-frame) sequence. The final sequence always includes the check field used for error detection. Characters are transmitted in series, without separate bits identifying the beginning or end character. After the MSB of the nth data character is transmitted, then the LSB of the (n + 1)-character is transmitted. For example, an information frame can include the result of a single measurement of constant voltage, or the results of a series of such measurements. A data segment of information frame from a single measurement includes a voltage polarity character (plus or minus), digits of the measurement result, a dot character separating integer parts from fractional parts of the result, V character denoting the unit of the measured value (volt), and spacing characters. Before sending the information constituting the frame, it should be recorded in the buffer register.

Transmission Protocol

The most important function of serial transmission is data delivery. The most important supplementary function in the synchronous serial transmission is to detect transmission errors and to make error correction, if needed. The rules of synchronous transmission, including this function, are defined by transmission protocols. There are character-controlled protocols (CCP) and bit-oriented protocols (BOP). The information frame of CCP protocol includes characters controlling the transmission—for example, synchronization characters (SYN), start of text (STX), end of text (ETX), end of text block (ETB), data link escape (DLE), and others. A known CCP protocol is bisync protocol, binary synchronous control (BSC). Character-controlled protocols, which have several dozen types, are replaced by more effective BOP protocols. The most important type of BOP is

High-level Data Link Control (HDLC). The structure of the HDLC protocol frame is shown in Figure 6.3.

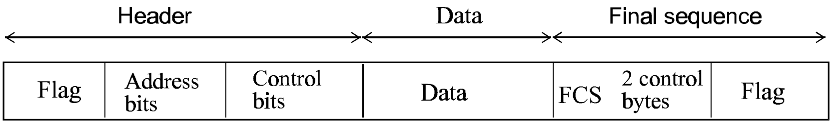


Figure 6.3 Structure of information frame for the synchronous transmission, according to the HDLC protocol.

The frame start and end is a flag (i.e., 1-byte sequence of bits: 01111110), reserved exclusively to denote the frame start or end. If the same sequence of bits occurred in data bits, the HDLC protocol assumes to insert 0 bit after five successive bits 1 before transmitting the frame, and, certainly, to delete the inserted bit 0 from the data sequence 011111010 after receiving the frame. The frame address field includes the address of the information recipient, and, in multipoint systems, it may be extended to 2 bytes. The role of the check field in the header is to control the transmission, depending on the content of information in the frame; differences concern the frame including data (bit number 7, $B_7 = 0$) and the frame including information controlling the protocol ($B_7 = 1$). The bits of check field of information frame include 3-bit numbers of transmitted frame NS ($B_6B_5B_4$) and received frame NR ($B_2B_1B_0$). It results from the structure of the check field that the HDLC protocol transmits in one sequence the maximum of eight numbered frames, and this number is limited to seven. The width of sending window of the HDLC protocol is equal to seven frames. Bit B_3 of the control field is denoted by symbol P/F (*Poll/Final*). The state of this bit denotes acknowledgment request P, acknowledgment itself, or indicates no successive data to be sent F. The result of a response to acknowledgment may be an automatic repeat request of frame number X and all successive frames transmitted after detecting transmission errors.

CRC Detection

Cyclic redundancy check (CRC) detection of transmission error is possible by adding redundancy bits to the data sequence in the receiver. Redundancy bits (2 bytes) are obtained from the so-called generating polynomial of the 16th degree, $g(x)$, defined in two ways:

$$g_{CRC-16}(x) = x^{16} \oplus x^{15} \oplus x^{2} \oplus 1 \qquad (6.2)$$

$$g_{CRC-CCITT}(x) = x^{16} \oplus x^{12} \oplus x^{5} \oplus 1 \qquad (6.3)$$

$\oplus$ “exclusive or” logical operation (EXOR).

Better overload protection is ensured by a generating polynomial of the 32nd degree $g_{\text{CRC-32}}(x)$ in the form determined in the V.42 recommendation, and the redundancy bits form four bytes.

$$g_{CRC-32}(x) = x^{32} \oplus x^{26} \oplus x^{23} \oplus x^{22} \oplus x^{16} \oplus x^{12} \oplus x^{11} \oplus x^{10} \oplus x^{8} \oplus x^{7} \oplus x^{5} \oplus \oplus x^{4} \oplus x^{2} \oplus 1. \tag{6.4}$$

Redundancy bits form a 2-byte or a 4-byte check word included in Frame Check Sequence (FCS). The CRC check word is obtained by dividing the information part of HDLC frame (i.e., address field + check field + data field) by the polynomial $g(x)$. The information part of HDLC frame is regarded as a polynomial with binary coefficients. The remainder of the division is inscribed in the FCS field. The division operation is performed "on the run," during the transmission of the information part of HDLC frame. The same operation of dividing the content of HDLC frame (the information part and the check part), regarded as a polynomial, by the accepted generating polynomial $g(x)$ is realized in the receiver. The result of the division is a word formed as a sequence of zeros 00...0, when the transmission is error-free, which enables acceptance of the frame. Obtaining a word different than 00...0 stands for detecting a transmission error. The protocol predicts the ARQ.

The ARQ correction method is not possible in the simplex transmission mode, because the transmitting device has no information about the correctness of transmission. In this transmission mode, it is possible to use data coding by means of self-checking codes (e.g., Hamming's code) characterized, however, by a much greater redundancy than the CRC method.

The users of serial measurement systems using an open communication network (public telephony or radio communication) apply original, dedicated (custom-made) transmission protocols, in order to make the systems inaccessible for nonauthorized persons.

The *synchronous transmission mode* is more effective than the asynchronous character transmission mode, but it is much more difficult because it is necessary to divide a multibit segment of received data (up to 2 KB) into characters. The efficiency of asynchronous character transmission may be compared to the efficiency of synchronous transmission according to HDLC protocol for exemplarily selected parameters:

- The efficiency of asynchronous character transmission, in which an SDU includes seven data bits, one start bit, one even parity bit, and one stop bit, amounts to 70%; the efficiency is computed as a percent of data bits included in SDU;
- The efficiency of synchronous transmission according to the HDLC protocol—in which a data segment includes 2 KB (i.e., 2,048 bytes), and

the header and the end sequence number six bytes altogether—amounts to 99.7%.

In spite of the better efficiency of the synchronous transmission in data transmission systems, including measurement systems, the asynchronous character transmission is applied more frequently, due to a simpler transmission mode and a simpler system for reading out the received data.

6.2.3 RS-232C Interface Bus

The lines connecting a DTE terminal to a DCE modem, or connecting two DTE devices directly, form the RS-232C interface system bus. In Table 6.1, various bus lines of the RS-232C interface system bus are shown, together with the pin numbers to 25-pin and 9-pin connectors. Physically, the DTE device is connected to a DCE device through an electrical cable. One side of the cable ends with a standard 25-pin socket of type DB-25P Canon, or with a 9-pin socket of type DB-9. The other side of the cable ends with a standard 25- or 9-pin connector. The DTE device has connectors of plug type (i.e., male part of connector) on its case, whereas the DCE devices are equipped with connectors of socket type (i.e., female part of connector).

The RS-232C interface bus in full version includes 4 data lines, 11 control lines, 3 synchronization lines, and 2 ground lines. All lines (apart from the ground line) are unidirectional lines (i.e., the direction of information flow through the line does not change). The asynchronous character transmission uses only part of control signals, and does not use the synchronization line. In order to ensure the asynchronous transmission, the cable connecting DTE to DCE or connecting two DTE terminals may have only nine wires (or even less), and the connectors used are 9-pin connectors. Below, all lines of the RS-232C interface are discussed.

Data Lines

TxD – transmitted data;

RxD – received data;

STxD – data transmitted in the secondary channel;

SRxD – data received in the secondary channel.

For the duplex or semiduplex data transmission, it is usually sufficient to use one transmission channel and two data lines: TxD and RxD. The secondary synchronization channel is used to transmit additional data controlling the transmission.

Control Lines

DTR (*Data Terminal Ready*) – the readiness of DTE terminal to cooperate further with DCE;

DSR (*Data Set Ready*) – DCE modem is ready to cooperate further with DTE terminal, understood as no holdbacks;

Table 6.1

RS-232C Interface Bus Lines and Pins to Connectors

Pin Number in Connector		*Line Name*	*Signal Source*	*Signal Descriptions*
DB-9	DB-25P	*RS-232C*		
–	1	AA		PG – protective ground
3	2	BA	DTE	TxD – transmitted data
2	3	BB	DCE	RxD – received data
7	4	CA	DTE	RTS – request to send
8	5	CB	DCE	CTS – clear to send
6	6	CC	DCE	DSR – data set ready
5	7	AB		SG – signal ground
1	8	CF	DCE	DCD or RLSD – received line signal detector
–	9	–		Reserved for diagnostics
–	10	–		Reserved for diagnostics
–	11	–		Not used
–	12	SCF	DCE	SRLSD – received signal level in secondary channel
–	13	SCB	DCE	SCTS – secondary channel clear to send
–	14	SBA	DTE	STxD – transmitted data in secondary channel
–	15	DB	DCE	Transmission signal element timing
–	16	SBB	DTE/DCE	SRxD – received data in secondary channel
–	17	DD	DCE	Received signal element timing,
–	18	–		Not used
–	19	SCA	DTE	SRTS – request to send in secondary channel
4	20	CD	DTE	DTR – data terminal ready
–	21	CG	DCE	SQD – signal quality detector
9	22	CE	DCE	RI – ring indicator
–	23	CH/CI	DTE	CH/CI data signal rate selector
–	24	DA	DTE	Transmit signal element timing, generated in DTE
–	25	–		Not used

RTS (*Request To Send*) – request to send data, signaled by DTE terminal;
CTS (*Clear To Send*) – the readiness to send signaled by DCE modem to DTE terminal;
RTS (*Request To Send*) – request to send data, signalled by DTE terminal,
DCD (*Data Carrier Detected*) – signal of detecting the distant DCE2 modem by DCE1 modem on the carrier (wave) of the distant modem; on DCD line the DCE1 modem transmits a signal of establishing communication with DCE2 to DTE1 terminal;
SQD (*Signal Quality Detector*) – on this line there is a secondary signal generated in DCE1 modem and transmitted to the input of DTE terminal, informing that data transmission from DCE2 to DCE1 is performed without holdbacks (logical 1), or with holdbacks (logical 0).

In measurement systems with the RS-232C interface the signals controling transmission in the secondary channel SRTS, SCTS, and SRLSD—being the equivalents of control signals in the primary channel RTS, CTS, and DCD—are rarely used.
CH/CI – The choice of transmission rate by DTE terminal, switching over between two transmission rates determined earlier. CH/CI and RI signal are not frequently used;
RI (*Ring Indicator*) – an output signal from DCE1, which informs DTE about receiving a ring (call) from DCE2 modem.

Synchronization lines are applied in synchronous transmission:
DA – time base signal, generated in DTE terminal; its function is the timing of sending data through DTE terminal on TxD line;
DB – time base signal, generated in DCE modem; its function is the timing of sending data through DTE terminal on TxD line;
DD – time base signal, generated in DCE modem; its function is the timing of sending data through DTE terminal at RxD input.

Ground Lines:
SG – Signal Ground;
PG – Protective Ground, connected to the device case.

Electrical Parameters of Signals
For the RS-232C interface system, electrical parameters of a circuit connecting respective pins of devices linked by a telephone line of the interface are defined. For example, it may concern the connection of TxD line of the signal source of DTE terminal to TxD input of DCE modem. The maximum (allowable) voltages on lines are the following:

- On data lines (see Figure. 6.4)

$$-15\ \text{V} \leq V_{sig}\ -3\ \text{V corresponds to logical 1,}$$

$+3V \leq V_{sig} \leq +15V$ corresponds to logical 0,

- On control lines:

$+3V \leq V_{sig} \leq +15V$ corresponds to logical 1,
$-15V \leq V_{sig} \leq -3V$ corresponds to logical 0.

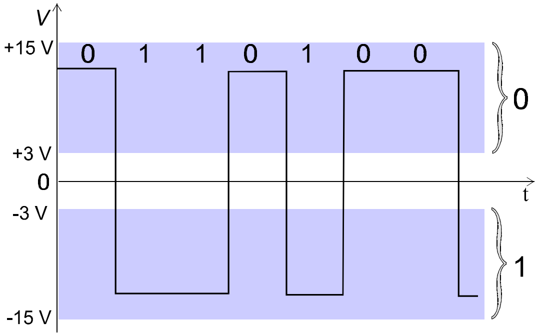


Figure 6.4 Voltage levels for signal on data lines in the RS-232C system.

Negative logic is obligatory on data lines, and positive logic on control lines. Sometimes the logical state on the control line is denoted by *ON* or *True* instead of 1, and respectively by *OFF* or *False* instead of 0. The levels of signal voltage on the RS-232C bus differ considerably from signal levels of TTL or CMOS digital systems. A wide range of RS-232C signal levels gives these signals high interference immunity. A possibility of inducing interference results from a large maximum length of the RS-232C interface bus, determined to be 15m in the standards. A relevant circuit parameter is load resistance of each bus line. The value of load resistance of each line should be included in a range between 3 and 7 kΩ. The load capacitance of bus line should not exceed 2,500 pF. Due to a possibility of overvoltage occuring on a line, the rate of changing signal voltage is limited to 30 V/μs. The duration of signal transition states (from 1 to 0 and from 0 to 1) on data lines and on synchronization lines should not exceed 3% of the duration T_b of bit.

6.2.4 Current Loop in the RS-232C Interface System

The length of the line connecting a DTE to a DCE in the RS-232C interface system, or connecting two DTE devices in the null modem system, is limited to 15m. The 15-m line length is not important, and correct operation of a system with a longer line (even 50m or 100m) is quite probable. Correct operation is, however, only probable and not certain. Too long of an electrical line is more susceptible to interference (a longer line is a better antenna for interferences), and it has a greater capacitance *C* and inductance *L*. In an *RLC* electrical circuit, which forms a measurement cable, an overvoltage in nonstationary states occurs during the transmission of pulse signals. Overvoltage occurring in a circuit with high capacitance and inductance may disturb the readout of logical states of digital data. Therefore, the suppression of overvoltage in the circuit measurement cable to a maximum (allowable) level is possible by limiting the rate of changes in signal voltage to 30 V/μs and the line length to 15m. The problem concerns mainly data lines and synchronization lines, because changes in logical states on control lines occur rarely (in time intervals of the order of seconds or minutes).

Measuring data transmission in the RS-232C interface system for a much greater distance (up to 1,500m) is possible with the use of the "20-mA current loop" circuit, as shown in see Figure 6.5. In a current loop, each line of the interface bus is replaced by a two-wire cable, which transmits a digital signal according to the convention: logical 1 is 20-mA current on the line, logical 0 is no current on the line. In distant devices linked by a current loop line, it is useful to ensure galvanic separation between the devices. Galvanic separation prevents the signal levels from shifting, due to the potential difference of the grounding of devices**.** In industrial conditions, the grounding potential difference may amount to a few or even several dozen volts between devices placed 1,500m apart.

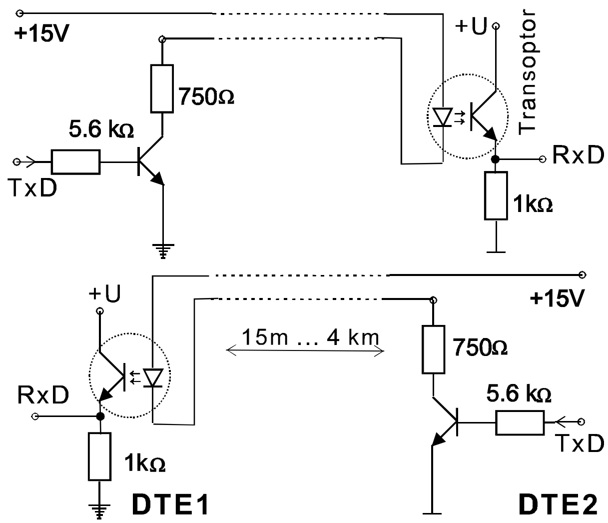


Figure 6.5 "20-mA current loop" for digital data transmission for a distance over 15m.

6.2.5 Null Modem Measurement System with the RS-232C Interface

Each PC has a standard driver for the RS-232C serial interface, enabling asynchronous character transmission. There are four ports prepared in the computer for the RS-232C interface (denoted as COM1 to COM4), and two pin-type connectors of this interface. One of the RS-232C connectors is usually used to connect a mouse, and the other one may be used to connect a measuring device.

Most of currently produced digital measuring devices (e.g., multimeters, oscilloscopes, or frequency meters) also have drivers for the RS-232C interface ports. Therefore, serial transmission of measuring data from a device, as well as transmission of instructions controlling the measurement, are possible. Connecting a computer and a digital measuring device to the RS-232C interface cable enables a simple measurement system without modems, composed of two parts (see Figure 6.6). It should be emphasized, that outputs of particular lines of the RS-232C interface (according to Table 6.1) are explicitly determined as inputs of interface driver circuits (e.g., RxD or CTS), or as outputs of these circuits. In connecting particular outputs, the following general rules of circuit theory should be observed:

- Outputs are connected to inputs;
- A line from one output may be connected to a few inputs simultaneously;
- Any output may not be shorted with another (e.g., RTS with DTR).

The interface driver interprets the logical state of disconnected input as inactive state (OFF), which means logical 0 for control lines.

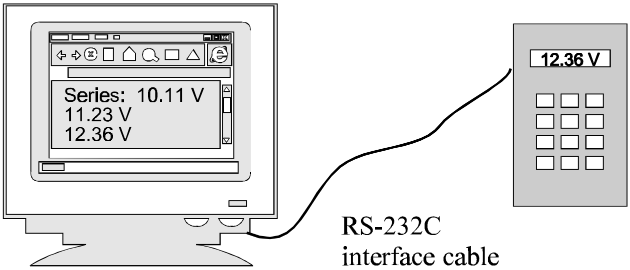


Figure 6.6 Measurement system of null modem with the RS-232C serial interface.

In the circuit presented in Figure 6.6, both the computer and the digital device are devices of type DTE in the system. There are no modems in the interface system, so the system in which two DTE devices are directly connected is called a *null modem system.*

The interface bus connecting two DTE devices for the asynchronous character transmission (duplex or semiduplex) is shown in Figure 6.7. In the null modem system shown in Figure 6.7, the data output TxD of DTE2 device is connected to the data input RxD of DTE1 computer, and respectively the data output of the computer is connected to the data input of the measuring device. Signals needed by the DTE device to control transmission are generated either in the device or in the opposite DTE device.

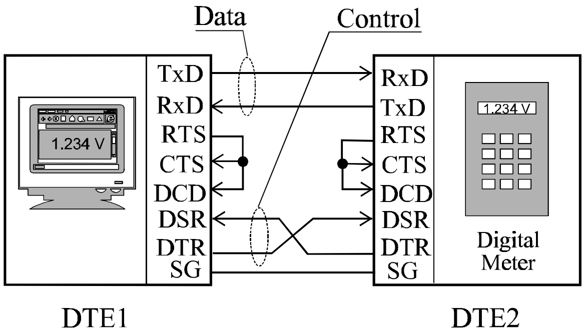


Figure 6.7 Null modem measurement system with the RS-232C serial interface for asynchronous character transmission.

But there are no modems in the null modem system, which in a full system (i.e., with modems) generate part of the signals needed to establish communication and control transmission. DTR1 output, informing about the readiness of DTE1 device to cooperate further, is connected to DSR2 input of DTE2 device, and, “per analogiam,” DTR2 output is connected to DSR1 input. At DSR input in a system with modems, the terminal obtains a signal about its readiness to cooperate further from DCE modem. In the null modem system, the crossover of DTR and DSR lines (i.e., DTR1→DSR2 and DTR2→DSR1), causes the terminals to inform each other about the absence of holdbacks, in order to establish communication. As the state of one of the DTR1→DSR2 or DTR2→DSR1 lines is inactive, the system obtains information about a holdback in transmission exchange in one direction. For example, DTR output of the terminal is inactive when the terminal is disconnected from supply. Then, DTR connections to DSR have an important function in the system. RTS1 output (data sending request) may be connected to CTS1 input (readiness to send data), and, respectively, RTS2 output to CTS2 input. We also have the DCD input, at which the terminal should obtain information about correct transmission (sufficient signal level) from the modem. Because there is no modem in the system, a signal into DCD input may be transmitted from RTS or DTR output of its terminal. In the connections realized according to this description and shown in Figure 6.7, the cable connecting the DTE2 measuring device to DTE1 computer has five wires. The METEX multimeters are equipped, among others, with a five-wire cable for the RS-232C interface.

Two DTE terminals, and particularly a computer and a measuring device, may be connected by a three-wire cable, as shown in Figure 6.8(a). Three-wire cable ensures the asynchronous transmission—full-duplex or semiduplex, like the previous version with a five-wire cable, but without transmission control. Such a configuration of measurement system without transmission control is used more frequently. An advantage of such a system is the lower price of a three-wire interface cable. In the system presented in Figure 6.8(a), only the state of DTR output of each terminal decides the readiness of this terminal to exchange data with the opposite terminal.

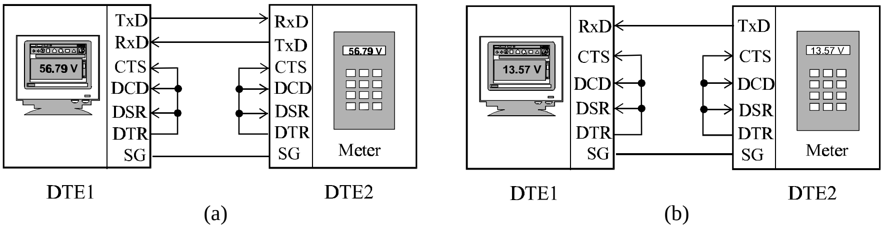
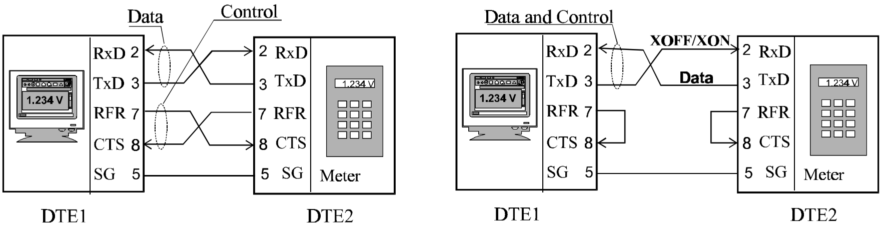


Figure 6.8 Null modem measurement system with the RS-232C serial interface for the asynchronous character transmission: (a) duplex transmission, three-wire cable; and (b) simplex transmission, two-wire cable.

The simplest possible measurement system includes two devices—a computer and a measuring device, as well as a two-wire cable enabling the simplex transmission, in which data flow is realized only from the device to the computer, as shown in Figure 6.8(b). In this case, the cable connecting two DTE devices may be a two-wire telephone twisted pair. Such a two-wire cable configuration is not always allowable. In a variety of devices, the RS-232C interface driver allows the TxD line to send data only after a defined instruction at the RxD data input is previously received by the device. It is obvious that the device requiring such an instruction must be connected to the computer by at least a three-wire cable. As we tend to reduce the number of wires in the RS-232C interface cable, the absolute limit is a single wire—an optical fiber, connecting the TxD2 output of the measuring device optically with RxD1 input of the computer. The use of an optical fiber, even in the form of one fiber, increases the line costs (an optical fiber is more expensive than an electrical wire), and implies the necessity of using converters of electrical signal into optical signal at TxD2 output, and converters of optical signal into electrical signal at RxD1 input. The advantages of optical signal transmission are high noise immunity, and small signal rejection on the optical fiber line. When using a telecommunication optical fiber with a rejection better than 0.2 dB/km, the line length may amount to many kilometers, and the transmission rate is not limited to electrical parameters of electrical cable.

Data exchange between DTE devices was standardized in a separate U.S. standard IEEE-1174, based on the RS-232C standard. The IEEE-1174 system bus has five lines, two of which are data lines (TxD and RxD), two control lines (RFR and CTS), and one ground line (SG). The CTS signal line has the same function as in the RS-232C standard. The RFR line, however, signals the readiness to receive data and replaces the RTS line of the RS-232C standard. According to the IEEE-1174, 9-pin connectors and a cable connecting two terminals are used in devices: five-wire or three-wire for the duplex transmission, as shown in Figure 6.9.



(b)

Figure 6.9 Null modem measurement system with the IEEE-1174 serial interface for the duplex asynchronous transmission: (a) signal-controlled transmission on control lines RFR and CTS; and (b) program-controlled transmission realized by means of XON or XOFF messages.

Data transmission between terminals is realized according to one of two protocols enabling transmission control: hardware control protocol and program control protocol. For the hardware transmission control, RFR→CTS line and a five-wire cable are used, as shown in Figure 6.9(a). A device ready to receive data (e.g., DTE1) informs the opposite terminal (in this example, DTE2) about the logical state 1 at RFR output (logical state 1 on control line is denoted by ON or True). Lack of readiness (e.g., due to terminal shutdown) is signaled by the logical state 0. The program control of data transmission consists of transmitting a message about the readiness to receive data XON or about lack of readiness XOFF through the TxD→RxD data line. The XOFF message results in delaying the start of sending data or in suppressing data transmission (e.g., in the case of overload of registers in the data receiving terminal). The XON and XOFF messages are transmitted as ASCII-coded characters. For the program-controlled duplex transmission, the number of wires in the interface cable is limited to three, as shown in Figure 6.9(b).

6.3 PROGRAMMING OF MEASUREMENT SYSTEM WITH THE RS-232C INTERFACE

6.3.1 Programming of the Null Modem System

The manufacturers of digital measurement instruments equipped with the RS-232C interface driver usually provide their own (standard) computer programs designed to control data transmission from a measuring device to a computer and to data processing and presentation. The use of such a program makes the completion of a measurement system much easier, but it implies limitations resulting from the fact that the program does not fit individual measurement tasks. The elaboration of an original computer program to control measuring data transmission and data processing avoids such limitations. Programming is easier, since one of the generally used programming languages of visual (object) programming is applied. In high-level programming languages, such as Visual Basic or Delphi, there are procedures prepared for both serial transmission service in the RS-232C system and data processing. To illustrate the programming mode, in this section we discuss two examples of programs for controlling data transmission between a multimeter and a computer. These are the ScopeView program prepared by Metex Co., and an original Thermo program written by an author in Visual Basic. Metex Co. is a significant provider of digital devices for the instruments market, and therefore, the computer program may be useful to the users of Metex meters with the RS-232C interface.

6.3.2 ScopeView Program for the Metex Multimeter

The ScopeView program, supported by the Metex Corporation with the Metex meter of type M-4650CR, is presented next [1]. The program enables communication between the meter (instrument) and the computer, measuring data and presenting results on a computer screen. It allows data recording to a text file for further processing.

Data transmission from the meter is realized in the form of 14 characters, including the result of the measurement and information on the settings of the measured value and the measuring range. The transmission parameters for a meter of type M-4650CR, given in the form [1,200, *n*, 7, 2], determine the transmission rate of 1,200 bps and the SDU format (the character format): *n*—no check even parity bit, 7—the number of bits of data character, and 2—the number of stop bits. The digital meter should be connected to a computer by means of a five-wire cable. The cable includes two signal lines (TxD and RxD), two control lines (RTS and DTR), and a signal ground line (SG). After connecting the meter supply from its front panel and running the computer program, the main menu of the program appears on the screen, as shown in Figure 6.10.

Figure 6.10 Main menu of the ScopeView program.

Apart from the main menu, the multimeter display can be seen on the screen, on which the following elements are displayed: the value of measured electrical quantity, together with its unit, and additional dc or ac signs. In order to configure the system, the Setup option should be run with Setup button, and the system parameters should be set (see Figure 6.11). The configuration concerns the type of Metex meter, the COM port number, and the transmission rate.

Figure 6.11 Setup window of the ScopeView program.

After returning to the main menu and turning on the power supply in program mode with Power button, the meter indicates the value of measured quantity on a digital indicator and an analog barograph (linear scale). This picture is also displayed on the computer screen, as shown in Figure 6.12. The measured quantity and the measuring range are chosen by means of the range switch on the front panel of the meter. In the program main menu the options Scope, Logger, or Meter can be chosen by means of icons with these names. The choice of Scope icon opens the ScopeView Control Panel window, as shown in Figure 6.13, in which the parameters of graphic presentation (diagram) of the measurement results in the function of time are selected. Four groups of presentation parameters are set:

- Automatic or manual choice of vertical scale for ScopeView (Auto Scale On), which leads to determining the resolution in the units of the quantity measured (e.g., 1 V/div);
- Sampling period in seconds or minutes (Time Base), (e.g., 10 s/div);
- Mode of triggering the measurement (Trigger On);
- Presentation parameters on the time axis (Sweep Mode). Possibilities include the presentation of one "screen contents," which means the diagram stops after reaching the end of the time axis (Single Sweep) or the diagram shifts on the horizontal axis to the left after reaching the end of the time

axis (Repetitive); the diagram stretches on the horizontal axis after the choice of a coefficient by means of buttons below the Sweep Magnify caption.

Figure 6.12 Main menu of the ScopeView program and the device indications after configuration.

Figure 6.13 The setting panel of the parameters of graphic presentation of the ScopeView program.

From the Control Panel window, it is possible to pass to the window of graphic presentation of the results (Scope button), to record the measurement data to file (Record button), or return to the main menu by means of the Close button. After choosing the Scope button, one can pass to the ScopeView Output window. This window, with an example of presentation of the results of measurement at constant voltage, is shown in Figure 6.14.

Figure 6.14 Graphic presentation of the results of measurement at constant voltage; settings: vertical scale 0.75 V/div, horizontal scale 15 s/div.

The measurement process is started with the Run button, while the function of the Record... button is to record data to file, and the Close button returns to the main menu. The choice of Meter—the last button of the main menu—opens the DMM Remote Display window, as shown in Figure 6.15. On the left side of the monitor, the current measurement result can be seen, and on the right side, a series of measurement results recorded in computer memory at the request of the system operator.

Figure 6.15 Presentation of measurement results.

The choice of the Logger icon from the program main menu opens the Data Logger Control Panel window, as shown in Figure 6.16. Within this window the following registration parameters can be set:

- Filtering of measurement results by means of the Window Comparator Data Filter, in which the Hi Limit and the Lo Limit are set independently; measurement data with values included within the window (Read Data Within Window) or data from outside the window (Read Data Outside of Window) are accepted;
- Sampling period (Time Base), independent from the period chosen in the Scope block;
- Delay (Logger Delay) between the beginning of measurements and the beginning of data registering by the computer.

The ScopeView program has a few possibilities of presenting measurement data as both the readout field of the measuring instrument and the time diagram of a series of measurements. Another form of data processing is data filtering. The program enables recording of a series of data to file from a few program windows.

Figure 6.16 Measurement parameters settings.

6.3.3 Thermo Program for Temperature Measurements

The Thermo program provides communication between the digital multimeter and the computer. The program is written in the high-level language Visual Basic (VB). The programming in Visual Basic embraces three stages:

- The first stage consists of choosing icons of objects for all necessary procedures from the Toolbox set. The Toolbox set is a part of the Visual Basic program, but in each version of the program, a different content of the Toolbox is included. Every icon from the set can be chosen many times, if the procedure assigned to the icon should be repeated many times for smooth operation of the program.

- In the second stage, the chosen objects are given suitable properties.
- The third stage consists of step coding, wherein short programs for objects are written, describing the operation of these objects and containing other data (e.g., addresses or formats of the operations).

The writing of the program in the high-level language Visual Basic is possible, provided that the installed version of the VB contains two special procedures that are not accessible in every version of VB. These are the MSComm procedure to the service of the serial port, and the Timer procedure (the clock) to the interruptions handling. Icons—symbols of these procedures—are shown in Figure 6.17.

Figure 6.17 Icons of the service of the serial port MSComm (two used icons in two versions of the language Visual Basic), and the icon of the Timer.

The functions of the Thermo program embrace:

- Sending the request of the measurement result transmission from a PC to a digital instrument (sending the D character through the TxD line is required);
- Sending the measurement result from a digital instrument to a PC. The result is formed by 14 characters (i.e., an SDU);
- Displaying the measurement result on the computer monitor;
- Stopping the data transmission from the instrument after sending a series of 18 results;
- Displaying the graph of results of a series of 18 measurements;
- Stopping the data transmission;
- The sound signal (beep signaling) of interrupting or ending the data transmission.

The handling of the program consists in control realized from the screen with buttons Start, Stop, and End. The result of the first step of programming is shown in Figure 6.18—the chosen objects. There are three control buttons visible in the figure: Start, Stop, and End, the etiquette of the result, the graphic object (the diagram), and the already mentioned Timer and MSComm.

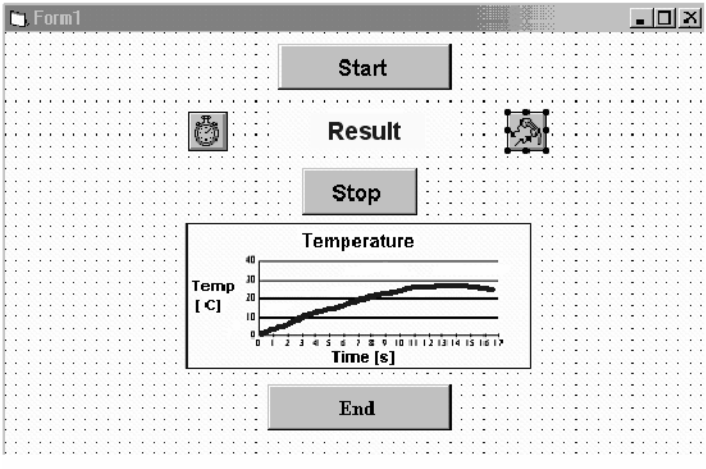


Figure 6.18 Screen view after the first stage of programming in VB language.

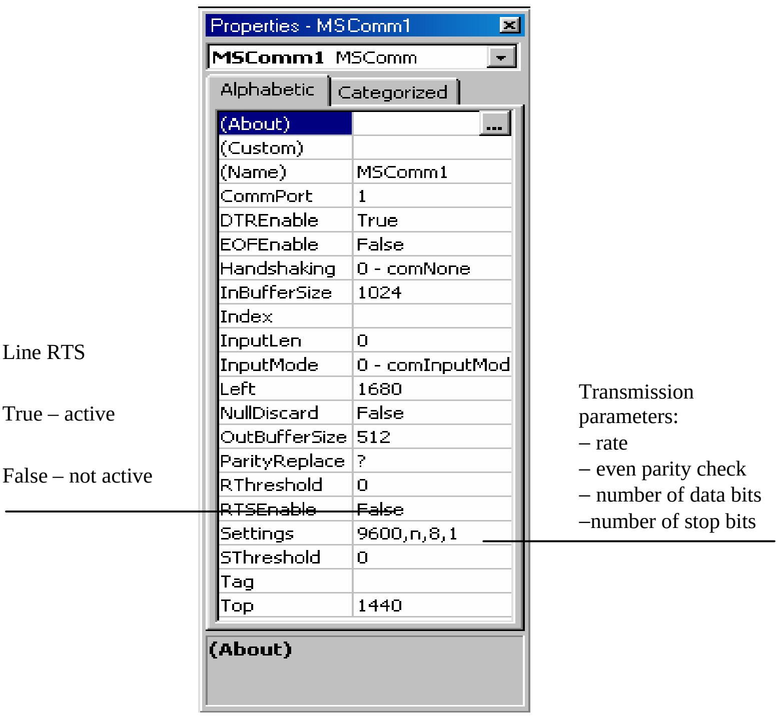


Figure 6.19 Window "Properties" of the object MSComm (service of a serial port).

In the second stage of programming, the proprieties are assigned to objects. The proprieties are assigned to every object visible in the Form1 are shown in Figure 6.18. For example, in Figure 6.19 the view of the Properties window is shown for the MSComm object of the service of the serial port in the state of default settings. In the Thermo program, the following options are chosen: the serial port Comm1, the state of the line DTR = True, and the state of the line RTS = False. The assumed (default) parameters of the transmission can be changed into the following values: the transmission rate—2,400 bps, the even parity check—n (no parity check), the number of data bits in one character—7, and the number of stop bits—2.

The third stage of programming comprises the coding of operations executed by objects. The code is written by means of well-known symbols of the Basic language. Codes of all operations of the Thermo program assume possible reproduction of the program by the reader and its usage in a given or fully developed form. In a listing given below, comments to the program are marked with italics. Comments are neutral for the program operation. Each comment starts with the character ‘, and finishes with Enter (passage to the new line). The procedure of programming in the VB language requires a double-click on an object or an area to open the code form.

1. The code of a form area for.Thermo

```
    ‘To declare a Table with a dimension 18
    Dim TabResult(18)
    ‘To declare an Indicator
    Dim i
    ‘To declare Variable
    Dim Result
```

2. The code of the Start button

```
    Sub cmd_Start_Click ()
        ‘To open the serial port Comm1
        Comm1.PortOpen = True
        ‘Start of a clock Timer
        Timer1.Enabled = True
    End Sub
```

3. The code of the Stop button

```
    Sub cmd_Stop_Click ()
        ‘To close the serial port Comm1
        Comm1.PortOpen = False
        ‘Stop a clock Timer
        Timer1.Enabled = False
    End Sub
```

4. The code of the End button

```
Sub cmd_Koniec_Click ()
    'Beep signalization
    Beep
    End
End Sub
```

5. The code of Timer object

```
Sub Timer1_Timer ()
        'To send a sign D from a computer to an instrument
        Comm1.Output = „D"
        'To read data from a serial port
        Result = Comm1.Input
        'To send a result to a display Result
        lbl_Result.Caption = Result
        'To write data in results Table
        Tab.Result(i) = Result
        i = i + 1
        If i = 18 Then
        i = 1
        End if
'To write data for a graphical display
        gph_Termo.GraphData = Val(Mid(Wynik, 7, 2))
    End Sub
```

6. The code of MSComm object

```
    Sub Comm1_OnComm ()
        'To send a sign D from a computer to an instrument
        Comm1.Output = „D"
        'To read data from a serial  port
        Result = Comm1.Input
        'To send a result to diplay Result
        lbl_Result.Caption = Result
        'To write data into the Table
        Tab.Result(i) = Result
        i = i + 1
        If i = 18 Then
        i = 1
        End if
    'To write data for plot drawing
        gph_Termo.GraphData = Val(Mid(Result, 7, 2))
        'To Draw a graph
        gph_Termo.DrawMode = 2
        End Sub
```

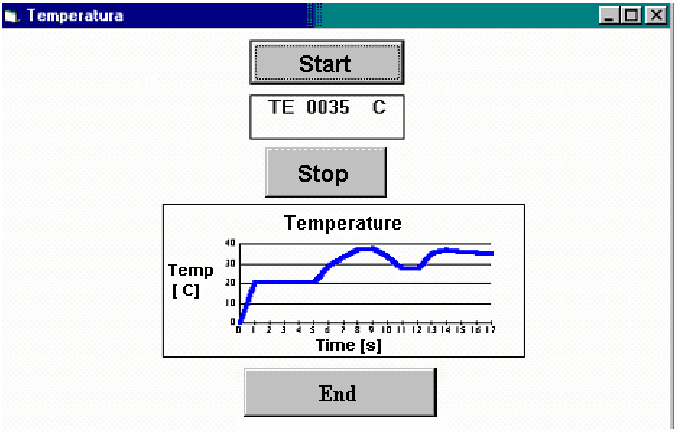


Figure 6.20 Screen view of temperature measurements according to the Thermo software.

The results of Thermo program are temperature measurements indicated in the *Result* field, and realized by means of a Metex ME-22 type multimeter, displaying the measurement result on the screen and showing the temporary graph of the temperature for 18 consecutive measurements, as shown in Figure 6.20. The program can be considerably enhanced in data processing and displaying. Individual programming of a simple measurement system composed of a PC and a digital instrument assures the flexibility of the program and its adaptation to the user's individual requirements. In this respect, it is a better type of system software than the use of standard softwares, like ScopeView.

6.4 MEASUREMENT SYSTEMS WITH THE RS-232C INTERFACE AND MODEM

6.4.1 Modem

A typical serial interface system for digital data conversion between DTE1 terminals and DTE2 over a telephone line includes two modems (i.e., *mo*dulation-*dem*odulation devices), denoted with DCE1 and DCE2 symbols, as shown in Figure 6.1. The modem function in the serial interface system is to convert digital data into analog signals transmitted over telephone lines, and to convert the received analog signals into digital signals in the data receiver, as shown in Figure 6.21.

It should be mentioned that modems as separate devices connected to a computer (DTE terminal) by the RS-232C interface are now almost completely replaced by modems produced as modem boards (or cards) installed within the computer, or as devices installed on the computer motherboard. Analog telephone networks transmit signals in a frequency range from 300 to 3,400 Hz, and the frequency of signals transmitted by modems must be included in this range. Modems cooperating with telephone networks of greater transmission rate (e.g., digital networks, optical fiber telephone networks) must satisfy different requirements.

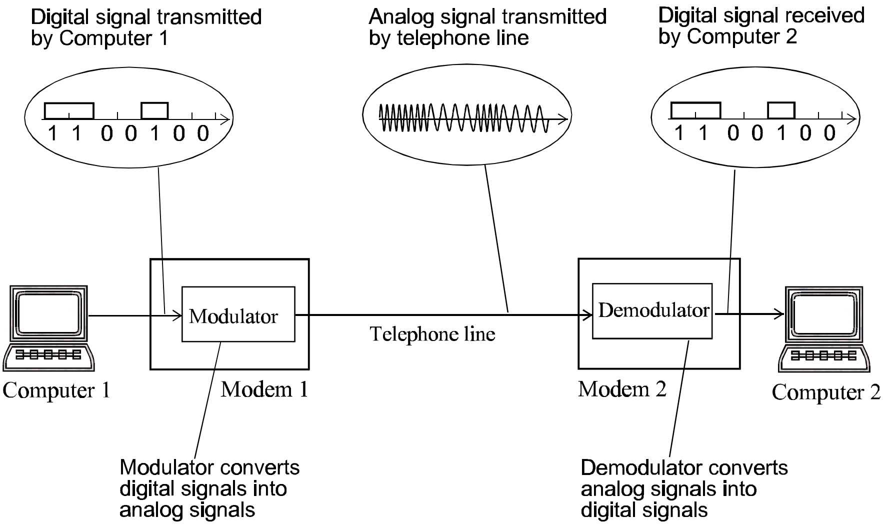


Figure 6.21 Digital data transmission by means of modems over a telephone line.

Modulation

The fundamental problem concerning a modem is the choice of the mode of digital data modulation. The signal transmitted over telephone lines is a carrier (wave) in the form of sinusoidal signal:

$$v(t) = V_a \sin(2ð f + j_o) \tag{6.5}$$

Modulation consists of making one of the carrier parameters dependent on the modulation signal, which is in the case of modems a binary signal. Then, modulation in a modem concerns the values of amplitude V_a, frequency f, or phase $j = (2\pi f + j_o)$ of the carrier, or more than one of these parameters at the same time. Simple modulation modes are the following:

- *Amplitude Shift Keying (ASK)*. It consists of giving the transmitted signal a greater amplitude to code logical 1, and a lesser amplitude to code logical 0. The carrier frequency is constant.

- *Frequency Shift Keying (FSK).* It consists of assigning a greater signal frequency at coding logical 1, and a lesser signal frequency at coding logical 0. The carrier amplitude is constant.
- *Phase Shift Keying (PSK).* It consists of changing the signal phase by 180°, as the state of data logical changes from 1 to 0 or from 0 to 1. The carrier amplitude and frequency are constant. Types of PSK modulation are Differential Phase Shift Keying (DPSK), Binary Phase Shift Keying (BPSK), and Quaternary Phase Shift Keying (QPSK).

Modulation methods are illustrated in Figure 6.22. From these methods, the FSK modulation as well as some other methods enabling higher data transmission rate are currently used. The frequency band of an analog telephone line, from 300 to 3,400 Hz, is a serious limitation for transmission rate. Simple modulation of amplitude, frequency, or phase ensures a maximum transmission rate of 1,200 bps (FSK, V.23 protocol). Simultaneous modulation of two carrier parameters can ensure a much higher data transmission rate. Two such methods are applied in modems—Quadrature Amplitude Modulation (QAM), and Trellis Coded Modulation (TCM).

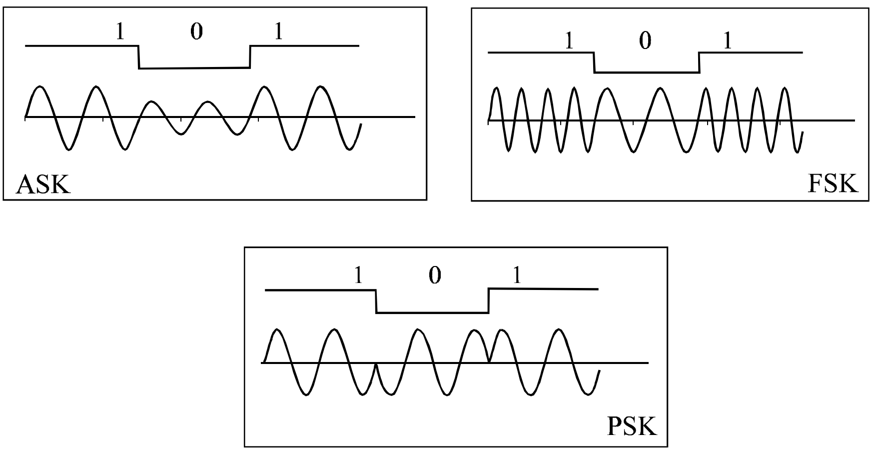


Figure 6.22 Comparison of modulated signals after the Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), or Phase Shift Keying (PSK) modulation.

QAM is a combination of ASK and DPSK, as shown in Figure 6.23. Three-bit binary words can be coded by changing the carrier signal phase by one of four phase angles (0°, 90°, 180°, and 270°), and changing the signal amplitude (e.g., $0.5V_a$ or V_a). As compared to the ASK or PSK modulation, this is a method for transmitting three times as many bits. When in the QAM, the carrier amplitude takes on four values instead of two, and a single change in the signal state enables coding a 4-bit word. The QAM modulation with a four-level amplitude signal allows the modems to transmit data at a maximum rate of 9,600 bps (V.29 protocol).

The TCM coding is a result of a series of operations—convolution coding and QAM. Discussion of the TCM modulation is not included in the scope of this handbook. The TCM modulation enables data transmission at a maximum rate of 56 kbps.

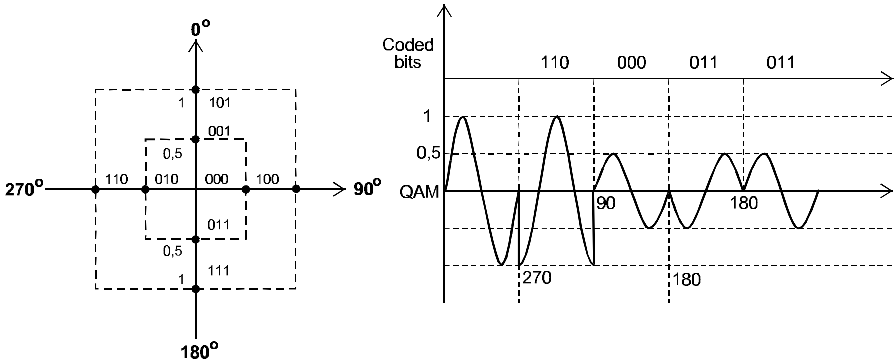


Figure 6.23 Quadrature amplitude modulation.

Protocols

Processing data by a modem is realized according to defined procedures named protocols. Three basic types of protocols are distinguished:

- Protocol of modulation;
- Protocol of error correction;
- Protocol of data compression.

The modulation protocols are used for coding digital signals. They define coding methods and transmission rate. The basic modem (transmission) rate is strictly dependent on protocols recognized by the modem. One of the first modulation protocols, which became an international standard, was a protocol proposed by CCITT, and defined as V.22bis. This standard applies the QAM modulation, and enables a transmission rate equal to 2,400 bps. Higher transmission rates are ensured by V.32, V.32bis, and V.34 protocols. The first is a standard for modems operating at a rate of 9,600 (and 4,800) bps. It uses the TCM modulation. It was accepted by CCITT in 1984, but modems applying the protocol were introduced into the market only at the beginning of the 1990s; the reason was the very high price of the modems.

Almost all modems with a transmission rate of 9,600 bps (or higher) have an emulation of this standard. The V.32 transmission protocol has become a world standard. The V.32bis protocol was established by CCITT in 1991 as a standard for 14.4 kbps modems. It can certainly also operate at a lower transmission rate. The third CCITT protocol, denoted as V.34, was established in 1993 as a standard for 28.8 kbps modems.

The highest transmission rate for modem connection is now 56 kbps. It is achieved by means of three protocols: the V.90 protocol established by the International Telecommunication Union (ITU), K56flex protocol established by the Rockwell Company, and the X2, created jointly by 3Com and U.S. Robotics. These standards have the asymmetric data transmission, which enables them to send a maximum of 33.6 kbps data and receive a maximum of 56 kbps data. This technique is useful for Internet connections because much more data is always received from the Internet (e.g., Web pages, FTP, and Internet broadcasting) than sent through the Internet.

There is an opinion that modems with the V.90 protocol are the last analog devices designed to realize communication over telephone lines, because the rate of 56 kbps is very close to the rate of 64 kbps, theoretically possible in transmission by means of analog signals in the band from 300 to 3,200 Hz.

6.4.2 System with the RS-232C Interface and Telephone Modem

The system of data exchange with the RS-232C serial interface in full version (with telephone modem) can also play the role of a measurement system. A measurement system block diagram is shown in Figure 6.24. Communication between modems by means of Public Switched Telephone Network (PSTN) can be realized over a commuted (switched) line or a leased line.

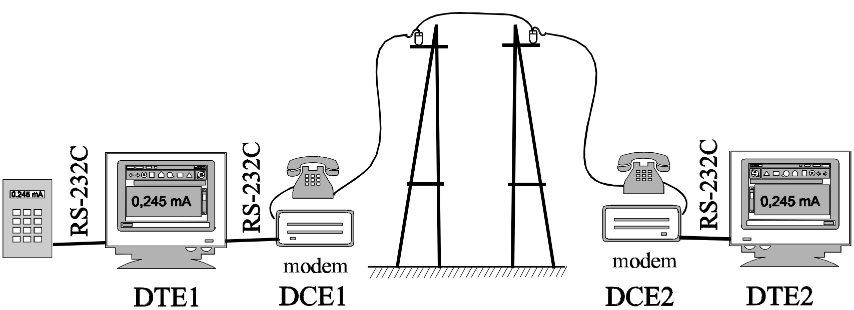


Figure 6.24 Measurement system with the RS-232C serial interface and modem.

The commuted line is established by the ordinary dial-up of a receiving station number, by switching telephone lines in telephone exchanges, and by establishing communication if there are no interrupts. The leased line is a dedicated line between stations (modems) without a need to dial the recipient’s number, and without a risk of an interrupt (e.g., the number is busy). The payment for leasing a telephone line from a network operator is higher than a regular payment for a switched line. In most cases communication between DTE devices by means of DCE and a telephone network is realized by the switched line. We will now discuss an example of communication between the devices shown in Figure 6.24 performed over the switched line in the semiduplex mode. The names of signal lines and the pin numbers to connectors are given in Table 6.1.

Semiduplex Transmission over the Switched Line

Let us assume that the operator of a DTE2 computer requires the results of measurements registered in a DTE1 computer. The communication will be established by dialing the telephone number of the DCE1 modem, which corresponds to the ring and is signaled by the active state of RI line in DCE1, as shown in Figure 6.25.

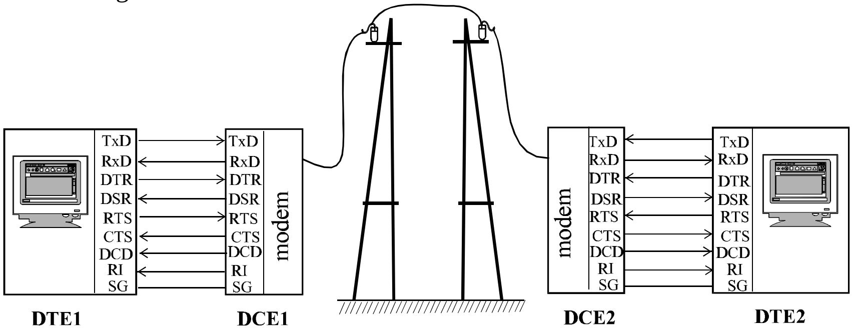


Figure 6.25 Control signals in a measurement system with a modem for asynchronous transmission over the commuted line.

When the DTE1 computer is ready to exchange data, there is an active state (logical 1) at its DTR1 output. In such a case, DCE1 at its DTR1 output sends a signal to the DCE2 modem, informing about the readiness of the DTE1 computer to exchange data. The DCE2 modem informs "its own" computer about that with an active signal on the DSR2 line. After checking if there is also an active state at the DTR2 output of the DTE2 computer, communication will be established, and the DTR output states remain active for the entire duration of the connection.

The procedure of exchanging data between terminals starts with sending the RTS1 signal (*Request To Send*, RTS1 = 1) by the DTE1 computer. After receiving the signal, the DCE1 modem checks if the transmission line is free. In the semiduplex transmission mode, only one transmission line is used. If the active state in RTS2 was set earlier than in RTS1, then the state of the DCD1 output will be active (DCD1 = 1), the transmission line will be busy, and the data transmission from the DTE1 computer to the DTE2 computer must wait until the DTE2→DTE1 transmission is terminated. If the transmission line is free, then the DCD1 output of the DCE1 modem is inactive, DCD1 = 0. The modem informs "its own" computer DTE1 about the free line, activating the CTS1 output (*Clear To Send*, CTS1 = 1). After receiving the CTS1 = 1 signal, the DTE1 computer can send data through the TxD1 output. After sending the prepared data packet, the state of the RTS1 output changes from 0 to 1, and then the logical state of the DCD2 output is changed from 1 to 0, which for the DTE2 computer is a signal that the transmission line is free. The transmission line will be occupied again by the computer that first signals the data send request at its RTS output. In case of no RTS signal, the connection between modems should be interrupted.

The DTR output of each computer is in an inactive state (logical 0) when the computer is disconnected from a power supply or from a modem. A change in the DTR line state from 1 to 0 will occur also after a manual or program command of connection termination. The program mode of type "connection termination" after exchanging a standard amount of information is particularly efficient, due to reducing the connection duration and diminishing the costs. The program mode of communication termination is frequently used as electronic mail, and is operated by means of a modem.

Duplex Transmission over the Switched Line

Setting up a connection between DTE1 and DTE2 terminals to realize the duplex transmission requires the same procedure as described for the semiduplex transmission. During the connection, the DTR outputs of both computers must be active (DTR = 1); however, the procedure of data exchange is simpler. As we have two transmission lines between the DCE1 and DCE2 modems, there is no need to check the line occupancy and to control the direction of data transmission. The states of the RTS outputs of both computers and the CTS outputs of both computers can be active (and usually are active) for the whole duration of the connection.

Semiduplex and Duplex Transmission over the Leased Line

Transmission over the leased line is used in the case of exchanging measuring and control data between devices of great technical or economic importance, as shown in Figure. 6.26. The duplex transmission over the leased line does not require either connection start-up or establishing the direction of data transmission. Therefore, the signal lines RI, DTR, RTS, and CTS are not used, and their states may be emulated, as it is in the null modem system. The duplex transmission may be realized continuously, and the control signals, which suppress the transmission, are inactive signals DSR1 or DSR2 at the outputs of modems. The inactive state at the DSR output will occur in the case of disconnection of the modem supply or a modem fault. Remote measurements (telemetry) and remote control engineering (telemechanics) over the leased line are economically justified in areas such as electrical power engineering and thermal engineering.

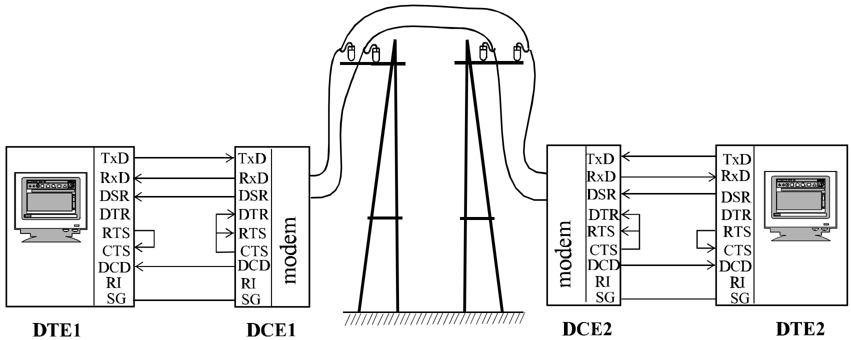


Figure 6.26 Control signals in a measurement system with modem for the duplex transmission over the leased line (two transmission lines).

6.4.3 Programs for Data Transmission Control in a Distributed Measurement System

The distributed measurement system with a telephone line as the communication channel is shown in Figure 6.27. There are the following functions of devices in the distributed measurement system:

- Functions of digital measuring device: acquisition of measuring data accessible in digital form at the device output;
- Functions of the transmitting computer with the DTE/DCE1 modem: measuring data acceptance and registration, text or graphic file creating, and realizing communication with the modem of the receiving computer;
- Functions of the receiving computer with the DTE/DCE2 modem: realizing communication with the modem of the transmitting computer, accepting data as files, measuring data processing, and the presentation of results.

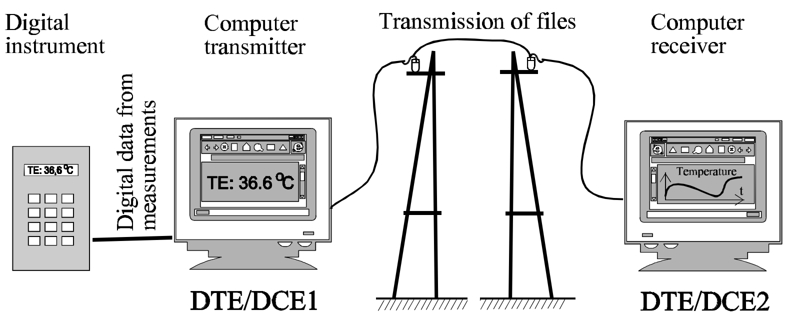


Figure 6.27 Functions of devices in a distributed measurement system with a telephone wire communication channel.

In Figure 6.27, the DTE/DCE1 computer is usually designated as the transmitting computer, due to its role of sending files with measuring data, and the DTE/DCE2 computer is designated as the receiving computer, because its main role in the system is to accept files with data and data processing. In the mode of duplex or semiduplex transmission, both computers have a twofold function: information transmitters and receivers. The DTE/DCE2 computer may be the transmitter of files with instructions controlling the measurements, which will be received by the DTE/DCE1 computer earlier than by the measuring device.

Dedicated softwares control the communication between computers in a measurement system, in order to send text or graphic files with measuring data or files with control instructions. Data exchange between computers in a measurement system may be realized in the form of sending electronic files by e-mail. This mode of data exchange in a measurement system is not recommended due to delays in communication.

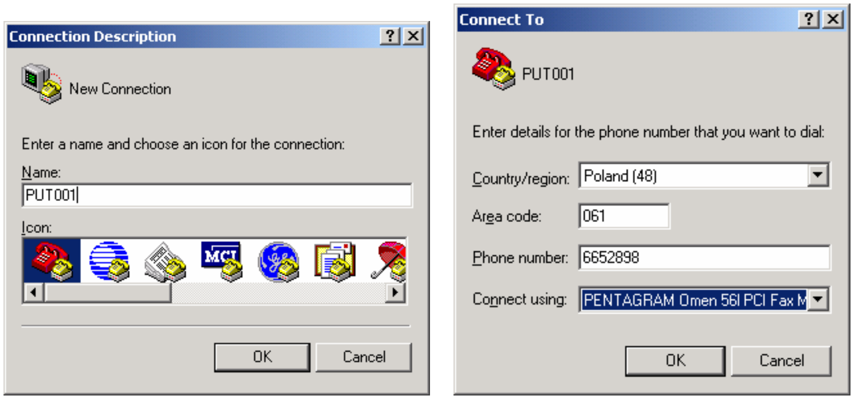
The HyperTerminal (HT) program may control files transmission through a modem and over the public switched telephone network PSTN. This program is included in the Windows operating systems (Windows 98, Windows 2000, and Windows XP), and is accessible in the menu (Programs ▸ Accessories ▸ Communication ▸ HyperTerminal).

The HyperTerminal program Version 1.2 (and later version) includes the Telnet program, the Zmodem program for file recovery after a fault, and the number redial function in the case of the telephone line being busy.

A mode of communication configuration between the transmitting computer and the receiving computer (named PUT001 station here) is presented. After running the HT program, it sets up a new connection, and chooses the icon of this connection, as shown in Figure 6.28(a).

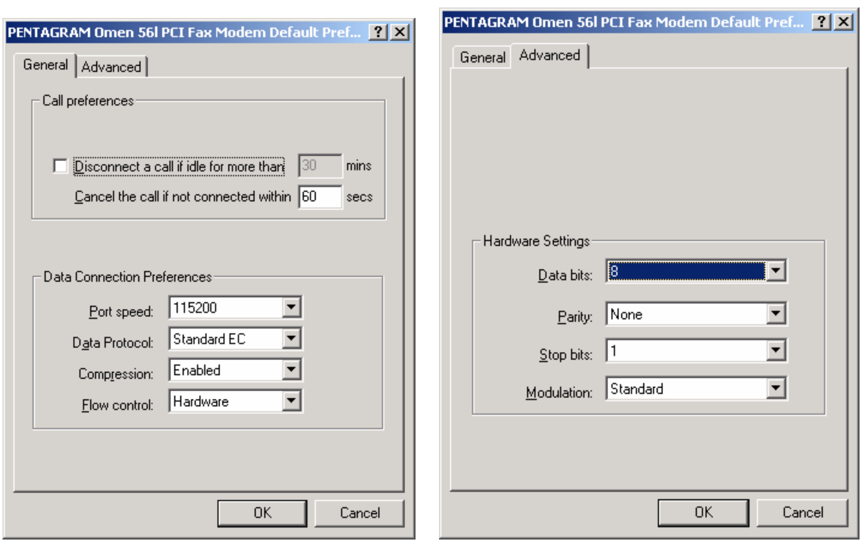
After establishing the telephone number for the receiving modem and the type of modem (the assumed modem type is the modem type installed in the computer), the basic parameters of transmission and ring indicator [see Figure 6.29(a)], as well as advanced parameters, are defined [see Figure 6.29(b)]. It should be emphasized that each connection of a computer to a peripheral device with an RS-232C or IR link has the data transmission parameters set separately and independently. It concerns both the number of data bits, the number of check and stop bits, and the transmission rate. Thus, for the computer-measuring device link, the serial transmission parameters are different from the parameters of (the same) computer-modem link. After establishing the connection parameters, the transmission may be prepared.

The transmission requires not only turning on the DTE/DCE2 computer, but also running the HyperTerminal program in this computer. After running the HT program in the DRE/DCE2 computer and choosing the icon of the transmitting computer, from which the data is expected, the ready to receive data state should be ensured by choosing the *Wait for call* option from the *Call* menu. In the DTE/DCE1 computer the icon of the sending station should be chosen and the command *Dial up* should be sent.



(a) (b)

Figure 6.28 Establishing the connection parameters in a system of data transmission: (a) establishing the receiving computer name and icon; and (b) establishing the telephone number (phone 6652898) of the modem of the receiving computer and the modem type of the transmission computer.



(a) (b)

Figure 6.29 Establishing the connection parameters in a system of data transmission: (a) the basic transmission and ring indicator parameters; and (b) advanced parameters.

After establishing communication we choose the *Transmission* command and the *Send file option* from the menu. The *Send file* window appears, as shown in Figure 6.30, which enables us to choose a file to be sent, and to send the file.

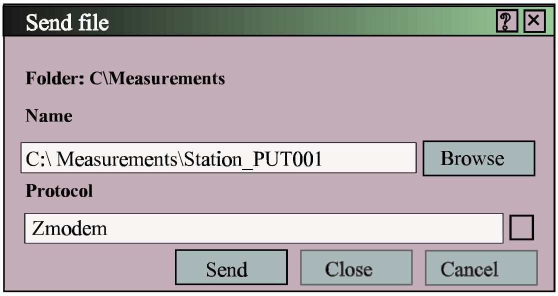


Figure 6.30 The window of the file choice and the send file command in the HyperTerminal program.

In the *Protocol* option of this window, the following transmission protocols can be chosen:

- Xmodem: widespread; the check sum is added to files with a capacity of 128 bytes;
- Ymodem: enables the transmission of a few files, one by one;
- Zmodem: enables a quick and immune-to-noise transmission; an advantage of this protocol is a possibility of retransmitting a file from the point of transmission interrupt.

After sending a data file, the next file may be sent by repeated use of the *Send file* window. A disadvantage of the HyperTerminal program in its application to data transmission in a measurement system is the time delay in receiving data, caused by the necessity to create a file from a series of measurements before sending the file. A great advantage of the HT program is the fact that it is supported in widely used Windows operating systems, which enables data transmission without designing or purchasing another program.

The *Measurement* software was elaborated at the Poznan University of Technology [2]. It is written in Visual Basic and consists of two procedures.

1. The procedure controlling the beginning and the end of measurements, and controlling the data transmission from the measuring device to the computer.

2. The procedure controlling the data transmission from the sending computer over a modem and PSTN network to the receiving computer.

The software must be installed in both the sending and the receiving computers. This software enables the semiduplex transmission of measurement and control data. It is an example of an original software, which takes into consideration individual requirements of the measurement system user. A connection configuration is also necessary in this case, including the establishment of the number of data bits, the check bit, the stop bit, and the transmission rate. One of the individual tasks is the possibility of remote or local measurement control. It means the possibility of controlling the measurements from the desktop of each of two computers in the system. The need for such a function can be easily imagined. The system operator works at the receiving computer, and gives the command to start the measurement in a distant station, at which the measuring device and the sending computer are located (see Figure 6.27). After receiving a series of measurements, the operator can terminate the measurements and their transmission. It is obvious that remote work is only possible if the connection between the DTE/DCE1 and DTE/DCE2 modems are set up and the *Remote operation* state still exists. The *Remote operation* window in the *Measurement* software is shown in Figure 6.31, for the transmitting computer in Figure 6.31(a), and for the receiving computer in Figure 6.31(b). A useful function of the *Measurement* program is transmitting the received data to the Excel program, and processing the data in the form of tables or diagrams.

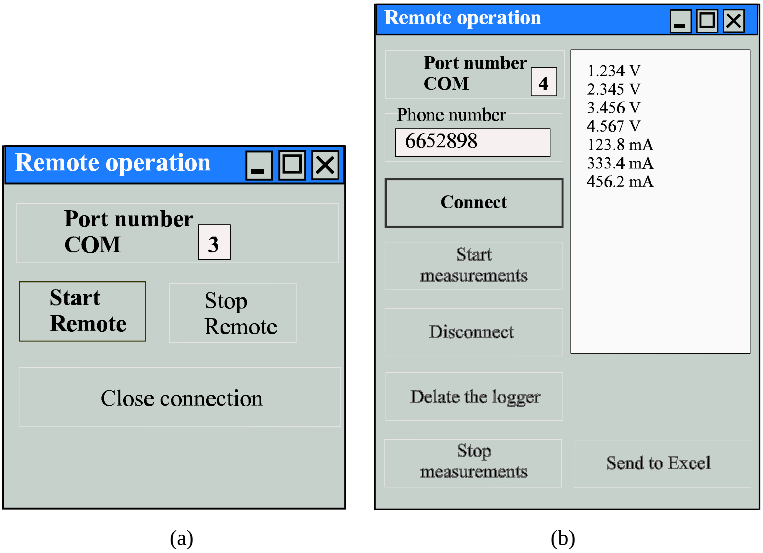


Figure 6.31 "Remote operation" window in the *Measurement* program: (a) for the receiving computer, and (b) for the transmitting computer.

6.5 OTHER SERIAL INTERFACE SYSTEMS

6.5.1 RS-449 and RS-530 Serial Interface Systems

The RS-232C interface system is used most frequently for series data transmission in measurement systems. However, this standard imposes many significant limitations on building measurement systems.

The most important are:

- The limit of the 15-m length of the wire line-connecting devices;
- The low transmission rate, up to 20 kbps;
- The number of digital devices included in the system, two.

Therefore, several serial interface systems were produced and standardized, with properties better than the parameters of the RS-232C. The RS-449 and the RS-530 standards are used most frequently; they determine the functional and mechanical parameters of serial interface. The parameters of electrical circuits for those two standards are included in the RS-423A, the RS-422A, and the RS-485 interfaces. In the RS-423A, the RS-422A, and the RS-485 interfaces the signal line immunity to noise is considerably higher since differential transmission circuits are used. In the RS-423A interface, the transmitter output is defined as asymmetrical (signal "hot" wire has reference to ground), and the receiver output as differential. The RS-422A and the RS-485 interfaces have fully differential transmission circuits.

The RS-449 serial interface standard includes the functional and mechanical parameters of the interface system designed for remote data transmission with or without a modem. A 37-pin connector and 35 lines in the interface bus were defined for that standard. In the RS-449 interface, an additional 9-pin connector is assumed in the case of installing the secondary channel, which is, however, used quite rarely. The greater number of lines needed in the RS-449 interface to realize data transmission with modems results from the existence of 10 differential transmission circuits, in which one signal is transmitted through two wires, denoted by A and B indices. For example, the transmitted data line is formed by a pair of wires connected to SDA and SDB pins (pin numbers 4 and 22 on a DB-37 connector), and the control line "data send request" RTS is formed by a pair of RTSA and RTSB. The greater number of signal lines of the RS-449 interface are not always needed, and the DB-37 connector is not practical for installation on the device case because of its size. Therefore, the RS-530 standard was elaborated as a modification of the RS-449 standard with fewer lines (25 lines) and a 25-pin DB-25 connector. There are no relevant functional differences between the RS-449 and the RS-530 standards. A list of signal lines and ground lines, together with the pin numbers on the connectors of both standards, is given in Table 6.2.

The rules of establishing communication and realizing transmission in a system with the RS-449 or the RS-530 interface are similar to those described in Section 6.4.2 for a system with the RS-232C interface. However, the possible transmission rate between the devices is much higher.

Table 6.2

Bus Lines of the RS-449 and the RS-530 Serial Interfaces and the Pin Numbers on Connectors

RS-449 Pin Number in DB-37	*Name in RS-449 Standard*	*RS-530 Pin Number in DB-25*	*Name in RS-530 Standard*	*RS-449 Line Description*
1	ground	1	ground	shield
2	SI	—	—	signal rate indicator
3	—	—	—	not used
4	SDA	2	TDA	send data A
5	STA	15	TCA	send timing A
6	RDA	3	RDA	receive data A
7	RTSA	4	RTSA	request to send A
8	RTA	17	RCA	receive timing A
9	CTSA	5	CTSA	clear to send A
10	LL	18	LL	local loopback
11	DMA	6	DSRA	data mode A (DSR)
12	TRA	20	DTRA	terminal ready A (DTR)
13	RRA	8	RLSDA	receiver ready A (DCD)
14	RLB	21	RL	remote loopback
15	IC	—	—	incoming call (RI)
16	SI	—	—	signal rate selector
17	TTA	11	TTA	terminal timing A
18	TM	25	TM	test mode
19	SG	7	GND	signal ground
20	RC	—	—	receive common
21	—	—	—	not used
22	SDB	14	TDB	send data B
23	STB	12	TCB	send timing B
24	RDB	16	RDB	receive data B
25	RTSB	19	RTSB	request to send B
26	RTB	9	RCB	receive timing B
27	CTSB	13	CTSB	clear to send B
28	IS	—	—	terminal in service

Table 6.2 (continued)

RS-449 Pin Number in DB-37	*Name in RS-449 Standard*	*RS-530 Pin Number in DB-25*	*Name in RS-530 Standard*	*RS-449 Line Description*
29	DMB	22	DSRB	data mode B
30	TRB	23	DTRB	terminal ready B
31	RRB	10	RLSDB	receiver ready B
32	SS	—	—	select standby
33	SQ	—	—	signal quality
34	NS	—	—	new signal
35	TTB	24	TTB	terminal timing B
36	SB	—	—	standby indicator
37	SC	—	—	send common

DB-37: 37-pin connector; DB-25: 25-pin connector.

In Table 6.3, the maximum transmission rate is given relative to transmission line length in the RS-449 or the RS-530 system, in which electrical circuits satisfy the requirements of the RS-422A or the RS-485 standards. The maximum transmission rates given in the table are difficult to achieve, since the PSTN is used.

Table 6.3

Maximum Rate of Data Transmission in the RS-449 or the RS-530 Interface System in the RS-422A or the RS-485 Circuits, Closed with Wave Impedance at the Ends

Transmission Line Length	m	10	17	40	100	1,000	1,200
Transmission Rate	bps	10^7	6×10^6	2×10^6	10^6	10^5	10^4 to 10^5

6.5.2 RS-485 and RS-422A Standards for Serial Interface Circuits

The RS-485 and the RS-422A serial interface standards determine the electrical parameters of circuits in the RS-449 or the RS-530 interface system. In the RS-423A, the RS-422A, and the RS-485, the immunity of signal lines to interferences is significantly improved with the use of differential (symmetrical) transmission circuits. The better interferences immunity results from of the difference of a signal voltage transmitted through two wires in the measurement line. If an electromagnetic field induces an interference voltage, the interference voltage value in both wires is almost equal, and the difference voltage is without interferences.

The differential I/O of a signal transmitter or receiver is also mentioned, which corresponds to the symmetrical I/O. In the case of the RS-423A interface, the transmitter outputs are defined as asymmetrical (i.e., signals have reference to ground), and the receiver input as differential. Two remaining interfaces have fully differential transmission circuits. The electrical parameters of the circuits in the RS-485 and the RS-422A standards have similar or identical values. The RS422 has no tri-state capability (i.e., its driver is always enabled), and it is therefore usable only in point-to-point transmissions. The RS-485 has tri-state capability, and can be used in multidrop systems. The RS-485 is more important than the RS-422A interface due to the structure of output circuits of its transmitters and is equipped with tri-state gates, as shown in Figure 6.32.

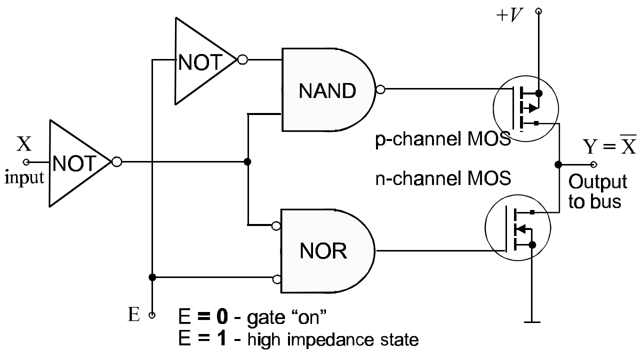


Figure 6.32 Logical diagram of inverter gate with a tri-state output (for E = 1, Y = the state of high impedance; E = 0 and X = 0, Y = 1; E = 0 and X = 1, Y = 0).

In tri-state gates, apart from the output signals corresponding to logical 1 or logical 0**,** the gate output may be in the state of high impedance. A transmitter in the RS-485 interface system, being in the state of high impedance, has no influence on the establishment of the logical state of the line to which it is connected. Therefore, more than one transmitter (up to 32 transmitters) can be connected to the RS-485 system bus. Only one transmitter can realize transmission at a given moment, and the remaining transmitters must be in the state of high impedance. In the RS-422A interface system, only one transmitter can realize point-to-point transmission.

Devices operating in the RS-485 system usually have a predefined function: *master* or *slave*. This corresponds in no way to the division of devices in a system into data transmitters and data receivers. Some of the system devices (e.g., drivers), may have the function of both the transmitter and the receiver. The *slave* device never starts communication with other devices in the system. In Figure 6.33, an example is shown of connecting a few digital devices to a pair of wires of the RS-485 interface bus in the null modem data transmission system.

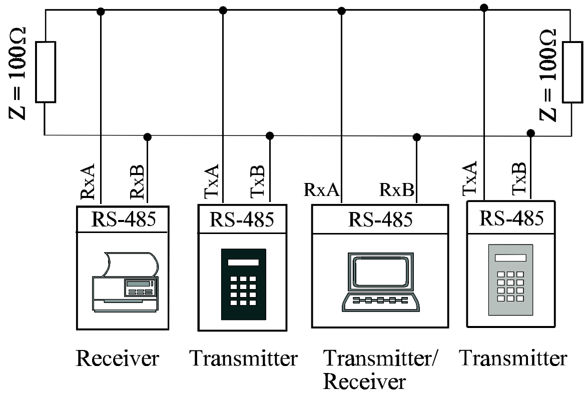


Figure 6.33 Connection of measurement system devices to the RS-485 interface bus.

The function of impedance devices Z in the measurement system shown in Figure 6.33 is to short each of the two ends of the transmission line with a distinctive wave impedance. The use of the Z elements avoids such wave effects on the lines as reflections or absorptions. The electromagnetic wave with a frequency of 10 MHz (maximum transmission rate) corresponds to the wavelength $l = c_w/f \approx 10$m (c_w is the rate of wave propagation in the wire, and $c_w \approx 10^8$ m/s). Due to the length l of the electromagnetic wave, which is less than the length of the transmission line, or is comparable to the length of line l (from a few meters to approximately 1 km), the influence of wave effects should be limited by matching devices Z. Usually, data transmission in the RS-485 (or the RS-422A) interface system is realized without a modem, and therefore the RS-485 standard is better known than the RS-449 (or RS-530) standard, which is necessary only when using modems.

In the RS-485 interface system data are always transmitted (using TxD and RxD lines), but the number of control signals in the system is very different. Sometimes in the system RS-485 one does not use control signals at all. Therefore, in the simplest version, a system of bidirectional transmission in differential circuits with the RS-485 devices can have a five-wire bus: TxA + TxB, RxA + RxB, and ground. Users and designers of serial interface systems take advantage of both the general usage of the RS-232C interface drivers and the good quality of transmission circuits of recently introduced interfaces, such as the RS-485. Therefore, in simple measurement systems, interface converters are applied, for example circuits converting the signals of the RS-232C interface into the signals of the RS-485 bus, as shown in Figure 6.34. According to the interface definition given in Section 6.1, such a converter is an interface in a strict sense, between the RS-232C system and the RS-485 bus. In Table 6.4, the basic parameters of the most important serial interfaces are compared.

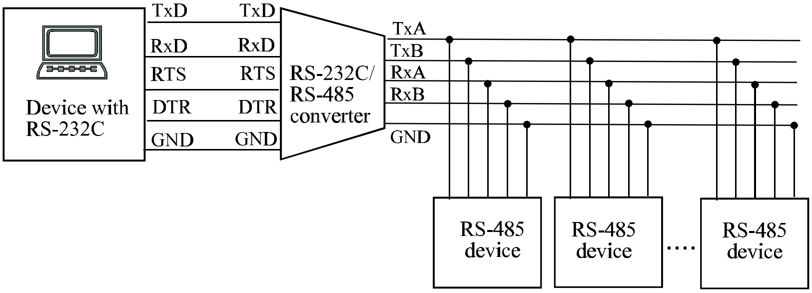


Figure 6.34 Measurement system with the RS-232C device, the RS-485 system bus, and the interface converter.

Table 6.4

Basic Electrical Parameters of Serial Interface Standards

Parameter	*RS-232C*	*RS-423A*	*RS-422A*	*RS-485*
Transmission Circuit	asymmetrical	asymmetrical	differential	differential
Number of transmitters (maximum)	1	1	1	32
Number of receivers (maximum)	1	10	10	32
Transmission rate	20 kbps	100 kbps	10 Mbps	10 Mbps
Cable length (maximum)	15m	1,200m	1,200m	1,200m
Output voltage of transmitter	minimum ±5V, maximum ±15V	minimum ±3.6V maximum ±6V	minimum ±2V	minimum ±1.5V
Load resistance of transmitter	3 to 7 kΩ	minimum 450Ω	minimum 10Ω	minimum 60Ω
Common voltage range	±25V	±6V	−0.25V to +6 V	−7V to +12V
Input resistance of receiver	3 to 7 kΩ	4 kΩ	4 kΩ	12 kΩ
Signal range	±3V	±200 mV	±200 mV	±200 mV

6.5.3 A Comparison of RS Serial Interface Standards

The RS-232C interface system is the most frequently used standard for serial data transmission, including the measuring data transmission. This standard, however, imposes a number of significant limitations on building measurement systems.

- The number of digital devices included in the system is limited to two.

- The length of the wire line connecting the devices is limited to 15m (without the current loop, which is described in Section 6.2.4).
- The standard transmission rate is limited to 20 kbps (transmission rate from the computer port may amount to 115.2 kbps, the value of 20 kbps is adjusted to the parameters of 15-m transmission line).
- The great susceptibility to noise of the line connecting the devices, due to asymmetrical wiring of interface lines.

Because of the great advantage of the RS-232 interface, the producers of measurement equipment offer computer boards with increased RS-232 ports, increasing the number of measuring devices that may be connected to a system. The computer boards produced by National Instruments enhances the RS-232 interface from 4 to 16 ports [3]. The boards offered can be connected to the PCI, ISA, or PCMCIA bus. For example, the PCI-232/16 computer board has a connector to the PCI parallel bus ("on the computer side") and a 100-pin connector ("on the external side") to connect a beam of 16 nine-wire cables ending with DB-9 sockets, typical for the RS-232 line. The maximum rate of serial transmission realized by this board is equal to 115.2 kbps. The purchase of a computer board increasing the number of the RS-232 ports in the computer and its application in a measurement system is justified when the digital measurement devices used in the system are equipped with the RS-232 line and the requested transmission rate is not high, as shown in Figure 6.35.

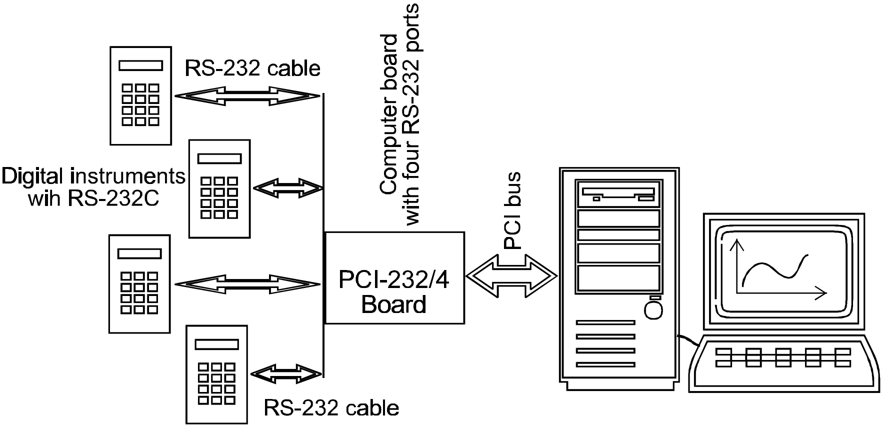


Figure 6.35 Measurement system with a serial interface and a computer board increasing the number of RS-232C ports.

Cheap digital multimeters connected into a system enable a variety of measurement tasks, such as automatic measurements of characteristics of objects or multipoint measurements. From among three recent standards of electrical circuits, RS-423A, RS-422A, and RS-485, the RS-485 standard is of the greatest importance. However, if a great influence of noise on a transmission line is not assumed, then the RS-423A standard with asymmetrical transmission and fewer wires in the bus is more useful. The arrangements included in *one* RS-232C standard correspond to the arrangements included in *a pair* of newer standards; for example in RS-449 and RS-423A, or in RS-530 and RS-485.

The RS-449 serial interface (RS-530) and the transmission circuits according to RS-485 (RS-422A) are useful in the case of measurement systems distributed for a distance of several dozen meters and including more than two interface devices. Apart from the interfaces in measurement-control systems described above (e.g., of PROFIBUS type), the HART and the IEC 1158-2 standards are also used, as shown in Table 6.5. The transmission lines of the systems shown in Table 6.5 enable not only digital signal transmission, but also power supply of actuators with a small power consumption, included in the system.

Table 6.5

Parameters of Serial Interface Standards to a Measurement-Control System

Parameter	*RS-232C*	*RS-485*	*HART*	*IEC 1158-2 (H1)*	*IEC 1158-2 (H2)*
Number of transmitters	1	32	>1	32	32
Number of receivers	1	32	>1	32 (126)	32
Transmission rate	115 kbps	10 Mbps	1.2 kbps	31.25 kbps	2.5 Mbps
Length of cable	15m	1,200m	2,000m	1,900m	500m
Signal voltage (or signal frequency)	±12V	5V	(1,200 Hz/ 2,200 Hz)	0.9V	7V
Supply from a line possible	no	no	yes	yes	yes

In the HART standard digital signals are frequency-coded in the FSK modulation (logical 0: 1,200 Hz; logical 1: 2,200 Hz). The new IEC 1158-2 standard was elaborated in two versions, of which the H1 version is slower: it enables transmission at a maximum rate of 32 kbps to a maximum distance of 1,900m. The H2 faster version enables data transmission at a rate of 2.5 Mbps for a maximum distance of 500m, or at a rate of 1 Mbps for a maximum distance of 750m. The IEC 1158-2 H1 version is designed to transmit data as well as to control actuators of small power consumption. The supply current of one device taken from the line should be less than 10 mA. Due to the small power of the interface signal, the IEC 1158-2 H1 is recommended in the areas with explosive danger. The number of devices connected to the nonbranched line is equal to 32, whereas the number of devices connected in the linear and the star configuration can amount to 126.

6.6 SMART SENSORS INTERFACES

6.6.1 Smart Sensors

Many objects or technical devices are monitored or controlled by means of a sequence of sensors. An example of such a technical device is a car, and examples of such objects are a public utility or an apartment building. A medium-class car is equipped with approximately 100 sensors of temperature, pressure, stresses, or chemical constitution of exhaust gas. Efficient use of information gained from so many sensors is possible after connecting the sensors into a computer (or micro-processor) measurement system. A measurement line in such system should transmit a digital signal. Due to needs reported by industry, and due to great progress in electronic technology, the production of a new generation of sensors has become possible, the so-called smart sensors. The adjective “smart” should describe the adjusting properties of such a sensor (e.g., automatic selection of analog signal amplification). Functionally, the smart sensor is a converter of a measured quantity into a digital output signal. As far as the sensor structure and functions are considered, an equivalent of a smart sensor is simply a *digital sensor*. A smart sensor is an integrated device including the following elements or functional blocks—a sensor of physical quantity (e.g., electronic analog temperature sensor); a measurement circuit (e.g., Wheatstone bridge in the case of resistance gauges); an ADC; memory; a serial interface; and a control system (see Figure 6.36).

Smart sensors as analog-digital integrated devices have a limited working temperature range (usually up to approximately 130°C) and a low accuracy. Examples of the group of smart sensors are digital temperature sensors presented in Chapter 2, Table 2.4.

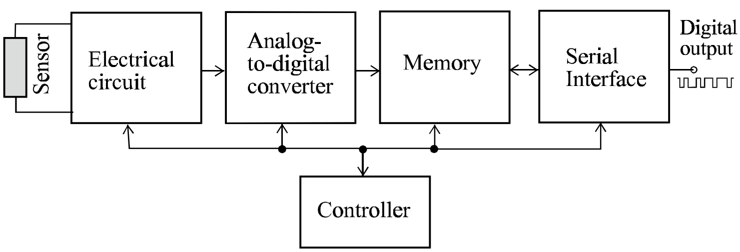


Figure 6.36 Functional diagram of a smart sensor.

Standardization of interfaces for smart sensors is of fundamental importance for the profitability of the production of such sensors. It is not by chance that the automotive industry is among the leaders in developing smart sensors and serial interfaces for smart sensors. At present, there are several dozen types of serial interfaces for smart sensors, designed at the request of significant producers of electronic components, or at the request of industrial branches. For example, the

PROFIBUS, the CAN, and the MicroLAN serial interface systems are discussed below.

6.6.2 PROFIBUS Interface System

PROFIBUS System Characteristic

The PROcess FIeld BUS (PROFIBUS) is a family of standards for data control and data exchange in distributed industrial systems of automatics [4], designed in Germany and applied in Europe. PROFIBUS is also frequently used in measurement-and-control systems. In a general scheme of information flow in a hierarchical industrial system (see Figure 6.37), the following levels are distinguished: sensor/actuator level, field level, and cell level. PROFIBUS is used to control devices at the field level and at the cell level. Devices at the field level are the following: I/O modules, measuring converters, valves, engines, and adjusters. Transmission at this level is realized in cycles, apart from alarm messages and diagnostic messages, which are transmitted instantaneously and not in cycles. At the cell level, information exchange is realized between programmable controllers of the programmable logical controller (PLC) type.

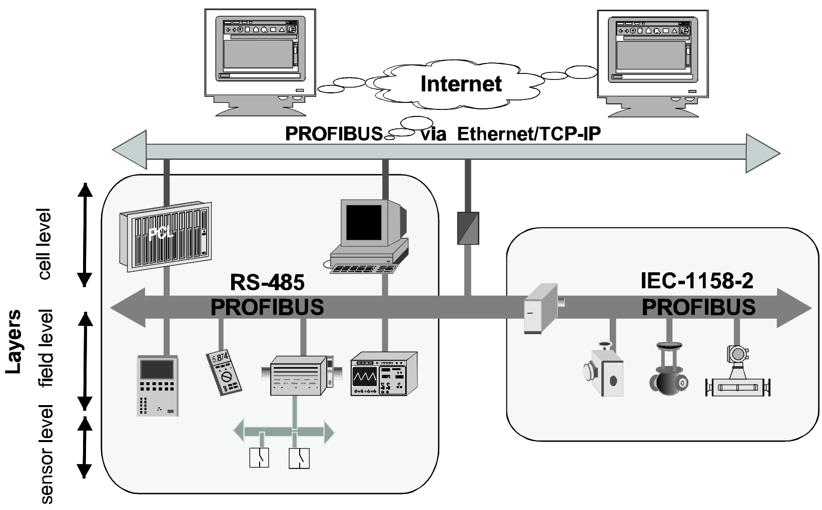


Figure 6.37 Industrial measurement-and-control system with the PROFIBUS interface.

PROFIBUS includes recommendations and standards concerning three profiles of distributed systems. The standards are the communication profile (including transmission protocols), the physical profile (defined by transmission media), and the application profile, as shown in Figure 6.38. Two communication protocols are most frequently used—PROFIBUS-DP (*Decentralized Periphery*), and PROFIBUS-FMS (*Fieldbus Message Specification*). The PROFIBUS-DP protocol is optimized according to the criteria of high transmission rate, efficiency, and low costs. The protocol is recommended for systems of automatics with distributed actuators. It can replace the previously used transmission systems of analog signals: circuits supplied with 24V, or systems with 4 to 20 mA current loop.

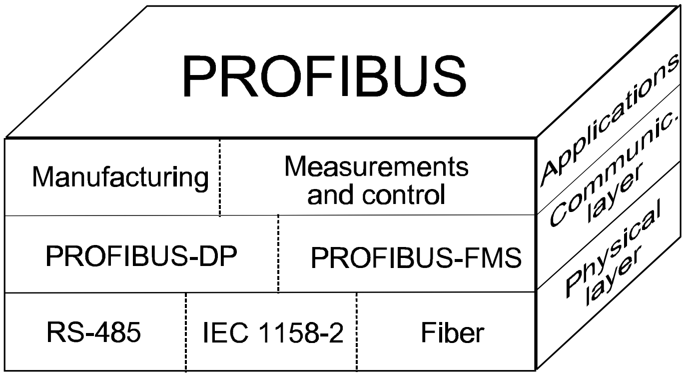


Figure 6.38 Structure of PROFIBUS communication standards.

PROFIBUS-FMS Protocol

The PROFIBUS-FMS protocol enables data exchange between "smart" system devices. Currently, it is replaced by the TCP/IP protocol, installed in devices at still lower levels of a hierarchical control system [4].

Geometrical dimensions of the PROFIBUS system result from the kind of transmission line, that is, the physical profile technology. When selecting the kind of line, one should include such elements as transmission rate, explosive conditions, necessity of components supply from a measurement (transmission) line, and additional possible factors. PROFIBUS recommends the following standards of transmission lines.

- RS-485 universal solutions of production systems or control-measurement systems; transmission rate in this standard is included in a wide range of values from 9.6 kbps (the line length $l \leq$ 1,200m) to 10 Mbps ($l \leq$ 10m).
- IEEE-1158-2 H1 version in systems of industrial automatics, particularly in chemical and petrochemical industries; each system module can be supplied from a transmission line (supply current in a steady state <10 mA), transmission rate up to 32.25 kbps (the line length $l \leq$ 1,900m dependent on, among other things, the wire cross-section in the cable).
- Optical fibers in systems with a transmission line longer than 2 km, at a high noise level, in an explosive danger area (no sparking in the case of

cable fault), and in order to provide galvanic insulation of system segments or data transmission rate increase. Differences in the quality of optical fibers used in the PROFIBUS system cause different allowable cable lengths. Multimode optical fibers with glass fiber are used on lines to 3 km long, one-mode glass optical fibers on lines to 15 km long, and optical fibers with artificial fiber on lines to 80 km long.

Now, the usage of the Ethernet network in the near future is assumed with a transmission rate up to 1,000 Mbps, as the recommended fourth element of the PROFIBUS physical profile (more about the Ethernet in Chapter 10).

PROFIBUS defines the technical characteristics of an industrial system in which distributed digital devices can be connected in a network at the field level or at the cell level. The devices of PROFIBUS system belong to two categories: active stations (master devices) or passive stations (slave devices). The difference between them consists, among other things, in the access right to the PROFIBUS bus. Active stations, which are different types of drivers, or a computer, have the right to send messages without previous instructions. Passive stations can send a message (e.g., a measurement result or a device state) only at the request of the active station. Passive stations are measurement converters, valves, servomotors, actuators, and other devices.

PROFIBUS-DP Protocol

The DP protocol is the most frequently used protocol of the PROFIBUS system. It is designed to exchange information at the field level. Important parameters of the communication protocol are transmission rate, simplicity of service, diagnostic possibilities, and immunity to transmission noise. The DP protocol ensures an optimum set of values of these parameters. In the DP protocol, the main driver (i.e., a *master* device), periodically reads input information from *slave* devices, and periodically sends commands to *slave* devices.

Internal diagnostic functions of the DP protocol enable fast fault location. Diagnostic messages are transmitted along the bus and received by a *master* device. These messages can be divided into three groups:

- Station diagnostics: a message that concerns a general status of a station (e.g., a message on exceeding the maximum allowable temperature of the station under inspection);
- Module diagnostics: a message that relates to a concrete module in the station (e.g., the range level overflow of an ADC by input voltage);
- Channel diagnostics: a message concerns an error at a concrete output of a corresponding module (e.g., output five of an I/O converter is shorted).

The DP protocol allows the system to work with one or many *master* devices. High flexibility in system configuration is possible, but the sum of *master* and *slave* devices cannot exceed 126. Three groups of devices are distinguished in the PROFIBUS system with the DP protocol.

- DPM1: master device of class 1 (DP Master Class 1) (i.e., the main system controller, only one in a system); the DPM1 device can be a PLC controller or a PC;
- DPM2: master device of class 2 (DP Master Class 2), a driver at a level lower than DPM1, usually a microprocessor driver. The DPM2 devices carry out diagnostic tasks, process the measuring data and the values of control parameters, and send commands to slave devices.
- Slave devices are measuring converters, valves, actuators, and I/O devices.

These devices receive output information or send input information. The volume of messages with these information items is limited to 246 bytes. The PROFIBUS interface system is usually applied in measurement systems.

6.6.3 CAN Interface System

General Information

The *Controller Area Network* (CAN) serial interface was prepared by the Bosch and Intel companies to respond to the requests and needs of the automotive industry. The CAN interface connects a number of sensors, control systems (usually microprocessor systems), and actuator systems to one serial bus, as well as exchange data between these systems through the bus [5]. At present, two versions of the interface are in use—standard CAN 2.0A and extended CAN 2.0B. Devices and circuits connected to the bus are named CAN modules or nodes. The organization of data flow in the CAN interface through its bus replaces the mode of data exchange previously used in equipment. The previous mode consists of many direct connections between communicating systems or sensors. Direct connections established to exchange data are named dedicated connections. The main purpose of CAN is to connect the components in a car, but CAN may also be used for measurements and control of other objects. The CAN interface is used, for example, in simple automatics systems or in the building industry (lift control). Due to specific, heavy working conditions of the CAN interface in a car, the following requirements for its parameters are determined.

- High data transmission rate, enabling prompt operation of such systems as air cushions or the Antiblocking System (ABS);
- High immunity to interference emitted in an object by electromechanical devices (e.g., a starter) or electronic devices (e.g., ignition);
- System flexibility, as far as the number of connected modules is concerned.

CAN Bus and Signals

The CAN designers met the assumed requirements, ensuring the following values of maximum data transmission rate in the function of bus length:

- 1 Mbps for a transmission line (a bus) of maximum length of 40m;
- 500 kbps for a transmission line of maximum length of 300m;
- 100 kbps for a transmission line of maximum length of 600m;
- 50 kbps for a transmission line of maximum length of 1 km;
- 5 kbps for a transmission line of maximum length of 10 km.

In the CAN systems with a transmission line longer than 1 km, line transmitters and receivers are applied in CAN modules. In a concrete CAN system, only one value of transmission rate is established (e.g., 200 kbps).

Signals in the CAN system are usually transmitted over a differential transmission line composed of two twisted wires, although CAN does not specify either the information carrier (electrical, optical, or radio signal) or the cable type (electrical differential line, coaxial cable, or optical fiber). Differential transmission circuits help to ensure good noise immunity of the transmission line. In order to avoid signal reflection at both ends of the transmission line, an impedance with the value of 125Ω is connected. For a transmission rate less than 100 kbps, the impedance value must be in a range of 150Ω to 300Ω. The CAN transmission bus is formed by two wires, to which CAN-H (high) and CAN-L (low) outputs of each module are connected, as shown in Figure 6.39.

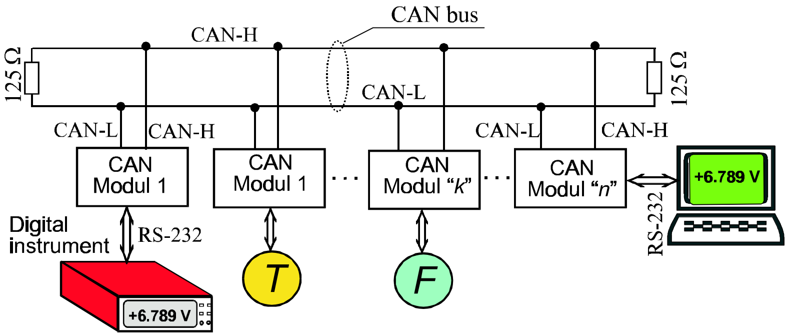


Figure 6.39 Measurement-and-control system with the CAN interface.

All modules in the CAN system can be both transmitters and receivers. The CAN modules have no addresses, and, therefore, the messages accessible on the bus must be received by all modules. The number of modules in the system is not limited by the number of addresses. Adding or deleting a module does not complicate the system operation. Due to the arbitration mode concerning the right of modules to transmission in the CAN system, logical signals on the bus are described with the following levels:

- The recessive level, which corresponds to logical 1;
- The dominant level, which corresponds to logical 0.

This description of signal correspondence results from a need to include in the CAN interface a situation in which the outputs of different logical states of two of more modules are shorted. If the logical states of shorted outputs of modules are incompatible (e.g., at the output of module 1—the recessive state, and at the output of module 2—the dominant state), the CAN transmission line takes on the dominant state (equivalent of 0). For the TTL or CMOS systems, the shorting outputs of digital devices and a nondetermined (logical) state of such shorted output is false. The voltage levels on the wires of a CAN bus for two logical states are equal to:

- The recessive state $V_{CAN\text{-}H}$ = 2.5V and $V_{CAN\text{-}L}$ = 2.5V; maximum potential difference $V_{CAN\text{-}H} - V_{CAN\text{-}L}$ = 0V to 0.5V, the recessive state corresponds to logical 1;
- The dominant state $V_{CAN\text{-}H}$ = 3.5V and $V_{CAN\text{-}L}$ = 1.5V; maximum potential difference $V_{CAN\text{-}H} - V_{CAN\text{-}L}$ = 0.9V to 2.0V, the state corresponds to logical 0.

Messages in the CAN Interface

Data exchange in the CAN interface system is realized by sending and receiving messages containing data or instructions [5]. A message sent by one CAN module is received by all modules in the system. Each module has the right to send messages. The start of transmission is possible only if the line is not busy (idle state). There are four groups of CAN messages:

- Data frame, containing data;
- Remote frame, containing the instruction to send data;
- Error frame, with the information about transmission error;
- Remote overload.

An instruction is addressed to a concrete CAN module or to a few CAN modules. The interface message forms a transmission frame composed of the following parts, as shown in Figure 6.40:

- A single start of frame (SOF) bit;
- Arbitration field, including a multibit identifier (11 or 29 bits), and one RTR bit;
- Check field: 6 bits;
- Fields of data grouped in bytes (from 0 to 8 bytes altogether);

- Redundancy check fields CRC (see Section 6.2.2) – 16 bits;
- Acknowledgment fields ACK: 2 bits;
- End of frame (EOF) fields: 7 bits;
- Frame space fields: 3 bits.

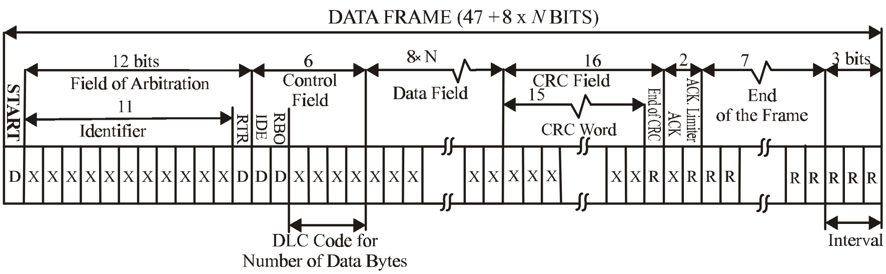


Figure 6.40 Format of message of type “data frame” in the interface of the CAN standard, version 2.0A (D: “dominant” bus state, R: “recessive” bus state, and X: state D or R).

The identifier follows the start bit. The identifier has 11 bits in the CAN 2.0A version, and 29 bits in the CAN 2.0B version. A contents of the identifier determines the type of transmitted message. The modules read out the whole message, but each of them accepts for further processing only some of the message types, dedicated for a given module. Filtering of received digital data, program-defined in the modules, is applied. In the CAN 2.0A version, 2^{11} = 2,048 message types can be defined, but only 2,032 types are applied. The remaining 32 combinations of the 11-bit word are used for special purposes. The arbitration field for the CAN 2.0B version amounts to 32 bits, including a 29-bit identifier, which allows to distinguish 2^{29}, or approximately 5×10^8, types of messages. The last bit in the arbitration field is the RTR bit of the remote transmission request. The logical state of this bit determines the message type. The dominant state of the RTR bit occurs for the data frame, whereas the recessive state occurs for one of the other three frame types.

The check field of a message consists of an IDE bit, an RBO bit reserved for a control purpose still not defined in CAN, and four data length code (DLC) bits, with the number of bytes forming the data field recorded. The dominant state of the IDE bit determines the message structure in the standard version (11-bit identifier), and the recessive state determines the message structure in the extended version (with 29-bit identifier).

Bits from the data field are then transmitted. The data field of the CAD message includes from 0 to 8 bytes of data.

The bits of the CRC polynomial (15 bits + CRC stop bit) are transmitted after a sequence of data. In the acknowledgment field, two acknowledgment bits are transmitted: the ACK bit (*ACKnowledgment*) in the recessive state, and the ACK END bit. The ACK bit remains in the recessive state on the bus if none of the modules (nodes) detects a transmission error. The detection of a transmission error sets the bus in the dominant state. The last part of the message consists of seven bits (in the recessive state) of the EOF sequence (*end of frame*). The next message can be transmitted after sending three space bits. From the balance of the bits number, it is evident that a message in the CAN 2.0A standard has from 47 to 111 bits (with the step of increase in length equal to eight bits), and in the CAN 2.0B version has from 67 to 131 bits.

Transmitting a message through the CAN module is preceded by checking the bus occupancy. If the bus is busy, the module delays the transmission start until the bus becomes free. The pulse edge of the START bit of each message is the synchronization signal for all modules in the system. All CAN modules have equal rights to start message transmission. Any collision on the bus (i.e., the start of message transmission by more than one module), is eliminated by using the Carrier Sense Multiple Access/Collision Detection (CSMA/CD). When two modules start the message transmission simultaneously, a collision in the access to the bus is eliminated by comparing the logical value of identifier bits and detecting the first state of inconsistence of logical states of bits, as shown in Figure 6.41.

For example, module 1 transmits a sequence of bits "← 001010010...," and module 2 – a sequence "←001011101...." After transmitting the sixth bit further transmission is realized only by module number 1; its bit on a collision position has a logical value 0, which sets the line in the dominant state.

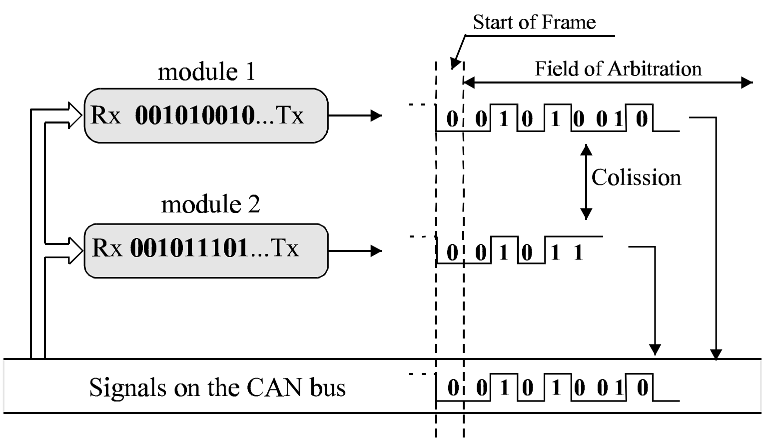


Figure 6.41 Arbitration of module access to transmission on the CAN bus.

CAN Module Structure

The CAN module in a measurement system must include components able to realize communication and data processing tasks. The CAN modules should include the following elements: a CAN *trans*mitter/re*ceiver*, a CAN microcontroller, a microprocessor, a digital sensor (or a group of sensors) or an actuator (e.g., an engine or a pump), and a system center, as shown in Figure 6.42.

The system center is regarded as a module of the CAN interface, having similar transmission rights, but—different from other modules—it includes a short control software, or can store data received from modules with sensors. An example of central modules are computer boards or cards produced by National Instruments, designed to be connected to defined buses in PC computers (e.g., PCI-CAN, AT-CAN, PCMCIA-CAN), and to the module measurement system PXI with the PXI-84XX parallel interface [3].

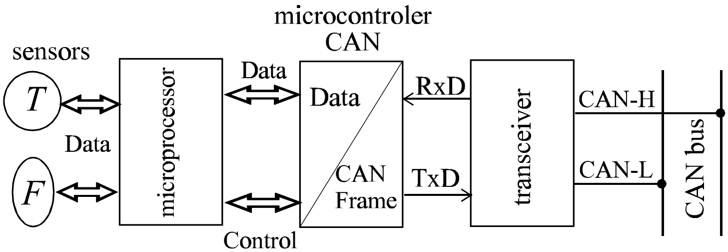


Figure 6.42 Block diagram of the CAN module including measurement sensors.

The following functions of the CAN module components are shown in Figure 6.42. Smart sensors provide digital measurement data. A microprocessor controls the A/D conversion (e.g., initializes the processing or records a measurement result in the register). The main part of the CAN message is formed in the microprocessor. The microprocessor fills in the arbitration field (identifier and RTR bit), the data field, and four bits of the DLC field of the data field length. The microprocessor of the CAN module can be any general purpose microprocessor, such as Intel 8051 or Motorola. Successive message bits are appended in the CAN microcontroller, including the CRC check word, before it is transmitted through the TxD output. The CAN microcontroller also realizes operations on the CAN message, read out at the RxD input. These operations are:

- Program filtering, in order to further processing of only selected messages;
- Arbitration, in case of a collision in message transmission;
- Computation of the check word, in order to confirm the correctness of transmission;
- Separation of bits of the data field from the remaining bits;
- Transmission of data bits to the microprocessor.

The CAN microcontrollers are produced by many enterprises as digital devices, as shown in Table 6.6. The SJA1000 (Philips) device is popular, and the C167CR and C515C devices (Siemens) are also known. The CAN transceiver is also available as an integrated digital device. An example of a CAN transceiver is the PCA82C250 device (Philips). The task of the transceiver is to match the levels of transmitted and received signals with the CAN standard on the side of the transmission line, and with the CMOS (TTL) standard on the side of the CAN microcontroller. The digital devices of CAN microcontrollers are offered in both basic and full versions. The devices in the basic version have a limited work program and are usually used to transmit data to sensors. The full version or basic version of a digital device have nothing in common with the type of CAN message—standard or extended.

Table 6.6

CAN Interface Microcontrollers

Type	*Number of Controllers*	*Additional Equipment*	*Remarks*	*Producer*
T89C51CC01 T89C51CC02	CAN controller	ADC	256 KB RAM	Atmel
DS80C390 DS80C400	2 CAN controllers	2 serial ports	addresses: 4 MB, 16 MB	Dallas Semiconductor
C505C	CAN controller	ADC	64 KB ROM	Siemens
PIC18C858	CAN controller	ADC	I^2C, SPI	Microchip
TMS320- -LF2406	CAN controller	16 ADCs	5 KB RAM	Texas Instruments
P87C592	CAN controller	—	16 KB RAM	Philips

6.6.4 MicroLAN Interface System

MicroLAN is the standard of a measurement system with a serial interface, designed by Dallas Semiconductor [6]. Communication between one *master* device (microcontroller or PC computer) and many *slave* devices (sensors and other devices) is possible in the system. The company advertises the system as having a measurement line named *1-wire* line. Actually, the measurement line is a pair of wires: a “hot” wire and a ground wire. The MicroLAN system consists of three main parts:

- Bus master and software;
- Connections (two-wire line);
- A set of slave devices, such as smart sensors, ADCs, and memory devices.

The *system master* may be a microcontroller or a PC computer equipped with an RS-232C serial port. The 1-Wire bidirectional transmission protocol is applied in the system. Cooperation of the MicroLAN line with the PC requires a converter, matching the voltage level of the RS-232 standard with the voltage level of the MicroLAN line. Dallas Semiconductor offers such a 1-Wire to RS-232C converter DS2480 type. Commands and data are transmitted bit-by-bit, starting with the least significant bit. Synchronization between the *master* and *slave* devices is determined by the trailing edge of the signal generated by the *master*. The logical state of the line after this synchronization signal defines the value of the transmitted bit, as shown in Figure 6.43. This method of operation is called data transmission in time slot. Each bit transmitted is preceded by the synchronization edge. Thus, possible breaks in transmitting successive bits do not cause communication errors.

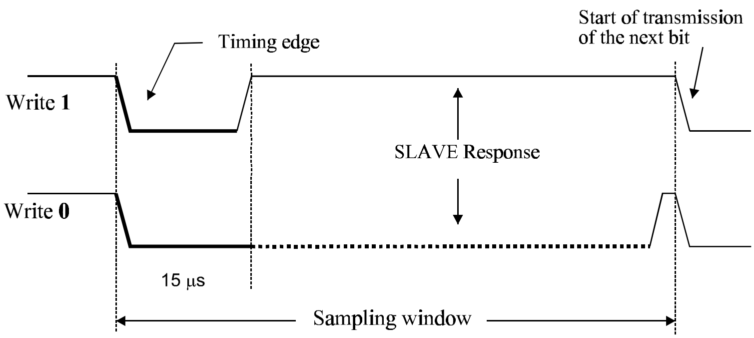


Figure 6.43 Recording logical values 1 and 0 in the *slave* device according to the 1-Wire protocol.

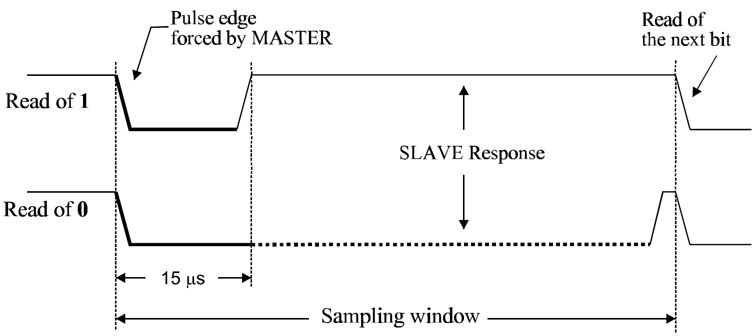


Figure 6.44 Readout of logical states 1 and 0 from the *slave* device according to the 1-Wire protocol.

Data readout from *slave* devices consists of a proper interpretation of the line state forced by a *slave* device, in response to the previous input function of the *master* device, as shown in Figure 6.44. At recording as well as reading out bits, the transmission is always forced by the *master* device. After the RESET start signal and the device acknowledgment with the PRESENT signal, commands related to the identification of the device on the line, data recording, and readout are transmitted to the *slave* device (sensor).

Each device connected to the MicroLAN network has its own 64-bit code *Silicon Serial Number* (SSN) placed in the device ROM memory. The following elements are recorded successively: 8 bits of the code determining the device type (*Family Code*), 48 bits (6 bytes) denoting a unique device serial number, and 8 bits of the CRC polynomial. The SSN device code places 2^{56} devices (mainly sensors) in the MicroLAN system, and, for example, a temperature measurement using a number of sensors.

The following electronic components produced by Dallas Semiconductor may be applied as *slave* devices in the MicroLAN system [6]:

- Temperature sensors of type DS1820 and DS1920;
- ADCs of type DS2450;
- RAM memory devices, with a capacity ranging from of 1 KB (DS1992 device) to 64 KB (DS1996 device);
- EPROM memory devices, from 1 KB (DS1982 device) to 64 KB (DS1986 device);
- Analog switches with addresses, devices of type DS2405A.

Temperature sensors enable temperature measurements in a different range: the DS1820 device in a range between −55°C and +125°C, and the DS1920 device in a range between −55°C and +100°C. In a range from 0°C to 70°C, the inaccuracy of processing for both devices is the least, and equal to 0.5°C. The measurement result is read out as a 9-bit word. The A/D conversion time for temperature sensors is equal to 1 second. The DS1820/1920 devices include the alarm functions for exceeding the set temperature range. Two bytes of EPROM memory store the values of the upper and the lower limits of temperature of the alarm state. If the current temperature is beyond the set range, the device will respond to the signal from the *master* device with an alarm signal. The properties of DS1820/1920 devices enable their use in a system for temperature measurements with a number of sensors (e.g., public utilities), with a two-wire measuring line. An example of such temperature measurement is shown in Figure 6.45. In this system, the *master* device is a PC. The replacement of the voltage level of the RS-232C standard in the system with the voltage level according to the 1-Wire MicroLAN standard is realized in the DS2480 converter (device).

The manufacturer recommends making the data transmission rate dependent on the length of the MicroLAN bus. A short bus—up to 10m in length—is defined, as well as a long bus—up to 300m in length. Three modes of transmission rate are defined:

- Regular: up to 16.3 kbps;
- Overdrive: up to 142 kbps, to be used only on short buses;
- Flexible, matched with the bus length.

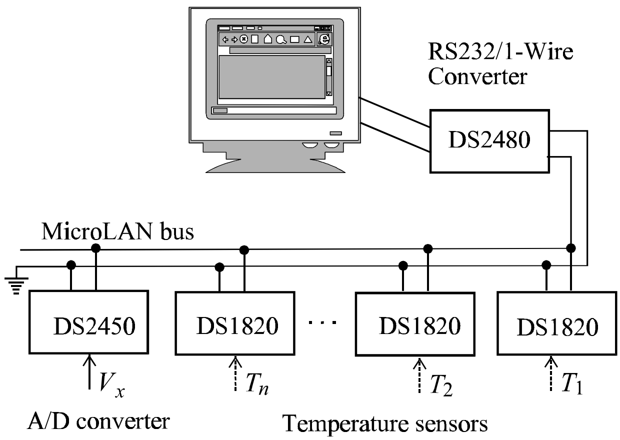


Figure 6.45 MicroLAN measurement system for voltage measurements and temperature measurements, using a number of sensors.

The MicroLAN line is controlled through a serial port of the RS-232C interface driver. The use of the MicroLAN line in the system of temperature measurement with a number of sensors is a solution compared to other systems based on serial interfaces (e.g., RS-422A or RS-485).

After connecting memory circuits into the MicroLAN bus, the system functions may be extended to the acquisition of measuring data. It is also possible to control the operation of devices by means of the MicroLAN bus, connecting actuators by means of DS2405A analog switches addressed on the bus.

6.7 POWER LINE COMMUNICATION FOR MEASUREMENTS

6.7.1 General Description of PLC

In 1899, a U.S. patent was issued for the use of the power network to control signal transmission. Information transmission over power network wires is called power line communication (PLC). Power networks of low ac voltage have a rated voltage of 230V and a frequency of 50 Hz (in Europe and a majority of countries worldwide), and a rated voltage of 110V and a frequency of 60 Hz (in the United States, Canada, and Japan). The greatest advantage of a data transmission channel formed by power network wires is the fact that the network is installed in almost every building.

Digital signal transmission over power network lines is used in many applications, especially in the following, as shown in Figure 6.46.

- Equipment control in an apartment building (e.g., remote switching on, remote setting of a heater or an air conditioner, automatic switch-off of gas valves after detection of a fire or explosive conditions);
- Internet connections. This application is rapidly developing; a maximum transmission rate of 45 Mbps was obtained in tests;
- Data transmission from measurement devices, in particular from electricity meters or water and gas meters. Such measurement systems are briefly described below.

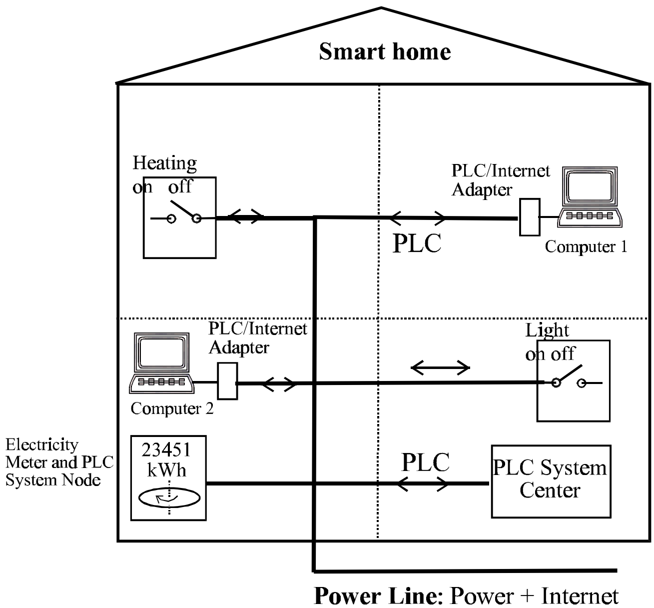


Figure 6.46 Smart home with PLC communications.

A number of factors, however, should be taken into consideration when designing a data transmission system over the power network.

- Impedance mismatch of transmitters and receivers of signals with the network impedance. The impedance of a power line changes in time, and is usually within a range of 0.1Ω and 10Ω. The mismatch causes signal power losses on the signal transmitter–power network and signal receiver–power network junctions.
- Signal rejection in the network. The power network has features of a lowpass filter. Measurements indicated the attenuation of low voltage power network in one building from 6 to 54 dB. The attenuation depends not only on the communication channel length, but also on the network configuration. The network configuration varies in different segments of

the building and varies in time, because electric equipment units are connected and disconnected from the network (i.e., switched on and off). Thus, the network attenuation for transmitted signals is high and varies in time.

- Noise and interference level in the network. Energy receivers are sources of interferences emitted into the network in the moment of connecting or disconnecting to the power network. Some energy receivers are interference sources also during their working time. Another source of interference is the electromagnetic field emitted by electric and radio equipment. The electromagnetic field induces spurious responses in the network wires, as in an antenna. The interference level in the power network may be so high that it makes transmission impossible during a major part of the day and night. The power network is a transmitting antenna of transmitted signals.

Only assigned frequency bands may be used for digital signal transmission over the power network. In Europe, an alliance was negotiated in this respect, the so-called Open PLC European Research Alliance (OPERA), which defines frequency bands in a range between 3 and 148.5 kHz, designed for communication in the power network, as shown in Table 6.7 [7].

Table 6.7

Frequency Bands and Signal Levels in the PLC System [Standard EN 50065]

Frequency Range	3 kHz to 9 kHz	9 kHz to 95 kHz	95 kHz to 125 kHz	125 kHz to 140 kHz	140 kHz to 148.5 kHz
Band User	Energy provider	Energy provider and authorized users	All users; Access protocol not required	All users; Access protocol required	All users; Access protocol not required
Signal Level	134 dB	134 dB for 9 kHz 120 dB for 95 kHz	For individual consumers		For industry
			116 dB		134 dB

Signal level 0 dB ⇒ 1 μV.

In the United States and Japan, a frequency range between 9 and 490 kHz was previously assigned for the PLC, by Recommendation of the Federal Communications Commission (FCC). Now, in the United States, there is neither division of this range into bands, nor any other requirements concerning the signal level in the network. Transmitted signals should meet general recommendations of the FCC concerning the electromagnetic compatibility [8]. The FCC recommends that the power of signals for transmission should be as low as possible, until correct transmission is maintained.

In computer networks (e.g., the Internet) with PLC, the carrier frequency in the megahertz range, and the so-called broadband transmission, PLC are used. At present, there are no legal regulations concerning the frequency and power of PLC signals in the megahertz range.

Table 6.8

Frequency Bands and Interference Levels in Electrical Devices and Lines

Frequency range	150 kHz to 500 kHz	500 kHz to 5.0 MHz	5 MHz to 30 MHz
Interference voltage, quasi-peak-peak value	66 dB at 150 kHz to 56 dB at 500 kHz	56 dB	60 dB
Interference voltage, mean value	56 dB at 150 kHz to 46 dB at 500 kHz	46 dB	50 dB

Signal level 0 dB ⇒ 1 μV.

For such systems, only the ETSI recommendations and European Standards are obligatory, which concern the emission of electromagnetic interference by any device. According to these recommendations, the PLC transmission is regarded as interference, the level of which should not exceed determined boundary values [9]. Acceptable signal levels in the frequency range from 150 kHz to 30 MHz are shown in Table 6.8. A basic interface circuit for a PLC measurement and control system is shown in Figure 6.47.

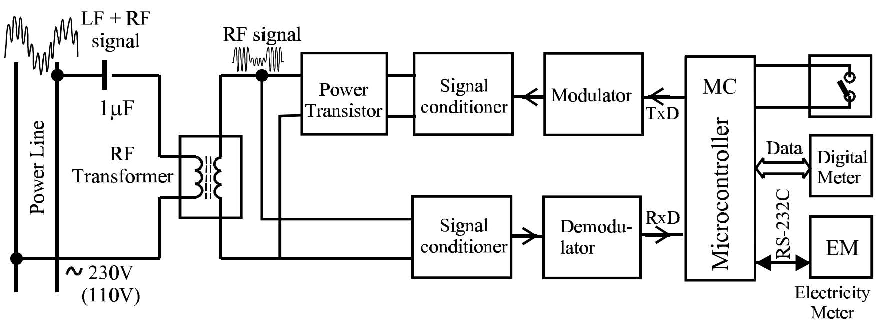


Figure 6.47 An interface circuit for a PLC measurement and control system.

6.7.2 Communication Protocols for PLC

Four communication protocols are of the greatest importance for PLC.

X10 protocol for electrical equipment control was elaborated in 1978. The ASK modulation is applied in the protocol. X10 is used to transmit simple commands (e.g., switch on, switch off, dim, or bright). The protocol assumes a maximum of 256 nodes in a system: receivers, transmitters, and transceivers. Each of these devices obtains its unique serial number in the system. The X10 protocol is applied when a simple device construction and a simple SA protocol are more important than the transmission rate or the volume of the transmitted information packet. The X10 protocol is widespread in the United States in the so-called “smart home.” X10 is not widely used in measurement systems.

CEBus protocol (EIA 600 standard) was elaborated under the supervision of the Electronic Industries Association. The protocol assumes that there is no master device (module) in the system, and that all device modules in the communication network are transmitters and receivers of information. The CEBus protocol was elaborated 25 years later than X10, and its transmission potential is much wider. The maximum transmission rate according to CEBus is 10 kbps. It is applied mainly to control electric equipment in the “smart home.” For transmission programming in CEBus, the Common Application Language (CAL) is recommended.

LonWorks protocol (EIA 709 standard) was elaborated by Echelon enterprise to control devices in the “smart home.” This protocol does not assume a master device in a system sense. The modules of communication network in LonWorks are microcontrollers servicing transmission to and from sensors, actuators, and computers connected to the LonWorks network. The LonWorks protocol is suitable for a measurement system with PLC transmission.

ISO10368 protocol is a simple protocol applied in systems for monitoring container loading on ships and trains.

Relatively small values of the wave frequency of PLC signal, as shown in Table 6.7, force low transmission rates, with a maximum of 10 kbps. For digital signal transmission in PLC communication, specialized integrated devices are applied. The following devices are frequently used: TDA 5051 (manufactured by Philips) with the ASK modulation and maximum transmission rate of 1,200 bps; ST 7537 (manufactured by ST Thomson Microelectronics) with the FSK modulation and maximum transmission rate of 2,400 bps; and IT 800 (manufactured by Itran) with an original Digital Code Shift Keying modulation and maximum transmission rate of 7,500 bps.

6.7.3 Data Acquisition System from Electricity Meters

A system for transmitting and acquiring measurement data from electricity meters is the best example of applying PLC for measurement purposes. The measurement system includes electricity meters in one apartment building designed for a number of families or, at most, electricity meters in the power supply area from one transformer to mean voltage of 15 kV/400V (standard in Europe), as shown in Figure 6.48.

A measurement system for data acquisition from electricity meters, designed and tested in Poland [10], is equipped in communication nodes with an ST 7537 integrated device. The characteristic of nodes and frequency in a measurement system:

- Carrier frequency equals 132.45 kHz;
- Signal level equals 1V rms;
- Receiver sensitivity is 1 mV rms;
- FSK modulation;
- Transmission rate is 1,200 bps.

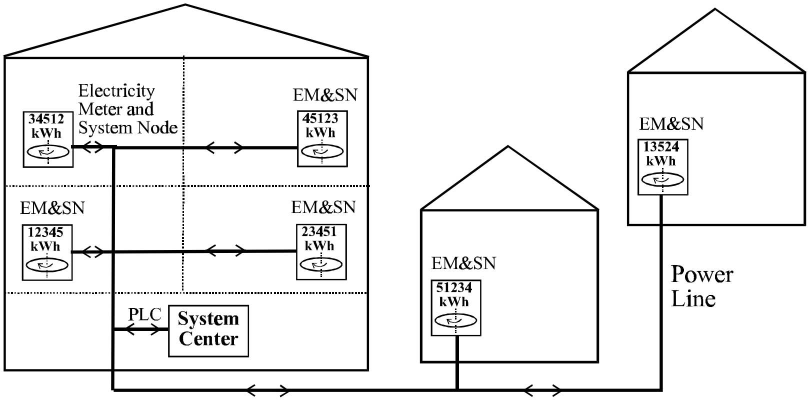


Figure 6.48 PLC measurement system for readout of electricity meters.

The measurement system collected data from 11 electricity meters in 3 buildings. The measurements were conducted for 6 months. It was found that during maximum demand hours and at the highest interference level (i.e., between 6 a.m. and 10 a.m., and between 2 p.m. and 11 p.m.), correct communication was possible with only 20% to 30% of nodes. An original transmission protocol was elaborated for the discussed measurement system. The best transmission quality was during the night, between 1 a.m. and 4 a.m. Due to interference with the most distant meters in the network, the communication was correct only during the night, once in a few days. Such transmission efficiency is sufficient to collect data from meters, but it is not sufficient for other purposes (e.g., to control tariff changes or devices).

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Chapter 7

Wireless Measurement Systems

7.1 WIRELESS TRANSMISSION OF MEASUREMENT DATA

Playing an increasingly more important role in technology, as well as in daily life, wireless communication systems from the very beginning have also been used for data transmission in distributed measurement systems. Wireless transmission is the only possible transmission method in systems where the object of measurement is moving (e.g., a vehicle), or is a large distance away from the measurement system center (e.g., radar sondes or spatial bodies), or is hardly accessible. When deployment or operating costs of a telephone or measurement line are high, wireless measurement systems can provide an alternative to their wired counterparts. Wireless data transmission is serial only, even in multichannel systems.

There are three types of measurement systems with wireless data transmission:

- Distributed measurement systems with data transmission through a cellular telecommunication network (mobile telecommunications);
- Distributed measurement systems with data transmission through dedicated (nontelephone) radio channels;
- Measurement systems with short distance wireless data transmission through infrared or radio frequency link.

The first two types of measurement systems are distributed within the coverage of communications systems, and thus their range can be practically global. In particular, such systems can involve spatial objects as well.

In contrast to the mobile phone network–based systems, principally designed for audio signal (mainly voice) transmission, and in which data transfer is just one of several functions, distributed systems using dedicated radio channels are designed and constructed for digital data transmission exclusively. A radio-transmission system comprises transmitters, receivers, a set of radiomodems, and measurement units. Besides their telemetric, or remote measurement functions, such systems often have remote control functions as well.

An entirely different role in a measurement system is played by short-distance wireless data transmission within the distance of 1m to 10m. An infrared link or a radio link can be used in place of an electric cable, an optical fiber, or a group of cables, due to difficult physical conditions for wiring, or insufficient space for connectors in the casing. An advantage of a shortdistance radio link is the possibility of using touch sensors with microtransmitters for moving (e.g, spinning) object measurements. In this case, wireless data transmission from sensor to receiver combines the benefits of contact and remote measurements. Two wireless data transmission standards of range 1m to 10m are likely to come into widespread use. One, referred to as IrDA, is an infrared link presently allowing transmission at speeds up to 4 Mbps within the range of 1m. The other standard is Bluetooth, a radio interface working in the 2.45 GHz frequency band, designed for data transmission within 10m and delivering data rates up to 1 Mbps. Bluetooth can connect two to eight digital devices, forming a so-called piconet.

A license, issued by a relevant government agency, is required for radio transmission. For open telephone network users, the license is obtained by the network operator. Transmission in other communication systems requires a special paid authorization, which is applied for by the user, and which is issued for specific frequency band, transmission power, and antenna height. No license is required to use low-power (i.e., less than 20 mW) transmitters in frequency bands below 800 MHz, but the certification of type is still necessary for such devices. Most of the currently licensed radio channels use the 450-MHz frequency band. Besides, a license-free Industry, Science, and Medicine (ISM) band is available in many countries. Though meant principally for industrial, scientific, and medical use, as indicated by its name, the ISM band can be used also for controlling household equipment (e.g., a garage door remote control) or modelers' devices with low-power transmitters. Two ISM bands are available worldwide, in frequency ranges from 2.4 to 2.4835 GHz, and from 5.72 to 5.85 GHz (in Europe, the United States, and Japan); a third band, from 902 to 928 MHz, is available in the United States. Bluetooth, HomeRF, IEEE-802.11, and HIPERLAN radio interfaces use the ISM band as well.

7.2 MEASUREMENT SYSTEMS WITH GSM-BASED DATA TRANSMISSION

7.2.1 GSM Mobile Phone Network

Voice transmission in the first mobile phone systems, referred to as first generation (1G) systems, was (and still is) analog. Those systems work in the 450- or 900-MHz frequency bands. Examples of 1G mobile phone systems are: Advanced Mobile Phone System (AMPS), still operating in the United States; and Nordic Mobile Telephone (NMT), used in Scandinavia and in other countries.

At present, the main mobile phone system is Global System of Mobile Communications (GSM), an entirely digital second generation (2G) system, working in the 900- or 1,800-MHz bands. Despite the word ”global” in its name, GSM is used only in Europe. Its counterparts elsewhere are Digital AMPS in the United States, and Japanese Digital Cellular (JDC) system in Japan and Asia, slightly differing from GSM, but based on the same technology. The North American digital mobile phone network is also called TDMA (IS-136 standard), from the Time Division Multiple Access (TDMA) technique used in this network. The U.S. mobile phone system uses the 1,900-MHz rather than the 1,800-MHz band. In GSM systems, digital data transmission (including data measurement transmission) is just one of several mobile phone functions, the main being voice transmission.

A step forward in the evolution of mobile telecommunications was the implementation of General Packet Radio Service (GPRS) in GSM. A substantial upgrade of basic GSM networks was necessary to launch this new data transmission service; new GPRS-supporting mobile phone models had to be designed as well. GSM networks with GPRS are referred to as 2.5G mobile communication systems.

The implementation of a third generation system (3G) referred to as Universal Mobile Telecommunications System (UMTS), operating in the 1,950-MHz and 2,150-MHz bands, is important progress in wireless data transmission. This is due to the assumed high data transfer speed values (up to 2 Mbps), a global access (beyond the mobile phone network coverage, the system is to be accessible via satellite), and a possibility of interworking with Public Switched Telephone Networks (PSTN), including Broadband-Integrated Services Digital Network (B-ISDN).

Although GSM can be used for data transmission, the maximum data transfer speed (rate), limited by the radio interface parameters, typically does not exceed 9.6 kbps with one channel used. GSM structure and data transmission in the system are shown in Figure 7.1. The system consists of mobile stations (mobile phones), base stations with controllers, a switching system, an operation and support system, and an interface to other telecommunication systems.

Mobile Stations (MS), commonly known as mobile phones, are in radio communication with base stations. The primary function of a mobile station is the same as that of a classic telephone with a handset, digital keys, a low-power transmitter, and a high-sensitivity receiver. However, getting more and more functions, a mobile phone is now able to process data, both keyed (in schedule or calculator functions), and transmitted via the telephone network.

A mobile station consists of two basic components: a Mobile Terminal (MT) and a Subscriber Identity Module (SIM). Each mobile terminal bears a unique number, referred to as International Mobile Equipment Identity (IMEI), which allows identification of the mobile phone in the global network. The SIM is an exchangeable smart card.

The *Base Station System* (BSS) comprises a number of base stations, installed on poles or towers, and a base station controller. The base stations work in the 900, 1,800, or 1,900 MHz frequency band. Each base station is equipped with an antenna, a radio wave receiver, a radio wave transmitter, and radio signal processing units. Each base station controller is connected to several base stations (usually through an electric cable or an optical fiber, although a radio link can be used as well). A controller switches channels for each station, controls mobile station power, and transmits signals in both directions between base stations and the mobile system center.

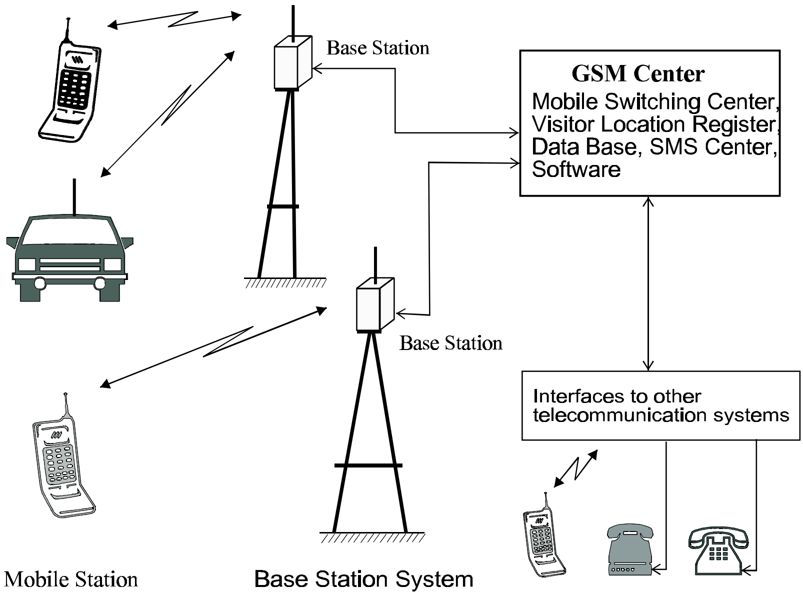

Figure 7.1 GSM system structure.

The *Switching System* comprises a Mobile Switching Center (MSC) and a database, as well as hardware and software necessary for communication with fixed phone networks (PSTN, ISDN, and data transmission network) and with other mobile phone systems. The database contains information on current mobile station localization, as well as all the data necessary for user identification and authorization.

Transmission in the GSM system is performed in duplex mode, which involves the necessity of using a double (duplex) transmission channel. In GSM 900 (the GSM system using the 900-MHz frequency band), separate frequency bands are allocated for mobile station–base station and base station–mobile station transmission channels, referred to as uplink and downlink channels, respectively; the uplink band ranges from 890 to 915 MHz, and the downlink band is from 935 to 960 MHz. The number of uplink channels is 124, equaling the number of downlink channels; the width of each channel band is 200 kHz. Channel-free 100-kHz bands are reserved on the limits of the uplink and downlink bands. Beside frequency, time slots must be allocated in order to create a transmission channel. The TDMA technique is used, allowing transmission channel multiplexing. The time interval, or TDMA frame, of period 4.615 ms, is divided into 8 time slots, 577 μs each. With 124 frequency channels and 8 time slots, 992 duplex transmission channels can be created simultaneously by a single base station, without taking into account the possibility of channel multiplexing through half-rate voice coding. Therefore, data transmission in GSM 900 is pulsed, with pulse duration modulation (PDM) one-eighth and one of the 124 duplex frequency channels used. In a channel pair, the downlink channel frequency is 45 MHz above the uplink channel frequency. Gaussian Minimum Shift Keying (GMSK), a radio signal frequency keying with binary signal, is used for carrier signal modulation. In GSM 1800 (the GSM system working in the 1,800 MHz band), there are 374 duplex channels and 8 time slots, which gives a possibility of creating 2,992 transmission channels simultaneously by a single base station. Parameters for GSM 900, GSM 1800, and GSM 1900 systems are presented in Table 7.1.

Table 7.1
Transmission Frequency Bands and Channels in GSM Network

Frequency Band	*Downlink Channel*	*Uplink Channel*	*Number of Frequency Channels*	*Number of Traffic Channels*	*Maximum Velocity of a Mobile Station*
900 MHz	890 to 915 MHz	935 to 960 MHz	124	992	250 km/h
1,800 MHz	1,710 to 1,785 MHz	1,805 to 1,880 MHz	374	2,992	130 km/h
1,900 MHz	1,850 to 1,910 MHz	1,930 to 1,990 MHz	299	2,396	120 km/h

7.2.2 GSM-Based Data Transmission

The GSM system can be used for digital data transmission as well. This entirely digital second generation mobile phone system was designed for both audio signal (voice) and digital data transmission.

Mobile Stations

For digital data transmission to be possible in the GSM system, all the system components, including mobile stations (phones), must be capable of transferring digital data. Figure 7.2 shows the block diagram of a typical mobile phone.

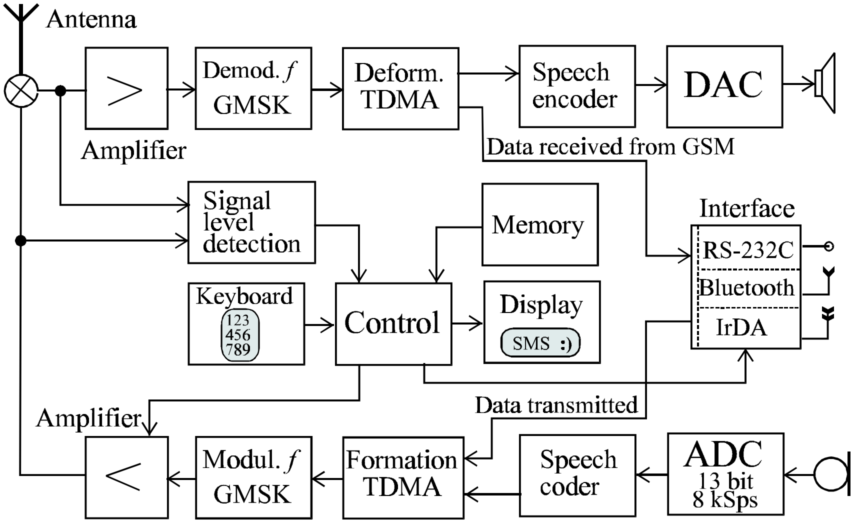

Figure 7.2 The functional diagram of a mobile station (mobile phone).

The telephone circuit includes a voice-processing transmission line from microphone to antenna, and a reception line from antenna to speaker. Besides the functional units within those lines, the telephone circuit must comprise a control system, a memory, a display unit, keys, and an interface system for communication with external digital devices, including computers. The block diagram shown in Figure 7.2 does not include auxiliary circuits, providing the mobile phone with extra functionalities, such as digital camera, GPS receiver, radio receiver, MP3 file player, noise level meter, thermometer, flashlight (Nokia 5210), or other gadget functionalities [1]. The flashlight functionality in a mobile phone is especially amazing, as it represents a combination of two devices of very different natures: a very simple and rather energy-consuming electric appliance (flashlight), and a high technology device with low energy consumption (mobile phone).

In the mobile phone transmission function, a voice signal (or audio signal, in general) is converted into an electric signal by the transmitter. An analog electric signal from the transmitter is sampled with 8-kHz frequency and converted to a digital form in a 13-bit ADC. The ADCs typically installed in mobile phones are successive approximation register (SAR) or half-flash types. The output serial bit stream leaves the converter with data rate 104 kbps (13 bit × 8,000 1/s) to pass through a speech coder, in which high-compression coding and channel coding (with redundancy bits added to secure transmission correctness) are performed. The coder output data flow is 22.8 kbps. In the next processing unit, the data is organized in packets, and prepared for TDMA transmission (i.e., transmission within a single time slot). The carrier frequency is keyed with a digital data signal in a GMSK modulator. The amplified digital signal with data rate 270.833 kbps is directed to an antenna branching filter, and then transmitted by the antenna. The duration of 1 bit is 3.692 μs, which corresponds to approximately 3,300 signal periods at signal carrier frequency of 900 MHz.

In the reception function, the incoming radio signal is amplified in an amplifier, then demodulated and unpacked from TDMA packets. The unpacked voice signal is decoded, and the digital data passed to the interface system. The decoded digital voice signal (or audio signal, in general) is converted by a DAC into an analog signal, and reproduced by the speaker.

Classified according to their capabilities of external digital data transmission, mobile phones can be divided into three groups (see Figure 7.3): MT0, MT1, and MT2. Note that the data in question is *external* digital data. Every GSM mobile phone transmits a voice signal converted into *an internal* digital signal.

An MT0 (Mobile Terminal 0) is a mobile phone with no external data interface. In its simplest form, an MT0 phone transmits voice and keyed short message service (SMS) messages only. It cannot transfer any data coming from another digital device. However, MT0 phones can be very advanced technologically. An example of such an MT0 phone is a mobile phone integrated with a palmtop. Being a source of digital data in itself, it needs no interface with external devices.

MT1 phones can transmit digital data. An MT1 communicates with an Integrated Services Digital Network (ISDN) through an S interface, but requires a separate device, referred to as a terminal adaptor (TA), for communication with a computer. The role of the TA is to adapt bidirectionally RS-232C standard computer signals to the ISDN, or mobile phone, standard. The terminal adaptation functions (TAF) are divided between a mobile phone and a TA. A TA can be a PCMCIA card, acting as a GSM modem. An example of such a PCMCIA card is a Cellular Data Card for Nokia 2110 MT1 phone.

MT2 phones can transmit digital data from a computer via an RS-232C interface electric cable, via an IrDA link (e.g., Nokia 6210 [1] or Ericsson T39m [2] models), or via a Bluetooth radio link. All TAF functions are performed by MT2 phone circuits.

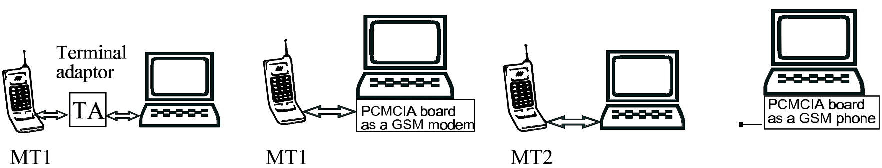

Figure 7.3 Different groups of mobile phones, classified according to digital data transmission capability.

However, the above classification does not cover two types of device, very useful in digital data transmission from a computer to a GSM system. One is a laptop PCMCIA card, functioning by itself as a mobile phone. An example of such a PCMCIA card is the Nokia Card Phone 2.0, with built-in antenna. When installed in a laptop and connected to a handset, this card functions as a dual band mobile phone, able to operate in GSM 900 or GSM 1800 bands, as shown in Figure 7.4. New products, such as the PMCIA Sony-Ericsson Card Phone GC 19E or the Nokia Card Phone D211, can be used for both HSCSD and GPRS transmission. They have an additional radio interface IEEE 802.11b, and can operate in many PC operating systems, such as Windows 98, Windows ME, and Windows XP [1, 2]. The Nokia Card Phone 2.0 has typical type II PC Card dimensions, $124 \times 54 \times 10$ mm, and a low weight (58 g). It allows transmission of SMS messages and digital data with asymmetric maximum speed: 43.2 kbps for reception and 28.8 kbps for transmission.

Figure 7.4 Mobile phones in the form of a laptop PCMCIA board.

The other type not covered by the above classification includes devices such as the GENERIC GPRS laptop with mobile phone module, or the Motorola palmtop (Accompli 09 palmtop). Their development is a step forward in the integration of GSM-based data transmission devices. GSM system offers a variety of digital data transmission services, including [3]:

- Short Message Service (SMS), which is the transmission of alphanumeric messages of up to 160 characters;
- Multimedia Messaging Service (MMS), which is the store-to-forward transmission of text, graphic, sound, and video files;
- Circuit Switched Data (CSD) transmission, which is the switched transmission of digital data with speeds up to 9.6 kbps via traffic channel; this type of transmission is also referred to as Switched Data Transfer (SDT);
- High Speed Circuit Switched Data (HSCSD) transmission, in which data is transferred through several assigned traffic channels;
- General Packet Radio Service (GPRS), a packet data transmission mode;

- Enhanced Data rates for GSM Evolution (EDGE), an upgraded data transmission mode designed to work side-by-side with existing GSM implementations.

Digital data transmission types in mobile telecommunications networks are presented in Table 7.2.

Table 7.2

Digital Data Transmission Types in Mobile Telecommunications Networks

Transmission Mode	*Description*	*Maximum Data Transfer Speed*	*Network*
CSD	Standard digital data transmission	9.6 kbps	GSM
CSD	Digital data transmission with data compression	14.4 kbps	GSM
HSCSD	High-speed digital data transmission	57.6 kbps	GSM + slight modifications
GPRS	Packet data transmission	115 kbps	GSM + GPRS backbone
EDGE	Enhanced data transmission in modified GSM system	384 kbps	GSM + substantial modifications
UMTS	UMTS-based data transmission	1,960 kbps	UMTS global network

Short Message Service

SMS allows transmission of short alphanumeric messages up to 160 characters in length, to GSM or e-mail users. Messages can also be sent, without interference, during a phone call. SMS is a person-to-person service, which means the user obtains the message directly into the mobile station without checking its message box.

Representing a very light channel load, SMS is the cheapest mode of data transmission. Optionally, a delivery report can be sent from recipient to sender, to verify that the message has been delivered. In the case of lack of communication with the recipient at the moment of sending, the message is stored in an SMS center, and forwarded to the recipient after affiliation. Typical message delivery time is a few seconds from the moment of sending, unless the communication is disturbed. However, delivery delays can be much longer. A message can be delivered after several hours or days, and in occasional cases can remain undelivered (which was the reason for creating the delivery report option). All SMS messages are transmitted via a Short Message Service Center (SMS-C), which is a part of the GSM switching system. Since SMS-C functions are not standardized, different SMS services can be offered by different operators. For measurement purposes, the short message service can be used in a technique of object monitoring by means of specialist instruments, with measurement data transmitted in the form of text messages. The maximum number of characters in an SMS message can actually be six times larger than the nominal number, and thus equal $6 \times 160 = 960$, but messages longer than 160 characters are divided by the system into shorter messages (up to 160 characters in length), which are sent and billed separately. However, the delivery delay of a measurement report message, typically in the order of 10 seconds, can be too long for some measurement or alarm systems.

Multimedia Messaging Service

MMS is a person-to-person transmission, like SMS, of multimedia files via the GSM network. Files can be transferred between users (i.e., from one subscriber to another) or between devices. MMS allows data transmission of:

- Text (plain text, not formatted, or rich text, with formatting instructions);
- Graphic, such as JPEG, GIF, and Portable Network Graphic (PNG) files;
- Sound (Basic files, MP3, or WAV);
- Video (MPEG files).

A highly significant feature of MMS is a possibility of transferring files from the Internet. Each MMS message, like an Internet packet, consists of an envelope (instructions required to deliver and interpret a message), and the message contents. The MMS standard uses a Wireless Application Protocol (WAP) as its transmission protocol. Therefore, MMS will take advantage of enhanced transmission modes (HSCSD, GPRS, EDGE) where the WAP is used as well. MMS is not used in measurement systems as yet. However, it can be in traffic monitoring or water level monitoring, as well as in monitoring/ alarm systems in industrial production. All these applications would involve the transmission of image or video files. No common MMS standards, including a standard volume of transmitted MMS files, have yet been adopted by GSM network operators. At present, the size of MMS messages varies between 10 to 100 kilo-octets [3].

Circuit Switched Data

CSD transmission via a telephone radio channel has been possible since the very creation of GSM. However, its use in measurement systems is limited, due to its low data transfer speeds (up to 9.6 kbps). The cost efficiency of CSD is affected by the fact that this type of transmission occupies the entire traffic channel, with the data connection being billed like a phone call (see Figure 7.5). Efforts are being made to develop techniques allowing higher data rates, and a solution is provided by the HSCSD transmission mode.

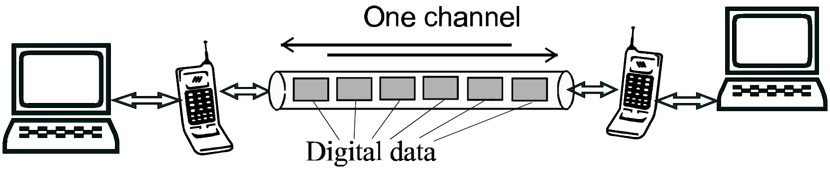

Figure 7.5 CSD transmission in a GSM system.

High-Speed Circuit Switched Data

Increased data rates in the HSCSD mode are obtained by two methods: through data compression, which enhances the capacity of a single transmission channel from 9.6 to 14.4 kbps and through the combination of several (up to four) traffic channels within a single physical channel (see Figure 7.6).

The number of channels used is increased by allocating a higher number (two to four) of time slots. With four traffic channels used, data rates can be up to 57.6 kbps. However, this requires operators to add some modifications to GSM base stations, and requires users to have appropriate mobile phones. At first, HSCSD transmission cost was proportional to data transfer speed, or the number of channels used. Presently, connection cost is independent of the number of channels used, but network operators do not warranty constant enhanced data rates throughout a connection.

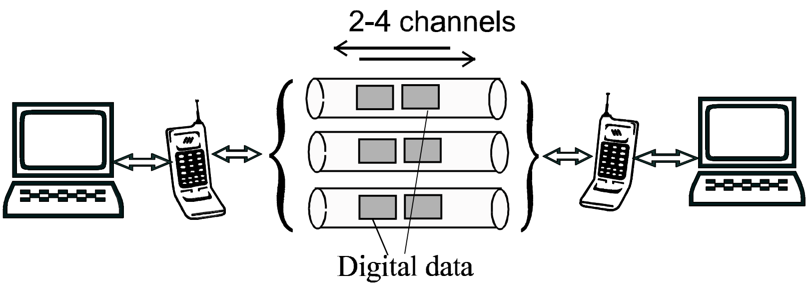

Figure 7.6 HSCSD transmission in a GSM system.

In both CSD and HSCSD transmission modes, data is transferred either between two GSM network users or between a GSM network user and a stationary telecommunications network (PSTN) user. Measurement data can also be sent to an Internet address. The data rates available in HSCSD are 14.4, 19.2, 28.8, 38.4, 43.2, or 56.0 kbps.

General Packet Radio Service

GPRS allows packet data transmission via the Internet without transmission channel switching. Whereas the transmission modes discussed above are based on channel switching, GPRS uses packet switching instead. A GPRS session can be activated in the "always connected" mode, and data can be transferred during phone calls without interference. Each packet, or set of data transferred, is an integrated whole, and can be transmitted independently of the other packets, with the destination Internet address being specified in the packet header, as shown in Figure 7.7. Copies of a data packet can be sent to a number of addressees at the same time.

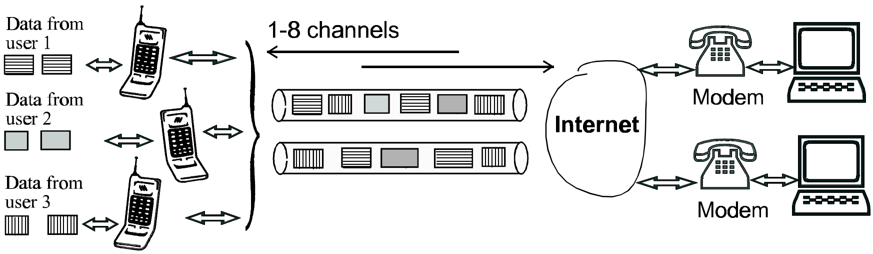

Figure 7.7 GPRS transmission in a GSM system.

Beside permanent access to the Web, a great advantage of GPRS is high data transfer speeds. This is due to the use of up to eight time slots allocated at transmission channel setup. The capacity of a single time slot, 14.4 kbps, multiplied by the number of the allocated time slots, gives the maximum GPRS data transfer speed, $8 \times 14.4 = 115.2$ kbps. Theoretically, even higher data rates, up to 170 kbps, are possible with different methods of data coding. The implementation of GPRS requires from network operators even larger modifications of base stations than in the case of HSCSD mode. However, those modifications are limited enough to qualify both GPRS and HSCSD transmission modes as *add-on services* to the GSM system (i.e., hardware and software are to be added to the core GSM network). GPRS is considered the first intermediate digital data transmission technology between GSM and UMTS. The second intermediate technology of this type is EDGE. Maximum data transfer speed in the GPRS mode depends on the GSM network quality, as well as on the mobile phone parameters, which should meet GPRS standards. For cost-effective reasons, GPRS mode is recommended for the following purposes:

- Nonperiodic data transmission;
- Frequent low-volume transfers, below 500 data octets each, performed several times per minute;
- Higher-volume data transfers performed with frequency several times per hour or less.

Many mobile phone models currently available on the telecommunications market support GPRS data transmission.

The maximum data rates specified for several applications may differ from those warranted by network operators. As an Internet-based transmission mode, GPRS involves the use of Internet Protocol (IP), whose procedures reduce maximum single-channel compressed data transfer speed from 14.4 to 13.4 kbps. On the basis of standardized GPRS protocols, a GSM network operator can provide a number of extra services, such as Internet data reading, remote meter reading, credit card authentication, and many others. These services involve, however, extra equipment at mobile stations.

Motorola Timeport 260 and Ericsson R520 were the first mobile phone models to have GPRS functionality. The Motorola Timeport 260 allows GPRS transmission with asymmetric data rates of 13.4 kbps (one channel) for transmission, and 40.2 kbps (three channels) for reception. Launched as a state-of-the-art mobile phone model, the Ericsson R520 (with GPRS and HSCSD functionalities, and IrDA and Bluetooth wireless interfaces) proved defective, and was withdrawn from sale for several months in 2001. GPRS-supporting mobile phones are manufactured by Nokia, Siemens, and Samsung. Packet data transmission can be used in distributed measurement systems, with the constraint that data is sent to a recipient (e.g., to system center) at an Internet address rather than at a telephone number.

The following computers can be useful in computer measurement systems with GSM-based wireless data transmission:

- GERICOM GPRS laptop;
- Motorola Accompli 009 palmtop.

Equipped with a mobile phone module supporting GPRS transmission, each of these mobile computers can be used in a wireless communication system as a system controller and a transceiver station at the same time. The GERICOM laptop has a built-in GPRS-supporting Siemens mobile phone module that delivers asymmetric data rates, due to its use of four channels for reception and only one channel for transmission.

Packet data transmission can be used in distributed measurement systems, especially those in which the system center collects data from several measurement stations. The data is sent to the system center e-mail address. From the user's point of view, the main advantage of GPRS is its low cost, depending only on the volume of the transmitted data packet. In its currently available form, GPRS allows data transmission between a mobile phone and the Internet (including WAP) only.

For example, technical data of the Ericsson T39m mobile phone (see Figure 7.8), which supports GPRS and is used at the Poznan University of Technology measurement system, includes:

- Frequency bands: 900 MHz, 1.8 GHz, and 1.9 GHz (the 1.9-GHz band allows a phone to operate in the U.S. mobile phone network);
- Maximum data transfer speed in HSCSD mode: 28.8 kbps;
- Maximum data transfer speed in GPRS mode: 53.6 kbps;

- Communication with computer through RS-232C port: 230.4 kbps;
- Communication with computer through IrDA port: 1 Mbps within 1m;
- Communication with a computer through Bluetooth port: 108.8 kbps within 10m.

Figure 7.8 Ericsson T39m mobile phone supporting GPRS transmission.

Data transmission between GSM and other telecommunications systems requires modems to convert binary GSM signals into analog signals. The modem is installed at the meeting point of the two networks, in the Interworking Functions (IWF) modules in the Gateway Mobile Switching Center (GMSC). The following modem standards are compatible with the GSM standard: V.21, V.22, V.22bis, V32, V90, and ISDN standards V.110 and V.120.

EDGE Transmission

Designed for data transmission in upgraded GSM networks and promising data rates of 384 kbps, EDGE is an intermediate step between GSM and UMTS wireless digital data transmission technologies. EDGE is to also be available in TDMA. The possibilities of this mode include transmission of moving images. GSM frequency bands and radio channels with 200-kHz spacing are assigned for EDGE transmission. This solution facilitates interworking between the classic GSM and EDGE/GSM systems, and allows a substantial reduction of EDGE technology implementation costs. The high data rates promised by EDGE are obtained through combining two modulation methods: 8-Phase Shift Keying (8-PSK), an octonary signal modulation mode, and Gaussian Minimum Shift Keying (GMSK), the binary modulation scheme used for digital signal coding in all other GSM-based transmission modes, as shown in Figure 7.9. The Minimum Shift Keying (MSK) is a special case of the FSK modulation, as discussed in Section 6.4), with a frequency pulse that makes the modulation more effective. The GMSK modulation is a type of MSK with signal filtering using the Gaussian filter [4].

The quality of an 8-PSK octonary-modulated signal must be substantially higher than that of a GMSK binary-modulated signal. Therefore, 8-PSK can be used only when the distance between the mobile station and the base station is not too long, and the mobile station velocity is not too high, since both factors affect signal quality. The choice of the modulation scheme and type to be used in the EDGE mode is adaptable and made by the system. GMSK (MCS-1 to MCS-4 type) or 8-PSK (MCS-5 to MCS-9 type) is used, depending on signal quality. The corresponding maximum data rates range from 8.4 kbps (GMSK, MCS-1) to 59.2 kbps (8-PSK, MCS-9), with one time slot used. With eight time slots used, the theoretical maximum data rate in EDGE is from $8 \times 8.4 = 67.2$ kbps, up to $8 \times 59.2 = 473.6$ kbps. The recommended data transfer speed for transmission of moving images is 384 kbps, far below the EDGE upper limit [according to an International Telecommunication Union (ITU) recommendation for moving images] [5].

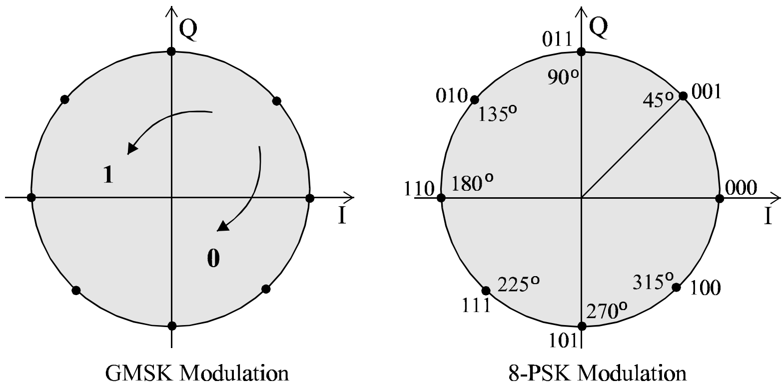

Figure 7.9 GMSK binary modulation scheme in "plain" GSM network, and 8-PSK octonary modulation scheme in GSM with EDGE transmission.

The key features of EDGE transmission are:

- The ability to operate in mobile phone networks, using the 800, 900, 1,800, 1,900, or 2,150 MHz frequency bands;
- Standard maximum data transfer speed 384 kbps;
- Symmetric and asymmetric transmission channels;
- Packet transmission function available;
- Roaming between GSM (European) and TDMA (American) telecommunications networks.

Implementation of the EDGE mode requires substantial modifications of both GSM network and mobile phone design. EDGE transmission was launched in 2002. EDGE-supporting mobile phones were launched on the world's markets in 2003. Examples of such mobile phone are the Nokia 6220 and the Nokia 6820. The Nokia 6220 delivers maximum data transfer speeds of 118 kbps in the EDGE transmission mode, and is supplied with digital camera, video recording, WAP, MMS, and Java functionalities [1].

7.2.3 AT Commands

Developed in the 1970s in Hayes Company for communication between computers and modems, AT commands were subsequently adopted as a standard by international telecommunications organizations [5, 6]. The name comes from the first two letters of the word “attention,” coded in ASCII and beginning every command. Alphanumerical characters and other character types used in AT commands should be listed in the International Reference Alphabet (IRA). AT command characters should be written in 8-bit words. If 7-bit characters (e.g., ASCII or ISO-7 characters) are generated by terminal equipment (TE), an eighth bit is to be added by a suitable TE unit in order to form a correct command. The functional diagram of a GSM–based data transmission system, according to the standard [6], as well as the command flow, are depicted in Figure 7.10. The following units are shown: Terminal Equipment (TE), Mobile Equipment (ME), and Terminal Adaptor (TA).

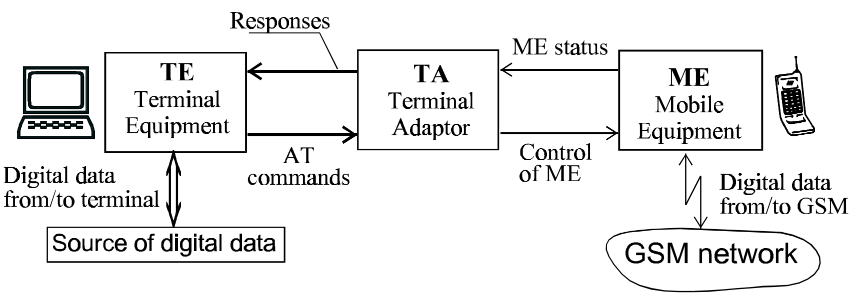

Figure 7.10 Organization of command flow between Terminal Equipment (e.g., a computer), Terminal Adaptor, and Mobile Equipment (e.g., mobile phone) in a GSM network.

ETSI recommendations relate *exclusively* to instructions transmitted between TE and TA (i.e., AT commands and responses). Usually, TE is a computer and ME is a mobile phone. By analogy to the RS-232 standard (see Chapter 6), TE and ME can be regarded as the GSM counterparts of DTE and DCE (modem), respectively, in RS-232. The physical connection between TE and TA is not defined. It can be an electric cable, a radio link, or an optical link.

The following four architecture variants of the system shown in Figure 7.10 are admitted by the standard [5]:

- TA, ME, and TE can be separate devices; in this architecture variant, an MT1 mobile phone (see Section 7.2.2) is used as ME;

- TA and ME can be integrated, with TE being a separate device (the most common variant of digital data transmission system architecture, with an MT2 mobile phone used as ME);
- TA and TE can be integrated, with ME being a separate device;
- TA, ME, and TE can be integrated (e.g., a Motorola Accompli 009 palmtop, functioning as a mobile phone as well).

The list of AT commands is very long, containing hundreds of items. Two AT command types can be distinguished—basic commands and extended commands. In another classification, AT commands can be divided into execution commands and set commands.

Following are some examples of AT execution commands and their meanings: “ATD××××” means station number ×××× dial-up, “AT&FO” commands default modem transmission parameter setup, and “ATH” orders connection end. Set commands carry instructions regarding a transmission parameter (or a number of parameters) to be set up, and specifying the desired parameter values.

Basic AT commands are of universal nature, and are used in both wired and wireless networks for controlling various devices, such as telephones, faxes, or radiomodems. A basic command contains a string of alphanumerical characters preceded by the AT prefix. Extended commands specify the selected network type (PSTN or GSM) or transmission mode (voice, data, fax, SMS, CSD, HSCSD, GPRS, or EDGE). In an extended command, the initial “AT” is followed by a “+,” after which come the other characters.

The AT commands used for control of GSM devices are divided into the following groups (according to ETSI documents [6]):

- Control and Identification;
- Call Control;
- Voice Call Control;
- Data Compression;
- Mode Management;
- Audio Control;
- Accessory Menus;
- Accessory Authentication;
- Accessory Identification;
- Interface Commands;
- GSM DTE-DCE Interface Commands;
- GSM Call Control;
- GSM Data;
- GSM High Speed Circuit Switched Data;
- GSM Network Services;
- GSM USSD;
- GSM Facility Lock;
- GSM Mobile Equipment, Control, and Status;

- GSM Mobile Equipment Error Control;
- GSM SMS and GSM PDU Mode;
- GSM GPRS;
- GSM Phonebook;
- GSM Clock, Date, and Alarm Handling;
- GSM Subscriber Identification;
- WAP Browser;
- AT Specific Commands (e.g., Ericsson Specific Commands for GSM).

AT commands for devices operating in the *GSM network* have a prefix +C (i.e., each such command begins with “AT+C… “). Depending on the data transmission service type, a subset of service-specific AT commands is used (e.g., SMS, CSD, or HSCSD command sets). Set commands contain the equality sign “=” followed by numbers that represent coded parameter values. For example, the “select Bearer Service Type” command has the following structure:

“AT+CBST= [<*speed*> [, <*name*> [, <*ce*>]]],” as recommended in [6].

The setup parameters are:

- <*speed*>: the maximum signal transmission speed for different signal modulation standards; speed value is coded with numbers from 0 to 116;
- <*name*>: transmission type by synchronization criterion: asynchronous or synchronous, packet or stream data transmission; coded with numbers from 0 to 7;
- <*ce*>: transmission type by another criterion: transparent (for data stream) or nontransparent transmission, any transmission type, or preferably nontransparent; coded with numbers from 0 to 3.

Transparent transmission is a data stream transmission without interference in the content of the data stream. This type of transmission is used when data transfer speed is a priority for the user. Nontransparent transmission involves error check procedures and adaptation of data transfer speed to reception capacities. In particular, the nontransparent transmission protocol includes an ARQ procedure that orders a data packet or frame re-sent when a transmission error is detected. Nontransparent transmission is used when transmission quality has priority over speed.

An example of “AT+CBST= [<*speed*> [, <*name*> [, <*ce*>]]]” command is “AT+CBST=43,4,0” (brackets are omitted in actual commands), which means: 43—data transfer speed set at 14,400 bps in V.120 standard modulation; 4—asynchronous data stream transmission (data circuit); and 0—transparent transmission.

A variety of set commands are query commands; for example, a “AT+CBST?” command means: “what are the set-up transmission parameter values (selected bearer service type)?" A message sent to TE in response to this command is of the set command structure; for example "AT+CBST= 43, 4, 0."

Let's study some examples of AT commands for HSCSD and GPRS transmission modes, and the meaning of symbols they include. Here are three examples of *HSCSD transmission AT commands* and their meanings.

1. "AT+CHS..." is the beginning of each AT command relating to HSCSD transmission in a GSM network.
2. "AT+CHSN=4,2,2,8" is a set command; 'AT+CHSN=...' commands non-transparent HSCSD transmission parameter setup; 4 means data transfer speed of 28,800 bps; 2 means two reception time slots in a time frame; the other 2 means two transmission time slots in a time frame; and 4 stands for TCH/F14,4 channel coding type.
3. "AT+CHSR=1" is an execution command that requests the transmission parameter report to be sent (after a connection is established); "AT+CHSR=0" commands that the report not be sent.

Now let's decipher some examples of *GPRS transmission AT commands*:

1. "AT+CG… " is the beginning of each AT command relating to GPRS transmission.
2. "AT+CGATT=1" is an execution command that orders GPRS mode to be enabled in an ME (mobile phone) (i.e., selects GPRS mode for data transmission); 'AT+CGATT=0' commands to disable GPRS mode.
3. "AT+CGAUTO=[<*n*>]" sets up automatic positive response to request of enabling Packet Data Protocol (PDP). Parameter *n* values range from 0 to 3 and means: 0—automatic response disabled (only for GPRS); 1—automatic response enabled (only for GPRS); 2—modem-compatible operation mode (only for GPRS); and 3—modem-compatible operation mode for GPRS or switched transmission modes (CSD or HSCSD).

Similar to the commands sent from TE to TA, responses can be either basic or extended. Here are two examples of basic response.

1. "<CR><LF>OK<CR><LF>," reporting successful execution of a command or a list of commands;
2. "<CR><LF>ERROR<CR><LF>," reporting obstacles and unsuccessful command execution; <CR> is the printer Carriage Return symbol, and <LF> is the Linefeed Character symbol.

7.2.4 GSM-Based Distributed Measurement Systems

The possibility of data transmission via a GSM network can be used in distributed measurement systems. Figure 7.11 shows a general block diagram of such a

GSM-based system, consisting of a number of digital measurement stations and a system center. Each measurement station is outfitted with a digital instrument (or a number of digital instruments), a computer, and a mobile phone. The digital instruments are connected to the mobile phone via the computer. MT1 or MT2 phones should be used as mobile stations in measurement systems of this type; a PCMICIA Card Phone (e.g., Nokia Card Phone 2.0) can be used in place of a mobile phone as well. The digital instruments can be connected to the mobile phone directly, without passing through the computer, but this requires a special interface system. At present, no standard interface of this type is available, although considering the tendency to standardize interfaces, digital instrument-mobile phone interfaces can be expected to appear on the market within the next few years. Typically, however, the system instruments are connected to the computer through standard interfaces, such as an RS-232C serial interface for a digital voltmeter, or an IEEE-488 parallel interface for a digital oscilloscope. An advantage of the computer's intermediary role in digital data transmission from instrument to mobile phone is the possibility of processing the measurement data before forwarding it to the system center.

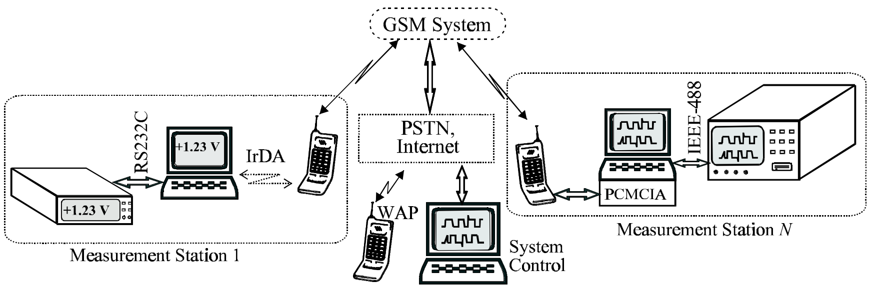

Figure 7.11 The block diagram of distributed measurement system with data transmission via a GSM network.

The digital data is transmitted to a computer in the measurement system center, either via stationary telephone network or via the Internet. In the latter case, the data can be received also by a mobile phone that allows access to the Internet through WAP protocol.

A separate problem is data transmission between a computer and a mobile phone within a measurement station. An electric cable, an IrDA link, or a Bluetooth radio link can be used as a physical medium for this transmission. Data transfer should be controlled by AT commands.

The GSM-Based Measurement System at the Poznan University of Technology

A measurement system with GSM-based digital data transmission in the HSCSD mode (see Figure 7.12) was designed, provided with software, and tested at the Poznan University of Technology (PUT) in 2001 [7]. The measurement system consists of a system center and a mobile measurement station. The system center is a PC connected to the stationary telephone network by means of a modem. The measurement station is equipped with a digital multimeter connected to a Toshiba laptop via RS-232 interface. A Nokia Card Phone 2 is used as a mobile phone. The measurement system operation is organized by two algorithms, one relating to the system center, and the other to the measurement station. The algorithms provided the basis for a control software written in the HP VEE 5 program language to operate both the system center and the measurement station. Standard AT commands are used for modem control. Once a telephone connection is established between the computers (connection setup time being 18 to 40 seconds), measurement data as well as control commands can be transmitted bidirectionally in HSCSD mode between the system center and the instrument.

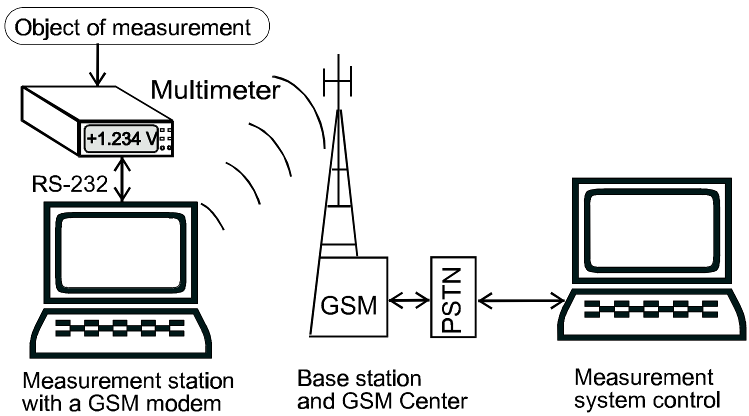

Figure 7.12 The GSM-based measurement system with HSCSD data transmission, designed at the Poznan University of Technology.

The system center operates in either transmission or watch mode. In transmission mode, the system center can connect the measurement stations (terminals). Once in communication with a measurement station, the system center sets up measurement parameters, such as measured quantity, number of measurements within a series, and repetition period. The required measurements are then performed by the measurement station, and the results sent on-line to the system center. According to a task included in the HP VEE software, the measurement data is recorded by the system center, and visualized as a function of time. Graphic representation of measurement data is performed after an automatic transmission of the results of a measurement series to MS Excel.

In watch mode, the system center waits for a connection to be initiated by a measurement station. Each measurement station can send a data transmission request. According to the corresponding operation algorithm, a measurement station connects to the system center for transmission of measurement results in two situations:

- When transmission of results is programmed (e.g., to be performed every hour);
- When a setup limit value of measured quantity is exceeded (i.e., in alarm mode).

Measurement stations operate in either local or remote mode. In remote mode, the measurements performed are controlled by the system center, and each measurement result is transmitted to the system center immediately. The digital data transfer speed in the described PUT measurement system is 28.8 kbps in both directions (in HSCSD mode), which involves the use of two channels for transmission and two channels for reception. Higher data rates (up to 43.2 kbps) are possible in data transmission to the Internet or to a receiving station connected to ISDN.

In the next version of the distributed measurement system with GSM data transmission, the multimeter was replaced by an NI DAQCard 6024E, which is a PCMCIA measurement board comprising an ADC with a resolution of 12 bits and a maximum sampling rate of 200 kSps. The system was used for measurements of signals with audio frequencies. Each measurement result was a 2-byte word. On-line data transmission was carried out correctly and without delay for sampling rates up to 1,600 Sps (with 2-byte samples grouped in packets, 100 to 1,000 samples each). Higher sampling rates involved a delay in data transmission, due to the limited dynamics of GSM.

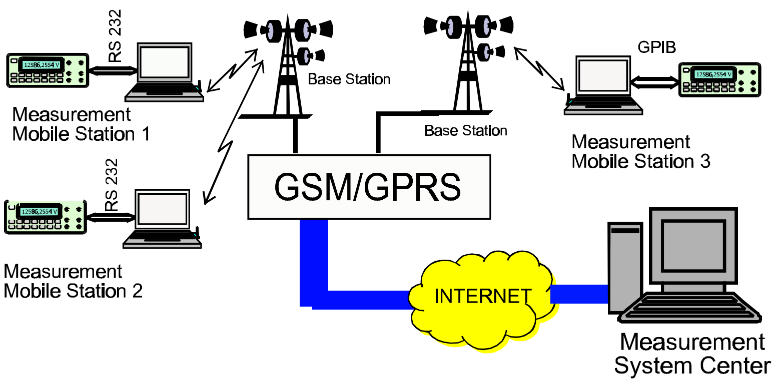

Figure 7.13 The GSM-based distributed measurement system with GDRS data transmission.

In a GSM-based distributed measurement system, one can use GPRS transmission technology as well. GPRS provides a packet switching via the Internet instead of channel switching. A transmission method and a transmission time of the packet are not determined. The packet with the measurement data can be delivered first to the measurement system center. The measuring system with GPRS transmission was developed and tested at the Poznan University of Technology. The system consists of three measurement mobile stations and the measurement system center equipped with a PC with an Internet access, as shown in Figure 7.13. The mobile stations in the system were GSM/GPRS modems Option Globetrotter (PCMCIA card). The average transmission rate in the system was 15 kbps, and the mean transmission period of the data packet with 1,000 samples was approximately 1 second, with a maximum of 3 seconds [7].

Measurement Systems with SMS Data Transmission

The route of an SMS message from the computer in a measurement station to the SMS Center (or SMS-C, in a GSM center) can be divided into two sections with different transmission protocols. The first section is from terminal adaptor (computer) to mobile phone. Since no standard protocol exists for digital data transmission between such devices, there is much freedom in the choice of protocol, and telephone manufacturers are not always willing to disclose protocols used in their mobile phone models. The other section of the message route is from mobile phone to the SMS-C. In this section, SMS data is transferred in Protocol Data Units (PDU) frames. There are two types of PDU [3]:

- SMS-SUBMIT type, conveying an SMS message from mobile phone to SMS-C;
- SMS-DELIVER type, conveying an SMS message from SMS-C to mobile phone.

The formats of both PDU types are shown in Figure 7.14. The gray UD fields contain SMS message text of size from 0 bytes (void message) to 140 bytes. The other PDU fields contain:

- PDU Type, specifying whether the PDU is of DELIVER or SUBMIT type, whether the message transmission is paid by the message sender or by the message recipient, and whether delivery report is requested or not;
- Message Reference (MR) number (0 to 255);
- Destination Address (DA), the recipient's phone number;
- Originator Address (OA), the sender's phone number;
- Protocol Identifier (PID), specifying data type (text, telex, or fax);
- Data Coding Scheme (DCS) used;
- Validity Period (VP), the maximum time of message storage in SMS-C in case of delivery failure;
- User Data Length (UDL), the length of the message;
- Service Center Time Stamp (SCTS), time of message reception by SMS-C.

SMS-SUBMIT PDU Format

1 byte	1 byte	2 to 12 bytes	1 byte	1 byte	1 to 7 bytes	1 byte	0 to 140 bytes
PDU Type	MR	DA	PID	DCS	VP	UDL	UD
PDU Type	Message Reference Number	Destination Address	Protocol Identifier	Data Coding Scheme	Validity Period	User Data Length	User Data

SMS-DELIVER PDU Format

1	2 to 12	1	1	1 to 7	1	0 to 140 bytes
PDU Type	OA	PID	DCS	SCTS	UDL	UD
PDU Type	Originator Address	Protocol Identifier	Data Coding Scheme	Service Center Time Stamp	User Data Length	User Data

Figure 7.14 PDU formats for SMS message transmission.

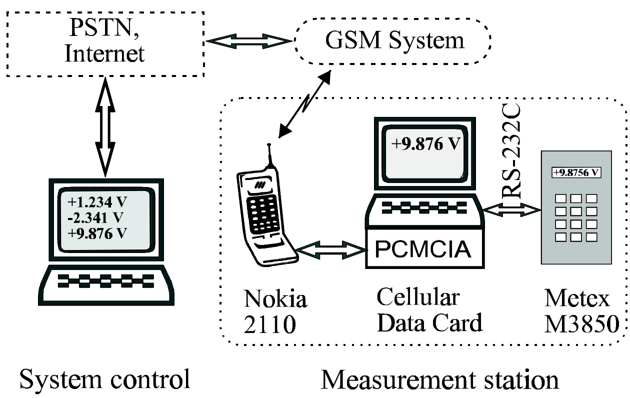

Figure 7.15 Block diagram of a distributed measurement system with GSM-based data transmission.

The block diagram of a GSM-based measurement system with SMS data transmission is shown in Figure 7.15. An Metex M3850 digital multimeter in the measurement station, and a PC in the remote system center, are the measurement system terminals. Measurements are controlled by a laptop connected to the digital multimeter through an RS-232C interface. Parameters of the RS-232C transmission are determined by digital signal from the multimeter. The transmission is of asynchronous character type.

Parameters of data transmission between the multimeter and the laptop are as follows:

- 7-bit SDU (see Chapter 6, Figure 6.2), an ASCII character;
- 2-bit stop;
- No parity control bit;
- Data transfer speed 1,200 bps.

A data frame sent by the multimeter contains 14 SDU (characters), and carries a single measurement result; the fourteenth character is CR, closing frame transmission. The mobile phone model used in the measurement system shown in Figure 7.15, Nokia 2110, is of MT1 type, and thus requires a terminal adaptor to support data transmission. A Cellular Data Card for Nokia 2110, also referred to as a GSM modem card, is used as a terminal adaptor [1].

Parameters of data transmission between the mobile phone (Nokia 2110) and the laptop are as follows:

- 8-bit SDU (an ASCII character);
- 2-bit stop;
- No parity control bit;
- Data transfer speed 115.2 kbps.

Measurements performed with the digital multimeter as well as transmission of their results are controlled by SmsMeter2000, a computer software written in Visual Basic 6. During a test run, the system proved capable of collecting and transmitting series measurement data with a sampling period of at least 10 seconds, and thus was able to monitor objects that cannot be connected to a stationary telephone network.

Though digital data transmission via the GSM network can provide a basis for distributed measurement system functioning, the following two limitations are imposed by the low (even in HSCSD mode) data rates:

- On-line result monitoring or measurement remote control requires moderate dynamics of measured processes;
- Measurement results cannot be transmitted in large files, which confines the choice of instruments to simple ones, such as voltmeters or frequency meters.

7.2.5 Universal Mobile Telecommunications System and Measurement Data Transmission

UMTS General Features

A characteristic feature of 1G mobile phone systems is analog voice processing; 2G systems use entirely digital transmission lines. A desired characteristic of 3G wireless communications systems is to provide conditions for Personal

Communications Network (PCN) deployment. The assumed features of PCN are as follows [4, 8]:

- Single individual user number to be used in any telephone network;
- Individual set of transmission services provided in any place and by any operator;
- Global access to the network.

An important step in the evolution of wireless data transmission technologies is the prospected deployment of UMTS, a 3G mobile phone system operating in the 1,950 and 2,150 MHz bands. UMTS is being developed by the European Telecommunications Standard Institute (ETSI). Along with UMTS, a parallel 3G mobile phone system, referred to as International Mobile Telecommunications-2000 (IMT-2000), is under development by the International Telecommunication Union (ITU). Efforts are made to ensure mutual compatibility of both systems, with special attention being paid to radio interface compatibility.

The structure of UMTS is determined by the assumed widespread use of and global access to the system [8]. Uninhabited areas, such as oceans or deserts, as well as regions in which population density is very low, are to be covered by large-area cells, or macrocells, using a satellite communication system to be organized within UMTS. In other parts of the world, UMTS is to be based on a terrestrial communication network. Peak population density zones, such as airports, business centers, or office buildings, are to be covered by small-area cells, or microcells, to ensure system availability to every potential user. Medium-sized cells are to be used in regions with intermediate population density, with cell area depending on expected telecommunications traffic. The UMTS system is to consist of two components: one terrestrial, the other satellite-based, as shown in Figure 7.16.

The organization of the terrestrial component is to be similar to that of the GSM system; moreover, partial use of the GSM infrastructure is planned in the UMTS deployment. Organization of terrestrial communication (i.e., system hierarchy and cell sizes) is to be operator-dependent. Satellite communication is to be based on a set of 50 to 500 nongeostationary (i.e., having variable positions over the earth surface) satellites traveling in low orbits (in the order of 1,000 km), or a set of approximately 100 medium-orbit (in the order of 10,000 km) satellites. However, delay in the deployment of the UMTS satellite component can be expected, after the commercial failure of the Iridium satellite communication system. Ready to use and in working order, the Iridium system proved unprofitable, due to its exclusively satellite-based character. The demand for satellite communication services, and the corresponding income, turned out to be below expectations, resulting in a decision to shut down the Iridium system in 2000.

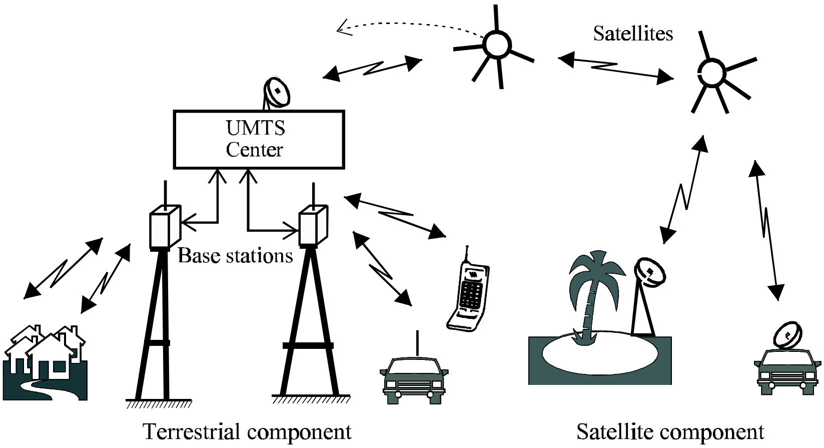

Figure 7.16 Pictorial diagram of a UMTS 3G wireless communication system.

Digital Data Transmission

Some of the telephone and data transmission services to be provided within UMTS are specified in Table 7.3. A very important aspect for measurement technology is a substantial increase in data rates, from 9.6 kbps, the typical GSM transfer speed, to approximately 2 Mbps as promised by UMTS. An example of a UMTS-based distributed measurement system configuration is shown in Figure 7.17.

Table 7.3

UMTS Data Transmission Services [2]

Service	*Data Transfer Speed*	*Allowable BER*
Telephone service	8 to 32 kbps	10^{-4}
Videophone service	64 to 384 kbps	10^{-7}
Data transmission in audio-frequency band	2.4 to 64 kbps	10^{-6}
SMS and call	1.2 to 9.6 kbps	10^{-6}
Digital data transmission	64 to 1,920 kbps	10^{-6}
Access to database	2.4 to 768 kbps	10^{-6}
Remote control	1.2 to 9.6 kbps	10^{-6}

BER: bit error rate

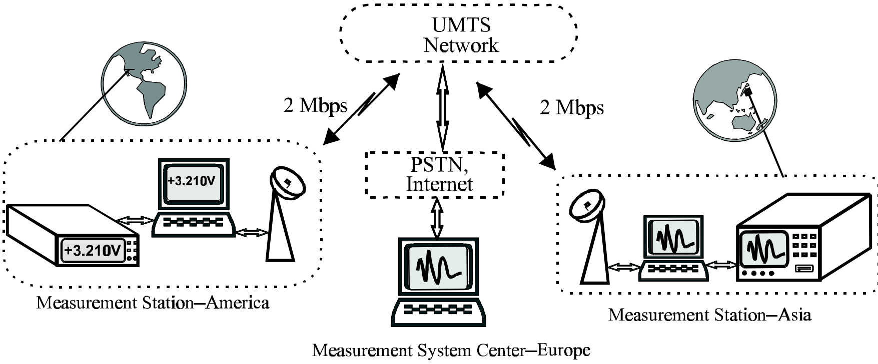

Figure 7.17 Intercontinental UMTS-based measurement system.

The key advantages of 3G wireless communication systems are:

- High data rates assumed (up to 2 Mbps in UMTS, and up to 20 Mbps in IMT-2000 after 2008);
- Global access (beyond the mobile phone network coverage, the system is to be accessible via communications satellite);
- A possibility of interworking with fixed networks, including Broadband-Integrated Services Digital Network (B-ISDN). It is noteworthy that UMTS-based measurement data transmission will substantially loosen the measurement limitations imposed by GSM-based transmission (see Section 7.2.4).

A UMTS-based measurement system will allow monitoring of more dynamic processes, and will be able to use more complex digital instruments delivering multibit measurement results. Moreover, as UMTS promises much higher data rates than those available in CSD or GPRS modes in GSM, transmission of large files containing measurement results will be much faster in UMTS-based data acquisition systems. For example, let’s compare the expected minimum time needed for a 1-MB file to be transferred using different transmission modes:

- 14 minutes in “plain” CSD transmission mode via GSM network (with data transfer speed 9.6 kbps);
- 1 minute 10 seconds in GPRS packet data transmission mode via GSM network (with data transfer speed 115 kbps);
- 20.8 seconds in EDGE transmission mode via upgraded GSM network (with data transfer speed 384 kbps);
- 4.6 seconds in UMTS digital data transmission (with data transfer speed 1,920 kbps).

Time of measurement data transfer is often the decisive factor in choosing transmission mode. As an experiment, the content of an 8-bit digital oscilloscope screen was transmitted in a bitmap file via RS-232C interface at the Poznan University of Technology; with data transfer speed 19.2 kbps, the transmission took approximately three minutes. Such long transmission times are unacceptable in most on-line measurement systems.

Instruments used in a UMTS-based measurement system can be distributed all over the globe. Among the possibilities that UMTS provides, are geophysical and astronomical experiments and observations involving simultaneous measurements in different points on the Earth, as well as a possibility of using nontransportable unique equipment in a distant laboratory (i.e., virtual equipment for the remote operator). Both the equipment control and the measurement result transmission are possible through the transfer of digital commands and measurement data via a UMTS mobile phone network.

UMTS was first set in operation in Japan, where it is referred to as 3G, with coverage limited to Tokyo, in September 2001. Data transfer speeds of up to 384 kbps, allowing transmission of moving images and increasing up Internet communication, was provided by Japanese mobile phone network operator NTT DoCoMo. Fifty thousand mobile videophones were distributed on the inauguration of the 3G system in Japan. UMTS is being set in operation in other countries, though its implementation, previously planned to have been completed by 2005, is likely to be delayed. Since June 2004, UMTS has operated in Germany where GMS networks Vodafone and T-Mobile offer videoconferences and other UMTS services. On the market are the first mobile phones with UMTS functions: Z105 (Samsung), Nokia 7600, and U15 (manufactured in cooperation between Siemens and Motorola). The U15 mobile videophone can transfer voice, moving image, audio files (WAV, MP3, AAC), pictures, and video files. The U15 has two photo cameras, and memory of 64 MB. In September 2004, UMTS started in Poland (GSM Plus network), however, only in the Warsaw region.

The UMTS implementation process is to be progressive in terms of coverage, service range, and service parameters. Great hopes built on the expected success of UMTS are expressed in the exorbitant license fees set as a result of tenders in 2000: $46 billion in Germany, and $34 billion in the United Kingdom.

Mobile Station Positioning in UMTS

The UMTS standards adopted include the mobile station (or mobile phone) positioning function. Several autonomous object positioning systems operate in the world today, the most widespread being the Global Positioning System (GPS), an American global-area satellite system with a measurement resolution of approximately 10m all over the globe [9]. Positioning systems are used for the following purposes:

- Maritime and land navigation;

- Truck position monitoring by transport bases;
- Location of expensive cars (e.g., in case of theft);
- Vehicle use optimization by traffic controller;
- Engineering (especially geodesic) work.

UMTS positioning has two fundamental advantages over the autonomous positioning systems:

- No investment in system infrastructure and no separate equipment (receivers) are needed;
- Additional information can be provided along with the positioning data.

Mobile station positioning in UMTS can be used for:

- Commercial purposes, such as sending SMS messages with information on stores or shopping centers nearby;
- System purposes, for operations such as mobile station handover (from one base station to another) or traffic level monitoring;
- Life-saving, when the mobile station user is in danger or an accident happens;
- Public security purposes (e.g., to find or follow individuals under suspicion).

The UMTS mobile station positioning methods are defined by the system standards. Three independent positioning methods are used:

- Measurement of signal level and of Round Trip Time (RTT), which is the time needed for a signal to get from the mobile station to the base station (uplink signal) and back from the base station to the mobile station (downlink signal);
- Observed Time Difference of Arrival (OTDOA) positioning, which is the measurement of differences t_{ij} between the time of signal arrival at the mobile station to be positioned from at least three nearby base stations managed by the same base station controller;
- GPS-based positioning by means of a built-in GPS receiver in a mobile station structure.

The choice of positioning method is up to the operator. No method should interfere with a connection in progress or impair transmission quality. The first of the above-mentioned techniques is not accurate, especially in large system cells; the third one is expensive. It is OTDOA positioning (see Figure 7.18), based on the existing terrestrial UMTS infrastructure and requiring add-on software only, that seems the most likely to come into widespread use [10].

The coordinates (x_i, y_i) of each UMTS base station must be available to the OTDOA software from its database. The coordinates of a mobile station to be positioned are calculated from a set of equations; for example, if three base stations are involved in mobile station positioning, the following three equations are to be solved [10]:

$$R_1 - R_2 = c\hat{o}_{12} = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_2 - x)^2 + (y_2 - y)^2}$$
$$R_1 - R_3 = c\hat{o}_{13} = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_3 - x)^2 + (y_3 - y)^2}$$
$$R_2 - R_3 = c\hat{o}_{23} = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} - \sqrt{(x_3 - x)^2 + (y_3 - y)^2}$$

where $c = 3 \times 10^8$ m/s is the speed of light in vacuum; t_{12} is the difference between the times of signal arrival at the mobile station from base station 1 and from base station 2, t_1 and t_2, respectively, ($t_{12} = t_1 - t_2$); and the meaning of t_{13} and t_{23} is analogous.

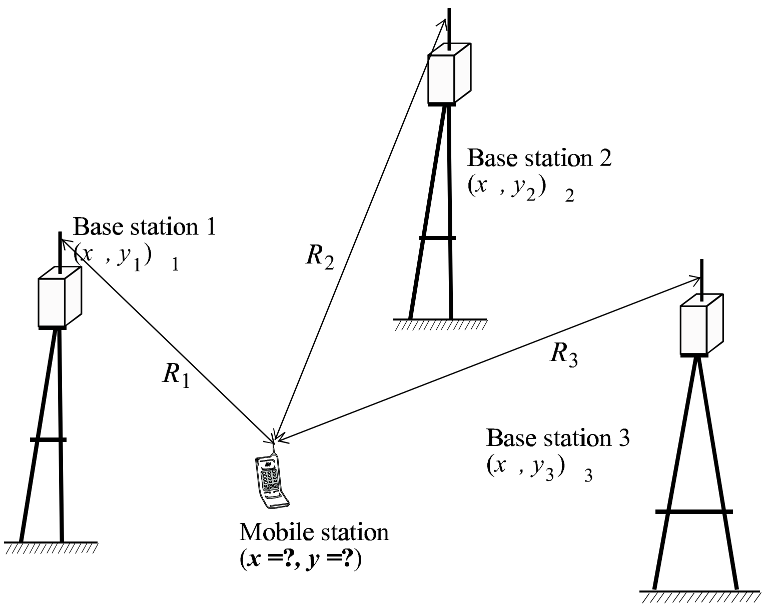

Figure 7.18 UMTS-based OTDOA mobile station positioning.

The estimated accuracy of OTDOA mobile station positioning is from a few to a few hundred meters.

7.3 RADIOMODEM-BASED MEASUREMENT SYSTEMS

7.3.1 Radio Channels and Radiomodems

In transmission of measurement data at distances from approximately 100m up to 100 km, radio communication through dedicated (nontelephone) channels provides an alternative to communication systems based on either wired (PSTN) or wireless (GSM) telephone networks. Crucial components of such radiocommunication systems are radiomodems. A radiomodem consists of a transmitter, a receiver, and signal conversion units, in which digital data is converted into transmitted radio signals, and incoming radio signals are conveted into digital data of the required standard. Some radiomodems (e.g., Radmor 7004) are supplied with peripheral voice transmission units. Radiophones (e.g., Radmor 3705 radiophone) with a suitable digital module can be used for digital data transmission. A radiomodem block diagram is shown in Figure 7.19 [7].

Frequency bands allowed for industrial radiocommunication use are assigned by a relevant government agency (such as Federal Communications Commission in the United States) in each country. Radio frequency bands are assigned in the range from 3 kHz to 400 GHz. Some industrial radiocommunication bands are specified in Table 7.4.

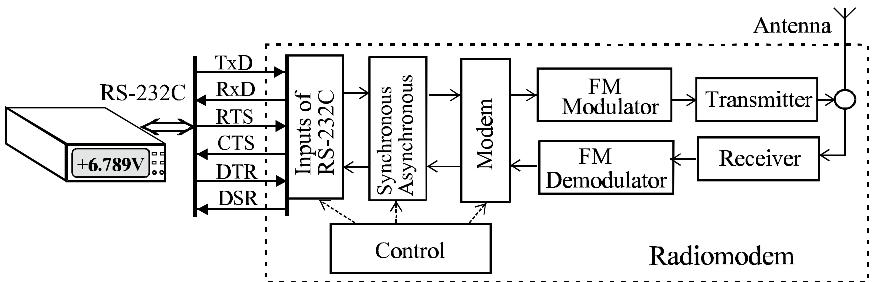

Figure 7.19 Radiomodem block diagram and data flow chart.

Table 7.4

Some Industrial Radiocommunication Frequency Bands

Frequency Band	*Channel Spacing*	*Antenna Height*	*Station Type*
77.5 to 79 MHz	12.5 kHz	site-dependent	Mobile
159.4 to 160 MHz	12.5 kHz	site-dependent	Mobile
299 to 309 MHz	12.5 or 25 kHz	25m	Mobile or fixed
335 to 345 MHz	12.5 or 25 kHz	25m	Mobile or fixed
452 to 457 MHz	12.5 or 25 kHz	25m	Mobile or fixed
890 to 919 MHz	12.5 or 25 kHz	25m	Mobile

For a radio frequency band to be legally used for measurement purposes, a license should be obtained from the relevant government agency; a license is issued against payment for radio transmission in a specific frequency band, with channel width 25 kHz, and with transmission power as stipulated (e.g., up to 10W). No license is required to use radiomodems with low-power transmitters (antenna transmission power less than 20 mW) on frequencies below 800 MHz. Beside the frequency band, maximum transmission power and maximum antenna height are stipulated in a license, with values of these parameters affecting the license fee. Modulation methods used in modems involve Frequency Modulation (FM) (applied to frequencies below 800 MHz), such as Frequency Shift Keying (FSK) or Fast Frequency Shift Keying (FFSK), as well as Frequency Hopping Spread Spectrum (FHSS) technology.

Among the many radiomodem manufacturers active on the electronic market, the best-known are SATEL, Advantech, Motorola, and Microwave Data Systems. To give an idea of radiomodem parameters, technical data of four radiomodem models are specified in Table 7.5; the respective manufacturers are SATEL (Finland), Motorola (the United States), Advantech (the United States), Radmor (Poland), and Radiometrix (the United Kingdom). The latter's BiM-433-F, in the form of a chip, is a low-power radiomodem designed for radio communication within the range of 30m indoors and 120m outdoors. This type of radiomodem was used at the Poznan University of Technology, in a wireless temperature measurement system as well as for small robot control [7].

Table 7.5

Some Radiomodem Models and Their Parameters

Type	*Frequency Band*	*Channel Spacing*	*Transmission Power*	*Operation Mode*	*Data Transfer Speed*
SRM6000	902 to 928 MHz	230 kHz, 112 channels	0.1W to 1W	duplex	1.2 to 115.2 kbps
Radmor 7004	450 to 470 MHz	12.5 or 25 kHz	0.1W to 5W	simplex, half-duplex, duplex	1.2 to 14.4 kbps
Satelline 3AS	417.5 to 460 MHz	12.5 or 25 kHz	0.01W to 1W	half-duplex	9.6 or 19.2 kbps
Radiometrix BiM-433-F	433.92 MHz	none	below 0.07W	half-duplex	up to 40 kbps

The currently available radiomodems and radiophones with digital data transmission use radio channel frequencies from 40 MHz (e.g., Radmor 3005M radiophone, delivering data transfer speed of 2.4 kbps), up to 2.45 GHz (e.g., Advantech's ADAM-4550, a miniature radiomodem operating in the range of 200m and allowing data rates up to 115 kbps). Digital data input and output circuits in radiomodems meet the RS-232C standard, and in some radiomodem types, the RS-485 and RS-422A standards as well. National Instruments' radiomodem SRM 6000, designed to be used in distributed measurement systems, operates in the 902- to 928-MHz frequency band from with transmission power 0.1W to 1W (transmission range up to 32 km), delivering data rates up to 115.2 kbps. Available free within ISM band in the United States, the 900-MHz frequency band is used by the GSM 900 mobile phone system (uplink channel 890 to 915 MHz), and thus will not be licensed for any other use in Europe.

7.3.2 Radiomodems in Measurement Systems

A radiomodem-based measurement system with data transmission via radio channel consists of a system center, in which data is collected and processed, and a number of measurement stations communicating with the system center by means of radiomodems. The structure of this type of measurement system is shown in Figure 7.20.

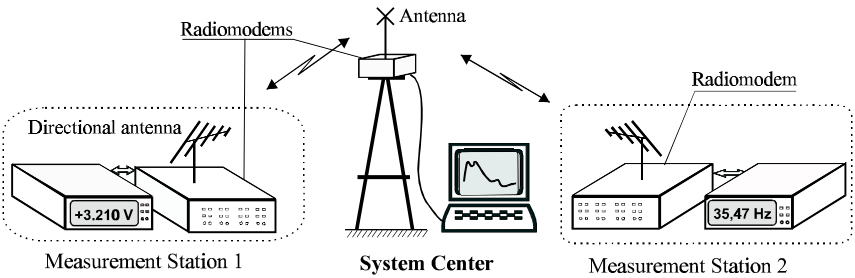

Figure 7.20 A measurement system with radiomodems and data transmission via radio channel.

As shown in the block diagram in Figure 7.20, a radiomodem is installed in each measurement station, and fitted with a directional antenna, which allows the reduction of transmission power, susceptibility of transmitters to interference, as well as signal transmission in an undesirable direction. Signals transmitted within a measurement system are an interference for external receivers. Directed signal transmission also reduces the risk of unauthorized data capture. Data transmission via nontelephone radio channel offers substantially higher security than transmission via public telephone network.

However, using radiomodems may involve problems such as unstable connection quality or interruptions. As diagnostics of the system may be necessary, it is recommended to use one of the numerous types of radiomodems with radiophone functionality. Radiophone allows simple, acoustic radio channel checkup. Another reason for signal fading may be a change, sensible for connecting radio stations, in radio wave propagation conditions. In this case, the quality of reception can be improved by increasing either transmission power or antenna height. However, both these parameters are limited by the license and the license fee.

The problem of poor connection quality and limited system area can be solved by using some measurement stations as repeaters, as shown in Figure 7.21.

In the system shown in Figure 7.21, measurement station 2 is used for signal retransmission. It transmits data from station 4 to the system center. In the opposite direction of transmission, commands addressed to either station 2 or station 4 are received by station 2 from the system center. Besides the address of station 2, additional information needs to be put into each transmitted message, specifying whether the command included in the message is to be carried out in station 2, or forwarded to station 4. This distinction should be allowed by the communication protocol used. Therefore, measurement or telemechanics systems with repeaters involve different communication protocol than systems without signal retransmission. Many radiomodem models can be used for retransmission, such as Satel's 2ASxE, 3AS EPIC, and 3AS(d) radiomodems.

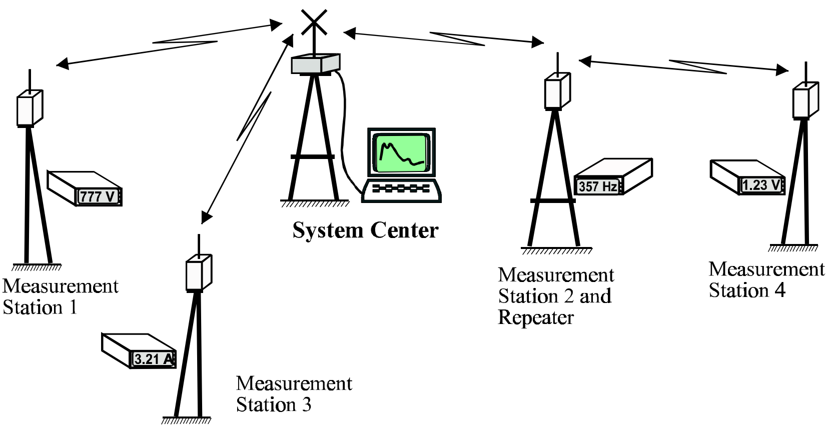

Figure 7.21 Radiomodem-based measurement system with two types of measurement station: "plain" (measurement stations 1, 3, and 4), or with additional data retransmission function (repeater and measurement station 2).

In contrast to data transmission via a GSM public mobile phone network, radiomodem-based transmission parameters, such as channel carrier frequency, modulation type, transmission type, transmission protocol, or data coding, are not available to outside users. Moreover, no delay occurs in radiomodem-based data transfer from the measurement station to the system center, and especially in transmission of commands from the system center to the measurement/control station. Unavoidable in data transmission via public phone network, the delay in switched data transfer is a consequence of the switching process, an obstacle of which radiomodem-based measurement/control systems are clear.

7.3.3 Distributed Measurement Systems with Radio Transmission: GSM-Based Versus Radiomodem-Based

The following factors are to be considered in order to compare GSM-based and radiomodem-based measurement systems, both using radio waves for data transmission:

- Coverage required;
- Maximum data transfer speed;
- Acceptable connection setup time;
- Data security level;
- Number of measurement stations;
- Cost of communication system deployment;
- System operating cost for data transfer volume assumed.

Distribution of measurement sites should be considered as well. Distributed measurement/control systems with radio transmission are used mainly in water supply and sewage systems, heat distribution and power networks, and gas grids. Though power systems use wired communication based on their own wired networks, alternative communication systems are to be available to support the wired system in case of failure.

The GSM network coverage offers a communication range larger by far than that of radiomodem-based communication systems. Additionally, global roaming extends data transmission within a GSM-based measurement system on an international scale. However, this advantage of extensive communication range is rarely used.

In radiomodem-based measurement systems, data transmission range is limited by maximum values of transmission power and antenna height, as well as by conditions for radio wave propagation. Typically, the range of a radiomodem-based system (i.e., the maximum distance between two stations) does not exceed 50 km.

The GSM network allows higher data transmission rates as well, delivering 56 kbps in HSCSD transmission mode, and 53 kbps in GPRS. Moreover, the implementation of EDGE in the GSM network, and then of UMTS, involve a substantial step-up in mobile phone network-based data transmission, with the respective maximum data rates being 384 kbps and 1,920 kbps. Radiomodem-based systems afford data rates from 1,200 bps up to 19.6 kbps with channel spacing of 25 kHz, and one-half as much with channel spacing of 12.5 kHz.

A disadvantage of public phone system–based data transmission is its delay, which is a consequence of the switching process. It is well-known from practice that transmission through a switched line can fail because of temporary network overload (i.e., line can be busy). No switching-related delays occur in radio-modem-based systems, neither in data transfer from the measurement station to the system center, nor in transmission of commands from the system center to the measurement/control station, each receiver being available continuously.

As regards the data security level, data transmission is potentially safer in radiomodem-based measurement systems than in GSM-based systems. Carrier frequency, modulation, transmission, and data coding used are individual radio link parameters in a radiomodem-based network. Moreover, the possibility of directional transmission of radio signal reduces the risk of unauthorized signal interception. In contrast to the above-mentioned features of radio transmission, signals transmitted in the GSM network must be freely available, and both transmission protocols and channel frequencies used are standardized and of public knowledge. Criminal press reports provide enough evidence that network operators' declarations on the effectiveness of mobile phone antitapping protection should not be taken too seriously.

The relative cost-effectiveness of both measurement systems depends strongly on the number of measurement stations, and consequently, on the number of transceiving stations, in the system considered. Only communication system deployment and operating costs are considered in this comparison, but not the cost of instruments. The costs incurred in deployment of a radiomodem-based communication system are mainly modems, antennas, and antenna installation. No cost of this type is assumed by the developer of a GSM-based system. In this case, communication system deployment cost involves the purchase of mobile phones only, while operating costs include standing and other charges.

7.4 SHORT-DISTANCE WIRELESS DATA TRANSMISSION

7.4.1 IrDA Infrared Link

Used for more than 30 years in industry as well as in daily life, wireless device control was widely accepted because of its convenience for the operator (e.g., TV set remote control), as well as for technical reasons. An infrared link can be used, for example, in place of a cable to connect a laptop with a printer or other peripheral device, avoiding wired connections to mobile equipment. Another indication of wireless data transmission via infrared link can be electrical insulation between transmitter and receiver circuits. In measurement technology, a great advantage of a short-distance wireless link is the possibility of using touch sensors for moving (e.g., spinning) object measurements, with wireless data transmission from sensor to receiver in a measurement system. Standards were adopted for wireless links to fit different devices made by different manufacturers. Wireless links referred to as IR links use infrared (IR) rays as a transmission medium [11]. IR links allow data transmission between two independent devices, such as a laptop and a printer, within the distance of 1m, when the devices are in the line of sight, as shown in Figure 7.22.

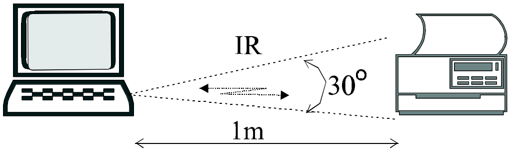

Figure 7.22 Typical use of IR link for digital data transmission.

An infrared link circuit usually consists of two integrated circuits (IC), as shown in Figure 7.23. One IC comprises an IR light-emitting diode (LED), a receiver photodiode, and transmitter and receiver amplifier units. An infrared digital data transmission standard referred to as IrDA was adopted by electronic equipment and hardware manufacturers within the Infrared Data Association (IrDA).

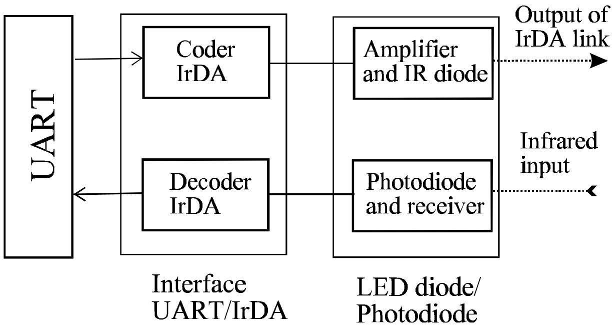

Figure 7.23 Block diagram of IR link electronic circuit.

Table 7.6

IR Link Parameters According to IrDA-1.3 Standard

Parameters	*Typical Value*	*Limit Value*
Linear range	1m	3m
Angular range	±15°	±30°
Transmission rate	2.4 to 4,000 kbps	16 Mbps (for IrDA-1.4)
Error rate	10^{-8}	—
IR wavelength	850 to 900 nm	900 nm
Pulse duration	3/16 of UART bit	—

This subcircuit is installed on the casing of an IrDA device. The key components of the other ICs are digital circuits that encode digital signals from a Universal Asynchronous Receiver Transmitter (UART) circuit into IrDA standard, and that decode incoming IR pulses into UART signals. Parameters of IrDA-1.3, a wireless link standard published in October 1998, are specified in Table 7.6

[11]. However, minimum IR pulse duration remains to be specified for higher data rates. Typical IR pulse duration in an IrDA link is three-sixteenth of a bit duration in the UART of a computer or other digital device, as shown in Figure 7.24. Wireless IR link parameters according to the IrDA-1.3 standard, including transmitter beam intensity and receiver sensitivity, are detailed in Table 7.7.

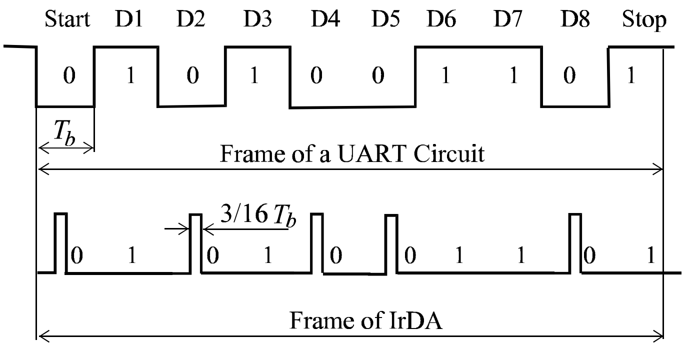

Figure 7.24 IrDA asynchronous transmission information frame, and UART (or RS-232C standard) information frame.

Table 7.7

IrDA-1.3 and VFIR Link Parameters (Transmitter Beam Intensity Values Are Specified in Watts per Steradian)

Transmission Rate	*Modu-lation*	*Minimum Pulse Duration*	*Nominal Pulse Duration*	*Transmitter Radiation Power*	*Receiver Sensitivity*
2.4 kbps	RZI	1.41 µs	78.13 µs	40 mW/sr	4 µW/cm^2
9.6 kbps	RZI	1.41 µs	19.53 µs	40 mW/sr	4 µW/cm^2
19.2 kbps	RZI	1.41 µs	9.77 µs	40 mW/sr	4 µW/cm^2
38.4 kbps	RZI	1.41 µs	4.88 µs	40 mW/sr	4 µW/cm^2
57.6 kbps	RZI	1.41 µs	3.26 µs	40 mW/sr	4 µW/cm^2
115.2 kbps	RZI	1.41 µs	1.63 µs	40 mW/sr	4 µW/cm^2
576 kbps	RZI	295.2 ns	434 ns	100 mW/sr	10 µW/cm^2
1,152 kbps	RZI	147.6 ns	217 ns	100 mW/sr	10 µW/cm^2
4 Mbps	4PPM	115.0 ns	125.0 ns	100 mW/sr	10 µW/cm^2
16 Mbps	HHH (1,13)	38.3 ns	41.7 ns	100 mW/sr	10 µW/cm^2

Note the way of encoding 0 and 1 signals transmitted via IrDA link: IR pulse corresponds to 0, and no pulse corresponds to 1. The following modulation methods are used: Return-to-Zero-Inverted (RZI), Four Pulse Position Modulation (4PPM), and an enhanced 4PPM code referred to as HHH (HHH is not an acronym). The parameters listed in Table 7.7 also include those of a proposed IrDA link qualified as Very Fast IR (VFIR), due to its transmission speeds of up to 16 Mbps. If accepted, the VFIR link will become a standard, IrDA-1.4. Another IrDA standard, delivering data rates up to 100 Mbps, is under development. Low-power IrDA link is specified by a separate set of parameter values, available in Infrared Data Association's Web site [11].

Data transmission through an IrDA link is an asynchronous character transfer in half-duplex mode. Although larger transmission range, transmission angle and reception angle values are possible, they are limited, in order to reduce interference with other devices, as well as interference susceptibility. The transmitting component of an IrDA link is a semiconductor IR diode, with typical beam intensity values of 40 mW/sr in IrDA links delivering up to 115 kbps, and 100 mW/sr in higher-capacity links. The virtues of wireless transmission through an IrDA link can be used in a measurement laboratory. Some computers, especially a considerable part of laptops, come supplied with an IrDA link. With a similar link installed in digital instruments, a measurement system with wireless data transmission can be set up, as shown in Figure 7.25(a).

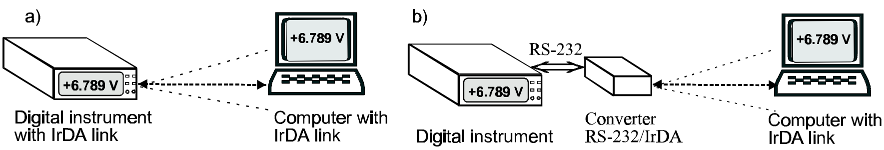

Figure 7.25 Measurement system with wireless data transmission through IrDA link: (a) IrDA link installed in both the instrument and the computer; and (b) an IrDA-equipped computer linked to the instrument via an RS-232C to IrDA converter.

Most digital instruments and all computers come supplied with RS-232C serial interface drivers. An RS-232C to IrDA converter can be employed to connect a digital instrument to a computer, as indicated in Figure 7.25(b), when setting up a wireless measurement system. According to Infrared Data Association's report, 300 million IrDA link installations have been performed so far in devices such as PCs, laptops, palmtops, mobile phones, and printers.

7.4.2 Bluetooth High-Frequency Radio Link

Bluetooth is a low-power radio link standard operating in the 2.45-GHz frequency band, and allowing digital data transmission at speeds up to 1 Mbps [12, 13] within the range of 10m. Designed for wireless communication between electronic devices such as mobile phones, computers, computer mice, headphones, and printers, Bluetooth was originally conceived by the Swedish company Ericsson, which proposed its specification in May 1998. The interface was named after Harald Bluetooth, a tenth-century king of Denmark.

The Bluetooth radio link is meant to complement or even replace the existing IrDA link. The main difference between IrDA and Bluetooth is that Bluetooth is a point-to-multipoint link, designed to network up to eight devices, while IrDA, being a point-to-point data transmission standard, allows data exchange between two devices only. Compared to IR waves, radio waves have a larger range, and their spherical propagation is easier to ensure. In laboratory conditions, Bluetooth radio waves with length l

$$l = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{2.45 \times 10^9 \text{ Hz}} = 13 \text{ cm}$$

propagate much better than IR waves with length 900 nm. The range of transmission via Bluetooth link is 10m, but can be extended to 100m by increasing transmission power. Laboratory measurement systems with wireless data transmission can be set up with Bluetooth-equipped digital instruments and computers.

Table 7.8

License-free Industrial Science Medicine (ISM) Bands

Frequency Band	*Transmission Power*	*Remarks*
902 to 928 MHz	< 10 mW	In the United States only
2,400 to 2,483.5 MHz	< 10 mW	In Europe, the United States, and Asia
5,725 to 5,875 MHz	< 25 mW	In Europe, the United States, and Asia

Bluetooth Standard Parameters

Bluetooth operates in the 2.402- to 2.4835-GHz radio frequency band, which is a public license-free ISM band (see Table 7.8). It should be mentioned here (though is not to be taken into consideration in the following) that in some countries (Japan, France, and Spain), the ISM band is narrowed down to the width of 23 MHz. The public availability of the ISM band involves the problem of possible interference with other devices (such as microwave ovens or garage door remote controls) operating in the ISM band, and thus the necessity of anti-interference protection. Communication in the 2.45-GHz band is possible either through finding a part of the band that is not in use, or through spread spectrum modulation. Bluetooth uses the latter method. Each device operating in the Bluetooth interface system has an individual address, referred to as Bluetooth Device Address (BDA), which is a 32-bit binary word. More than 4 billion (2^{32}) Bluetooth devices can be identified in this way. FSK modulation method is used for binary signal coding (see Figure 6.22). A logic 1 corresponds to a carrier frequency value 160 kHz above the fundamental frequency value, and a logic 0 corresponds to a carrier frequency value 160 kHz below the fundamental frequency value. The allowable offset is 160 (–20, +15) kHz. Bluetooth network can include up to eight devices, each of them functioning as transmitter or receiver. This type of network is referred to as piconet, as shown in Figure 7.26.

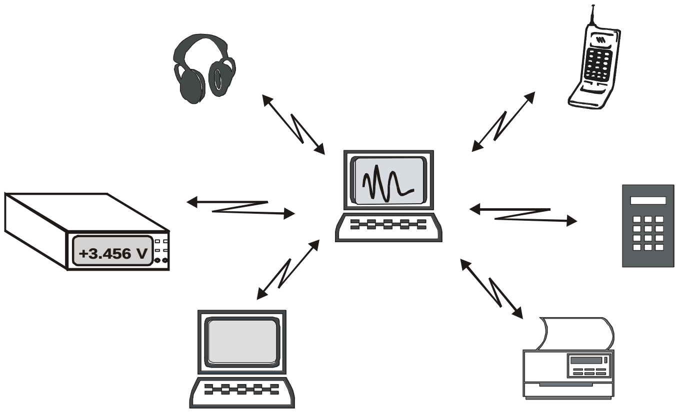

Figure 7.26 A piconet formed by a digital data transmission system with Bluetooth interface.

One device within a piconet acts as the master, with all other piconet units being its slaves. Each Bluetooth device can be a master or a slave, but for the time of a piconet existence, it is the piconet originator unit that acts as a master. Each device can participate in several piconets at a time. A device can act as a master in one piconet only, and functions as a slave in any other piconet. A number of piconets having common units form a scatternet, an example of which is shown in Figure 7.27.

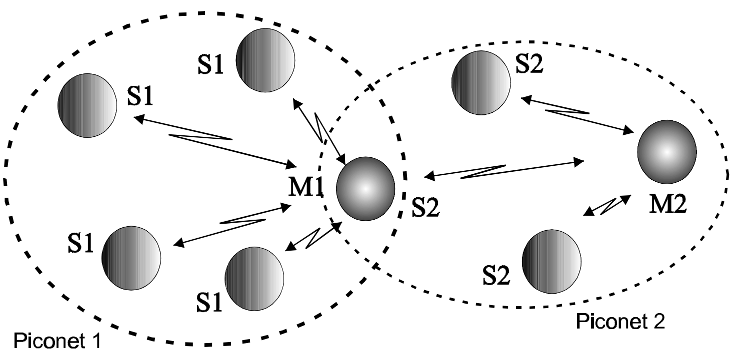

Figure 7.27 Scatternet with Bluetooth interface: M1 is the piconet 1 master, S1 are piconet 1 slaves, M2 is the piconet 2 master, and S2 are piconet 2 slaves.

The Bluetooth system provides half-duplex communication according to a one-to-one rule. Within a single time slot, a transmitter can send information to one receiver only, and a receiver can get information from only one transmitter. Therefore, a device participating in a number of piconets needs separate time slots to communicate with other devices within different piconets.

Transmission Channel Assignment in Bluetooth Standard

Bluetooth link standard uses Frequency Hopping Spread Spectrum (FHSS) modulation and is based on the Time Division Duplex (TDD) scheme. The frequency band from 2,402 to 2,480 MHz allows assignment of 79 frequency channels with channel spacing 1 MHz. The system divides the band into channels with hopping frequency values. The frequency hopping pattern is pseudorandom, and follows a sequence with a repetition period of 23 hours. In addition to the hopping frequency, a 625-μs time slot is used to define a transmission channel. One data packet is transmitted within a single time slot. The frequency hopping period is 625 μs, which corresponds to 1,600 hops per second. The carrier frequency hopping sequence should be known to both the transmitter and the receiver communicating within a piconet. The frequency hopping sequence is adopted as a result of data processing in the transferred packet [13].

In the Bluetooth interface system, data is transmitted in packets consisting of three parts, as shown in Figure 7.28: Access Code (AC), Packet Header, and Payload (i.e., data proper). An access code consists of a 64-bit synchronization word (sync word), four start bits (opening the code), and four end bits (closing the code). The information on the pseudorandom sequence of channel frequency hopping is contained in the sync word. More precisely, this information is coded in a new 64-bit word that begins with the 40 most important bits transcribed from the sync word, the remaining 24 bits being the result of a modulo-2 logic operation, XOR, performed on the 24 least important bits of the sync word and the 24 least important bits of the transmitter's BDA. A 54-bit Packet Header includes a 3-bit active piconet member address (Active Member Address, or AMA), a 4-bit packet type specification, one flow bit, one Automatic Repeat reQuest (ARQ) bit, and Header Error Check (HEC) bits. A payload field can contain from 0 to 2,745 bits. Data packets larger than 2,745 bits are transferred in multislot mode (i.e., in three or five time slots).

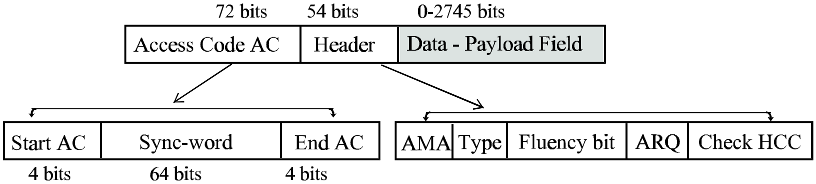

Figure 7.28 Format of data packet in Bluetooth transmission.

Carrier frequency remains constant throughout a multislot transmission, and upon its completion, changes (hops) to take the same value, determined by the pseudorandom sequence, as would be taken in transmission of packets up to 2,745 bits.

Communication

Up to eight Bluetooth devices can operate within a piconet. Communication between piconet units is carried out in the master-slave configuration, and controlled by the master. Slave units cannot communicate directly. For example, in the piconet shown in Figure 7.26, communication between the mobile phone and the headphones passes through the laptop, which acts as the piconet master. Still, the piconet configuration depicted in Figure 7.26 was meant to illustrate the variety of electronic devices that can be equipped with Bluetooth, rather than to represent an actual piconet. In reality, a mobile phone and headphones would rather form a separate two-component piconet. Master-to-slave transmission always occurs in even-numbered time slots, while slave-to-master transmission always takes place in odd-numbered time slots. Communication is initiated by the master's polling of a slave unit. The latter's address, in the form of a 3-bit AMA word, is contained in the header of the data packet used to poll the slave. Note that it is the length of AMA that limits the number of piconet units to $2^3 = 8$.

Bluetooth Applications

The high chances of Bluetooth's widespread commercial acceptance can be deduced from the participation of as many as 1,900 telecommunications and IT companies, including market leaders such as Ericsson, IBM, Intel, Toshiba, Nokia, or Motorola, in the Special Interest Group (SIG), founded to promote Bluetooth technology. Proposed in 1999, first prototypes of Bluetooth-equipped devices were R520m and T32m mobile phones (both manufactured by Ericsson) that could be connected via Bluetooth interface with an Ericsson headphone set. Other Bluetooth device prototypes were developed in the following years. The number of Bluetooth devices is still growing.

Ericsson offers a Bluetooth Development Kit, designed to allow integration of the Bluetooth standard into device prototypes. A Bluetooth antenna, with dimensions $22.9 \times 12.7 \times 0.8$ mm and weight 1g, was designed by RangeStar Wireless.

In addition to its applications in the field of telecommunications, Bluetooth is likely to become a measurement system wireless link standard. The advantages of wireless interface are obvious. First of all, the problems of junction standardization and contact wear are eliminated, since no junctions and no cables are needed in wireless communication (in some connections, quality is warranted for only up to 1,000 connections/disconnections). Another advantage of wireless interface is the possibility of data transmission from a moving, especially spinning, object within the range of the wireless interface (10m). For example, with an ADC and a Bluetooth unit added to a temperature sensor, contact measurements of temperature of a rotating object can be performed, as shown in Figure 7.29. Contact measurement is preferred to noncontact measurement for better accuracy. Bluetooth is tested in medical measurements as well.

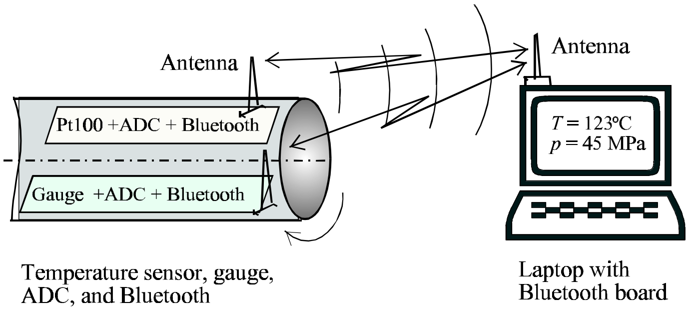

Figure 7.29 A Bluetooth-based system allowing contact measurements of temperature of a spinning object.

7.4.3 Short Distance Wireless Transmission Systems under Development

The current short distance digital data wireless transmission standards are IrDA and Bluetooth. Primarily designed for providing wireless connection between telecommunication devices, Bluetooth gets more and more new applications in industry, radio, and television equipment, as well as in measurement systems. IrDA is an infrared link standard allowing communication within the range of 2m. An advantage of IrDA is high data transfer speeds, up to 4 Mbps, to be increased to 100 Mbps. However, the IrDA standard involves some constraints, the most important of which includes the number of devices interconnecting in an IrDA system. Only two devices can form the system. As well, the devices must be in the line of sight (the angle of sight being ±15°). The transmission range is limited to 1m, typically. At least five short distance wireless digital data transmission standards, collectively referred to as Virtual Home Environment (VHE), are being implemented currently. Parameters of those new standards are specified in Table 7.9.

Area Infra Red interface is an extended version of IrDA, with a 120° angle of sight and a capability of connecting up to 10 devices. An advantage of Area Infra Red is its compatibility with some 300 million IrDA-equipped devices that are either in use or available on the market [11].

HomeRF interface is designed to network digital devices of common (home) use, such as computers, LAN terminals, radio and TV equipment, telephones, and home heating systems. HomeRF operates on radio channel frequencies within the license-free 2.45-GHz band. Like Bluetooth, HomeRF interface uses FHSS modulation and TDMA technology, but with 50 (rather than 1,600) channel frequency hops per second.

Table 7.9

Parameters of Wireless Interface Standards under Development

Interface Type	*Frequency or Wavelength*	*Transmission Rate (maximum)*	*Linear Range*	*Angular Range*	*Number of Devices*
IrDA	IR 900 nm	16 Mbps	2m	30°	2
Area Infra Red	IR 900 nm	4 Mbps	8m	120°	10
HomeRF	2.45 GHz	2 Mbps	50m	360°	128
Bluetooth	2.45 GHz	1 Mbps	10m	360°	8
IEEE 802.11b	2.45 GHz	11 Mbps	≈50m	360°	—
IEEE 802.11b	IR 900 nm	2 Mbps	10m	360°	—
HIPERLAN2	5.2 GHz	54 Mbps	150m	360°	10

HomeRF will allow both voice and digital data transmission. In voice transmission, six calls will be possible in HomeRF duplex mode. Digital data transmission speeds will up to 2 Mbps. HomeRF interface is being developed by HomeRF Working Group, formed in 1998 within the U.S. Federal Communications Commission, and associating computer hardware and electronic equipment manufacturers as well. The assumed interface specifications, as well as Shared Wireless Access Protocol (SWAP), have been proposed so far.

IEEE 802.11 Wireless Local-Area Network (WLAN), or *Wireless Fidelity* (WiFi) interface is aimed at connecting devices within either ad hoc or infrastructure wireless computer networks. In ad hoc networks, direct communication between computers is possible, without the agency of a network base or center. An infrastructure network needs at least one access point; having a role similar to that of base stations in the GSM network, access points additionally provide connection with wired LAN. IEEE 802.11 signal transmission is to use radio frequencies (from the 2.45- or 5.4-GHz bands) or infrared rays. Two methods of carrier frequency coding can be used in radio transmission:

- Direct Sequence Spread Spectrum (DSSS);
- Frequency Hopping Spread Spectrum (FHSS).

Whatever the physical medium of transmission channel, access to a computer interface (to a device, in general) is controlled by the Distributed Foundation Wireless Medium Access Control (DFWMAC) protocol, designed for local networks and being a part of the IEEE 802.11 standard. One of the latest IEEE 802.11 versions, IEEE 802.11b, affords a maximum transmission speed of 11.5 Mbps. IEEE 802.11b interface hardware includes a transmission moderation system, adjusting the transmission speed to the interference level [2]. When the interference level is high, the transmission rate is slowed down. One of the following maximum data transfer speed values is chosen by the system: 11.5, 5.5, 2, or 1 Mbps, depending on the interference level. The IEEE 802.11b interface is widely used in the United States. For a wireless measurement system to operate with this interface, laptops with IEEE 802.11b interface modules must be used. Instruments can be connected to the laptops by means of standard wired interfaces, such as RS-232C.

HIPERLAN2 (HIgh PERformance Radio Local Area Network, type 2) interface is designed to provide wireless connection with Local Area Networks (LANs) [14]. The use of this interface is determined by its range (up to 150m). HIPERLAN2 will to operate within a building or a number of buildings. Different modulation schemes (see Section 6.4.1) are to be used in the HIPERLAN2 interface, depending on the assumed transmission rates: Binary Phase Shift Keying (BPSK) at 6 or 9 Mbps, Quaternary Phase Shift Keying (QPSK) at 12 or 18 Mbps, or Quadrature Amplitude Modulation (QAM) at 27 to 54 Mbps. Many of the IEEE 802.11 standard specifications are adapted in the development of HIPERLAN2.

The limit parameter values of different wireless interfaces are listed in Table 7.9. The limit values usually cannot coincide. For example, increasing Area Infra Red transmission range to 8m involves a reduction of maximum data transfer speed from 4 Mbps to 250 kbps. As seen from Table 7.9, the interfaces discussed in this paragraph are complementary to one another, and they seem unlikely to be equally widely used. Radio interfaces HomeRF (developed in the United States) and Bluetooth (developed at Ericsson, Sweden) have similar specifications and applications. Therefore, there is little chance that both will come into widespread use. The development of Bluetooth is more advanced, and its chances of commercial acceptance are higher. However, the success of each of the wireless interfaces specified in Table 7.9 will be decided by the users. Bluetooth is likely to become a wireless interface standard in computer measurement systems, provided that it becomes as widespread as presently forecast. Another interface likely to be widely accepted is Area Infra Red, due to its high transmission rates (16 Mbps at present) and the possibility of further enhancements.

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Chapter 8

Measurement Systems with IEEE-488 Interface

8.1 IEEE-488 (IEC-625) PARALLEL INTERFACE STANDARD

8.1.1 Parallel Interfaces

Parallel transfer of digital data (including measurement data) offers much higher data rates than serial data transfer. Two factors contribute to this transfer step-up. One is simultaneous transfer of information in the form of 4-bit (in Centronics standard) to 32-bit (in VXI standard) words. The other factor refers to the fact that parallel data transfer avoids some routines necessary in serial transfer, such as error check and correction procedures used in dividing the bit stream into words [1, 2]. Parallel interface can be used in measurement systems arranged within a limited area (10 m^2 to 100 m^2, typically). Larger areas involve longer multiwire (at least 24-wire) cables, which is disadvantageous for cost-effectiveness reasons, and additionally involves some technical problems due to the *RLC* parameters of such cable, and its wave properties at transfer rates in the order of 100 KBps or more. Parallel transfer can be carried out through wired channel only.

There are several parallel interface standards, the dominant one being ANSI/IEEE-488 (ANSI is the acronym for American National Standard Institute). Developed by Hewlett-Packard under the name of HPIB (Hewlett-Packard Interface Bus), IEEE-488 is also known as IEC-625 (international standard). The generic name of IEEE-488 is GPIB (General Purpose Interface Bus). IEEE-488 is the first interface standard developed exclusively for measurement systems. The IEEE-488 interface is designed to interconnect measurement system components such as digital instruments, other electronic devices (e.g., generators, power supply units, and loggers), and a controlling computer (controller). An advantage of the IEEE-488 interface system is its flexible use in those instruments in which it is physically installed. The IEEE-488 interface standard allows an instrument to operate either in interface system or autonomously (i.e., allows system or non-system operation).

Another important parallel interface standard is VXI, designed for setting up modular measurement systems. Those specialist systems consist of a number of modules that contain system functional units and are arranged in cassettes. The modules are designed for operation in the VXI system exclusively. Due to these features, the VXI interface system allows the highest measurement data rates (up to 40 MBps). A new standard of measurement system with parallel interface is PXI, a modular system using the PCI interface bus (the basic PC bus).

A cheap method of setting up a measurement system with parallel data transfer consists of using a printer interface (e.g., Centronics or its replacement IEEE-1284). The port and the transmission driver for this interface are installed in every desktop and in every laptop. However, very special software is required for measurement data to be transferred through a printer interface.

This chapter is entirely devoted to the IEEE-488 standard, and to measurement systems using this interface. The structure and organization of an IEEE-488 system, as well as different controllers used in this type of system, are discussed in Sections 8.1.2 and 8.1.3. Sections 8.1.4 and 8.1.5 introduce IEEE-488 interface functions, and give a description of the interface bus structure defined by the IEEE-488 and IEC-625 specifications. Different types of messages transferred in IEEE-488 interface systems, as well as the handshake used in signal transmission, are discussed in Section 8.2. Section 8.3 is devoted to enhancement of essential parameters of IEEE-488 interface systems, such as transfer rates or the number of devices in the system, as well as to methods and devices that build distributed systems using the IEEE-488 interface. Section 8.4 discloses the mystery of the IEEE-488 interface functions, by presenting the algorithms of their execution by respective electronic circuits. Other parallel interface systems, less widespread and thus discussed less extensively, are reviewed in Chapter 9.

8.1.2 IEEE-488 Interface Basic Specifications and Applications

The IEEE-488 parallel interface standard was developed by Hewlett-Packard as HPIB between 1965 and 1970. The HPIB interface was adopted in the United States as standard IEEE-488 (IEEE is the acronym for the Institute of Electrical and Electronic Engineers) in 1975, and then accepted internationally as standard IEC-625 (IEC is the acronym for the International Electrotechnical Commission) in 1976. Although slightly differing in connector and cabling specifications, the IEEE-488 and IEC-625 interface standards have identical functional and control aspects. IEEE-488 is often used under the name GPIB by companies such as Tektronix and National Instruments, leading manufacturers of measurement system hardware and software. The standard specifies the organization of digital data exchange within the system, the electrical parameters of signals, the mechanical parameters of connectors, and basic programming procedures. The IEEE-488 standard evolved into ANSI/IEEE-488.2, an extended specification adopted in 1987 and revised in 1992 [3]; the original version was renamed ANSI/IEEE-488.1. The version IEEE-488.1-2003, with extensions to the interface functions, definition of new interface functions, and possible extensions to the remote message codes defined in IEEE-488.1, was published in 2003 [4]. The ANSI/IEEE-488.2 standard, also referred to as IEEE-488.2 or GPIB, extends the original specification by defining the following:

- Communication protocols (defining the way the controller of the interface system communicates with the instruments);
- Data formats and time sequences for command execution in the system;
- Procedures required in case of detected transmission error;
- Controller requirements.

The new standard, IEEE-488.2, is compatible with the original IEEE-488 specification. The structure of measurement system with IEEE-488 (IEC-625) interface is shown in Figure 8.1.

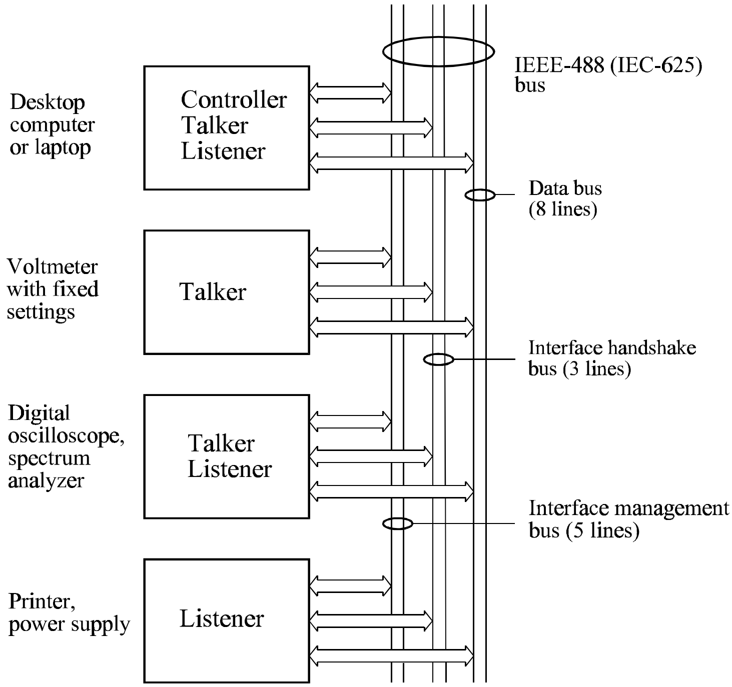

Figure 8.1 Structure of the measurement system with IEEE-488 (IEC-625) interface.

The IEEE-488 (IEC-625) interface is designed to interconnect the following devices to form a measurement system:

- Digital instruments, both specialist and of common use (the latter instruments including digital voltmeters, multimeters, oscilloscopes, frequency meters, chronometers, frequency analyzers, and logic analyzers);
- Digitally controlled electronic devices, such as signal generators, power supply units, controlled current sources, switches, and specialist devices;
- Printers, digital loggers, and plotters;
- Control units, or controllers, of the interface system.

The IEEE-488 interface system has a bus (linear) configuration. An IEEE-488 device (i.e., a device able to operate in an IEEE-488 interface system) can act as a talker, a listener, or both (in the latter case, "talking" or "listening" in separate time intervals). A controller acts as a talker, a listener, and a control unit. Data exchange within a system is carried out through transfer of messages; three types of message are transmitted: command, address, or data messages. Messages are transferred between system units via the IEEE-488 interface bus, to which all the IEEE-488 devices are connected in either daisy chain or star configuration, as shown in Figure 8.2. Although the bus configuration of the system is maintained in each case, the wiring type affects the L and C parameters of the transmission line, and consequently, the transfer rates in the system.

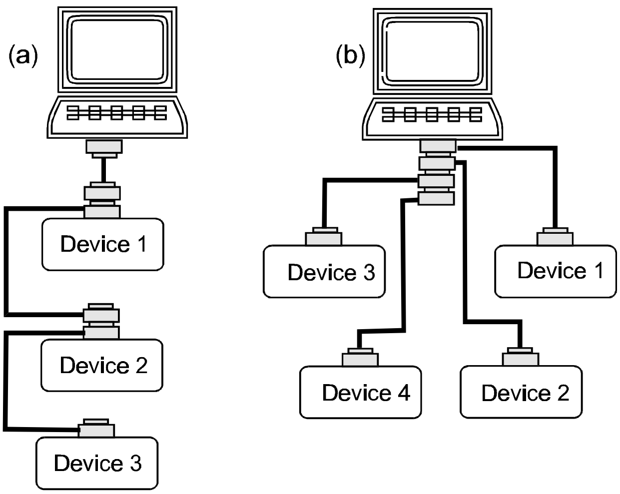

Figure 8.2 Two types of wiring in measurement system with bus configuration: (a) daisy chain, and (b) star wiring.

8.1.3 Controller of IEEE-488 System

A controller of an IEEE-488 (IEC-625) system is typically a desktop or a laptop with an IEEE-488 (IEC-625) interface board (a printed circuit board plugged into the computer bus through bus connector) and an interface driver. In personal computers, an IEEE-488 (IEC-625) interface board is installed inside the computer casing. It can be plugged into the 32-bit PCI bus or into the "slower" 16-bit ISA bus. Each interface board is able to operate with one bus type only [5, 6].

In the case of data transfer according to the full handshake protocol, the data rates do not depend on the type of bus (PCI or ISA) to which the interface board is connected, as shown in Figure 8.3. Each of these two buses provides sufficiently high message transfer rates. A substantial difference occurs, however, when the system operates with rates above the standard (e.g., by HS488 protocol, as described in Section 8.3.1): an interface board operating with PCI allows maximum data rate 8 MBps, and 1.6 MBps is provided by an interface board operating with ISA [5]. If no room is available inside a desktop computer for an IEEE-488 interface board to be plugged in, or if a board is to be plugged into a laptop, then the IEEE-1284 (a parallel interface standard for printer control, replacing the popular Centronics standard), USB, or IEEE-1394 connector and port can be used (see Sections 1.3.3 and 1.3.4 for more details on USB and IEEE-1394). When a board is to be plugged into a laptop, a PCMICIA board connector can be used as well. Each interface board is designed to interwork with one bus and connector type.

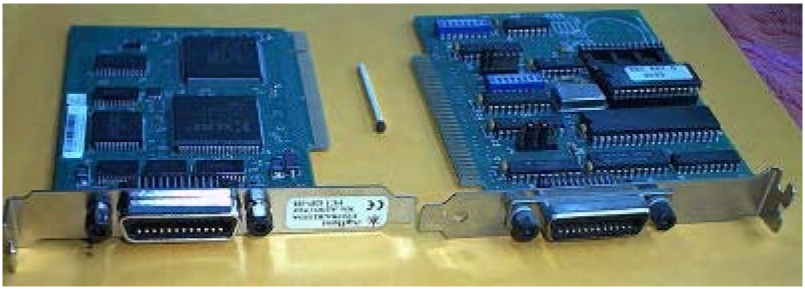

Figure 8.3 IEEE-4888 interface boards: for PCI bus (on the left) and for ISA bus (on the right).

Some examples of IEEE-488 interface boards (manufactured by National Instruments, Keithley, and IOtech) designed to interwork with the above-mentioned buses, and together with a computer able to act as controller of an IEEE-488 system, are specified in Table 8.1 [5, 6]. IEEE-488 interface boards are also made by a few other manufacturers, including Agilent Technologies (formerly Hewlett-Packard) or Capital Equipment Company (both U.S. companies).

An IEEE-488 interface system can be managed by more than one controller, but only one controller can be active (i.e., manage the system) at a time. The simplest systems can operate with no controller at all. In such simple systems, devices are addressed permanently for talking or listening. If an interface system is managed by a number of controllers, one acts as a master "system controller," starting the system operation on power-on. It is also the system controller that has the right to clear all the devices in the interface system (i.e., to reset their interface circuits to the state they had on power-on). During operation of the system, the system controller can pass control to any of the other controllers.

Although a pass control routine has been established, allowing several controllers for IEEE-488 interface management, the use of an interface system is seldom managed by more than one controller. The talker and listener functions in an IEEE-488 interface refer to its role on the interface bus only. In other words, the only basis for classifying a device as a talker, a listener, or a talker and listener, is whether it sends or receives interface messages (commands, addresses, or data) or both sends and receives them. For example, a broadcast transmitter with digitally set up parameters may act only as a listener in an IEEE-488 interface system.

Table 8.1

IEEE-488 Interface Boards Operating with Different Types of Computer Bus (National Instruments, Keithley, and IOtech Products)

Bus	*National Instruments*	*Keithley*	*IOtech*	*Computer Operating System*	*Maximum Data Rates with NI Board*
PCI	PCI-GPIB	KPCI-488	Personal 488/PCI	Windows 2000	1.5 MBps
ISA	AT-GPIB	KPC-488.2AT	Personal 488/AT	Windows 2000	1.5 MBps
PCMCIA	PCMCIA-GPIB	KPCMCIA-GPIBNT	Personal 488/CARD	Windows 2000	1.3 MBps
USB	GPIB-USB	—	—	Windows 2000	600 KBps
IEEE-1394	GPIB-1394	—	—	Windows 98	1.5 MBps
IEEE-1284	GPIB-1284CT	—	—	Windows 3.1	300 KBps

Source: [5, 6].

The parameters and tasks of the controller are specified by the IEEE-488.2 standard [3]. By this specification, the controller of an IEEE-488 interface must perform the following tasks:

- Send and read instructions, data, and protocols according to IEEE-488.1 or IEEE-488.2 standards;
- Send the Interface Clear command by asserting the IFC signal for more than 100 μs;
- Assert and unassert the REN line;
- Send and receive instructions on the EOI line;
- Recognize the state of the SRQ line (interrupt line);
- Detect and store transmission errors;
- Signal timeout error, resulting from different operation rates of devices in the system.

In addition to these mandatory tasks, some recommended tasks are defined by the IEEE-488.2 standard, requiring the controller to perform the following:

- Assign individual timeout values to each device in the system;
- Monitor all the lines within the interface bus for diagnostic purposes; in particular, the NDAC line is to be monitored, in order to identify the active devices in the system.

The IEEE-488.2 standard requires each sequence of data transferred over the interface bus to end with the “new line” character (“0A hex” in ASCII). Before this requirement was introduced, the device manufacturers had complete freedom whether or not to use a closing character, and to choose the closing character arbitrarily.

An important point of the IEEE-488.2 standard is the definition of control sequences and protocols of control tasks. Before these regulations were introduced, control sequences were manufacturer-dependent; consequently, devices manufactured by different makers were often incapable of interworking within one IEEE-488 system. The standardized control sequences are listed in Table 8.2.

The complete version of the IEEE-488.2 standard specifies the sequence of control instructions, the states of management lines during execution of these instructions, and the respective device responses. The controller protocols specified by the IEEE-488.2 standard include two required protocols and six optional protocols. The protocols specified by the IEEE-488.2 standard are listed in Table 8.3.

- RESET protocol (required) is used for resetting all devices on the IEEE-488 bus to their initial state.
- ALLSPOLL protocol (required) is used for conducting a serial poll of all devices on the interface bus in order to identify their status.
- FINDLSTN protocol (optional) consists of sending the full list of available addresses (31 addresses) from the controller to devices in the system, in order to determine the addresses from which the devices respond. This allows the controller to create a list of addresses to be used during system operation. Neither the FINDLSTN protocol nor any of the following five protocols, are required.
- FINDRQS protocol is used for establishing priority among service requests sent by devices.
- SETADD protocol assigns addresses to the devices found in the system. The aim of this operation is to harmonize the device addresses set by the user or programmer with the addresses used by the controller.
- TESTSYS protocol defines the procedure of device self-testing and the way the controller should use the self-test results.

- PASSCTL protocol is used for nonrequested control pass to another controller in the interface system. This protocol is rarely used, as is the next one, since interface systems with more than one controller are uncommon.
- REQUESTCTL protocol is used for requested control pass.

Table 8.2

Required and Optional Control Sequences in the IEEE-488.2 Standard

Control Sequence	*Description*	*Compliance*
SEND COMMAND	Send ATN – true commands	Required
SEND SETUP	Set address to send data	Required
SEND DATA BYTES	Send ATN – false data	Required
SEND	Send a program message	Required
RECEIVE SETUP	Set address to receive data	Required
RECEIVE RESPONSE MESSAGE	Receive ATN – false data	Required
RECEIVE	Receive a response message	Required
SEND IFC	Pulse IFC line	Required
DEVICE CLEAR	Place devices in DCAS	Required
ENABLE LOCAL CONTROLS	Place devices in local state	Required
ENABLE REMOTE	Place devices in remote state	Required
SET RWLS	Place devices in remote with local lockout state	Required
SEND LLO	Place devices in local lockout state	Required
READ STATUS BYTE	Read IEEE-488.1 status byte	Required
TRIGGER	Send group execution trigger (GET) message	Required
PASS CONTROL	Give control to another device	Optional
PERFORM PARALLEL POLL	Conduct a parallel poll	Optional
PARALLEL POLL CONFIGURE	Configure parallel poll responses of devices	Optional
PARALLEL POLL UNCONFIGURE	Disable parallel poll capability of devices	Optional

Table 8.3

Controller Protocols in the IEEE-488.2 Standard

Controller Protocol	*Description*	*Compliance*
RESET	Reset system	Required
ALLSPOLL	Serial poll all devices	Required
PASSCTL	Pass control	Optional
REQUESTCTL	Request control	Optional
TESTSYS	Self-test system	Optional
FINDSTN	Find listeners	Optional
SETADD	Set address	Optional
FINDRQS	Find devices requesting services	Optional

The mandatory common commands specified by the IEEE-488.2 standard are listed in Table 8.4.

Table 8.4

Mandatory Common Commands in the IEEE-488.2 Standard

Mnemonic	*Description*	*Group*
*IDN?	Identification query	System data
*RST	Reset	Internal operation
*TST?	Self-test query	Internal operation
*OPC	Operation complete	Synchronization
*OPC?	Operation complete query	Synchronization
*WAI	Wait for complete	Synchronization
*CLS	Clear status	Status and event
*ESE	Event status enable	Status and event
*ESE?	Event status enable query	Status and event
*ESR?	Event status register query	Status and event
*SRE	Service request enable	Status and event
*SRE?	Service request enable query	Status and event
*STB?	Read status byte query	Status and event

Basic Specifications of the IEEE-488 (IEC-625) Interface System

For message exchange to be initiated between devices in an IEEE-488 interface system, one message source, or talker, and one or more acceptors, or listeners, must be appointed (i.e., addressed for talking or listening, respectively) by the controller. The appointed, or addressed, talker sends messages over the data bus, and the addressed listeners read the messages byte after byte, with acceptance of each byte being acknowledged. The data transfer rate is adapted to the reading capacity of the slowest listener. Basic features of the IEEE-488 (IEC-625) interface system include:

- Parallel asynchronous transfer of information in the form of 8-bit messages sent over the data bus;
- Transmission using handshake protocol, with confirmation of message acceptance; the handshake protocol allows adaptation of the data rates to the reading capacity of the slowest listener;
- Negative (low-true) logic convention used for signals in the bus: low voltage level on a signal line corresponds to logical 1 (or T, for true), and high voltage level corresponds to logical 0 (or F, for false); the signal lines use TTL voltage levels;
- Maximum data rate: 1 MBps;
- Maximum number of devices in the system: 15;
- 24-line (25-line in the IEC-625 standard) interface bus cable with maximum total length 20m, and recommended maximum length between two devices 2m.

Although IEEE-488 is a U.S. standard, and IEC-625 is an international standard, quite often the end user of the system has no choice between them, since the standard of a device and its cabling are manufacturer-dependent. Products of American companies, such as Hewlett-Packard or National Instruments, have 24-pin interface sockets and IEEE-488 compliant cabling. European manufacturers tend to keep to the IEC-625 standard, with 25-pin sockets and IEC-625 cabling [1, 7]. The functional aspects of both standards are identical. Hewlett-Packard keeps the original name HPIB, rather than using the designation IEEE-488, while National Instruments, a global manufacturer of digital instruments and measurement system software, uses the name GPIB. Due to the dominant position of American companies in the measurement instrumentation market, devices with IEEE-488 connector and cabling are more common than those compliant with the IEC-625 standard. Therefore, it is the U.S. version of parallel interface standard, IEEE-488, that is more often referred to and illustrated here. Of the approximately 50 digital devices with parallel interface the author has experience with, all were IEEE-488 compliant (i.e., consistent with the U.S. standard).

8.1.4 IEEE-488 Interface Bus and Cable

The interface bus is used for transferring messages (data or instructions), as well as signals that control message transfer and operation of the devices in the system. The IEEE-488 interface bus consists of 24 lines, 16 of which are signal lines. The signal lines are grouped into three sets: data bus (eight lines), interface management bus (five lines), and interface handshake bus (three lines). The remaining eight are seven ground lines and one shield line. The IEC-625 interface bus consists of 25 lines, with eight ground lines (rather than seven) as the only difference with respect to its IEEE-488 counterpart.

Data Bus

The data bus consists of eight signal lines, named DIO (Data Input Output) and numbered from 1 to 8. The DIO lines are used for transferring messages, both data and instruction types, the latter carrying addresses or commands. The type of a message (data or instructions) available on the data bus is signaled by the active controller on a dedicated management line, referred to as ATN, as described below. Messages are transferred by bytes, bidirectionally from talker to listeners, the latter signaling readiness to accept messages and confirming message acceptance. Data in the form of alphanumeric or printer control characters is usually transferred in the 7-bit ISO-7 code (identical to the American ASCII code). The eighth bit can be used as the parity bit in transmission error check, or can remain unused.

Interface Management Bus

The interface management bus comprises five signal lines:

- *IFC* (InterFace Clear) line, used by the system controller. When the interface system is powered on, the IFC signal is asserted by the system controller for at least 100 μs. ("Asserting" means setting logical signal 1, or low voltage level, on the line.) The IFC signal clears all the IEEE-488 devices (i.e., resets their interface circuits to initial state). When the clearing is completed, the IFC line is unasserted (which corresponds to logical state IFC = 0, or high voltage level) and remains so during message transfer between devices.
- *ATN* (ATteNtion to message type) line, used by the active controller. Logical state ATN = 1 indicates that the messages sent over the data bus are instructions (addresses or commands), and logical state ATN = 0 indicates that the messages are data.
- *REN* (Remote ENable) line, used by the system controller. This line switches between remote (system) and local (manual) control of all the IEEE-488 devices. In the case of remote control, enabled by asserting the REN line (REN = 1), an IEEE-488 device is operated either automatically,

or like a virtual instrument, by means of a computer keyboard or mouse and a screen display in the front panel. Local control, or response to the front-panel controls and switches, is enabled by unasserting the REN signal (REN = 0).

- *SRQ* (Service ReQuest) line, used by any IEEE-488 device. The SRQ line can be regarded as an interrupt line. Each device in the system can request service by asserting the SRQ signal. For example, adjustment of measurement range setup can be requested as a service in case of overrun. Another example of a service request is an order to transfer necessary setup data before the next step in the measurement procedure.
- *EOI* (End Or Identify), used by the active controller or by the talker. The name of this line refers to the double sense of its assertion; the valid meaning is determined by the type of message on the data bus, indicated by the logical state of the ATN line. In data mode (i.e., in the case of data transfer, indicated by ATN = 0), the EOI signal is asserted by the talker (EOI = 1) to indicate the end of a data segment (END function). In instruction mode (i.e., when ATN = 1), the EOI signal is asserted by the active controller to conduct a parallel poll of IEEE-488 devices, in order to identify their status.

Interface Handshake Bus

The interface handshake bus consists of three lines, used for interlocking, or synchronizing, the processes of sending and reading each byte on the data bus. The word “synchronize” used to describe handshake in the IEEE-488 interface does not imply that bytes are transferred synchronously, to the beat of the system clock. Used with reference to handshake, “synchronizing” means “interlocking” of data sending and reading. Although using handshake, data transfer itself is asynchronous.

The three handshake lines are defined as follows:

- *DAV* (DAta Valid) line, used by the talker. By asserting the Data Valid signal (DAV = 1), the talker indicates to its listeners that the processes of signal change and settling are over, and a new byte is valid and available on the data bus.
- *NRFD* (Not Ready For Data) line, used by all the addressed listeners. Logical state 1 on the NRFD output of an IEEE-488 device indicates that the device is not yet ready to accept data. Since logical state 1 corresponds to low voltage level (according to the negative logic convention), when at least one listener is not ready for data, and indicates its state by low voltage level, the NRFD line is set to low voltage level as well, which corresponds to asserting its signal (NRFD = 1). The NRDF line voltage level will not become high (i.e., the line will not be unasserted) unless all the addressed listeners are ready for data. The logical value of a message sent by an

individual listener may differ from that of the resultant message received by the talker. A listener may be ready for data and send an NRFD = 0 message, but the logical state of the line will remain NRDF = 1 if at least one of the listeners is not ready for data. Active and passive message values are distinguished to avoid collision, as described in Section 8.2.1).

- *NDAC* (Not Data ACcepted) line. Like the NRFD line, the NDAC line is used by all the addressed listeners. Logical state 1 (or low voltage level) on the NDAC output of a listener indicates that the listener has not yet read a byte. This can be associated, for example, with processing previously accepted bytes, or with input buffer overflow. Logical state 1 on the NDAC output of at least one listener sets the NDAC line to logical 1 as well. Only when the current byte has been accepted by all the listeners, will the NDAC line become unasserted (i.e., NDAC = 0, or high voltage level on the NDAC line).

Interface Cable and Connector

The parameters of cable and connector to be used in an interface system are covered by the IEEE-488 and IEC-625 interface standard specifications. The IEEE-488 and IEC-625 connector contact assignments are specified in Table 8.5. The maximum total cable length in an IEEE-488 interface system is 20m. Although the cable length limit between two devices is 4m, the recommended maximum length is 2m. The resistance of the cable conductors should not exceed 140 mΩ/m, and the capacity between each signal line and ground should be no more than 150 pF/m. The connector for the interface cable has a plug-and-socket construction that allows a number of cables to be connected to a single socket by stacking connectors on top of one another, as shown in Figure 8.4.

Figure 8.4 IEEE-488 interface cable connectors.

The IEC-625 interface standard requires a 25-pin Canon connector, and the IEEE-488 interface standard uses a 24-pin connector manufactured by Amphenol or Cinch. The connector parameters are as follows:

- Current-carrying capacity: 5A per contact;
- Maximum contact resistance: 20 mΩ per contact;

- Minimum insulation resistance: 1 GΩ;
- Minimum number of connections/disconnections: 1,000.

Table 8.5

IEC-625 and IEEE-488 Connector Contact Assignments

Contact Number	*Line*		*Contact Number*	*Line*	
	IEC-625	*IEEE-488*		*IEC-625*	*IEEE-488*
1	DIO 1	DIO 1	14	DIO 5	DIO 6
2	DIO 2	DIO 2	15	DIO 6	DIO 7
3	DIO 3	DIO 3	16	DIO 7	DIO 8
4	DIO 4	DIO 4	17	DIO 8	REN
5	REN	EOI	18	Ground (5)	Ground (6)
6	EOI	DAV	19	Ground (6)	Ground (7)
7	DAV	NRFD	20	Ground (7)	Ground (8)
8	NRFD	NDAC	21	Ground (8)	Ground (9)
9	NDSC	IFC	22	Ground (9)	Ground (10)
10	IFC	SRQ	23	Ground (10)	Ground (11)
11	SRQ	ATN	24	Ground (11)	Digital ground
12	ATN	Shield	25	Ground (12)	—
13	Shield	DIO 5	—		

8.1.5 IEEE-488 Interface Functions

Each IEEE-488 device consists of three functional blocks, their respective functions being [4]:

- Device functions, which are the functions that the device is designed for (for example, a digital voltmeter operating in an IEEE-488 interface system must perform voltmeter functions, or a generator must be a generator);
- Interface functions, allowing the device to receive and interpret incoming messages, as well as to generate and send messages over the interface bus;
- Signal conditioning, which allows outgoing/incoming signal processing by coders and decoders, as well as by line talkers and listeners, involving signal voltage level, format, and power adjustment, as shown in Figure 8.5.

Interface functions are performed by devices operating in an interface system. The following 10 interface functions, also referred to as interface capabilities, are defined in the IEEE-488 specification:

- Source Handshake (SH);
- Talker (T) and Extended Talker (TE);
- Acceptor Handshake (AH);
- Listener (L) and Extended Listener (LE);
- Service Request (SR);
- Remote/Local (RL);
- Parallel Poll (PP);
- Device Clear (DC);
- Device Trigger (DT);
- Controller (C).

A circuit executing an interface function can be regarded as a finite state automaton activated by a number of signals. The operation of an interface function automaton can be described clearly by a state diagram. Below, we give a brief description of the interface functions. For a more exhaustive description, as well as for the corresponding state diagrams, refer to Section 8.4.

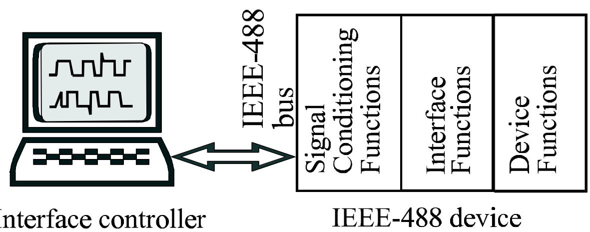

Figure 8.5 Functional block structure of an IEEE-488 device in an interface system.

Interface functions 1 to 4 handle message transfer within the interface system: the *Source/Acceptor Handshake* functions prepare an IEEE-488 device to send/receive messages, and the *Talker/Listener* functions allow the very action of message sending/reading. The Acceptor Handshake and Listener functions, illustrated by their state diagrams, are discussed in detail in Sections 8.4.2 and 8.4.3.

The *Service Request* function allows a device to request a program service by asserting asynchronously the SRQ line (SRQ = 1). In response to a service request, the controller must identify the requesting device, as well as the type of program service requested. In the next step, the controller should start the program service according to the system operation algorithm.

The *Remote/Local* function allows a device to switch between response to commands sent over the interface bus (remote) and response to the device front-panel controls (local). The RL function is carried out through asserting or unasserting the REN line. Since the REN inputs of all the IEEE-488 devices are connected in parallel to the REN line, the selected control mode applies to all devices in the system.

The *Parallel Poll* function allows the parallel check of up to eight devices by the controller. The status of each device is indicated on data lines DIO 1 to DIO 8. Each IEEE-488 device is assigned one of the DIO lines, which allows up to eight devices to be polled simultaneously. For example, a parallel poll is conducted when a program service is requested by asserting the SRQ signal (SRQ = 1). In this situation, the controller performs a parallel poll in order to determine which device has requested service. In addition to a parallel poll, a serial poll is possible in IEEE-488 interface system.

The *Device Clear* function resets all devices in the IEEE-488 system to their initial state. This interface capability is reserved for the system controller, which performs the Device Clear function by asserting the IFC line (IFC = 1).

The *Device Trigger* function allows an addressed listener, or a number of addressed listeners, to be “triggered” (i.e., to start operation). For example, Device Trigger can be used to start voltage reading by remotely triggering a digital voltmeter in the system.

The *Controller* function allows control of the system operation. This function is performed through sending commands and addressing devices. The commands sent include: Interface Clear (IFC), Remote Enable (REN), and Parallel Poll (PP).

An IEEE-488 device need not have all 10 interface capabilities. This applies not only to the Controller capability, reserved for controllers of the system, but also to any other interface capability. An IEEE-488 device needs only those capabilities that are necessary for its operation in the system. For example, an IEEE-488 device that acts only as a talker does not need the Acceptor Handshake, Listener, Device Trigger, or Controller capabilities. However, large-scale integrated circuits (LSIC) that are provided with all the interface capabilities are now cheaper to manufacture than custom-designed integrated circuits able to perform only selected interface functions. For more details on the interface functions, as well as for state diagrams describing their execution, see Section 8.4.

8.2 IEEE-488 INTERFACE MESSAGES AND THEIR TRANSFER

8.2.1 Interface Message Types

Pieces of information transmitted within an IEEE-488 interface system are generally referred to as messages [3, 4]. The messages can be grouped into two categories:

- Interface messages, used for controlling the interface system;
- Device messages, sent over the interface, but not directly used or processed by the interface system.

A different classification defines the following two message types:

- Remote messages, transferred between devices over the interface bus;
- Local messages, transferred within an IEEE-488 device between its device function block and its interface function block, as shown in Figure 8.5.

Lower or upper case mnemonics are used to refer to local or remote messages, respectively, in the interface function state diagrams. Remote messages can be uniline or multiline.

A message can be received as true or false. In the case of uniline messages, the message value corresponds with the logical state of the signal line: logical 1, or low voltage level, for "true," and logical 0, or high voltage level, for "false." The value of a multiline message is determined by the logical states of all the signal lines. True and false multiline messages are split into two subsets.

Uniline remote messages with different logical values can be sent to the interface bus by two or more IEEE-488 devices. Passive and active messages are distinguished to avoid collision. A remote message can be sent as:

- Active true;
- Passive true;
- Active false;
- Passive false.

An "active" message value means that the value of the message sent is the same as that of the message received (i.e., sent true, and received true; sent false, and received false). A "passive" message value means that the value of the message sent may differ from that of the message received. When a passive false message is sent by a device, the received message may be either false or true, the latter taking place when a true message is sent by another device on the same signal line. A symmetric situation occurs in the case of a passive true message.

Uniline messages are 1-bit instructions sent via single interface management lines (i.e., control instructions, such as IFC, ATN, or SRQ) or via handshake lines (i.e., DAV, RFD, and DAC instructions). Multiline messages are byte messages sent over the data bus. The type of message available on the DIO lines is signaled by the logical state of the ATN line: ATN = 0 means the messages are data proper (i.e., measurement results or device settings), and ATN = 1 means the messages are control commands (i.e., device addresses).

Multiline remote messages have a standardized structure, as specified in Table 8.6. Note that the logical state of the bit on the DIO 8 line is not specified; this bit can be used as the parity bit in error check. The functional classification groups all the messages into the following seven sets:

- Addresses (AD);
- Universal Commands (UC);

- Addressed Commands (AC);
- Handshake (HS) instructions;
- SEcondary (SE) messages;
- Device-Dependent (DD) messages;
- STatus (ST) messages.

8.2.2 Remote Messages

Addresses

Address instructions are used for appointing interface message listeners or talkers among the devices on the IEEE-488 interface bus. The logical state of the DIO 8 line is not defined for multiline messages.

Table 8.6

Multiline Remote Message Structure

Message Group	*DIO Line Logical State*							
	DIO 8	DIO 7	DIO 6	DIO 5	DIO 4	DIO 3	DIO 2	DIO 1
Listen Addresses	Ø	0	1	L5	L4	L3	L2	L1
Talk Addresses	Ø	1	0	T5	T4	T3	T2	T1
Universal Commands	Ø	0	0	1	U4	U3	U2	U1
Addressed Commands	Ø	0	0	0	A4	A3	A2	A1
Secondary Messages	Ø	1	1	S5	S4	S3	S2	S1

Ø: logical state not specified by the standard.

The logical states of lines DIO 7 and DIO 6 specify the message functional type. The logical state DIO 7 = 1 and DIO 6 = 0 indicates a Talk Address instruction, and the logical state DIO 7 = 0 and DIO 6 = 1 corresponds to a Listen Address instruction. The address of each appointed device is specified by the logical states of the remaining five data lines, from DIO 5 to DIO 1. A Talk ADdress (TAD) instruction is interpreted by the device as My Talk ADdress (MTA). If a TAD instruction is sent to a currently addressed listener, the listener is unaddressed and becomes an addressed talker. A Listen ADdress (LAD) instruction is interpreted by the device as My Listen Address (MLA). A LAD instruction sent to a currently addressed talker implies unaddressing the device as a talker. All the addressed listeners can be unaddressed at one time by the UNListen (UNL) command. The five address bits allow $2^5 = 32$ combinations, 31 of which are used for device addressing. The Listen Address combination 32, corresponding to the word L5L4L3L2L1 = 11111, is reserved for the UNL. Similarly, the Talk Address combination 32, or the word T5T4T3T2T1 = 11111, is the UNTalk (UNT) command. Both UNL and UNT unaddress all the devices in the system. As the maximum number of devices in the interface system is 15, and the number of possible addresses is 31, more than one address can be assigned to a single device, although this is rarely used in practice. The surplus number of addresses is useful in configuring expanded systems (comprising more than 15 devices), which can be set up by means of special expanders, as described in Section 8.3.2.

Universal Commands

Universal commands are sent to all devices in an IEEE-488 interface system, with no prior addressing required. Uniline universal commands include ATN, IFC, REN, and IDY (Identify). These commands are sent over the ATN, IFC, REN, and EOI signal lines, respectively. The IDY command is sent over the EOI line with ATN asserted. The IDY command is executed by parallel-polling the devices in order to identify the device that has requested service. The remaining three uniline commands are discussed in Section 8.1.4, along with the corresponding signal lines. Apart from the uniline commands, the following five multiline universal commands are defined:

- Device Clear (DCL) resets all devices in the system to their initial state. The DCL command should not be confused with the IFC command. The uniline IFC command clears the interface circuits of all devices in the IEEE-488 system, while the multiline DCL command clears the device function block.
- Local Lock-Out (LLO) disables response to the local front-panel controls and switches.
- Parallel Poll Unconfigure (PPU), executed by the Parallel Poll interface function, and causes the parallel poll system (automaton) to return to its initial state.
- Serial Poll Enable (SPE) orders a serial poll to be conducted in order to identify the device that has requested service by asserting the SRQ line. The serial poll procedure consists of the following steps: the active controller is listen-addressed, and the devices are talk-addressed one by one, each addressed talker sending a status byte, which is read by the controller.
- Serial Poll Disable (SPD) closes the serial poll. The device that has requested service is identified as a result of the poll; once the SPD command is executed, the controller can start the service procedure (e.g., read the result of a completed measurement).

Addressed Commands

The following five multiline addressed commands are defined by the IEEE-488 specification:

- Selective Device Clear (SDC) is analogous to the DCL universal command, but affects the addressed listeners only; the SDC command resets the addressed listeners to their initial state.
- Go To Local (GTL) sets the addressed listeners back to local (front-panel) control mode.
- Group Execute Trigger (GET) directs to one or more addressed listeners in order to initiate their operation.
- Take Control (TCT) is sent by the active controller in order to pass control of the interface system to the addressed talker.
- Parallel Poll Configure (PPC) prepares the system for a parallel poll; as a result of the PPC command, executed along with the secondary command Parallel Poll Enable (PPE), each device to be polled is assigned one of the eight DIO lines as its parallel poll address; up to eight devices can be addressed in this way.

Secondary Messages

Secondary messages are byte messages sent in addition to other commands to add command functionality. The following four secondary messages are defined by the IEEE-488 standard:

- My Secondary Address (MSA) is a message with a 5-bit device address sent over lines DIO 1 to DIO 5. The logical state of the next two bits is specific to secondary messages: DIO 6 = 1, DIO 7 = 1. The MSA message addresses a device to perform the Extended Talker (TE) or Extended Listener (LE) interface functions.
- Other Secondary Address (OSA) unaddresses a currently addressed extended talker.
- Parallel Poll Enable (PPE). Combined with the PPC addressed command, the secondary command PPE assigns each IEEE-488 device to be polled one of the eight DIO lines as its parallel poll address. The PPE bits on lines DIO 1 to DIO 3 correspond to the device address (a binary-coded number from 0 to 7), and the logical state of line DIO 4 is the device response.
- Parallel Poll Disable (PPD) resets the parallel poll system (i.e., all devices involved in execution of the Parallel Poll function) to its initial state.

Device-Dependent Messages

Device-dependent messages are data or information on data stream. This type of message is sent by an addressed talker. The following three types of device-dependent message are defined by the IEEE-488 standard:

- Data Byte (DAB) contains a character of the data transferred (alphanumeric or printer control character), usually coded in ISO-7 (ASCII);
- Null Byte (NUL) is a byte in which every bit has logical value 0: NUL = 00000000;
- End Of String (EOS) is sent by the talker to indicate the end of a transferred data string; note that the same information is carried by uniline message END, sent over the EOI signal line.

Status Messages

A device sends a status message on the interface bus in order to declare the status of its interface. A status message can be sent in response to a query (poll) or without query. The status messages include two uniline messages, SRQ and END, as well as three multiline messages, STB, RQS, and PPR. The status messages of both types are briefly described below.

Uniline status messages:

- Service Request (SRQ) is a message on the SRQ line that is the logical sum of the messages sent by all devices in the IEEE-488 system through their respective SRQ outputs. Logical state 1 (low voltage level) on the SRQ output of any of the IEEE-488 devices sets the SRQ line to logical state 1 as well.
- END is a message sent over the EOI line (with ATN unasserted) to indicate the end of a data string; message END = 1 is sent along with the last data byte.

Multiline status messages:

- Status Byte (STB). The definition of the STB bits put on lines DIO 1 to DIO 6 and DIO 8 is device-dependent; the bit sent over line DIO 7 carries the information contained in the Request Service message sent along with the STB; and the STB message is sent in response to a serial poll request;
- Request Service (RQS). As mentioned above, the RQS message is carried by the Status Byte over the DIO 7 line; message RQS = 1 sent by a device in the interface system means that this device has requested service.

- Parallel Poll Response (PPR) is sent in response to a parallel poll. The message byte is sent over lines DIO 1 to DIO 8, with each DIO line carrying information on the status of the device it has been assigned to.

Handshake Instructions

Handshake instructions are uniline messages sent over the interface handshake lines. The meaning and effects of these instructions are discussed in Section 8.1.4. Handshake instructions include:

- Data Valid (DAV), sent over the DAV line;
- Ready for Data (RFD), sent over the NRFD line;
- Data Accepted (DAC), sent over the NDAC line.

8.2.3 Local Messages

Local messages are transferred within an IEEE-488 device between its device function block and its interface function block. Only messages sent from the device (or, to be precise, from its functional block performing the device functions) to the interface (i.e., to the functional block performing the interface functions) are standardized. Messages from the interface to the device, although equally necessary, are not covered by the standard. Nineteen standardized local messages from device to interface, along with the interface functions affected by each message, are listed below in alphabetical order:

- ‘end of byte string’ (end), affecting the T and TE functions;
- ‘go to standby’ (gts), affecting the C function;
- ‘individual status’ (ist), affecting the PP function;
- ‘listen’ (ltn), affecting the L and LE functions;
- ‘listen only’ (lon), affecting the L and LE functions;
- ‘local poll enable’ (lpe), affecting the PP function;
- ‘local unlisten’ (lun), affecting the L and LE functions;
- ‘new byte available’ (nba), affecting the SH function;
- ‘power-on’ (pon), affecting all interface functions;
- ‘ready for next message’ (rdy), affecting the AH function;
- ‘request parallel poll’ (rpp), affecting the C function;
- ‘request service’ (rsv), affecting the SR function;
- ‘request system control’ (rsc), affecting the C function;
- ‘return to local’ (rtl), affecting the RL function;
- ‘send interface clear’ (sic), affecting the C function;
- ‘send remote enable’ (sre), affecting the C function;
- ‘take control asynchronously’ (tca), affecting the C function;
- ‘take control synchronously’ (tcs), affecting the C and AH functions;
- ‘talk only’ (ton), affecting the T and TE functions.

Some of the key interface-to-device local messages, and the respective interface functions, are:

- ‘data valid’ (dvd), affecting the AH function;
- ‘device clear’ (clr), affecting the DC function;
- ‘last byte’ (lsb), affecting the L and LE functions;
- ‘service requested’ (srq), affecting the C function;
- ‘talker active’ (tac), affecting the T and TE functions;
- ‘trigger device’ (trg), affecting the DT function.

8.2.4 Message Transfer in Handshake Mode

Handshake consists of interlocking the processes of sending and reading each byte sent over the data bus. Two full handshake cycles (i.e., interlocked sending and reading of two successive bytes), are shown in the time diagram in Figure 8.6.

The time diagram begins at $t = 0$, when byte $k - 1$ is being processed. The DAV line, controlled by the talker, is unasserted (DAV = 0, which corresponds to high voltage level). Hence, the byte available on the data bus is not valid. The NRFD line, used by the listeners, has logical state NRFD = 1 (low voltage level), indicating that some of the listeners are not yet ready to accept byte *k*.

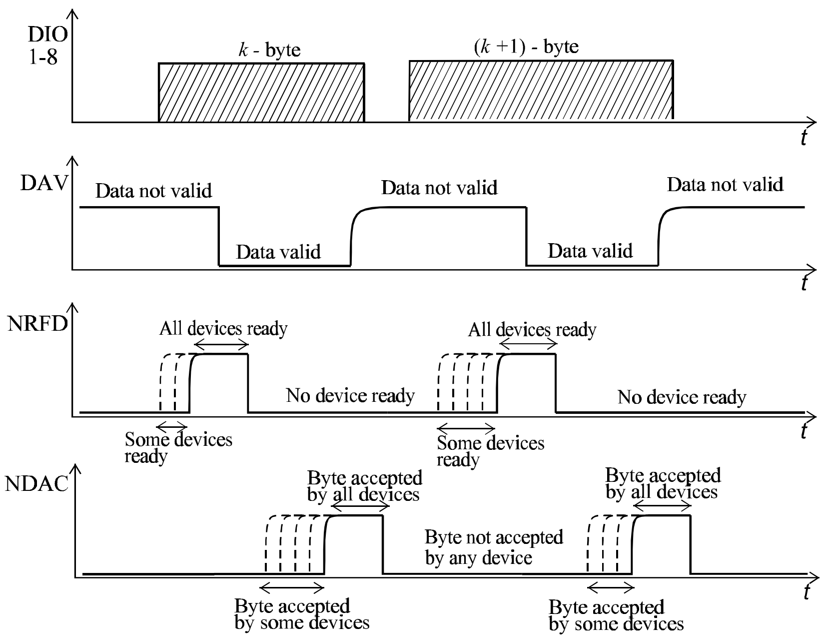

Figure 8.6 Handshake, or interlocked sending and reading of successive bytes on the data bus.

The NDAC line has logical state 1 as well, indicating that some of the listeners have not yet finished reading byte ($k-1$). Next, byte k is produced by the talker and placed on the DIO lines. At the same time, all the listeners become ready to accept byte k; this results in unasserting the NRFD line (NRFD = 0). The talker asserts the DAV line (DAV = 1) to indicate to the listeners that byte k is valid. The listeners start reading the data, and the first one to start reading asserts the NRFD signal (NRFD = 1). Once the information has been read by all the listeners, the NDAC line is asserted (NDAC = 1). The logical states of the DAV, NRFD, and NDAC lines are again as at $t = 0$. The talker can already place byte ($k + 1$) on the DIO lines. Having processed byte k, the listeners will unassert the NRFD line (NRFD = 0), which will enable the talker to indicate a valid byte by asserting the DAV line (DAV = 1). The subsequent process of byte ($k + 1$) reading follows the same pattern as in the case of byte k.

8.3 ENHANCEMENTS IN MEASUREMENT SYSTEMS WITH IEEE-488 INTERFACE

8.3.1 Enhancing Transfer Rates in Measurement Systems: HS488 Protocol

Basic technical parameters of measurement systems with the IEEE-488 interface delimit the number of devices in the system to 15, and the device separation to 20m, which corresponds to the maximum cable length. The speed of message transfer within the system is limited as well, with typical throughput ranging from 250 to 500 KBps. This section is devoted to methods of overcoming these constraints and enhancing measurement system parameters.

Message transfer in a system with an IEEE-488 parallel interface is carried out asynchronously in handshake mode, with acceptance of each data byte being confirmed. The maximum data transfer rate in the system, specified in Section 8.1.3, is 1 MBps. The limit throughput of 1 MBps can be achieved on condition that the length of each segment of interface cabling (i.e., of each cable connecting two devices) does not exceed 1m, and total cable length (the sum of the segments) is limited to 10m. With cable length per device extended to 2m, and total cable length up to 20m, the throughput is reduced to 500 KBps. On the other hand, special IEEE-488 interface boards (also referred to as GPIB or HPIB boards) exceed the standard transfer rate limits. For example, TNT4882C ASIC board, manufactured by National Instruments, allows transfer at speeds up to 1.5 MBps, provided that other conditions necessary for high-speed data transfer are fulfilled in the measurement system [5].

Three factors contribute to limitation of transfer rates. The first one is the time necessary for an entire handshake cycle to be performed; that is, for the listeners to indicate that they are ready to accept data, for the talker to signal valid data, and for the listeners to confirm data acceptance. Each of these events requires some time to be reserved.

The second factor limiting the transfer rates is distortion of the pulse signals transmitted over the interface cable and representing digital data. Signal distortions are due to transient electrical states in the cable, and increase with L and C parameters (i.e., with the inductance and capacity of the cable lines). The L and C values are proportional to the cable length. In case of major distortions, the transmitted signals can become illegible as digital data. The IEEE-488 cable itself forms a lowpass filter which suppresses higher harmonic of transmitted signals. The signal attenuation is larger at higher transfer rates and at larger L and C parameters.

The third limitation of transfer rates is associated with limited rates of arithmetical and logical operations performed by the controller (computer or microprocessor chip). However, this obstacle, playing an important role when HPIB (later, IEEE-488 and IEC-625 standard) was being developed, can be easily overcome now by using fast computers as controllers of IEEE-488 system.

A substantial enhancement of transfer rates is provided by HS488, a high-speed handshake protocol developed by National Instruments (NI) in 1993 [5]. Transfer by the HS488 protocol requires devices in the IEEE-488 interface system to be fit for high-speed operation (i.e., to be HS488 capable). The HS488 protocol defines simplified handshake signal exchange. Three hardware conditions must be fulfilled to allow implementation of HS488:

- All IEEE-488 devices on the interface bus must be powered on;
- All devices must have three-state line transmitters;
- Capacity of each signal line within the interface bus should not exceed 50 pF.

The HS488 protocol is designed for data transfer only; instructions must be transferred in full handshake mode. The HS488 protocol simplifies the handshake procedure, since only the first byte is transferred in full handshake mode. Once this byte is accepted, the talker sends the next bytes continually, requiring the listeners to send neither the RFD message to indicate that they are ready to accept data, nor the DAC message to confirm data acceptance, as described in Figure 8.7.

Each byte placed on the DIO lines is accompanied by a DAV message sent by the talker, and must be accepted within a preprogrammed acquisition time, T_{acq}. Since the T_{acq} value depends on the interface cable length, the maximum rate of data transfer using the HS488 protocol can vary from 1.5 to 8 MBps, as shown in Figure 8.8. The upper limit of 8 MBps can be achieved only when messages are transferred between two devices, the length of the cable between them being limited to 2m. An additional condition necessary for the transfer rate to reach 8 MBps is that the IEEE-488 interface board must be plugged into the 32-bit PCI bus in the computer. With 15 devices in the system, and total cable length 15m, the maximum rate of HS488 transfer over the PCI bus is reduced to 1.5 MBps.

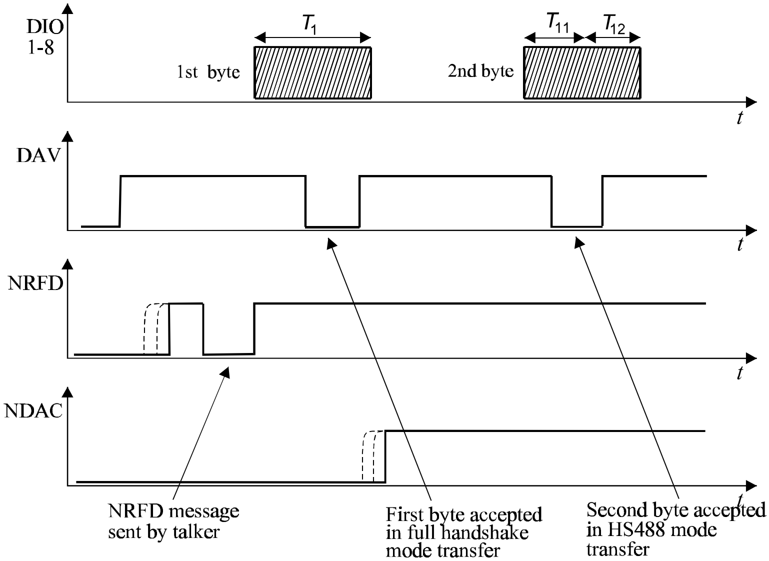

Figure 8.7 Data transfer using the HS488 protocol in IEEE-488 system.

When the IEEE-488 interface board is plugged into the much "slower" 16-bit ISA computer bus, the maximum rate of HS488 transfer between two devices connected by a 2-m cable is 2 MBps. Both PCI and ISA bus segments can be present in one computer, but an interface board can operate with only one specific bus type. For example, National Instruments' interface board PCI-GPIB is fit for the PCI bus, while interface board AT-GPIB/TNT, also manufactured by NI, operates with the ISA bus [5].

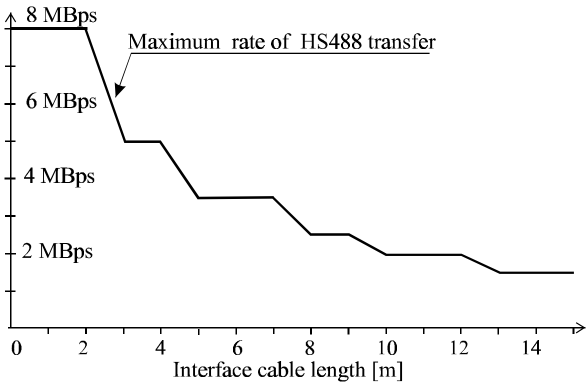

Figure 8.8 Maximum HS488 transfer rate as a function of interface cable length [5].

The maximum data rates allowed by the PCI-GPIB and AT-GPIB/TNT boards are 7.7 and 1.6 MBps, respectively, in a transfer using the HS488 protocol. However, actual transfer rates depend on the length of the interface cable used. When configuring an IEEE-488 interface system to use the HS488 protocol, the cable length should be specified in order to prevent transmission errors due to underestimation of the acquisition time. For the entered value of interface cable length (1m to 15m), the acquisition time, T_{acq}, and the data throughput are calculated automatically by the appropriate NI software.

8.3.2 Increasing the Number of Devices in Measurement Systems

The limit of 15 devices set by the IEEE-488 standard can be exceeded either by plugging more than one interface board in the computer used as controller of the interface system, or by using special system expanders. A substantial increase of the maximum number of devices in the measurement system is obtained by using two to four IEEE-488 interface boards, as shown in Figure 8.9.

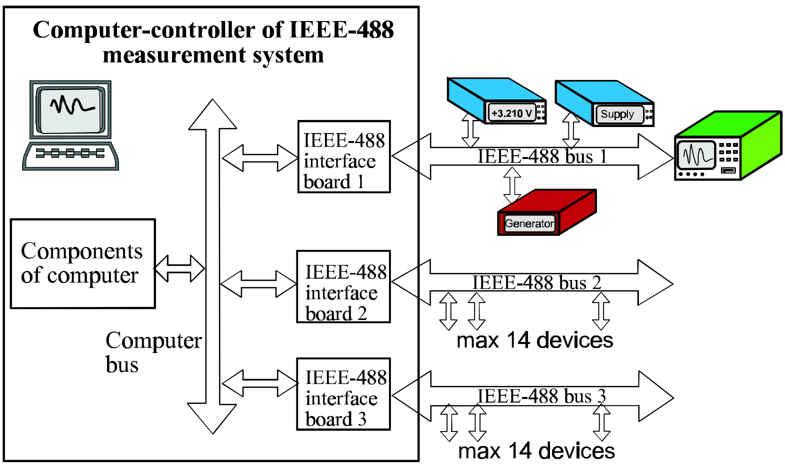

Figure 8.9 Measurement system with several IEEE-488 interface boards.

According to Hewlett-Packard, up to eight interface boards can be used in an IEEE-488 system, the board types being HP 82340, HP 82341, or HP 82335 [6]. However, the possibility of installing as many as eight interface boards is theoretical only. Each of the interface boards creates a segment of interface bus, to which up to fourteen IEEE-488 devices can be connected. A separate technical problem is the availability of a sufficient number of slots and computer bus connectors required for the interface boards to be plugged in. Using more than one interface board involves time-divided control of the system, since the controller can communicate with only one interface board at a time, and through this board, with the devices on the respective interface bus segment. Control of such measurement systems is more complicated and slower than that of systems with a single interface board. All universal commands, including the vital Interface Clear command, must be sent separately to each interface board, through which they are transmitted to the respective group of devices. Control commands from the devices, including Service Request, are received in the time ‘allocated’ to the respective board, rather than directly. This procedure slows down the measurement system operation.

Another method of increasing the number of devices in the system consists of using special devices referred to as expanders. An expander can be connected to the interface bus as one of the 15 devices allowed by the standard. An important feature of an expander is its transparency for transmitted signals. Unlike the other IEEE-488 devices, an expander is not assigned any address. Its main role is to extend the IEEE-488 interface bus by creating a supplementary segment, referred to as a secondary bus or bus extension, as shown in Figure 8.10. Fourteen more devices can be connected to this secondary segment of interface bus.

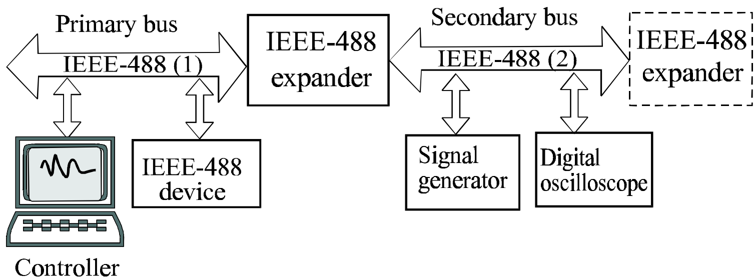

Figure 8.10 Measurement system with an IEEE-488 interface and serially connected expanders.

The measurement system can be expanded still further by connecting another expander to the secondary bus, as shown in Figure 8.10. Connected in this way, expanders provide a possibility of serial extension of the interface bus, and consequently, of increasing the allowed number of devices in the system. Expanders are also used for purposes other than increasing the number of devices in the system. Some expander types have specific parameters, and are used, for example, for connecting devices that are insulated from the interface primary bus. National Instruments’ GPIB-120A expanders provide 1,600V of electrical isolation between interface bus segments [5].

The direct star connection of two or more expanders to the IEEE-488 interface primary bus is also possible. In this configuration, up to fourteen devices can be connected to each expander, as shown in Figure 8.11.

The above-discussed methods allow the number of devices in an IEEE-488 interface system to substantially exceed the limit of 15 devices. However, measurement systems with expanders have the following disadvantages:

- The number of devices addressed with a single byte is limited by the number of available addresses (31);
- Increasing the number of devices to be controlled by a single controller slows down the system operation.

There is a tendency in the evolution of measurement systems toward their hierarchical structure, with a number of subsystem controllers managing a few devices each, and with a master system controller (PC or workstation) processing synthetic data from the subsystems.

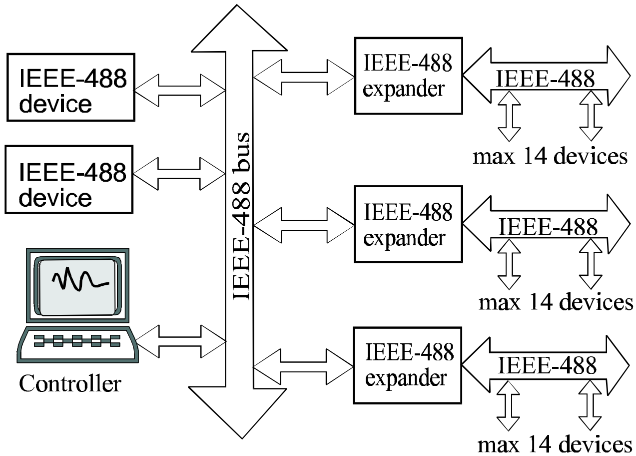

Figure 8.11 Measurement system with an IEEE-488 interface and a number of expanders connected in star configuration.

The relatively low prices of personal computers, typically used as controllers, are a favorable factor for such hierarchical organization of measurement systems. Another advantage of large hierarchical measurement systems over their non-hierarchical counterparts is their capability to operate faster. Message transfer within subsystems, in which interface buses are short, can be performed with higher speeds, which steps up the operation of the system as a whole; moreover, transmission in hierarchical systems is not slowed down by serial control signal reading from interface secondary buses.

8.3.3 Distributed Measurement Systems with IEEE-488 Interface

The linear (geometrical) extent of an IEEE-488 (IEC-625) measurement system is limited by the interface cable length, which cannot exceed 20m. Virtually every method of major enlargement of IEEE-488 device separation involves replacing parallel signals with serial signals. As a result of applying such a method, a measurement system with parallel interface becomes a half-parallel, half-serial hybrid. Message transfer rates, the most important parameter of measurement systems with parallel interface, usually deteriorate. A measurement system in which devices can be from 20m to thousands of kilometers apart is referred to as a distributed measurement system. A general block diagram of a distributed measurement system with an IEEE-488 interface, comprising a system center and one or more remote units, is shown in Figure 8.12.

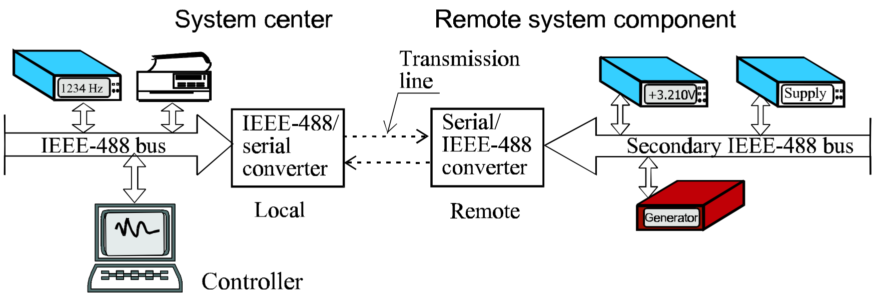

Figure 8.12 Distributed measurement system with an IEEE-488 interface.

The transmission line connecting the remote components of the measurement system depicted in Figure 8.12 can be either wired or wireless (radio channel). Measurement systems with wireless transmission are the subject of Chapter 7, and will not be discussed in detail here. Distributed measurement systems with an IEEE-488 interface and wired transmission can be grouped into three categories, by the type of transmission line and its corresponding converter of IEEE-488 interface signals:

- Measurement systems with extenders used as converters, and electric or fiber optic cable used as measurement line (e.g., IOtech's Extender488 with an RS-422 electric or fiber optic line [6]);
- Measurement systems with RS232/IEEE-488 converters and transmission via telephone network;
- Measurement systems using network interface boards and network cabling.

Measurement Systems with Extenders

An extender is a special IEEE-488 device that extends the length of the interface bus in a measurement system to as much as a few kilometers. Rather than simply sending and receiving signals from the 24 lines in the IEEE-488 interface bus, an extender first of all converts the signals from parallel to serial words (outgoing signals) and vice versa (incoming signals). Similar to an expander, an extender should be "transparent" to signals transmitted over the interface bus (i.e., should not affect their transmission). The block diagram of a measurement system with extenders is shown in Figure 8.13. Fourteen IEEE-488 devices can be connected to each segment (primary or secondary) of the interface bus. Therefore, in addition to allowing device separation to exceed the standard limit of 20m, extenders increase the maximum number of devices in the system.

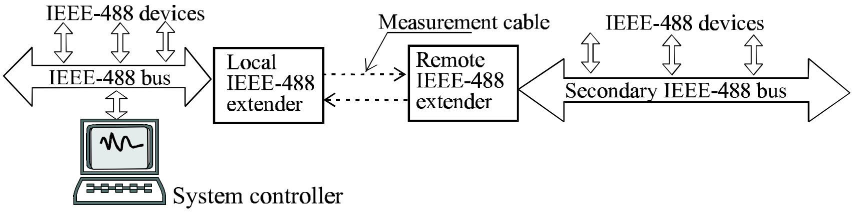

Figure 8.13 Distributed measurement system with IEEE-488 extenders.

When a fiberoptic cable is used as the transmission line in the measurement system, the length of the line can be up to 2 km, with the transfer rates being similar to those in a system without extenders. Examples of extenders fit for fiber-optic cable are National Instruments' GPIB-140 series extenders, allowing transfer rates up to 1.1 MBps in full handshake mode, and up to 2.8 MBps in transfers using HS488 [5]. A pair of GPIB-140A/2 or GPIB-140A extenders used in a measurement system stretches out its maximum length to 2 km or 1 km, respectively. The actual length can be shorter, depending on the type of fiber-optic cable used. Another advantage of transmission through fiber-optic cable is its interference immunity. With a pair of GPIB-130 extenders (manufactured by NI), the IEEE-488 bus can be extended to 300m, with parallel message transfer maintained. Using GPIB-130 extenders involves transmission through an expensive multiwire electric cable, which should allow transfer rates up to 900 KBps.

Measurement Systems with an RS232/IEEE-488 Converter

A distributed measurement system with a converter and modem-based message transfer via telephone network is depicted in Figure 8.14.

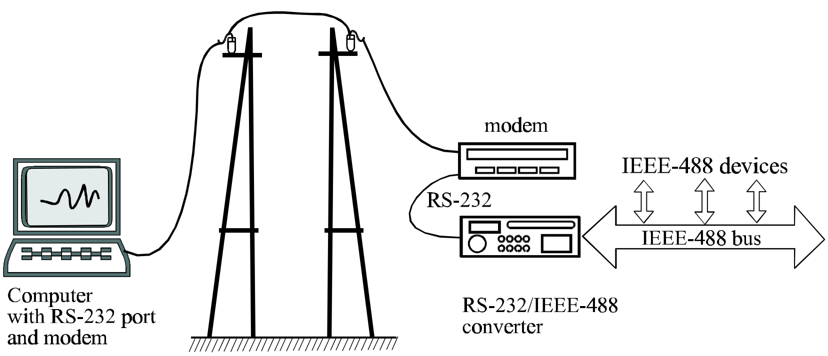

Figure 8.14 Distributed measurement system with an RS-232/IEEE-488 converter and modem-based message transfer via telephone network.

A peculiarity of this system is that the controller is separated in space from the rest of the system. No expensive IEEE-488 interface boards are required to be installed in the computer used as the controller of this type of system. An RS-232 port, an RS-232 interface driver, and a modem board are necessary for modem-based message transfer and are standard computer fittings. When only one device is connected to the interface bus in this type of system, a better solution than that shown in Figure 8.14 is to fit this device with an RS-232 interface and set up a measurement system with serial interface only. A variety of measurement systems with RS-232/IEEE-488 converters use primary and secondary segments of interface bus, with the primary bus situated at the controller, and the secondary bus connected to the primary segment by means of RS-232/IEEE-488 converters, modems, and telephone network.

Measurement Systems in Computer Network

There is an important trend in the evolution of distributed measurement systems toward computer network–based interconnection of instruments and control units. A computer operating in a network needs a set of TCP/IP network protocols, principally designed for wide area networks (WAN), but also used in some local area networks (LAN). More details about such measurement systems are in Chapter 10. A computer with implemented TCP/IP protocol can be used as a controller of a distributed measurement system. IEEE-488 devices can be connected to the LAN through a converter, such as a GPIB-ENET converter manufactured by NI [5], or an AD007 converter manufactured by Tektronix [6], as shown in Figure 8.15.

Ethernet allows serial message transfer between networked devices (see Chapter 10). Messages are transferred in packets, up to 1 KB each. Ethernet is capable of spanning distances up to 1 km, with maximum data rates ranging from 10 to 100 Mbps [7, 8]. However, a computer network–based measurement system requires special software, which is not yet available on the market.

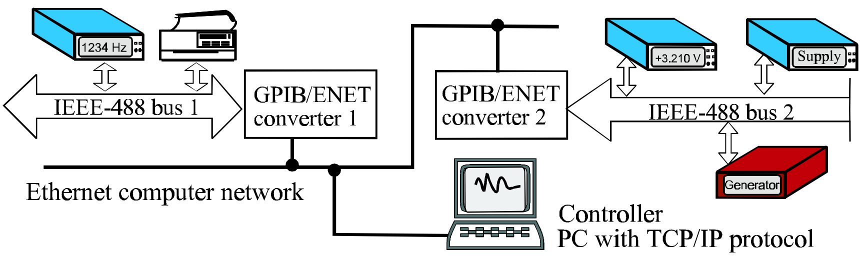

Figure 8.15 LAN-based distributed measurement system with an IEEE-488 interface and GPIB/ENET converters.

8.4 IEEE-488 INTERFACE FUNCTION STATE DIAGRAMS

8.4.1 Execution of Interface Functions

The operation of an IEEE-488 interface system comprises programmed operation of individual devices in the system as well as their program interworkings. An electronic circuit executing an interface function can be regarded as a finite state automaton. A finite state automaton (finite state machine) is represented graphically by a state diagram, with circles corresponding to states. An automaton can be in only one state at a time. Its passing from one state to another is governed by control signals, represented by arrows in the state diagram. An automaton is controlled by messages, which can be remote or local, and must respect some time limitations, as specified in Table 8.7 [4].

Table 8.7

Time Limitations in Interface Function Execution
(Taken into Account in Interface Function State Diagrams)

Time Symbol	*Interface Function*	*Description*	*Value*
T_1	SH	Settling time for signal on DIO line	≥ 2 μs
t_2	SH, AH, T, L	Time for interface function automaton to respond to ATN	≤ 200 ns
T_3	AH	Time for automaton to receive command (device designer-defined)	> 0
t_4	T, TE, L, LE, RL, C	Time for automaton to respond to IFC or REN	< 100 μs
t_5	PP	Time for automaton to respond to ATN $\wedge$ EOI = IDY	≤ 200 ns
T_6	C	Time for parallel poll	≥ 2 μs
T_7	C	Time for current talker to receive ATN instruction	≥ 500 ns
T_8	C	IFC or REN signal duration	> 100 μs
T_9	C	Delay after command on EOI	≥ 1.5 μs

In the case of some interface functions, the operation of the corresponding automaton is conditioned by active states of other interface functions as well, as shown in Figure 8.16.

Interface functions are executed by microprocessors. Output signals generated by the device electronic circuit (automaton) executing an interface function are either interface messages sent to the system, or local messages used for internal device control. Interface function state diagrams are presented and discussed in the following paragraphs. The Acceptor Handshake and Listener functions are discussed in detail. Special attention is given to the Controller function.

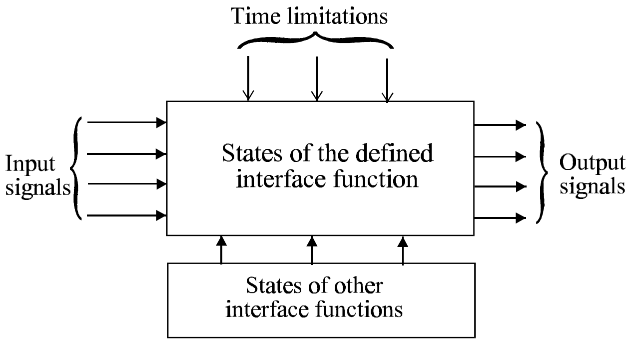

Figure 8.16 Graphic definition of the interface function.

Each state diagram is accompanied by a list of states of the respective function. Signals activating state transition are specified as well. These signals include input signals, remote messages, local messages, and states of other interface functions. Only the basic version of the Listener and Talker functions are discussed, but not the Extended Listener and Extended Talker functions, which are rarely used. The interface function state diagrams presented below are also described in national standard specifications.

8.4.2 Acceptor Handshake Function

The Acceptor Handshake (AH) function synchronizes the process of reading each multiline message byte with the process of its sending. The automaton executing the AH function is defined by the state diagram shown in Figure 8.17.

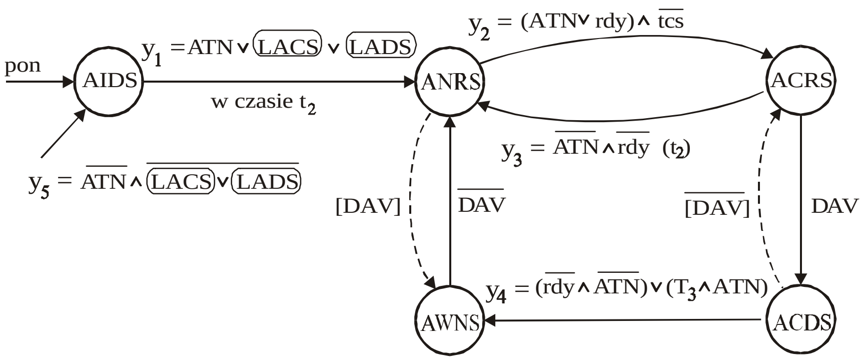

Figure 8.17 Acceptor Handshake function state diagram; ∨ stands for logical sum (OR); ∧ denotes logical product (AND); $\overline{\text{DAV}}$ means negation of the item under the line; dashed line is used to represent optional signals, which are not necessary for automaton functioning, but can facilitate automaton construction.

The AH function automaton has the following five states:

- Acceptor IDle State (AIDS);
- Acceptor Not Ready State (ANRS);
- ACceptor Ready State (ACRS);
- ACcept Data State (ACDS);
- Acceptor Wait for New Cycle State (AWNS).

Output signals generated by the electronic circuit (automaton) executing the AH function are remote messages RFD and DAC, with state-dependent values listed in Table 8.8.

Table 8.8

Interface Messages Sent by the AH Function Circuits

State of AH Function	*Remote Message Type/Value*	
	RFD	*DAC*
AIDS	(T)	(T)
ANRS	F	F
ACRS	(T)	F
ACDS	F	F
AWNS	F	(T)

Message values: T: active true (T = 1), F: active false (F = 0), (T): passive true (sent 1, received 1 or 0), (F): passive false (sent 0, received 0 or 1).

The RFD and DAC messages are sent over lines NRFD and NDAC, respectively. Each signal transmitted over the NRFD line or over the NDAC line is the logical product (i.e., result of AND operation) of the corresponding signals coming from all the addressed listeners in the interface system. Consequently, the logical state of the line is 0 only when all the addressed listeners send 0 signals. For example, for the NRFD line to be in logical state 0, all the addressed listeners must send NRFD = 0 signals (corresponding to high voltage level by the adopted negative logic convention). The signals must be passive true RFD messages [(RFD = (T) = 1)], according to the message value convention discussed in Section 8.2.1. As a result of the AND operation performed on the signals sent on the NFRD line, although a listener sends message RFD = (T) = 1, the line signal will be asserted (NRFD = 1) if at least one of the listeners sends message RFD = F = 0.

The operation of the Acceptor Handshake automaton is determined by the following factors:

- States of the Listener function: Listener ADdressed State (LADS) and Listener ACtive State (LACS);
- Remote messages: Attention to message type (ATN) and Data Valid (DAV);
- Local messages: "power-on" (pon), "ready for next message" (rdy), and "take control synchronously" (tcs).

At power-on, local message pon is sent to set the AH automaton to the Acceptor Idle State (AIDS), in which the automaton takes no part in handshake. In this state, messages RFD = (T) and DAC = (T) are sent on lines NRFD and NDAC, respectively. Signal y_1, defined by function $y_1 = \mathrm{ATN} \vee \mathrm{LACS} \vee \mathrm{LADS} = 1$, causes the automaton to quit the Acceptor Idle State and pass to the Acceptor Not Ready State (ANRS). The transition must be completed within $t_2 \leq 200$ ns. Signal y_1 represents the logical sum (alternative) of the following events: the ATN line is asserted (ATN = 1, indicating that instructions are transmitted), or the Listener function is in the Listener Active State (LACS), or the Listener function is in the Listener Addressed State (LADS). In the Acceptor Not Ready State, messages RFD = F and DAC = F are sent by the listener. Signal $y_2 = (\mathrm{ATN} \vee \mathrm{rdy}) \wedge \overline{\mathrm{tcs}} = 1$ makes the automaton quit the Acceptor Not Ready State and pass to the Acceptor Ready State (ACRS). The y_2 signal corresponds to a situation when synchronous control takeover is not requested ($\overline{\mathrm{tcs}} = 1$), and at the same time, either instructions are transmitted over the DIO lines (remote message ATN = 1), or the listener is ready to accept the next byte (local message rdy = 1). In the Acceptor Ready State, messages RFD = (T) and DAC = F are sent by the listener, which is ready to accept a message available on the DIO lines. If the Data Valid signal is asserted (DAV = 1), the automaton quits the Acceptor Ready State and passes to the Accept Data State (ACDS).

From the Acceptor Ready State the automaton can also return to the Acceptor Not Ready State, in response to signal $y_3 = \overline{\mathrm{ATN} \vee \mathrm{rdy}}$; the transition must be completed within time t_2. In the Accept Data State, messages RFD = F and DAC = F are sent by the listener. Having accepted a data byte, the automaton quits the Accept Data State and passes to the Acceptor Wait for New Cycle State (AWNS) in response to signal $y_4 = (\overline{\mathrm{ATN}} \wedge \overline{\mathrm{rdy}}) \vee (\mathrm{ATN} \wedge T_3) = 1$. Signal $y_4 = 1$ corresponds to one of the following two situations: either data is transferred (ATN = 0), but the listener is not ready to accept new data ($\overline{\mathrm{rdy}} = 1$); or instructions are transferred (ATN = 1) but time T_3, necessary for signal $y_4 = 1$ to be settled, has not yet elapsed. In the Acceptor Wait for New Cycle State, the listener sends message RFD = F to indicate that it is not ready to accept new data, and message DAC = (T) to indicate that it has accepted the current data. Transition from the Acceptor Wait for New Cycle State to the Acceptor Not Ready State takes place as a result of unasserting the asserted DAV signal (DAV = 0). Note that direct return to the Acceptor Idle State is possible from any other state through signal $y_5 = 1$, which corresponds to the situation when the Listener function is neither in Listener

Active State (LACS) nor in Listener Addressed State (LADS) (the listener is not addressed), and at the same time, the ATN signal is unasserted (ATN = 0) to indicate data mode.

8.4.3 Listener Function

The Listener (L) function allows an IEEE-488 device to accept data (to perform its device functions) or instructions addressed to its interface functions (other than Listener). The automaton executing the L function is defined by the state diagram shown in Figure 8.18.

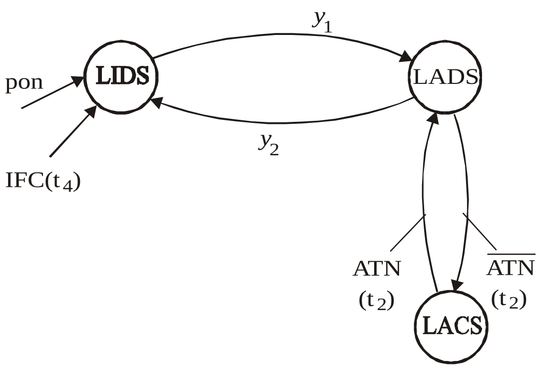

Figure 8.18 Listener function state diagram.

The L function automaton has the following three states:

- Listener IDle State (LIDS);
- Listener ADdressed State (LADS);
- Listener ACtive State (LACS).

The operation of the L function automaton is determined by the following factors:

- The Accept Data State (ACDS) of the Acceptor Handshake function;
- The Controller Active State (CACS) of the Controller function;
- Remote messages: Interface Clear (IFC), Attention to message type (ATN); Unlisten (UNL), My Listen Address (MLA), and My Talk Address (MTA);
- Signal $y_1 = (\text{MLA} \wedge \text{ACDS}) \vee \text{lon} \vee (\text{ltn} \wedge \text{CACS})$;
- Signal $y_2 = (\text{UNL} \wedge \text{ACDS}) \vee (\text{lun} \wedge \text{CACS}) \vee (\text{MTA} \wedge \text{ACDS})$;
- Local messages: “power-on” (pon), “listen only” (lon), “listen” (ltn), and “local unlisten” (lun);
- Time limitations: time for response to ATN message ($t_2 \leq 200$ ns), and time for response to IFC message ($t_4 \leq 100$ μs).

Execution of the Listener function consists of receiving multiline messages by the corresponding circuit (automaton) in a device with Listener capability. Since no remote messages are sent by the Listener circuit, no message table is defined for this interface function.

The L function automaton is set to the Listener Idle State (LIDS) in two situations: at power-on, or in response to the Interface Clear message. In the Listener Idle State, the device can receive neither data nor addressed commands. Activated by signal $y_1 = 1$, the automaton quits the Listener Idle State and passes to the Listener Addressed State (LADS). Signal y_1 is the logical sum of the following events: the MLA address message is issued and the Acceptor Handshake function is in Accept Data State, or local message “listen only” (lon) is sent, or local message “listen” (ltn) is sent and the Controller interface function is in the Controller Active State (CACS). In the Listener Addressed State, the listener is ready for message transfer, but takes no part in it yet. No remote messages are sent by the Listener circuit.

Signal $y_2 = 1$ unaddresses the listener, causing the automaton to quit the Listener Addressed State and return to the Listener Idle State. Unasserting the asserted ATN signal (ATN = 0) (i.e., switching to the data mode) causes the automaton to pass from the Listener Addressed State to the Listener Active State (LACS). In the Listener Active State, the listener receives data. When the ATN signal is asserted again (ATN = 1), the automaton returns to the Listener Addressed State.

8.4.4 Source Handshake Function

The Source Handshake (SH) function synchronizes the process of sending each multiline message byte with the process of its reading. The automaton executing the SH function is defined by the state diagram shown in Figure 8.19.

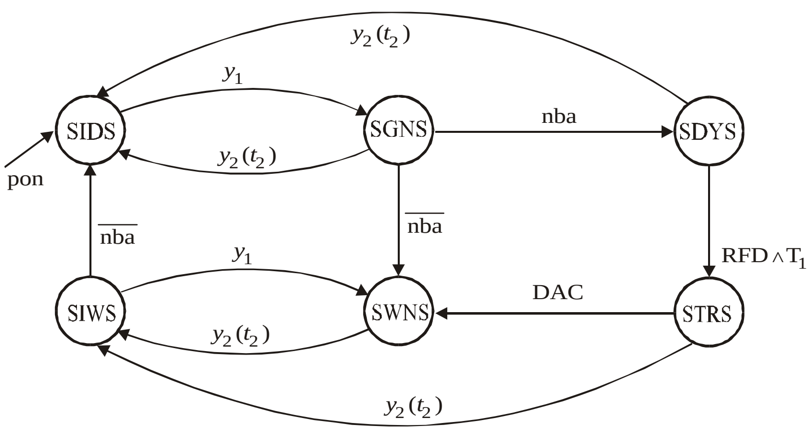

Figure 8.19 Source Handshake function state diagram.

The SH function automaton has the following six states:

- Source IDle State (SIDS);
- Source GeNerate State (SGNS);
- Source DelaY State (SDYS);
- Source Transfer State (STRS);
- Source Wait for New Cycle State (SWNS);
- Source Idle Wait State (SIWS).

The electronic circuit (automaton) executing the SH function generates remote message DAV, with state-dependent values listed in Table 8.9.

The operation of the SH function automaton is determined by the following factors:

- States of the Talker interface function: the Talker Active State (TACS) and the Serial Poll Active State (SPAS);
- States of the Controller interface function: the Controller Active State (CACS) and the Controller Transfer State (CTRS);
- Remote messages: Attention to message type (ATN), Data Accepted (DAC), and Ready for Data (RFD);
- Signal y_1 = TACS $\vee$ SPAS $\vee$ CACS;
- Signal $y_2 = [\mathrm{ATN} \wedge (\overline{\mathrm{CACS} \vee \mathrm{CTRS}})] \vee [\overline{\mathrm{ATN}} \wedge (\overline{\mathrm{TACS} \vee \mathrm{SPAS}})]$;
- Local messages: "power-on" (pon) and "new byte available" (nba);
- Time limitations: setting time for signal on DIO lines ($T_1 \geq 2$ μs), and time for response to ATN message ($t_2 \leq 200$ ns).

Table 8.9

Interface Messages Sent by the SH Function Circuits

State of SH Function	*DAV Message Value*
SIDS	(F)
SGNS	F
SDYS	F
STRS	T
SWNS	T or F
SIWS	(F)

8.4.5 Talker Function

The Talker (T) interface function is performed by an IEEE-488 device with Talker capability to send messages or to send a status byte in serial poll. Only one device in the system can act as a talker (i.e., have active Talker function) at a time. The T function is activated either manually or remotely, through talk-addressing.

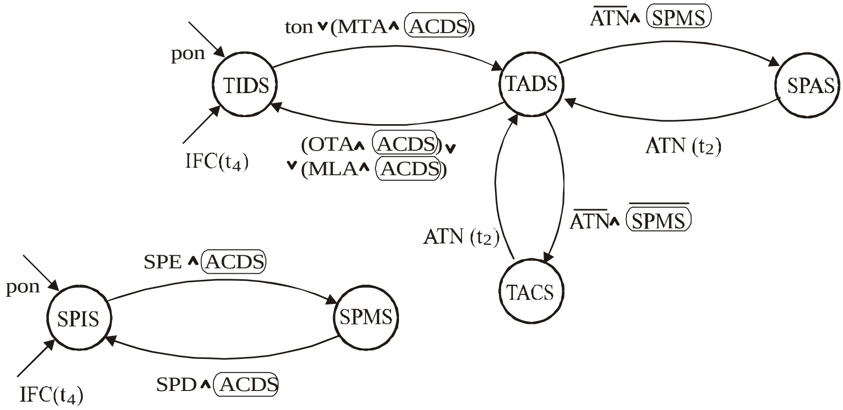

Figure 8.20 Talker function state diagram.

The T function automaton has the following six states, as shown in Figure 8.20:

- Talker IDle State (TIDS);
- Talker ADdressed State (TADS);
- Talker Active State (TACS);
- Serial Poll Active State (SPAS);
- Serial Poll Idle State (SPIS);
- Serial Poll Mode State (SPMS).

Remote messages generated by the automaton executing the T function, and their state-dependent values, are listed in Table 8.10.

Table 8.10

Interface Messages Sent by the T Function Circuits

State of T Function	*Remote Message Type/Value*			*Remarks*
	Group Message	*END*	*RQS*	
TIDS	(NUL)	(F)	(F)	—
TADS	(NUL)	(F)	(F)	—
TACS	DAB or EOS	T or F	(F)	—
SPAS	STB	T or F	F	APRS inactive
SPAS	STB	T or F	T	APRS inactive

The operation of the T function automaton is determined by the following factors:

- The Accept Data State (ACDS) of the Acceptor Handshake interface function;
- Remote messages: Attention to message type (ATN), Interface Clear (IFC), Serial Poll Disable (SPD), Serial Poll Enable (SPE), My Listen Address (MLA), and My Talk Address (MTA);
- Local messages: “power-on” (pon), “talk only” (ton), and “talker active” (tac);
- Time limitations: time for response to ATN message ($t_2 \le 200$ ns) and time for response to IFC or REN message ($t_4 < 100$ μs).

8.4.6 Service Request Function

The Service Request (SR) function allows a device to request service by sending the SRQ message. Execution of this interface function consists of asserting interrupts in the microprocessor system. The SR function automaton has the following three states, as shown in Figure 8.21:

- Negative Poll Response State (NPRS);
- Service ReQuest State (SRQS);
- Affirmative Poll Response State (APRS).

The operation of the SR function automaton is determined by the following factors:

- The Serial Poll Active State (SPAS) of the Talker function;
- Local messages: “power-on” (pon) and “request service” (rsv).

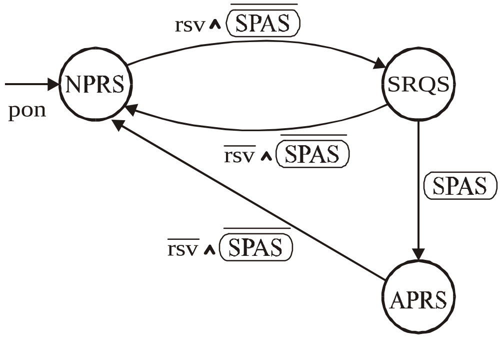

Figure 8.21 Service Request function state diagram.

The SR function automaton generates remote message SRQ, with state-dependent values listed in Table 8.11.

Table 8.11

Interface Messages Sent by the SR Function Circuits

State of SR Function	*SRQ Message Value*
NPRS	(F)
SRQS	T
APRS	(F)

8.4.7 Remote/Local Function

The Remote/Local (RL) function switches between local and remote control of settings of all devices in an IEEE-488 system. Devices (e.g., an oscilloscope and a generator) can be set up either from their front-panel controls (local mode) or by the measurement system software (remote mode).

The RL function automaton has the following four states, as shown in Figure 8.22:

- LOCal State (LOCS);
- REMote State (REMS);
- Local With Lockout State (LWLS);
- Remote With Lockout State (RWLS).

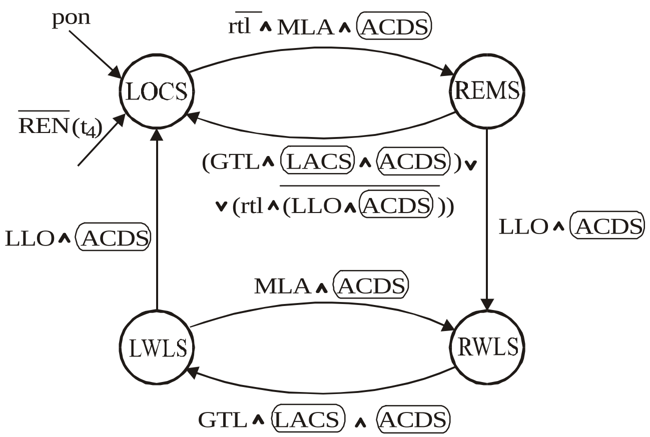

Figure 8.22 Remote/Local function state diagram.

The operation of the RL function automaton is determined by the following factors:

- The Accept Data State (ACDS) of the Acceptor Handshake function;
- The Listener Addressed State (LADS) of the Listener function;

- Remote messages: Remote Enable (REN), Local Lock-Out (LLO), My Listen Address (MLA), and Go To Local (GTL);
- Local messages: “power-on” (pon) and “return to local” (rtl);
- Time for response to IFC or REN signal ($t_4 < 100$ μs).

No remote messages are sent by the RL automaton to the interface bus.

8.4.8 Device Clear Function

The Device Clear (DC) function clears devices in the system (i.e., resets them to their initial state). The DC function automaton has the following two states, as shown in Figure 8.23(a):

- Device Clear Idle State (DCIS);
- Device Clear Active State (DCAS).

The operation of the DC function automaton is determined by the following factors:

- The Accept Data State (ACDS) of the Acceptor Handshake function;
- The Listener Addressed State (LADS) of the Listener function;
- Remote messages: Device Clear (DCL) and Selective Device Clear (SDC);
- Local message “device clear” (clr).

No remote messages are sent by the DC automaton to the interface bus.

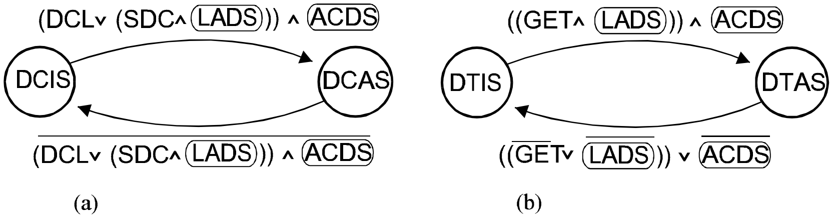

Figure 8.23 (a) Device Clear function, and (b) and Device Trigger function state diagrams.

8.4.9 Device Trigger Function

The Device Trigger (DT) function allows a device to be triggered remotely (e.g., to start measurement, to generate signal, or to perform other device functions). Only addressed listeners can be triggered by the DT function. The DT function automaton has the following two states, as shown in Figure 8.23(b):

- Device Trigger Idle State (DTIS);
- Device Trigger Active State (DCAS).

The operation of the DT function automaton is determined by the following factors:

- The Accept Data State (ACDS) of the Acceptor Handshake function;
- The Listener Addressed State (LADS) of the Listener function;
- Remote message Group Execute Trigger (GET);
- Local message "trigger device" (trg).

No remote messages are sent by the DT automaton to the interface bus.

8.4.10 Parallel Poll Function

The automaton executing the Parallel Poll (PP) function has the following states, as shown in Figure 8.24:

- Parallel Poll Idle State (PPIS);
- Parallel Poll Standby State (PPSS);
- Parallel Poll Active State (PPAS);
- Parallel Poll Unaddressed to Configure State (PUCS);
- Parallel Poll Addressed to Configure State (PACS).

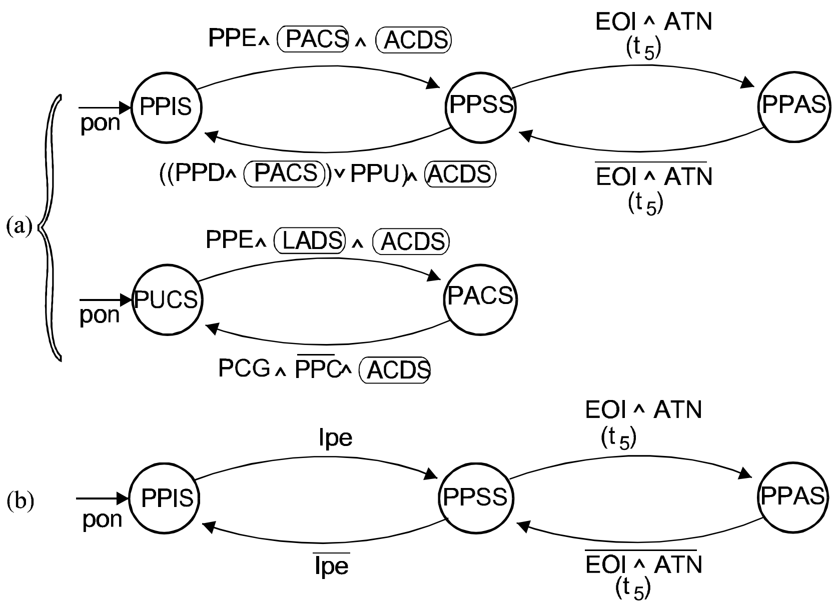

Figure 8.24 Parallel Poll function state diagram: (a) remote configuration, and (b) local configuration.

The PP function automaton generates remote message PPR, with state-dependent values listed in Table 8.12.

Table 8.12

Interface Messages Sent by the PP Function Circuits

State of PP Function	*PPR Message Value*	*Remarks*
PPIS	(F)	—
PPSS	(F)	—
PPAS	T	ist = S
PPAS	(F)	ist ≠ S

The operation of the PP function automaton is determined by the following factors:

- The Accept Data State (ACDS) of the Acceptor Handshake function;
- The Listener Addressed State (LADS) of the Listener function;
- Remote messages: Attention to message type (ATN), message sent over the End Or Identify (EOI) line, Parallel Poll Enable (PPE), Parallel Poll Disable (PPD), Parallel Poll Configure (PPC), Parallel Poll Unconfigure (PPU), Primary Command Group (PCG), Parallel Poll Response (PPR), and Identify (IDY);
- Local messages: “power-on” (pon), “local poll enable” (lpe), and “individual status” (ist);
- Time for response to signal ATN $\wedge$ EOI = IDY ($t_5 \leq 200$ ns).

8.4.11 Controller Function

A device with the Controller (Contr) capability controls the system by sending messages over interface management lines ATN, IFC, REN, and EOI, and checking the state of the SRQ interrupt line. The Contr function is also used for sending addresses over the data bus, and for device identification in parallel poll. At least one device in an IEEE-488 system must have the Contr capability. If more devices in a system have the Contr capability, two types of controllers are distinguished: system controller and active controller (or controller in charge). While any of the devices with the Contr capability can act as the active controller, only one designated device is the system controller. Only one controller can be active (i.e., manage the system) at a time. The automaton of the active controller can take any state except the Controller Idle State (CIDS). The system controller remains in the System Control Active State (SACS) throughout the system operation, from the moment the system is powered on. The system controller has control over the IFC and REN lines, and thus can clear device interface circuits or switch between remote and local device control, even when it is not the active controller.

State subsets (SIIS, SINS, SIAS) and (SRIS, SRNS, SRAS) are mutually exclusive. Usually only one device in a system has the Contr capability, and thus acts as both the system controller and the controller in charge. For convenience, the Contr function state diagram can be split into two independent parts, corresponding to two subfunctions: System Controller (SC), as shown in Figure 8.25, and Active Controller (AC). This separation is arbitrary, and its only objective is to facilitate the explanation of the C function execution [7]. The names and symbols used for the subfunctions are not included in the standard.

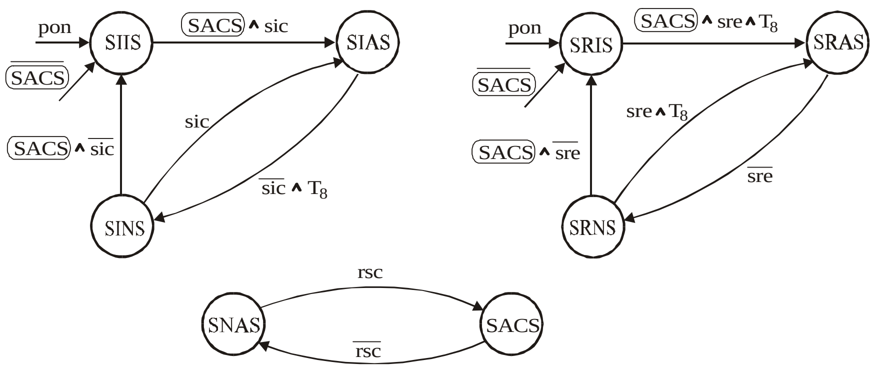

Figure 8.25 System Controller subfunction state diagram.

The SC subfunction automaton handles the IFC and REN lines, as shown in Table 8.13. All other control tasks are performed by the AC subfunction automaton.

Table 8.13

Interface Messages Sent by the SC Subfunction Circuits

State of SC Subfunction	*IFC Message Value*	*REN Message Value*
SIIS	(F)	Not defined
SINS	F	Not defined
SIAS	T	Not defined
SRIS	Not defined	(F)
SRNS	Not defined	F
SRAS	Not defined	T

The SC subfunction automaton has the following eight states, as shown in Figure 8.25:

- System Control Not Active State (SNAS);
- System Control Active State (SACS);
- System Control Remote Enable Idle State (SRIS);
- System Control Remote Enable Not Active State (SRNS);
- System Control Remote Enable Active State (SRAS);
- System Control Interface Clear Idle State (SIIS);
- System Control Interface Clear Not Active State (SINS);
- System Control Interface Clear Active State (SIAS).

Transitions between the last six of the SC subfunction states listed above are conditioned by the System Control Active State (SACS) of this very subfunction. Apart from SACS, transitions between the SC function states are determined by the following factors:

- Uniline remote messages: Interface Clear (IFC) and Remote Enable (REN);
- Local messages: “power-on” (pon), “request system control” (rsc), “send interface clear” (sic), and “send remote enable” (sre).

Symbol T_8 in the state diagram denotes the IFC or REN signal hold time. True IFC message (IFC = T = 1) sets the following interface functions to idle state: Talker (TIDS), Listener (LIDS), and Active Controller subfunction (CIDS). True REN message (REN = T = 1) enables remote control of device settings by means of the Remote/Local function.

The AC subfunction automaton has the following eleven states, as shown in Figure 8.26:

- Controller IDle State (CIDS);
- Controller ADdressed State (CADS);
- Controller Transfer State (CTRS);
- Controller Active State (CACS);
- Controller Standby State (CSBS);
- Controller Parallel Poll Wait State (CPWS);
- Controller Active Wait State (CAWS);
- Controller Synchronous Wait State (CSWS);
- Controller Parallel Poll State (CPPS);
- Controller Service Not Requested State (CSNS);
- Controller Service Requested State (CSRS).

The operation of the AC function automaton is determined by the following factors:

- The Accept Data State (ACDS) of the Acceptor Handshake function;
- The Acceptor Not Ready State (ANRS) of the Acceptor Handshake function;

- The Source Transfer State (STRS) of the Source Handshake function;
- The Talker Addressed State (TADS) of the Talker function;
- Remote messages: Attention to message type (ATN), Interface Clear (IFC), and Take Control (TCT);
- Local messages: "power-on" (pon), "go to standby" (gts), "request parallel poll" (rpp), "take control asynchronously" (tca), and "take control synchronously" (tcs);
- Time limitations: time for response to IFC or REN signal (t_4 < 100 μs), time for parallel poll ($T_5 \geq 2$ μs), and time to receive ATN signal ($T_7 \geq 500$ ns).

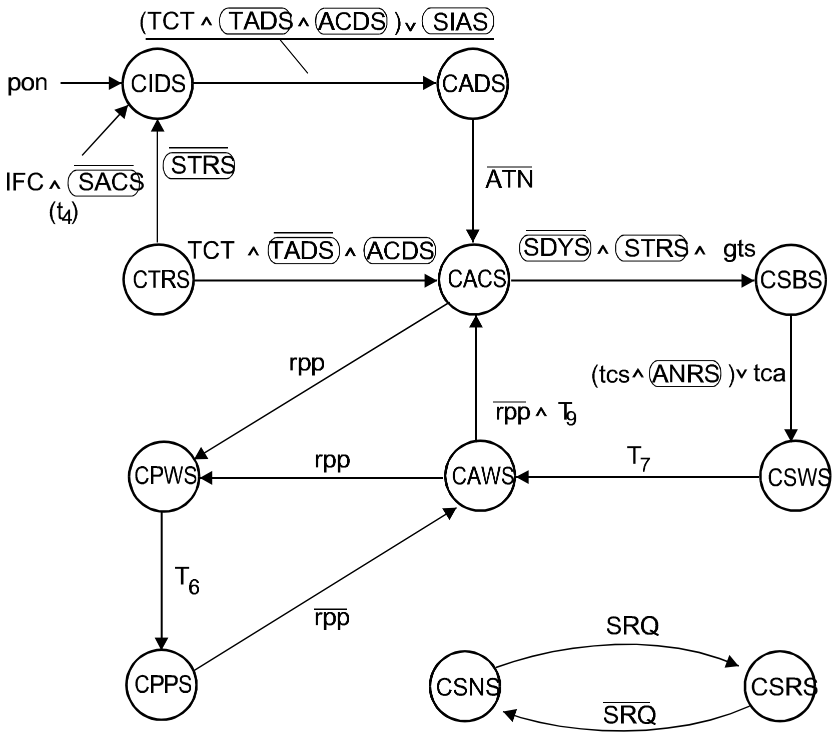

Figure 8.26 Active Controller subfunction state diagram.

The AC subfunction is set to the Controller Idle State (CIDS) at power on or after interface clear. No control task is performed by the automaton in this state (remote messages are false). Transition to the Controller Addressed State (CADS) takes place either as a result of the Take Control (TCT) command, or when the SC subfunction is in the System Control Interface Clear Active State (SIAS). In the Controller Addressed State, the automaton performs no control tasks, but the controller is active (in charge) and ready to control the system.

Table 8.14

Interface Messages Sent by the AC Subfunction Circuits

State of AC Function	*Remote Message Type/Value*		
	ATN	*IDY*	*Multiline*
CIDS	(F)	(F)	(NUL)
CADS	(F)	(F)	(NUL)
CACS	T	F	Any interface message can be sent
CPWS	T	T	(NUL)
CPPS	T	T	(NUL)
CSBS	F	(F)	(NUL)
CSWS	T	F or (F)	TCT
CAWS	T	F	(NUL)
CTRS	T	F	TCT

The automaton passes to the Controller Active State (CACS) in response to message ATN = F, generated by the automaton itself. In the Controller Active State, the AC subfunction automaton can send addresses, universal commands, addressed commands, and secondary commands, as described in Table 8.14.

True ATN remote message is sent in this state. The Controller Parallel Poll Wait State (CPWS) and the Controller Parallel Poll State (CPPS) handle a parallel poll. The Controller Standby State (CSBS), the Controller Synchronous Wait State (CSWS), the Controller Active Wait State (CAWS), and the Controller Transfer State (CTRS) allow collision-free state transition. The Controller Service Requested State (CSRS) and the Controller Service Not Requested State (CSNS) allow interrupt (service request) handling.

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Chapter 9

Crate and Modular Measurement Systems

9.1 CAMAC SYSTEM

9.1.1 Crate and Modular Measurement Systems: An Overview

The highest measurement data rates are provided by crate and modular measurement systems with parallel interface. In crate systems, instruments are arranged in crates, also referred to as chassis or mainframes, containing measurement system functional modules, as shown in Figure 9.1. Crates are mounted in racks, a short distance (approximately 30 to 50 cm) from one another, which favors low transmission line capacity and affords high transfer rates. Two types of crate measurement systems are in widespread use: Computer Aided Measurement And Control (CAMAC) systems, which are rather out of date now, and VXI systems (VME eXtensions for Instrumentation), the former's junior by 20 years [1, 2]. Although VXI systems have been supplanting their CAMAC counterparts for about 10 years, CAMAC crates, functional blocks, and mechanical constructions are still manufactured and used.

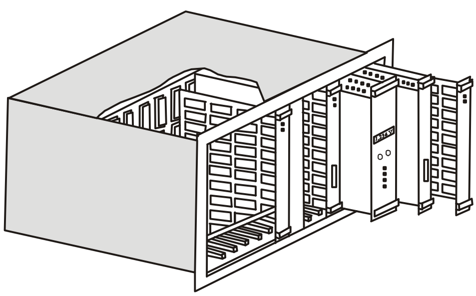

Figure 9.1 A crate with measurement system functional modules.

VXI, another standard of crate measurement system using parallel interface, is a specialist system composed of modules that are designed exclusively for operation in this type of system. Modules are arranged in a chassis and are mounted in racks. Due to these features, the VXI interface system allows very high rates (up to 40 MBps) of measurement data transfer. VXI measurement systems are used in military technology and nuclear engineering, fields in which data processing rate is crucial for security.

A new standard of measurement system with parallel interface is PXI, a modular system based on PCI (the key PC bus). A key difference between crate (CAMAC, VXI) and modular (PXI) systems lies in the flexibility of module operation. Modules of a crate system can operate only in the system they have been designed for. PXI modules can be either inserted in a mainframe and used as PXI measurement system devices, or embedded in a computer to act, together with a graphical software, as stand-alone virtual instruments [1–3].

A cheap method of building a computer measurement system with parallel transmission is based on using a printer interface, such as Centronics or its replacement IEEE-1284. The port and the transmission driver for this type of interface are installed in almost every PC. However, the instruments used in a measurement system with a printer interface must also have a Centronics (or IEEE-1284) port, which is rare. Only a few higher-class digital instruments have an IEEE-1284 (or Centronics) port in their standard fittings. The Centronics interface is principally designed for unidirectional data transfer (from computer to printer or other data receiver), which is the main reason for its limited usability. Transfer in the opposite direction (to the computer) is possible, but only in 4-bit words. Bidirectional data transfer in 8-bit words is allowed by the IEEE-1284 interface. However, very special software is necessary for the printer interface to support such transmission.

9.1.2 CAMAC System Organization

Developed at the end of the 1960s to allow fast data processing and device control in nuclear engineering, the CAMAC system specification was subsequently adopted as a national standard in many countries. The specification covers the organization of the system as well as its electric and mechanical parameters. The basic structural block of a CAMAC system is a crate, which is an autonomous unit equivalent to a measurement system, with separate digital instruments and other electronic devices. A crate contains printed circuit boards (with connectors) referred to as modules, and has standardized dimensions: length equal to 30 cm, height equal to 20 cm, and width equal to a multiple of 17.2 cm, as shown in Figure 9.2. Each module contains a circuit or a device (e.g., an ADC or a display). A CAMAC crate can comprise up to 25 modules, each 17.2 cm wide, or a correspondingly lower number of wider modules. Two modules are necessary in each crate: a control module (referred to as crate controller), and a power supply module. CAMAC functional modules are of no use beyond the crate, where they would be deprived of both power supply and controller.

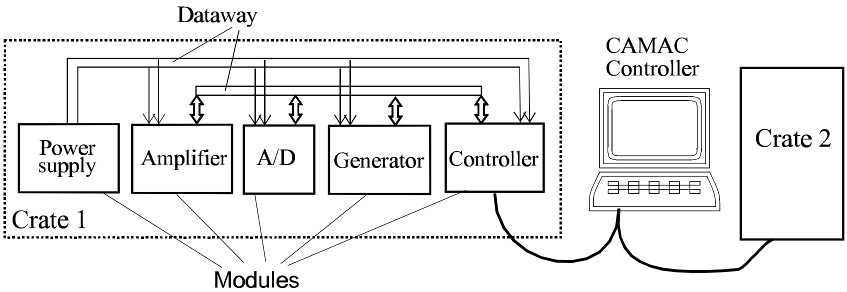

Figure 9.2 Organization of a CAMAC measurement system.

Input/output connectors, indicators, switches, and controls are accessible from the module front panel; connector pins at the rear allow the module to be plugged into the crate backplane, referred to as a dataway. Providing the corresponding sockets, the dataway comprises both power supply and signal lines. Modules are inserted into the crate on special slides. A CAMAC system can consist of a single crate or a number of crates; in practice, the number of crates is usually larger than one. Crates are connected by their controllers. A number of connected crates form a branch. The controller of a single crate, or a number of crates, is interfaced to the controller of the CAMAC system. Data in the system is processed in 24-bit words, at rates up to 1 million words per second. Due to a separation of the data bus from the address and control buses, control of a CAMAC system can be much faster than that of its IEEE-488 counterpart.

9.1.3 CAMAC Dataway

The CAMAC dataway consists of power supply and signal lines (approximately 120 lines in total, depending on the number of modules in the system). The lines are grouped into the following buses:

- Power bus;
- Function bus (5 bus lines);
- Write bus (24 bus lines);
- Read bus (24 bus lines);
- Address bus (24 individual lines);
- Status bus (24 individual lines and 3 bus lines);
- Subaddress bus (4 lines);
- Common control bus (3 lines: Initialize, Clear, and Inhibit);
- Strobe signal lines (2).

Connected to all module sockets, the bus lines run throughout the crate. Individual lines are led differently, with each line (e.g., an address line) connecting the crate controller with a single module. Such direct connection provides the fastest method of module addressing and status check. The 4-bit subaddress bus, allowing selection of 16 subaddresses assigned to module subsections, is used for selecting the module circuit or circuits to be controlled. The separation of write and read data lines represents another factor contributing to the high data processing rates offered by the CAMAC system. Data processing in modules is controlled by a 5-bit function code signal, sent over the function bus. Each module is connected to 86 lines. An operation on a data word in a crate is performed by the following scheme: a module is selected by the controller through an individual address line, and a circuit within the module (e.g., register 1) is specified through the subaddress bus; then, one of the 32 possible commands (e.g., copy data available on the write bus to register 1) is sent by the controller over the 5-bit function bus.

The maximum data rate allowed by the CAMAC system is 1 million 24-bit words per second, or 24 Mbps. Due to the incomparably faster circuit addressing, operation control, and interrupt handling, the effective performance and throughput offered by the CAMAC system exceed by more than three times those offered by the IEEE-488 system (allowing maximum transfer rate of 1 MBps, or 8 Mbps).

CAMAC is the first measurement system standard to cover device mechanical specification, the system organization, and the system bus. The adoption of the CAMAC standard initiated a large-scale international cooperation in manufacturing measurement system components. CAMAC measurement systems were manufactured and installed in many countries in the 1970s and 1980s, and many CAMAC crates and modules are still in use.

9.2 VXI MEASUREMENT SYSTEM

9.2.1 General Specification

The VXI crate measurement system was developed in 1987 by a consortium of American companies (including Hewlett-Packard and Tektronix) as an adaptation of Motorola’s Virtual Machine Environment (VME), an interface designed for computer networks and widely accepted in the United States [1]. Far from being a mere adaptation, VXI extends the VME specification by adding some instrumentation-specific parameters. A VXI system has a hierarchical structure, as shown in Figure 9.3:

- A lowest-level unit is a single device, usually contained in a single module;
- An intermediate-level unit is a VXI subsystem composed of up to 13 modules and comprised by a single chassis (also referred to as mainframe or crate); a subsystem represents an autonomous measurement system in itself, but can be a part of a larger system as well;
- On its highest level, a VXI system is composed of a number of chassis.

A basic unit of a VXI system is a chassis, an intermediate-level subsystem composed of up to 13 modules having standardized Eurocard dimensions and inserted in chassis slots. Modules contain functional blocks of the measurement system. A module is a structural unit of a VXI system; its organizational unit is a device. Each VXI device is assigned an individual VXI address.

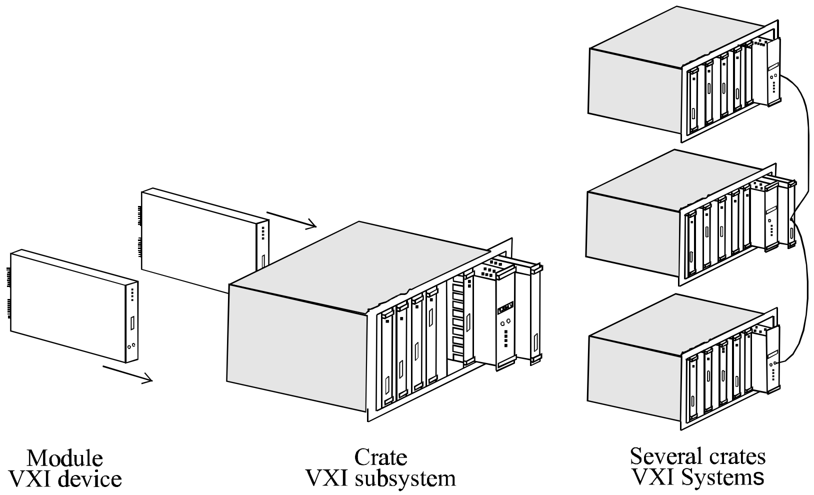

Figure 9.3 Hierarchical structure of a VXI measurement system.

Typically, a module contains one device (e.g., an ADC or a frequency meter), although this is not a rule. A number of VXI devices can be contained in a single module, or in a number of modules within a chassis. A VXI system can comprise up to 256 devices. A subsystem control module (referred to as slot 0 controller) is inserted into an outermost slot in the chassis and assigned number 0. Four module sizes are defined by the VXI standard, as shown in Figure 9.4.

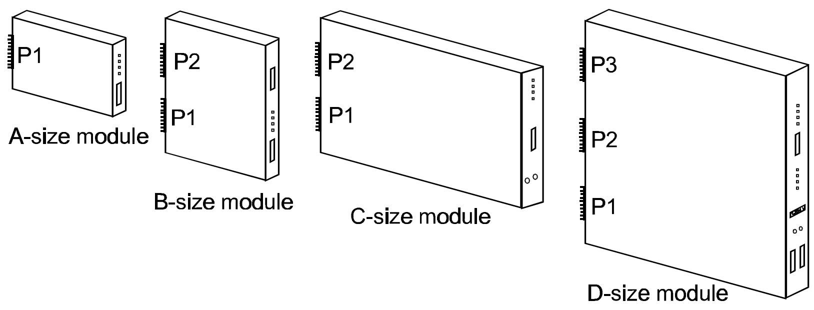

Figure 9.4 Four VXI module sizes (height × length × width). Module A: 100 × 160 × 20.3 mm (0.8 inch width); module B: 233 × 160 × 20.3 mm; module C: 233 × 340 × 30.5 mm (1.2 inch width); and module D: 367 × 340 × 30.5 mm.

The VXI system has a linear (bus) configuration. Modules are connected to the VXI bus by means of 96-pin connectors. One, two, or three connectors are installed in a module, depending on its size: P1 in module A; P1 and P2 in modules B and C; and P1, P2, and P3 in module D. Modules are plugged into VXI bus sockets in the chassis backplane. A separate room at the back of the chassis is reserved for a power supply unit, which is not a chassis module, and for cooling systems. The latter are often necessary, as chassis subassemblies are densely packed, and because of high power losses on the devices (on the order of 1,000W per chassis).

A VXI system can be controlled either by an external computer, or by a computer in the form of VXI module, referred to as an embedded controller. The latter solution, though more expensive, offers better system performance.

When the VXI system was being developed from 1985 to 1987, the IEEE-488 parallel interface standard was already widely accepted, with a wide choice of control software available. The VXI system designers were challenged to find a solution of the system control that could use software developed for IEEE-488. The challenge was met. Data processing in the VXI measurement system uses 16-bit or 32-bit words, depending on the size of the modules in the system. When the system contains at least one type A module, having a single P1 connector with 16 data line pins, data is processed in 16-bit words. When the system comprises no A module, and consequently, all modules have P1 and P2 connectors, 32-bit data words can be used in data processing.

An extremely important point in the VXI specification is a requirement of automatic system configuration performed by the controller. The standard requires every VXI device to have the configuration data stored in four configuration registers. This data specifies the device type, status, memory requirements, and control procedures.

9.2.2 VXI Buses

Physically, the VXI bus consists of module sockets in the chassis backplane and its wiring [1]. The VXI bus was designed on the basis of the VME bus by adding lines necessary in measurement systems.

Due to the large number of lines, the VXI bus is divided into three parts, each composed of a number of sub-buses, as shown in Figure 9.5:

- Global bus, comprising:
  - VME bus;
  - Power bus;
  - Trigger bus;
  - Analog sum bus.
- Unique bus, comprising:
  - Timing and synchronization bus;
  - Module identification bus;

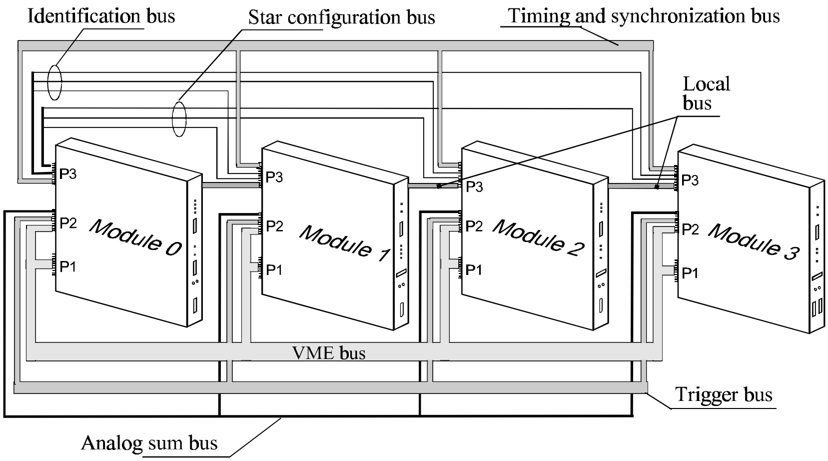

Figure 9.5 Structure of a VXI bus.

    - Star bus.
- Private bus, consisting of a single local bus.

A new element, not appearing in the system buses discussed in preceding paragraphs, is the analog sum bus, dedicated to analog signals. Another innovation is the local bus, allowing communication between adjacent modules in a chassis. The core of the VXI bus is the VME bus, defined by the VME specification. The VME bus is installed by means of P1 and P2 connectors. A P1 connector is installed in every module, regardless of its size.

Global Bus

The global bus consists of the following sub-buses:

- The VME bus, comprising:
    - Data transfer bus, with data lines (16), address lines (16, 24, or 32), and control lines;
    - Data transfer arbitration bus, which ensures that data transfer is controlled by a single controller when the system is managed by two or more controllers;
    - Priority interrupt bus, used for identification of interrupter (device asserting an interrupt line) and its status (the cause of the interrupt);
    - Utilities bus, comprising power lines, clock lines, and module damage signal lines.
- The trigger bus, comprising eight TTL trigger lines for digital signals with frequency up to 12.5 MHz, and six ECL trigger lines for digital signals with frequency up to 62.5 MHz.

- The analog sum bus, used for processing analog signals, available on this bus in the form of current signals. The analog sum bus can be used for analog simulations or for generation of nonstandard waveforms by summing standard analog signals. The analog signals are generated by controlled current sources installed in modules.
- The power bus, connecting the modules to stabilized power supplies with seven voltage values: +5V, –5.2V, –2V, ±12V, and ±24V.

Unique Bus

The unique bus consists of the following parts:

- Timing and synchronization bus, comprising three lines: 10- MHz clock line, 100-MHz clock line, and synchronization line;
- Star bus, allowing maximum reduction of intermodule communication time within a subsystem, as well as that of allowable time deviation (reduced to 2 ns) of signals synchronizing the operation of different modules; modules are connected in star configuration with slot 0 module in the center; since the star connection, using connector P3, involves only some management lines within the unique bus (see Figure 5.2), the overall bus configuration of the measurement system remains unaffected;
- Module identification bus, comprising 12 lines, each connecting the control module with one of the remaining 12 modules in the chassis; this method of identification allows a substantial reduction of interrupt handling time.

Control of VXI System

The VXI standard allows several methods of measurement system control. Note that the number of devices in a VXI system can be very large (up to 256 devices). Effective control of such large numbers of devices, organized hierarchically, is provided by a number of controllers managing different levels of the hierarchical system. A controller of a VXI system or subsystem is typically a PC equipped with an IEEE-488 (GPIB, HPIB, IEC-625) interface board. On the computer side, the controller is connected to the system through the interface board; its counterpart on the VXI chassis side is a GPIB/VXI converter, as shown in Figure 9.6(a). Data transfer rates over a VXI bus are determined by the VXI device parameters. The instruction transfer rate must be adapted to the capacities of the IEEE-488 interface board used. With the HS488 protocol, transfer rates can be enhanced to 8 MBps.

Another way of VXI system control consists of using an embedded controller (i.e., a controller computer in the form of a VXI module), as shown in Figure 9.6(b). Though much more expensive than a mass-produced PC, such a module computer, used as a controller of a VXI system, allows much higher data rates (up to 40 MBps).

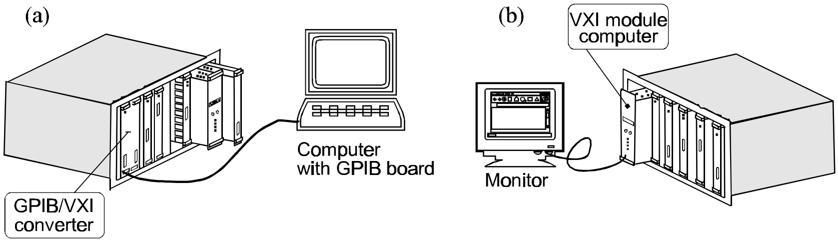

Figure 9.6 VXI measurement system control: (a) using an external PC with GPIB (IEEE-488) interface board; and (b) using an embedded computer.

VXI measurement systems provide the second highest data throughput of all measurement interface standards; the highest rates are allowed by the PXI modular system. However, a disadvantage of the VXI system is the high cost of its components. Individual prices of VXI modules are comparable to those of brand-name digital instruments. The VXI chassis and accessories are relatively expensive.

9.3 PXI MODULAR MEASUREMENT SYSTEM

9.3.1 General Specification

PCI eXtensions for Instrumentation (PXI), defining a PC-based modular measurement system with parallel interface, is a solution halfway between IEEE-488, which is common, and VXI, which is fast but expensive [3]. The structure of a PXI system is based on PCI, the key bus in personal computers, used as a measurement system interface bus. PCI includes a 32-bit data bus timed with a 33 MHz clock (66 MHz in PCI 2.1 version) and allowing data rates up to 132 MBps. The data bus can be extended to 64 bits, which involves throughput enhancement to 264 MBps.

In the computer architecture, PCI is the closest to the central processing unit (see Section 1.3, Figure 1.4), and therefore allows the highest data rates. The computer main board has three to six expansion slots with PCI connectors, through which high-speed peripheral boards can be plugged into the PCI. However, high transfer rates allowed by the PCI are not the only factor contributing to the high system performance offered by PXI. Another important factor is a specialized role of computers used in a PXI system. A PXI controller can use an operating system optimized for the measurement/control system requirements rather than for the user's convenience. Obviously, a computer with a specialized operating system will be a more efficient controller of a PXI system than a PC with a standard operating system, such as Microsoft Windows. In the latter case, the operating system will be more occupied with itself than with the measurement system control. PXI was developed by National Instruments and published as an open industry standard in 1997 [3]. Apart from NI, the industrial group promoting PXI (the PXI Systems Alliance) comprises almost 60 companies, including LeCroy, manufacturer of digital oscilloscopes.

PXI modules can be either inserted into a mainframe and used as PXI measurement system devices, or embedded in a computer to act, together with a graphical software, as stand-alone virtual instruments. The PXI system concept gives a developer a wide choice of universal modules with a PCI connector, such as controllers, measurement boards, or data acquisition (DAQ) boards. In addition to PCI hardware (modules), the rich PCI software for Microsoft Windows can be used in designing a PXI system. The choice of programming languages includes LabVIEW, Visual Basic, and Visual C/C++.

Modules connected to a PCI must have the plug-and-play capability (i.e., must come supplied with a driver). This feature is very useful in designing and running a measurement system. Hardware to be used in other types of measurement systems typically comes supplied with programming instructions only. In the case of PXI modules, both hardware and software have to be supplied by the manufacturer. Plug-and-play devices are recognized when plugged in, with automatic reconfiguration of all devices and circuits on the PCI. Apart from PCs, PCI is used in Power-PCs (e.g., those manufactured by Apple), as well as in work stations. Therefore, PCI interface and I/O boards (with ADCs and DACs) can be used in computers of these classes to form computer measurement systems.

9.3.2 PXI Bus

The signal flow in the PXI system is illustrated by the PXI bus diagram shown in Figure 9.7. The PXI bus includes:

- PCI, specified by the standard as a 32-bit bus with a 33 MHz clock;
- Local buses for communication between adjacent modules;
- 10 MHz clock line;
- PXI trigger bus;
- Star trigger bus (optional).

The PCI parameters in a PXI device are principally the same as in a PC. The only difference is the number of slots per segment: seven in the PXI system, against three or four in most desktop PCI systems. The standard 32-bit PCI bus offers a throughput of 132 MBps, increased to 264 MBps by the 64-bit version. This represents the highest rates of data transfer over a measurement system bus.

The *local buses* comprise 13 lines each. Local bus lines carry both analog (up to 42V) and digital signals, including high-frequency TTL signals.

The *trigger bus* comprises eight trigger lines used for synchronizing the operation of PXI system modules and module circuits.

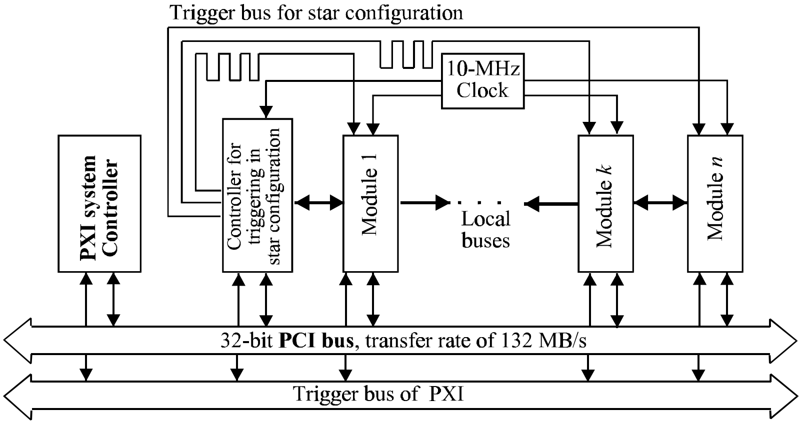

Figure 9.7 PXI system bus.

The *star trigger bus* offers high-quality synchronization of operation of system modules through star-connected trigger lines. As the star connection involves only selected lines, the overall linear (bus) configuration of the PXI system is not affected. Synchronization and trigger signals are generated by an optional star trigger controller, as shown in Figure 9.7.

9.3.3 PXI System Modules

PXI functional blocks are contained in modules, which are printed circuit boards with Eurocard dimensions. Two module sizes are specified by the PXI standard: regular 3U (l = 160 mm, h = 100 mm), and large 6U (l = 160 mm, h = 233 mm), as shown in Figure 9.8(a). PXI modules are inserted into slots; their electric connection to the PCI must comply with the IEC-1076 standard. Each module has two connectors: J1 for signals on the PCI 32-bit data bus, and J2 for other PCI signals: timing, synchronization, trigger, and local bus signals. Nearly 1,000 different PXI devices and components are available on the market, from chassis to controllers and specialized analog and digital modules.

A *chassis*, or *mainframe*, features a backplane with module slots and two types of system bus connectors, J1 and J2. PXI chassis are available in two sizes, with four or eight module slots. For example, a PXI-1000B chassis (manufactured by NI) has eight slots fit for 3U (160 × 100 mm) modules. Portable chassis, with carrying handles, are available as well, such as NI's PXI-1025 MegaPAC chassis with eight slots fit for 3U modules and a built-in 10.4-inch LCD screen in the front panel, as shown in Figure 9.8(b). PXI chassis are supplied with built-in +3.3V, +5V, and ±12V dc power supplies.

A PXI *controller module* is a computer with parameters similar to those of a PC. For example, PXI-8170 series controllers, offered by NI in 2001, have the following specifications: 850 MHz Pentium III central processing unit; 256 MB of RAM; 6 GB of hard disk memory; and standard ports: serial RS-232, serial USB, parallel IEEE-1284, and PS/2 mouse and keyboard connectors. The cheaper PXI-8155B and PXI-8156B controllers have inferior parameters (e.g., 333 MHz processor). As an alternative to a module controller, a standard desktop can be used as controller of a PXI system.

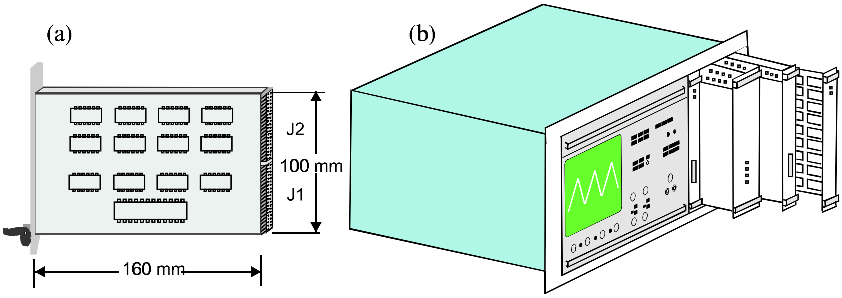

Figure 9.8 PXI system subassemblies: (a) 3U module; and (b) PXI chassis with LCD.

PXI instrument modules manufactured by NI include ADCs, multimeters, signal generators, DAQ circuits, analog multiplexers, and high-frequency switches. Here are some examples of PXI modules [3, 4].

- NI 5112, a two-channel 8-bit ADC with sampling rate 100 MHz and measurement range ±25 mV to ±25V. NI 5911, another converter model, allows A/D conversion with flexible resolution ranging from 8 bits at sampling rate 100 MHz, to 21 bits at sampling rate 10 kHz.
- NI 4060, a digital multimeter with a 5.5-digit display, designed for both dc and ac voltage and current measurements (up to 300V and 10A, respectively), as well as for resistance measurements (up to 200 MΩ). The measurement accuracy is determined by many factors. The best accuracy (error 0.01% to 0.02%) is obtained in dc voltage measurements up to 10V.
- NI 5411, a signal generator with a 16-bit DAC processing 40 million samples per second. Both standard (sine or square) and user-defined analog signal waveforms, as well as digital signals (such as TTL signals with a frequency up to 16 MHz) can be generated by this arbitrary waveform generator.
- NI 2591, a four-channel multiplexer with maximum frequency 4 GHz, switching analog signals with voltage up to 30V, and current up to 330 mA per channel.
- NI PXI-8320, an interface controller, enables VXI control and VME control from PXI.
- NI PXI-GPIB, an IEEE-488 controller from PXI.
- NI PXI-8231, an Ethernet controller from PXI.

- NI PXI-8232 (and NI PCI-8232) includes two interface converters in one device: the PXI ⇔ IEEE-488 converter and the PXI ⇔ Ethernet converter.
- The PXI-8232 can support LAN-based measurement systems with one of three Ethernet standards: 10BaseT, 100BaseTX, and 1000BaseT (LAN-based measurement systems are discussed in Chapter 10). The PXI-8232 makes possible the data transfer with the rate of 1.5 MBps by the IEEE-488.1 standard and of 7.7 MBps according to the HS488 mode.

9.3.4 PXI Measurement System Configuration

National Instruments, the initiator of PXI, recommends configuring a PXI system by the following five steps [3, 4]:

1. *Define Your Objective*
   The measurement system structure and operation requirements are to be defined first. The objective of the measurements should be set, and the following questions answered: Will the PXI system be integrated into another system, or will it be entirely autonomous? What are the benefits offered by PXI? How might the PXI system be expanded in the future?
2. *Choose Your Software*
   As the PXI interface is based on the key PC bus, the large number of software developed for PCs can be used in PXI systems. Specialized graphical programming languages, such as LabVIEW, Visual Basic, or C++, can be used for high-level programming.
3. *Select Your PXI Chassis*
   The main criterion for choosing a chassis is the number and size (3U or 6U) of the modules to be used in the PXI system.
4. *Select a Remote or Embedded Controller*
   Two factors should be considered when choosing a PXI controller: the required rate of measurement data processing, and the method of system control, which can be either remote or local. An embedded controller (i.e., a controller computer in the form of a PXI module), allows higher data acquisition and processing rates. A remote controller (i.e., an external PC used for controlling a PXI system), must be connected to the system bus through the Multisystem eXtension Interface (MXI). In spite of the very high transfer rates offered by the MXI interface (up to 1.5 Gbps in version MXI-3), its intermediacy slows down the measurement system operation.
5. *Select Your PXI Modules*
   The choice of PXI modules to be used in the measurement system should be guided by the type of measurements the system is intended for, and by the method of measurement data presentation. Modules should be chosen from the following major groups: instrument modules, data acquisition modules, motion controllers, and image acquisition modules.

9.4 CENTRONICS AND IEEE-1284 INTERFACES IN MEASUREMENT SYSTEMS

9.4.1 Centronics Interface

Complex digital instruments, such as digital oscilloscopes or spectrum analyzers, are often fitted with an IEEE-1284 parallel interface port, socket, and driver. The IEEE-1284 interface supplanted, with slight modifications, the common printer interface Centronics. Quite often, the commonly known name Centronics is used by manufacturers of instruments and computer hardware to designate the actually installed IEEE-1284 interface.

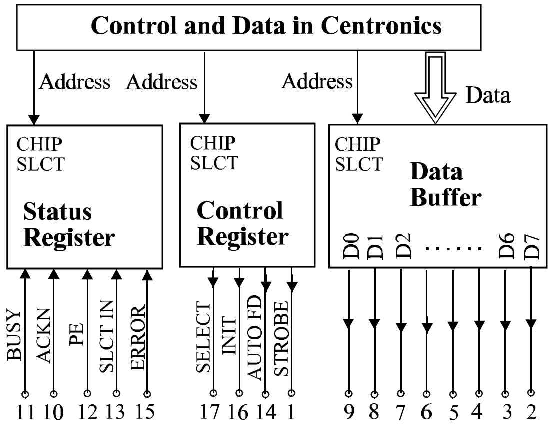

Figure 9.9 Centronics interface registers and signal lines (in the computer).

The Canon 25-pin plug-and-socket connector DB 25 is the most commonly used for this interface type. Occasionally, a 36-pin connector is used. Centronics transmission lines are unidirectional.

The Centronics interface bus, as shown in Figure 9.9, comprises eight data lines (from computer outputs to peripheral device inputs), four control lines (outputs in the computer), and five status lines (outputs in the peripheral device). The peripheral device is usually a printer, but it can be a digital instrument (e.g., a digital oscilloscope) as well. The signal level on these lines is consistent with the TTL standard. Data is sent from computer to printer along with a STROBE pulse (corresponding to logical state 0, minimum duration 1 μs). During this pulse, data is loaded to the printer register. Two signals sent by the printer, ACKN and BUSY, are typically used for controlling the rate of data transfer, as shown in Figure 9.10. After a data byte has been transferred and loaded to the printer buffer (input data register), an acknowledgement signal, ACKN (a pulse corresponding to logical state 0 and held for 5 μs to 10 μs), is sent by the printer.

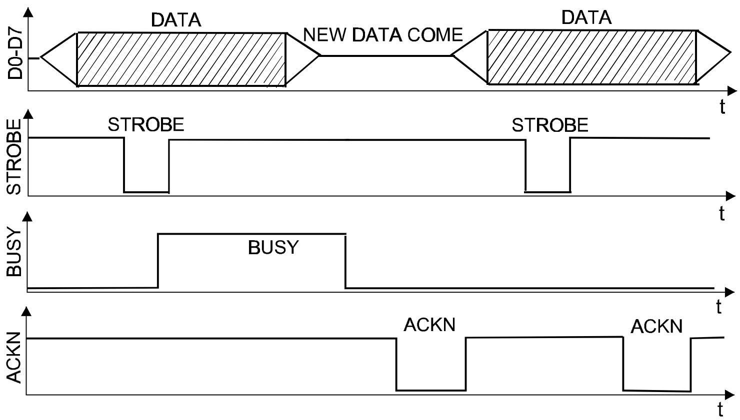

Figure 9.10 Control of data transfer in the Centronics interface.

The computer can then send the next byte. However, if the printer buffer is full, the printer sends the BUSY signal instead of the ACKN signal, which is a pulse corresponding to logical state 1 and held on-line until the input data register becomes available again. Data transfer is suspended at that time. When the BUSY signal is unasserted, then the printer unasserts the ACKN signal to indicate that data has been accepted, and the next byte can be sent by the computer. Figure 9.10 shows time relations between different pulse edges.

Installed in almost every PC, Centronics has become a standard parallel interface in this type of computer. If the Centronics or IEEE-1284 interface is installed in an instrument with a display, then measurement data can be sent from the instrument to a connected printer, and the screen content printed out, as shown in Figure 9.11. No computer is required for this method of documentation.

Since Centronics was commonly used in computers, attempts were made to use it for bidirectional data transfer. However, data transfer from a peripheral device to a computer in this interface is performed via the four status lines; therefore, only 4-bit words can be transferred in this direction. Maximum transfer rate in both directions ranges from 50 to 100 KBps.

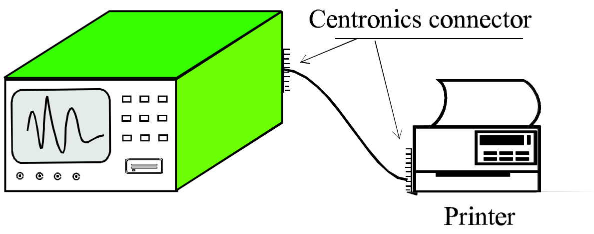

Figure 9.11 Printout of measurement data transferred via a Centronics or IEEE-1284 interface in compatibility mode.

In response to a demand for bidirectional data transfer over a printer interface, the Centronics standard was suitably modified and published under the name of IEEE-1284 in 1994.

9.4.2 IEEE-1284 Interface

Similar to its Centronics counterpart, the IEEE-1284 computer interface is designed principally for printer control. Its advantage over Centronics is bidirectional data transfer [1, 5]. The large number of IEEE-1284 port operation modes results from an attempt to satisfy a variety of computer hardware manufacturers' needs.

Table 9.1

IEEE-1284 Interface Operation Modes and Their Specification

Operation Mode	*Word Size (in bits)*	*Transfer Direction*	*Maximum Transfer Rate*
Compatibility	8	PC ⇒ peripheral	150 KBps
Nibble	4	PC ⇐ peripheral	50 KBps
Byte	8	PC ⇐ peripheral	Variable
ECP	8	PC ⇔ peripheral	2 MBps
EPP	8	PC ⇔ peripheral	2 MBps

Table 9.1 specifies the details of five IEEE-1284 interface operation modes, which include:

- Compatibility mode;
- Nibble mode;
- Byte mode;
- Extended Capability Port (ECP);
- Enhanced Parallel Port (EPP).

The *compatibility mode*, sometimes referred to as Standard Printer Port (SPP), is the regular 8-bit data transfer over the data bus from PC to peripheral device, exactly the same as in the Centronics interface. This mode is designed for older printer control.

The *nibble mode* is a 4-bit data transfer over the status lines from peripheral device to PC. This mode has the least hardware and interface driver requirements.

The *byte mode* is a bidirectional (half-duplex) adaptation of Centronics, allowing 8-bit data transfer between PC and peripheral device.

The *Extended Capability Port* (ECP) allows half-duplex transmission of 8-bit data words or 7-bit addresses over the data lines between PC and peripheral device. The addressing can be of use when the interface connector is outfitted with a concentrator, to which several (up to 128) devices are connected, or if one device (typically a printer) has multiple functionality (e.g., printer, fax, or modem). The ECP mode uses the Direct Memory Access (DMA), as well as interrupt handling.

Similar to the ECP, the *Enhanced Parallel Port* (EPP) mode allows half-duplex transmission of 8-bit data words or 8-bit addresses over the data lines between PC and peripheral device, with an enhancement consisting of the possibility of addressing up to 256 devices. However, the limitations (e.g., the need for a concentrator) are as in ECP.

Although using the same lines as Centronics, IEEE-1284 interface modes differ in connector wiring. Consequently, only one IEEE-1284 interface mode can be used in a computer provided with the suitable driver. Byte, ECP, and EPP modes involve hardware implementations: bidirectional interface ports are to be installed, and an input for transmission direction control to be added. The ECP and EPP modes allow transfer rates up to 2 MBps, which is more than 20 times those achievable in the Centronics standard. When operating in the ECP or EPP modes, the IEEE-1284 interface allows bidirectional data transfer, which can be used, for example, in two-component measurement systems, composed of a computer and a digital instrument, as shown in Figure 9.12.

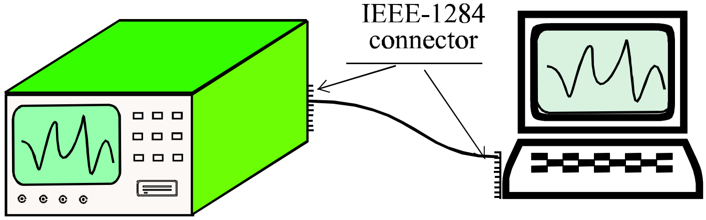

Figure 9.12 Two-component measurement system with IEEE-1284 parallel interface.

The ECP mode is especially useful in measurement systems, due to its high transfer rates and the possibility of using the fast DMA communication mode. On device power-up, the IEEE-1284 interface is automatically set to the compatibility mode. Passing to any of the remaining four modes is software-forced. It is noteworthy that the IEEE-1284 interface can be also used to connect an IEEE-488 interface controller board (such as the National Instruments' GPIB-1284CT) to a PC.

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Chapter 10

LAN-Based Measurement Systems

10.1 INTRODUCTION

Computer network–based solutions represent an important trend in the evolution of measurement systems [1, 2]. Computer networks are grouped into three classes: Local Area Networks (LAN), Metropolitan Area Networks (MAN), and Wide Area Networks (WAN). Wired and wireless computer networks are distinguished by the physical medium used in the transmission line. Computer network-based measurement systems use principally LANs and the Internet [3]. The high-speed WANs are used as backbone networks, providing interconnection of LANs and computer centers. LANs can have bus, tree (multiple star), or loop (ring) topology, as shown in Figure 10.1.

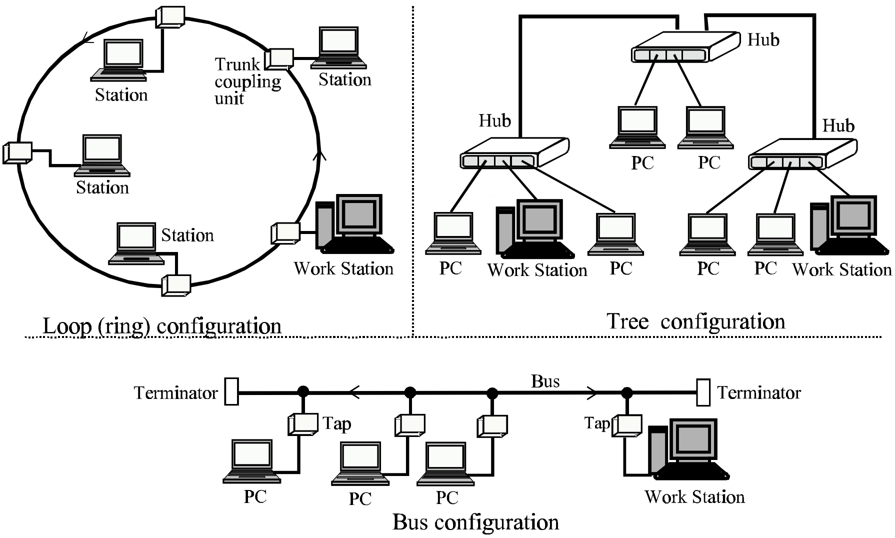

Figure 10.1 LAN configurations (topologies).

There are many LAN types, such as Ethernet, Token Ring, ARCNet, 100VG-AnyLAN, or the wireless IEEE-802.11. The most widespread type is Ethernet. Different LANs, defined by IEEE-802 and American National Standards Institute (ANSI) standards, are specified in Table 10.1. All the LAN types listed in Table 10.1 are used in practice. Many LANs are mixed-standard networks. For example, the author's computer is connected to a Fast Ethernet/FDDI mixed-standard network, operating so efficiently that users hardly realize its existence.

Table 10.1

Local Area Network Standards

Standard	*LAN Name*	*Transfer Rate*	*Configuration*
IEEE-802.3	Ethernet, Fast Ethernet, Gigabit Ethernet	1 Mbps to 10 Gbps	Bus, Star, Tree
IEEE-802.4	Token Bus	10 Mbps	Tree
IEEE-802.5	Token Ring	4 to 16 Mbps	Loop
IEEE-802.9	Iso-Ethernet	16 Mbps	Star, Tree
IEEE-02.11	Wireless LAN, WiFi	11 Mbps	Star, Tree
IEEE-02.12	100VG-AnyLAN	100 Mbps	Star, Tree
ANSI	FDDI, FDDI II	100 Mbps	Star, Tree

10.2 ETHERNET HARDWARE

Used in companies, research laboratories, teaching laboratories, and households, LANs provide a natural physical layer for measurement applications. LAN to IEEE-488 parallel interface converters are offered by instrument manufacturers, such as Tektronix or Keithley, in response to a very quick expansion of computer networks. Ethernet, as the most widespread type of computer network, is discussed in detail below.

Ethernet was developed by Xerox, Intel, and Digital Equipment in 1980, and accepted by the IEEE as standard IEEE-802.3 in 1985. Different Ethernet variations are designated *XBaseY*, *X* indicating data throughput, *Base* denoting unmodulated transmission, and *Y* being the symbol of transmission line medium or length. Ethernet offers four ranges of signal transmission rate. The respective network variations are presented in Table 10.2. Their maximum throughput values are as follows:

- Standard Ethernet, up to 10 Mbps;
- Fast Ethernet, up to 100 Mbps;
- Gigabit Ethernet (GE), up to 1,000 Mbps;
- 10 Gigabit Ethernet (10GE), up to 10 Gbps.

Table 10.2

Ethernet Types and Their Specification

Ethernet Variation	*IEEE Protocol*	*Transfer Rate*	*Maximum Distance per Cable Segment*	*Connectors*
10Base5	IEEE-802.3	10 Mbps	500m	AUI
10Base2	IEEE-802.3a	10 Mbps	185m	AUI, BNC-50
10BaseT	IEEE-802.3i	10 Mbps	100m	RJ-45
10BaseF	IEEE-802.3j	10 Mbps	1 km	Optical
100BaseTX	IEEE-802.3u	100 Mbps	100m	RJ-45
100BaseT4	IEEE-802.3u	100 Mbps	100m	RJ-45
100BaseFX	IEEE-802.3u	100 Mbps	10 km	Optical
100BaseSX	IEEE-802.3u	100 Mbps	300m	Optical
1000BaseCX	IEEE-802.3z	1,000 Mbps	25m	RJ-45
1000BaseT	IEEE-802.3ab	1,000 Mbps	100m	RJ-45
1000BaseSX	IEEE-802.3z	1,000 Mbps	500m	Optical
1000BaseFX	IEEE-802.3z	1,000 Mbps	10 km	Optical
10GE	IEEE-802.3ae	10 Gbps	40 km	Optical

Ethernet signals are transmitted over unshielded twisted-pair, shielded twisted-pair (STP), coaxial, or fiber optic cable. Current Ethernet installations tend to use the star configuration (topology), instead of the previously used bus configuration, which offers poor reliability. Ethernet signals are transmitted differentially: one signal per conductor pair or per optical fiber. Network nodes use separate leads for incoming and outgoing signals. Consequently, each node is connected to the network through two twisted pairs or two optical fibers.

Signals transmitted over 10BaseY have voltage values from –2.5V to +2.5V, and those in 100BaseY and 1000BaseY from –1V to +1V [3]. The central unit of a star network is either a *hub* or a *switch*. A media converter, converting electrical signals to optical signals and vice versa, as well as a single-mode to multimode optical signal converter, can be incorporated in an Ethernet network.

The following Ethernet variations allow transfer rates up to 10 Mbps (10BaseY):

- *10Base5*, a rather obsolete Ethernet standard having bus configuration and using a thick RG-8 coaxial cable with 50Ω impedance. Maximum cable segment length is 500m. Computers and other network nodes are plugged into LAN sockets through AUI connectors.

- *10Base2*, having bus configuration and using a thin RG-58 coaxial cable with 50Ω impedance. Maximum cable segment length is 185m. Nodes are attached to the network through BNC-50 or AUI connectors.
- *10BaseT*, having star configuration and using an unshielded twisted-pair cable. Maximum network radius, or cable length between the hub or switch and a socket, is 100m. Eight-pin RJ-45 connectors are used on twisted-pair links. A high-category (category 5) twisted-pair cable provides a substantial enhancement of 10BaseT data rates, which can even exceed the limit of 100 Mbps, if suitable network cards and hubs are used in the computers. 10BaseT is the most commonly used Ethernet variation, and RJ-45 is the most common LAN connector.
- *10BaseF*, having star configuration and using a fiber optic cable (a pair of cheap multimode optical fibers); maximum network radius is 1 km.

100BaseY variations (allowing transfer rates up to 100 Mbps) are as follows:

- *100BaseTX*, having star configuration and using a category 5 cable (two twisted pairs); maximum network radius is 100m. RJ-45 connectors are used on twisted-pair links.
- *100BaseT4*, having star configuration and using a category 3 cable (four twisted pairs); maximum network radius is 100m. RJ-45 connectors are used on twisted-pair links.
- *100BaseFX*, having star configuration and using a fiber optic cable (a pair of single-mode fibers); maximum network radius exceeds 10 km.
- *100BaseSX*, having star configuration and using a fiber optic cable (a pair of multimode fibers); maximum network radius is 300m.

1000BaseY variations (allowing transfer rates up to 1000 Mbps) are as follows:

- *1000BaseCX*, having star configuration and using a shielded twisted-pair cable; maximum network radius is 25m.
- *1000BaseT*, having star configuration and using a category 5 cable (four twisted pairs); maximum network radius is 100m. RJ-45 connectors are used on twisted-pair links.
- *1000BaseSX*, having star configuration and using a fiber optic cable (a pair of multimode fibers); maximum network radius is 500m.
- *1000BaseFX*, or Gigabit Ethernet (GE), having star configuration and using a fiber optic cable (a pair of single-mode fibers); maximum network radius, depending on the transceiver used, can exceed 10 km.

Network Cards and RJ-45 Connector

A computer or other Web server gets physical access to the LAN through network interface circuits. These are usually included in a printed circuit board referred to as a network interface card, as shown in Figure 10.2. However, LAN interface circuits are increasingly integrated in the computer motherboard. A network interface card has two connectors: one for a specific computer bus (usually PCI, formerly ISA), the other for the network cable. The electronic system in a network interface card includes at least three functional blocks: a Network Interface Controller (NIC), a Serial Network Interface (SNI), and the card memory. Obviously, network interface cards differ in specification, as they are designed for operation with different LAN types at different transfer rates.

Figure 10.2 Computer Ethernet card for PCI bus.

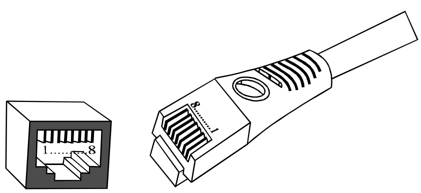

Figure 10.3 RJ-45 connector for Ethernet: a socket and a plug

In LANs using an electric cable, the network connector is typically RJ-45, as shown in Figure 10.3. The RJ-45 contact assignments in four Ethernet standards are specified in Table 10.3.

Table 10.3

Contact Assignments in RJ-45 Ethernet Connector

Contact Number	*10BaseT*	*100BaseTX*	*100BaseT4*	*1000BaseT*
1	Tx+	Tx+	Tx_D1+	BI_D1+
2	Tx–	Tx–	Tx_D1–	BI_D1–
3	Rx+	Rx+	Rx_D2+	BI_D2+
4	Not used	Not used	BI_D3+	BI_D3+
5	Not used	Not used	BI_D3–	BI_D3–
6	Rx–	Rx–	Rx_D2–	BI_D2–
7	Not used	Not used	BI_D4+	BI_D4+
8	Not used	Not used	BI_D4–	BI_D4–

10.3 ETHERNET TRANSFER PROTOCOL

The Transmission Control Protocol and Internet Protocol (TCP/IP) allow computers of different classes, running different operating systems, to communicate with each other [4]. Being in fact a protocol suite, TCP/IP forms the basis for communication between more than 100 million computers in the Internet, as well as between two computers in a LAN. This crucial protocol suite is introduced in order to provide a basis for further discussion of Ethernet and its use in designing and building computer measurement systems. TCP/IP consists of four layers, as shown in Figure 10.4, namely: Application Layer, Transport Layer, Network Layer, and Link Layer.

The *Application Layer* deals with the details of a particular application. Some of the most common TCP/IP applications are:

- Telnet for remote login;
- Browser support for displaying Web pages;
- File transfer applications by File Transfer Protocol (FTP), allowing file exchange between hosts running different operating systems;
- File transfer by HyperText Transfer Protocol (HTTP);
- E-mail applications.

The *Transport Layer* is responsible for data transfer between two hosts. Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) can be used by this layer, although the latter is rarely employed. TCP guarantees that data received is exactly the same as data sent. Received from the application, data is divided by TCP and forwarded, in the form of appropriately sized chunks, to the network layer below; received packets are acknowledged and lost packets retransmitted. The much simpler UDP allows higher data transfer rates, but does not guarantee transfer reliability. UDP is used in real time systems.

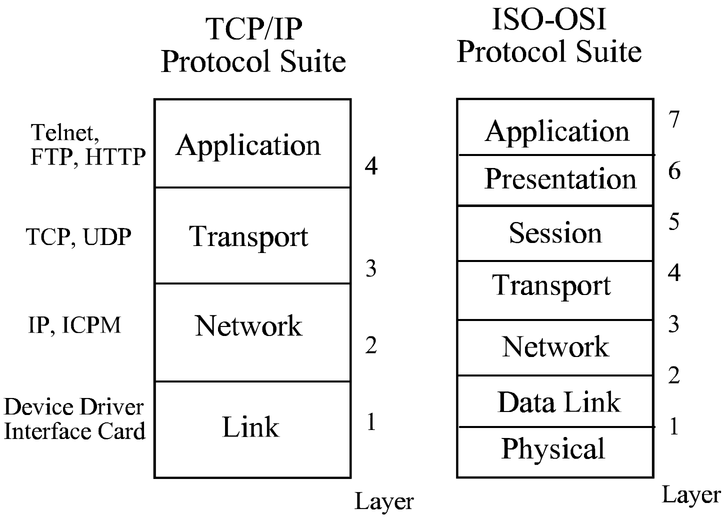

Figure 10.4 TCP/IP Protocol Suite (four layers), and ISO-OSI Protocol Suite (seven layers according to the Open Systems Interconnection Reference Model).

The *Network Layer* (also referred to as the Internet Layer) consists of Internet Protocol (IP) and Internet Control Message Protocol (ICMP). The IP component deals with file addressing and transfer, also between systems of different types. ICPM handles the message transfer.

The TCP/IP *Link Layer* uses existing network standards, mainly Ethernet. The device driver in the operating system and the corresponding network interface in the computer (network interface card) are usually comprised by the Link Layer.

The International Standards Organization (ISO) defined the Open Systems Interconnection Reference Model, a seven-layer protocol suite for data (file) exchange between networked computers, as shown in Figure 10.4. Known as ISO-OSI protocols, this communication protocol suite specifies some communication issues in more detail than TCP/IP. The TCP/IP Application Layer is split into three ISO-OSI layers: Application, Presentation, and Session; and the TCP/IP Link Layer into two ISO-OSI layers: Data Link Layer, and Physical Layer. Rather than being an alternative to TCP/IP, the ISO-OSI protocol suite provides a more detailed definition of the uppermost and lowermost TCP/IP layer.

TCP/IP defines the formation of the frame, or the stream of bits transferred over a computer network (e.g., Ethernet). For example, when measurement data is sent in a data packet, successive headers are added by each layer as the packet goes down the protocol "stack": measurement data header, TCP/IP header, IP header, and Ethernet header, as shown in Figure 10.5. This process of adding headers by the successive TCP/IP layers is referred to as encapsulation.

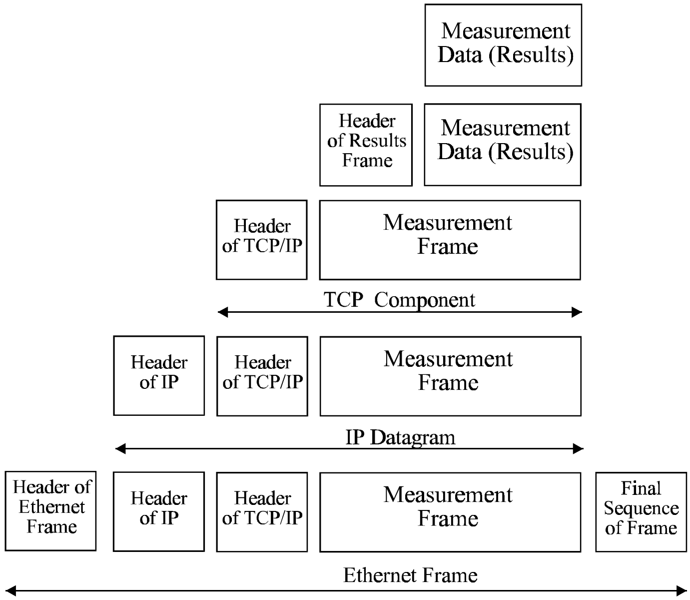

Figure 10.5 Data encapsulation by the Ethernet (IEEE-802.3) transfer protocol.

The Ethernet protocol requires all network stations to continually listen for traffic on the network, in order to determine whether the line is busy or quiet, or whether there is an interframe gap (IFG). The interframe gap is a minimum idle period between transmission of successive frames (sent by any computer in the network). Its definition is necessary for LAN stations to know if the line is quiet indeed, or the next frame is about to be transferred. IFG is defined as the time necessary to transfer 96 bits (10.6 μs in 10BaseY networks), and specified on the basis of the maximum distance between stations and the rate of signal propagation over network lines.

Another important parameter defined by the IEEE-802.3 protocol is slot time S, corresponding to the time necessary to transfer 512 bits in 10BaseY or 100BaseY networks, or 4,096 bits in 1000BaseY. This slot time defines the minimum frame length, in order to prevent confusion between short packets of pulses indicating collision or noise with regular signal transmission. All frames shorter than 64 bytes, or 512 bits (4,096 bits in 1000BaseY), are discarded. Maximum frame length is 1,518 bytes. According to the IEEE-802.3 transfer protocol, an Ethernet packet consists of a frame and a preamble, as shown in Figure 10.6.

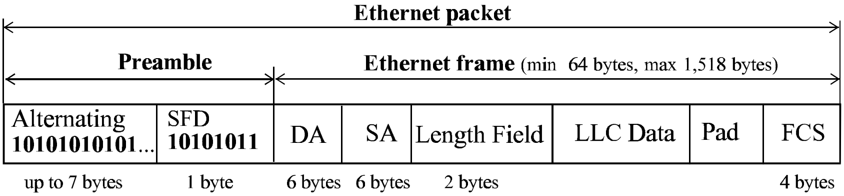

Figure 10.6 Ethernet frame and packet, according to IEEE-802.3.

A Preamble consists of a sequence of 56 bits that have alternating 1 and 0 values (101010...10), and the word 10101011 used as a Start of Frame Delimiter (SFD).

A frame is composed of six fields, and can contain from 64 to 1,518 bytes in total. The frame fields are: Destination Address (DA) (6 bytes), Source Address (SA) (6 bytes), Length Field (2 bytes), LLC (Logical Link Control) Data, Pad, and Frame Check Sequence (FCS), containing a 4-byte cyclical redundancy check (CRC) value.

The Pad field contains bits with logical value 1, appended to the data field to bring its length up to the minimum of 512 bits (4,096 bits in 1000BaseY), if the data field contains less.

10.4 ETHERNET-BASED MEASUREMENT SYSTEMS

10.4.1 Ethernet-Based Measurement Systems with LAN/IEEE-488 Converters

LANs provide an infrastructure that can be used in computer measurement systems. LAN-based measurement systems can be grouped into three types: hierarchical systems, systems with LAN interface, and systems with IEEE-488/LAN converters [5–7].

Hierarchical measurement systems, mentioned in Chapter 1, are composed of subsystems, subsystem controllers, and a system controller. Subsystems, forming the bottom level of a hierarchical system, use interfaces such as IEEE-488 or RS-232, as shown in Figure 10.7. Each subsystem is individually controlled by a PC.

The top level of a hierarchical measurement system is organized by means of a LAN, connecting the subsystem controllers and the system controller, which can be a PC or a workstation. Used in hierarchical measurement systems, LAN provides standard communication between computers, based on data and message exchange. In measurement systems with a LAN interface, both the controller (PC) and the instruments are attached directly to the LAN, with no interface converter. This type of system is discussed next.

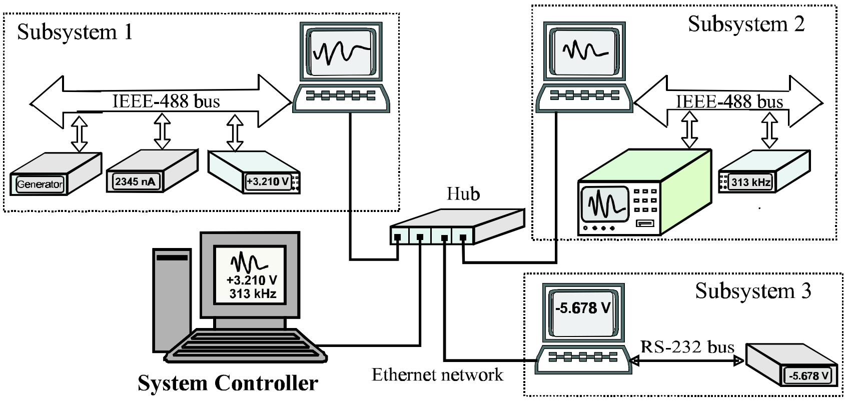

Figure 10.7 Ethernet-based hierarchical measurement system.

IEEE-488 interface systems with IEEE-488/LAN converters, representing the third group of LAN-based measurement systems, are composed of the following parts:

- System controller with LAN interface card;
- Instruments attached to an IEEE-488 interface primary bus;
- One or more IEEE-488 interface secondary bus segments;
- Computer Local Area Network;
- IEEE-488/LAN converters (also designated GPIB/LAN or GPIB/Ethernet), through which IEEE-488 bus segments are connected to the LAN, as shown in Figure 10.8.

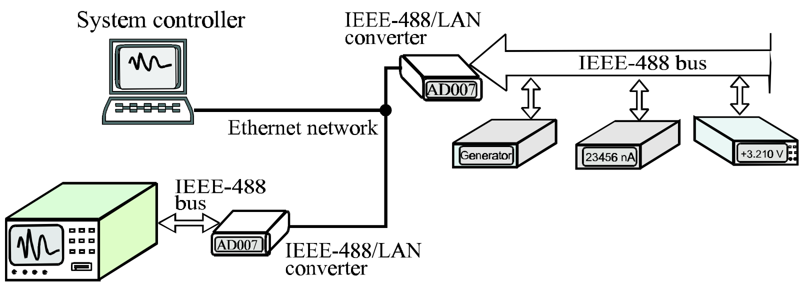

Figure 10.8 Ethernet-based measurement system with an IEEE-488 interface and IEEE-488/LAN converters.

A computer connected to the network should have an implementation of the TCP/IP network protocol suite. A computer with TCP/IP can be used as a controller of a distributed measurement system with IEEE-488/LAN converters. LAN allows transmission of control signals from the controller to the instruments, and transmission of measurement data from the instruments to the controller.

A schematic a of measurement system with interface converters is shown in Figure 10.8. The system shown uses AD007 LAN/IEEE-488 converters, manufactured by Tektronix and designed for operation with 10BaseT Ethernet [7]. In 100BaseTX and 10BaseT Ethernet variations, a GPIB-ENET/100 [5] converter can be used, which allows data transfer to and from the IEEE-488 interface at rates up to 900 KBps by IEEE-488.1 transfer protocol, and up to 1.2 MBps in transfers using HS488 protocol (see Section 8.3.1). Note that the transfer rates are specified in bytes per second. This is because IEEE-488 is a parallel interface using byte (8-bit) transfer. The throughput limitations in the measurement system are due to the presence of IEEE-488. Various interface converters are listed in Table 10.4.

Table 10.4

LAN to IEEE-488 Converters

Converter Model	*Ethernet Type*	*Transfer Rate in IEEE-488 Interface*	*PC Operating System*	*Manufacturer*
AD007	10BaseT	No data available	Windows 95 and later versions	Tektronix
GPIB-ENET [1]	10BaseT 100BaseTX	50 KBps	Windows 95 and later versions	National Instruments
GPIB-ENET/100	10BaseT 100BaseTX	900 KBps, (1.2 MBps by HS488)	Windows 2000, Windows ME, Windows XP	National Instruments
E2050B [2]	10BaseT	100 KBps	Windows 98, Windows ME	Agilent Technologies
E5810A	10BaseT 100BaseTX	1 MBps	Windows 98, Windows 2000, Windows XP	Agilent Technologies

[1] GPIB-ENET is replaced by GPIB-ENET/100
[2] E2050B is replaced by E5810A

10.4.2 Measurement Systems with a LAN Interface

In measurement systems with a LAN interface, both the controller and the instruments are equipped with LAN interface cards, allowing direct connection to the network, without interface converters. In this type of system, the LAN is used as a bus interface. Measurement systems with a LAN interface (or more specifically, Ethernet interface) represent a new solution, since instruments equipped with LAN interface cards have been manufactured for only a few years. Each instrument with a LAN interface card is supplied with suitable software, allowing the instrument to act as a Web server. This is a very important feature of instruments with a LAN interface. Using a Web browser, which is included in almost every PC, a remote computer (client) can access a Web server instrument to get measurement data or operate the instrument. Installation of a measurement system with a LAN interface and Web server instruments does not involve purchasing specialized system software, and thus allows substantial savings. Although currently only higher class (and higher price) instruments are supplied with a LAN interface, the range of available instruments is rapidly growing. A schematic of a measurement system with a LAN (Ethernet) interface is shown in Figure 10.9.

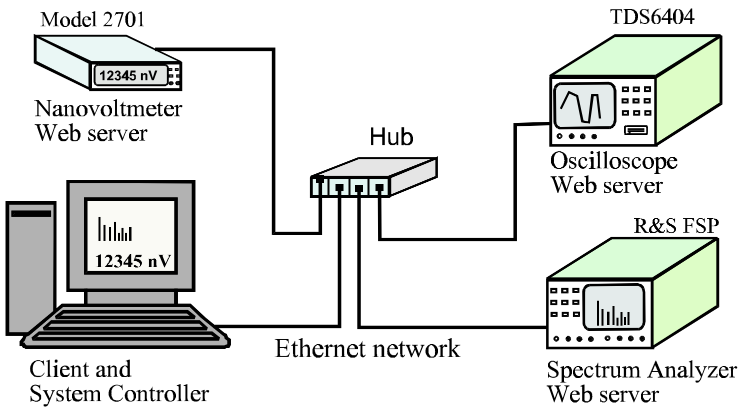

Figure 10.9 Measurement system with an Ethernet interface.

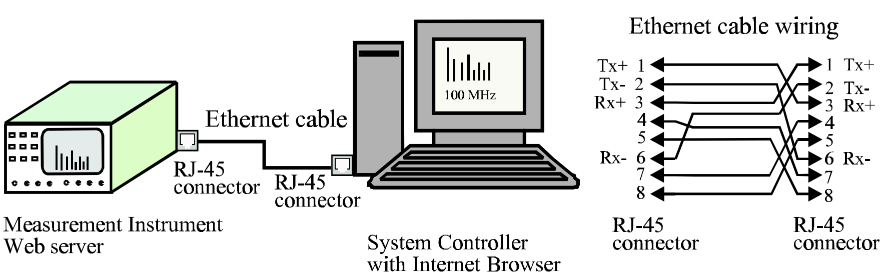

Figure 10.10 Two-component measurement system with an Ethernet interface and the cable wiring for such system.

If a measurement system with a LAN interface consists of two devices only (a PC-client and an instrument acting as a Web server), direct connection is possible, without LAN and hub intermediacy, as shown in Figure 10.10.

Such two-component systems represent an overwhelming majority of all measurement systems. Two-component systems use the same communication procedures as more complex systems. When connecting two devices with an

Ethernet interface, attention should be paid to the cable connection: contacts Tx+ and Tx– of one device must be connected to contacts Rx+ and Rx– of the other.

The list of LAN interface implementations in instruments includes, but is certainly not limited to, products and product lines of the following companies.

- *Tektronix*, which implemented the 10/100BaseT Ethernet interface as standard fitting in the TDS3000, TDS5000, and TDS6000 (e.g., TDS6404, and TDS6604) series digital oscilloscopes, as well as in the TG700 signal generator (10/100BaseT designates both 10BaseT and 100BaseTX Ethernet variations). Another example of a Tektronix device with a LAN interface is the AWG610 arbitrary waveform generator, fit for operation in 10BaseT Ethernet [7].
- *LeCroy*, the manufacturer of digital oscilloscopes, which equipped the WaveRunner 6000 and WaveSurfer 400 series with a 10/100BaseT Ethernet interface.
- *Agilent Technologies* (formerly a part of Hewlett-Packard), which implemented the 10/100BaseT Ethernet interface in its Infiniium series (e.g., in the 54800 oscilloscope) and the 33220A function generators.
- *Keithley*, the instrument manufacturer offering high class digital multimeters, including the Model 2701 Multimeter/Data Acquisition System with 10/100BaseT Ethernet interface, offered since 2004. The Model 2701 includes a digital voltmeter with a 22-bit integrating ADC.
- *Rohde & Schwarz*, which fitted its higher class spectrum analyzers (e.g., R&S FSO), as well as some standard analyzers (e.g., R&S FSP), with the 10BaseT Ethernet interface.
- *Micron Optics*, offering the si720 Optical Sensing Analyzer with either Ethernet or IEEE-488 interface.
- *L-3 EMP Systems*, offering the ACU-21 Antenna Control Unit with an Ethernet interface option (along with RS-232 and IEEE-488 options).

These devices all have RJ-45 sockets, compatible with the 10/100BaseT Ethernet standards. The list includes only arbitrarily selected products of arbitrarily selected manufacturers. Although certainly not exhaustive, it illustrates the growth of measurement systems with a LAN interface as an important trend in measurement system evolution. Each device with a LAN interface can be used as a Web server, allowing access to measurement data and remote operation from a Web browser.

10.5 INTERNET-BASED MEASUREMENT SYSTEMS AND SYSTEMS WITH EMBEDDED WEB SERVERS

Instruments with a LAN interface can be connected to the Internet to form a measurement system that can be distributed all over the globe. Scientific, educational, or government centers, as well as large corporations, use Internet servers with gateways providing direct connection to the Web. Smaller companies and individual users access the Internet through Internet service providers. Many of the Internet service providers are operators of wired (PSTN) or wireless (GSM) phone networks.

A schematic of an Internet-based distributed measurement system, with computers and Web servers connected to the Web, is shown in Figure 10.11.

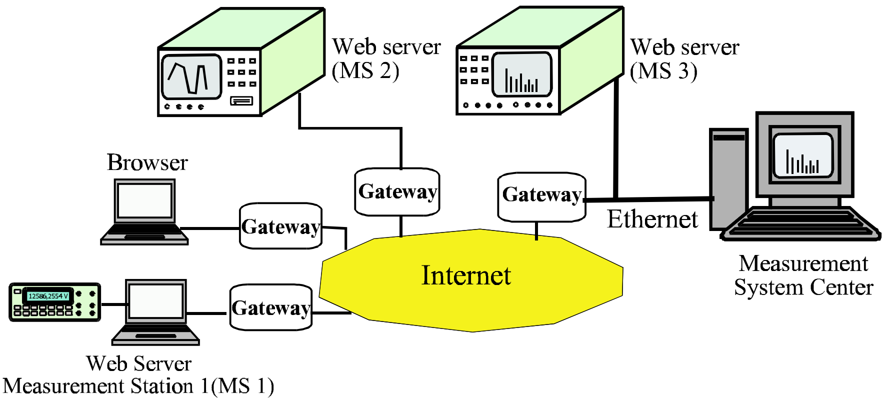

Figure 10.11 Distributed measurement system with Web servers connected to the Internet.

In the measurement system depicted in Figure 10.11, messages (measurement data and instructions) are created sequentially, and transferred as frames that have structures as shown in Figure 10.5. Computers in the system collect measurement data and control the measurements by means of software. The measurement system is composed of sensors, Web servers, a network with the TCP/IP protocol, and stations with Web browsers. However, in transfers over the Internet, the path of a transferred packet, as well as its transfer time, are much longer that in a LAN. Different packets can (and usually do) follow different paths, and arrive at the destination out of order. Therefore, although an Internet-based measurement system is a very good solution for acquiring data from distributed measurement stations and providing access to the data from distributed client computers, it is not recommended for on-line measurements or control of dynamic processes.

Sensors and actuators in the system can be connected to computers (through suitable interfaces) or to simple Web servers referred to as embedded Web servers or mini Web servers. Some embedded Web servers are listed in Table 10.5.

Embedded Web servers are modules or printed circuit boards of different complexity which are equipped with necessary connectors, including Ethernet connectors. A measurement system with embedded Web servers connected to the Internet (directly or via Ethernet) is shown in Figure 10.12. Programming of such systems is described in Section 11.3.2.

Table 10.5

Embedded Web Servers

Web Server	*Ethernet Variation*	*Interfaces*	*Memory*	*Manufacturer*
AVR 460	10BaseT	RS-232	256 kB	Atmel
PICDEM.NET	10BaseT	RS-232	32 kB	Microchip
C7520	10BaseT, 100BaseTX	RS-232, I^2C, Fast SPI	8 MB	IO Limited
Series TINI, (e.g., TBM390)	10BaseT	CAN, RS-232, 1-Wire	1 MB	Maxim, Dallas Semiconductor
Vinci COM	10BaseT	Bluetooth	Compact Flash to 512 MB	Embedded Artist AB (Sweden)
Co-Box-Micro	10BaseT	RS-232	No data	Lantronix
WEB-6590	10BaseT, 100BaseTX	RS-232, USB, IrDA	256 MB	Intel
webDAQ/100*	10BaseT	RS-232	to 64 MB	Capital Equipment Company

*See WebDAQ/100 server operating on-line as a weather station: http://208.218.131.246/.

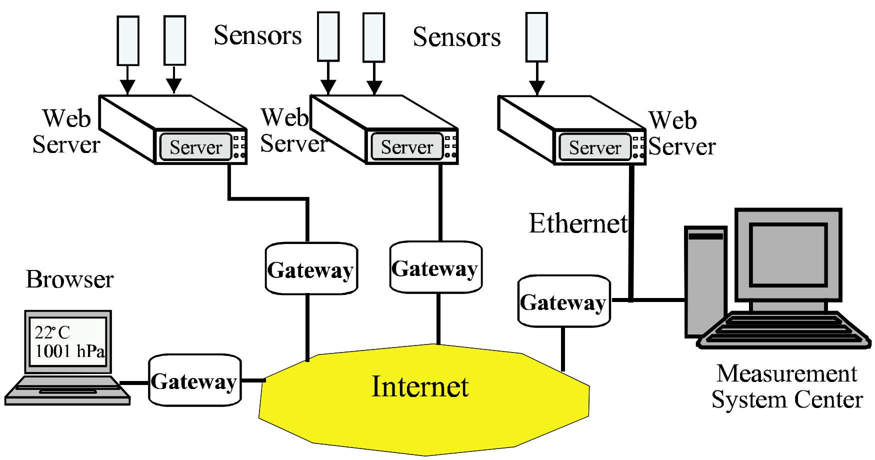

Figure 10.12 Distributed measurement system with embedded Web servers connected to the Internet.

AVR460 Embedded Web Server

An example of an embedded Web server is the AVR460 with built-in 10BaseY Ethernet interface. By means of an RJ-45 connector, the AVR460 circuit can be connected either to a PC with network interface card, or to an Ethernet hub. The AVR460 block diagram shown in Figure 10.13 illustrates the basic structure of an embedded Web server.

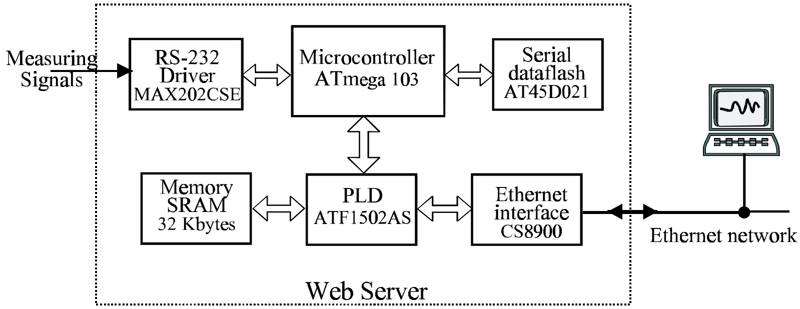

Figure 10.13 Block diagram of AVR460 embedded Web server.

Figure 10.14 AVR460 embedded Web server.

An embedded Web server comprises a microcontroller (Atmel's ATmega 103), an Ethernet interface controller (Cirrus Logic's chip CS8900), a programmable logic device (PLD) (ATF1502AS), and memory chips, supplementing the microcontroller memory. The memory chips determine the amount of information that can be acquired and stored by the server. The AVR460 server is an electronic circuit built on a single printed circuit board, as shown in Figure 10.14.

IEEE-488 Versus Ethernet

The IEEE-488 has been the dominant interface standard in measurement systems for 20 years. However, numerous technical and cost advantages of Ethernet, introduced into the measurement systems, make it an important option to be considered by measurement system developers. Ethernet and IEEE-488 are compared in [2]. Some aspects of these two standards are compared next.

- Maximum transfer rate in the IEEE-488 interface is 1 MBps, with possible enhancement to 8 MBps in transfers using the HS488 protocol and HS488-capable devices (IEEE-488 transfer rate limitations are discussed in Chapter 8). Ethernet allows throughput from 10 Mbps (1.2 MBps) in 10BaseT to 1,000 Mbps (120 MBps) in 1000BaseT. Therefore, transfer rates offered by Ethernet are much higher than those achievable in IEEE-488.
- Maximum cable length between two instruments in the IEEE-488 interface is 2m, against 200m (device-hub-device distance) allowed by Ethernet.
- The price of a 2m IEEE-488 cable is $100, against approximately $10 for 200m of Ethernet cable.
- A plug-in IEEE-488 interface card for a PC costs $400 to $500. Ethernet interface cards are installed in PCs as standard fitting; if an Ethernet interface card is to be purchased, it costs as little as $10 to $20.
- Measurement systems with the IEEE-488 interface require special software, which is developed by means of expensive graphical programming environments, such as LabVIEW or TestPoint (more than $5,000 each). A basic LAN control software is included in Windows, and thus need not be purchased separately. Instruments with either an IEEE-488 or a LAN interface should come supplied with appropriate drivers.
- Expansion of an Ethernet-based measurement system (i.e., increasing the number of devices or the distance between them), involves additional hubs. In an IEEE-488 system, this is achieved by means of expanders or extenders, which are expensive and require special software.
- The number of available instrument models with an IEEE-488 interface or the possibility of its implementation is much higher than the number of instruments with an Ethernet interface.

To sum up, although IEEE-488 is still the dominant interface standard in the field of measurement systems, its predominance in the next five years is seriously threatened by the LAN interface.

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Chapter 11

DAQ Boards and Virtual Instruments

11.1 COMPUTER DAQ BOARDS

11.1.1 Structure and Functions of a DAQ Board

Certain measurement tasks cannot be performed better than by means of a computer measurement board. Combined with a computer and software, such measurement boards makes up a virtual instrument. Due to its extensive data acquisition functionality, a computer measurement board is referred to as Data Acquisition (DAQ) card. Card designations often include additional symbols—DAQBoard designates a board that is designed for installation inside a computer (pluggable onto the PCI or ISA bus); and DAQ PCcard designates a PCMCIA card. The functions of a measurement card involve much more than just A/D conversion [1, 2]. Modern computer DAQ boards provide the following functions:

- Digitize a single signal (voltage or sometimes current) from one of the multiple analog inputs;
- Digitize multiple signals received on multiple analog inputs;
- Perform antialiasing analog filtration of the input signal;
- Set the analog input signal trigger levels and time-outs;
- Present the required signals (voltage or current) onto analog outputs through D/A conversion;
- Read and send digital signals from/to data inputs/outputs (DIO);
- Produce signals of a preset frequency or pulses of a preset duration;
- Measure the input signal frequency or pulse duration;
- Synchronize with the triggering lines of computer-based RTSI real-time systems (optional);
- Store measurement data and configuration settings in the card's memory.

Figure 11.1 shows a functional diagram of a DAQ board. A typical DAQ board consists of an analog multiplexer, a programmable amplifier, a sample-and-hold (S&H) or sample-and-trace (S&T) circuit, an ADC, a DAC, a high quality reference voltage source, a calibration circuit, a triggering block, registers, memory circuits, and a control block. Some boards provide a DMA interface for a direct access to the PC memory, without involving the CPU.

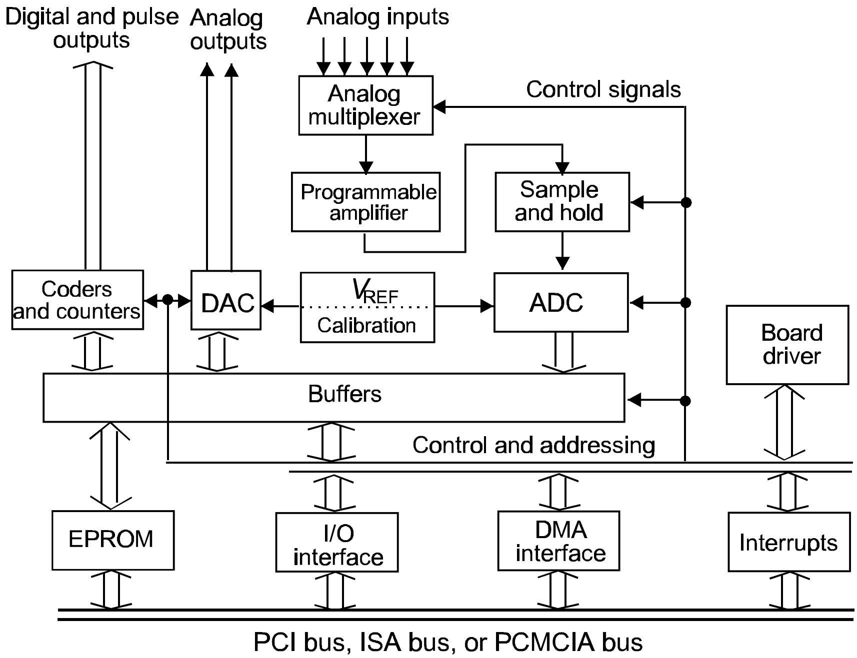

Figure 11.1 Functional diagram of a computer DAQ board.

Compared to conventional digital instruments with an interface circuit, DAQ boards provide the following benefits:

- Support multichannel measurements;
- The same card can be set to function as a digital multimeter, a function generator or an oscilloscope;
- Send analog and digital activation or test signals to the measurement system;
- Require no additional space if plugged into the PCI, ISA, or PCMCIA bus inside a computer.

High-performance HiTech DAQ boards are manufactured by a number of companies, such as National Instruments, Keithley, IOtech, Advantech, and ComputerBoard. The prices range from $1,000 to $5,000. A number of small companies make dedicated DAQ boards or boards providing limited capabilities.

11.1.2 DAQ Board Specifications

The quality of A/D conversion or digital measurement can be quantified as the product of sampling rate and measurement resolution, expressed as the number of bits in a digital word after digitization. DAQ boards provide the highest value of this index [3]. A digital oscilloscope with an ADC providing a resolution higher than 8 bits can be built as a virtual instrument only, using a DAQ board and suitable software (at least the author could not find any corresponding hardware unit in products from Tektronix, LeCroy, Agilent, and Stanford Research System). These two indices can be used to evaluate the performance of DAQ boards. DAQ board specifications include:

- The number of analog inputs (channels) and their types: differential (DI) or single-ended (SE);
- ADC resolution expressed as the number of bits in a digital word;
- Maximum sampling rate;
- Input range and absolute resolution;
- Measurement accuracy;
- On-board EPROM storage capacity;
- The type of PC bus interface.

In addition, a dozen more parameters, usually less important to the user, are specified: the number of analog outputs, their control resolution (number of bits), analog output voltage range, analog output control rate (samples per second) and measurement triggering method (analog or digital), input impedance, input current, common-mode rejection ratio (CMRR), power supply mode, and power consumption.

The number of analog inputs ranges from 1 to 64 (e.g., NI-6031E) and can usually be increased (even up to 256) by adding more analog multiplexers on an additional expansion card. Therefore, a single DAQ board and a PC can be used to build a multipoint measurement system. The number of DI inputs specified is one-half of that of SE inputs. The reason is the number of signal lines being switched by the multiplexer: two lines from each DI input and just one line from each SE input.

The number of bits in a digital word after digitization (bit resolution) ranges from 8 to 24 (e.g., the NI-4350 card for temperature sensors), with the upper range significantly exceeding the resolution of digital instruments within the same price group. Usually, the number of effective bits in a digital word is quoted for the specific board model as the range of values (e.g., from 8 to 16 bits), where the extreme word lengths apply respectively to the lowest sampling rate (the longest word, e.g., 16 bits) and the highest sampling rate (the shortest word, e.g., 8 bits).

Sampling rate, expressed as the number of samples per second (Sps), is what best proves the advantage of a DAQ board–based measurement system against a stand-alone voltmeter-based system. The sampling rate ranges from several thousand Sps to 100 MSps (e.g., NI-5911). The figures quoted in catalogs refer to the conversion capacity of the on-board ADC converter and DSP circuitry (unless specified otherwise). The sampling rate is specified synthetically for the whole multi-input board. When measuring voltage on multiple inputs (channels) of a multichannel board, the maximum sampling rate per input is obtained by dividing the overall sampling rate by the number of active channels. For example, if a board features the maximum overall sampling rate of 1 MSps and has eight active channels, then the maximum sampling rate per channel is 125 kSps. However, if only one channel is active on the same board, then the maximum sampling rate in this channel is 1 MSps.

The input range of a DAQ board is specified as a range of voltage values symmetrical in relation to zero, or as a positive voltage range. On various boards, the input range spans from millivolts to several hundred volts (300V on some DAQ boards from IOtech). The selected input range and bit resolution define the board's *absolute resolution*. Take, for example, the NI-6111E 12-bit board which supports input ranges from ±0.2V to ±42V. In the ±1V range, the absolute resolution of ΔV voltage measurement by means of this board is:

$$\Delta V = \frac{V_{\max} - V_{\min}}{2^{12}} = \frac{1\text{V} - (-1\text{V})}{4{,}096} = 0.488\ \text{mV}$$

Once the input voltage has been amplified by the programmable amplifier with the k_u factor, the absolute resolution improves from ΔV to $\Delta V k_u$. For example, on the Keithley KPCI-3107 multifunction board, the user can set one of the 12 voltage gain values (1, 2, 4, 8, 10, 20, 40, 80, 100, 200, 400, or 800 V/V).

The board's *measurement accuracy* is usually specified in a tabular format, since it depends on a number of factors: the selected input range, temperature, and test period (24 hours, 90 days, or 1 year). According to the theory of measurement, the board's accuracy can be roughly estimated to be between 2 and 10 times worse than its resolution.

On-board memory buffer can be used to store several hundred thousand or even many million samples before uploading the data via the bus to the PC. High sampling rate DAQ boards are provided with EPROM memory to store measurement data samples. In addition to the EPROM for the samples, boards have much smaller memory chips to store the selected configuration and settings. The NI-5112 board incorporates 16 or 32 MB memory buffer per input channel; the NI-5102 board has 663 KB.

The bus interface of the board is another parameter. Boards are available for the following buses: PCI, ISA, PCMCIA (PC Card), USB, or IEEE-1394. PCI, ISA, and PCMCIA boards are designed as plug-in boards for installation inside a PC, as shown in Figure 11.2. USB and IEEE-1394 boards are designed as stand-alone units, to be installed outside a PC and connected via a multiwire cable.

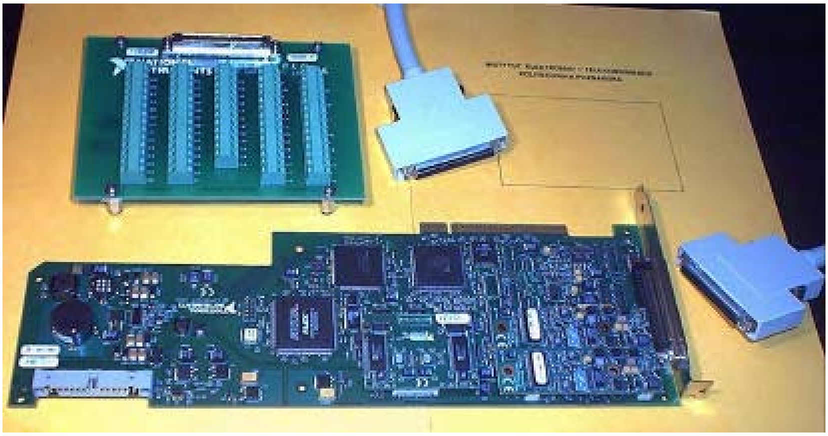

Figure 11.2 DAQ board for the PCI bus, with a connector and a cable.

11.1.3 Selected DAQ Board Model Specifications

This section presents a number of major specifications of two board models chosen as an example: IOtech *DaqBoard/2000* [4] for PCI, and NI DAQCard 6024E [3] for PCMCIA.

DaqBoard/2000 measurement performance.

1. ADC:
   – Successive approximation SAR type;
   – Resolution: 16 bits;
   – Conversion time: 5 μs per input;
   – Maximum sample rate: 200 kSps per input;
   – Nonlinearity: ±1 LSB.
2. Analog inputs:
   – 16 SE inputs or 8 DI inputs;
   – Expandable up to 256 inputs while keeping the 5-μs conversion time per channel (an expansion card required);
   – Input voltage ranges: from ±0.156V to ±10V;
   – Input impedance: R = 10 MΩ (SE) or 20 MΩ (DI);
   – Bias current: < 1 nA;
   – Overvoltage protection: ±35V;
   – CMRR: > 86 dB for gain > 8.
3. Analog outputs:
   – Number of outputs: two;
   – Control resolution: 16 bits;
   – Output voltage range: ±10V;

Table 11.1

DAQBoard/2000 Input Ranges and Relative Processing Error *d*
(Test Period: One year, Temperature Range: 0°C to 35°C) [4]

Input Range	*Error d =* $d_{read} + d_{range}$	*Input Range*	*Error d =* $d_{read} + d_{range}$
0V to +10V	0.015% + 0.005%	±10V	0.015% + 0.005%
0V to +5V	0.015% + 0.005%	±5V	0.015% + 0.005%
0V to +2.5V	0.015% + 0.005%	±2.5V	0.015% + 0.005%
0V to+1.25 V	0.015% + 0.008%	±1.25V	0.015% + 0.005%
0V to +0.625V	0.015% + 0.008%	±0.625V	0.015% + 0.008%
0V to +0.3125V	0.015% + 0.008%	±0.3125V	0.015% + 0.008%

d_{read}: percentage of reading, d_{range}: percentage of range

– Output current: ±10 mA;
– Sample generation frequency range: from 1.5 Hz to 100 kHz.

4. The board's input ranges and accuracy are specified in Table 11.1.
5. Digital and pulse outputs:
   – Number of outputs: 2 × 16 bits;
   – Square wave output signal at 1 MHz base frequency, divided by 1 to 65,535 (programmable);
   – TTL pulse level.
6. Power supply and power consumption:
   – Supply voltage: between 4.75V and 5.25V dc from the PCI bus;
   – Power consumption: 3.5W (up to 10W with external accessories).

DAQCard-6024E for PCMCIA measurement performance (see Figure 11.3).

1. ADC:
   - Successive approximation type;
   – Resolution: 12 bits;
   – Conversion time: 5 μs per input;
   – Maximum sample rate: 200 kSps per input;
   – Nonlinearity: ±0.75 LSB (typical).
2. Analog inputs:
   – 16 SE inputs or 8 DI inputs;
   – Input voltage ranges: ±0.05V, ±0.5V, ±5V, and ±10V, set by selecting the gain factor: 100, 10, 1, or 0.5 V/V (respectively) on the input amplifier;
   – Gain error: ±2.75% without calibration or ±0.02% after calibration;
   - Input impedance: R = 100 GΩ in parallel with C = 100 pF;
   – Bias current < 200 pA;

– Signal input overvoltage protection: ±42V,
– CMRR = 85 dB for gain 0.5 or 1, CMRR = 90 dB for gain 10 or 100.

Figure 11.3 PCMCIA DAQ card: top view and side view of the I/O connector, next to a 1 Polish zloty coin for the comparison of dimensions.

3. Analog outputs:
   – Number of outputs: two;
   – Control resolution: 12 bits;
   – Output voltage range: ±10V;
   – Output current: ±5 mA;
   – Output impedance: 0.1Ω;
   – Sample generation frequency range: 1 kSps.
4. The card's input ranges and accuracy are specified in Table 11.2.
5. Digital and pulse outputs:
   – Number of outputs: 8 TTL pulse outputs;
   – Square wave output signal at 10 MHz or 100 kHz base frequency, programmable 4-bit frequency scaler;
   – Maximum frequency: 20 MHz, minimum pulse duration: 10 ns.
6. Power supply and power consumption:
   – Supply voltage: between 4.74V and 5.25V dc from the PCMCIA;
   – Power consumption: 1.35W (supply current: 270 mA).

Table 11.2

DAQCard-6024E Input Ranges and Relative A/D Processing Error *d* (Test Period: One Year)

Input Range	±10V	±5V	±0.5V	±0.05V
Error $d = d_{read} + d_{range}$	0.0914% +0.005%	0.0314% +0.005%	0.0914% +0.005%	0.0914% +0.005%

d_{read}: percentage of reading, d_{range}: percentage of range

11.2 VIRTUAL INSTRUMENTS

Combined with a PC and software, a DAQ board makes up a virtual instrument [6], as shown in Figure 11.4. Unlike "virtual reality," or imitation world that can be experienced through computer peripherals (e.g., screen, speakers), a virtual instrument is an actual appliance. It is "virtual" because you need to use a computer interface (e.g., screen, keyboard, and mouse) to communicate with this appliance, and because the board is hidden inside the PC (except external boards with the USB or IEEE-1394 interface). A virtual instrument has input terminals to connect input signals. Virtual instruments usually provide better measurement performance or utility characteristics than their conventional digital counterparts. In a virtual instrument, readings are displayed on the computer screen, and manual adjustment of settings, such as input range or trigger level, is performed using the mouse.

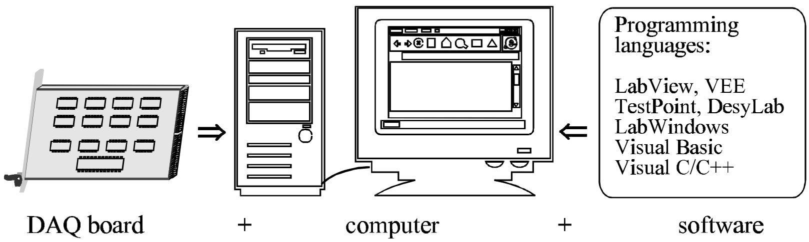

Figure 11.4 The structure of a virtual instrument.

While the computer DAQ board concept raises no controversy, there are various definitions of the virtual instrument category. In addition to the "virtual instrument = DAQ board + computer + software" concept described above, the following are sometimes classified as virtual instruments:

- A computer-based measurement system incorporating one or more instruments (such as a digital voltmeter), interfaced to a computer and operated remotely from a GUI control panel, by means of computer peripherals;
- Measurement simulation software whose graphical form (control panel) may be identical to actual measurement systems.

We opt for the narrower meaning of the virtual instrument concept. Although we do not question the usefulness of simulation software for teaching purposes, we do not classify it in the instrument category. Furthermore, we believe that remote operation of an instrument (e.g., a digital voltmeter), interfaced to a computer does not necessarily make it a virtual instrument. There are usually two operating modes available: remote or local, as in the IEEE-488 system.

Instead of a DAQ board, a virtual instrument can incorporate stand-alone devices, interfaced to the chosen PC bus, via cable and providing the same functionality as a DAQ board. Such data acquisition devices are often delivered under brand names, such as WaveBook (designed for PC operation only), or LogBook (operating as a PC peripheral or stand-alone) from IOtech [4].

Figure 11.5 Two types of DAQ board connectors: (left) with terminals and BNC coax connectors, and (right) with screw terminals for unshielded cables.

In addition to a computer, a DAQ board and a connector, as shown in Figure 11.5, virtual instrument-based measurement system hardware may and usually does include additional components:

- A conditioner card to match the input levels to the DAQ board's input range;
- A conditioner card for temperature, pressure, or displacement sensors;
- Expansion cards to provide additional analog inputs, high-voltage inputs, or low-voltage inputs;
- An optically isolated analog/digital input card;
- A BNC coax input card;
- A lowpass filter card or other cards.

Figure 11.6 shows a measurement system with a virtual instrument and additional cards. An adapter board is used to connect more than one conditioner card or expansion card to the DAQ board input. A virtual instrument-based measurement system, as shown in Figure 11.6, can be used to measure and process various physical quantities (e.g., temperature, pressure, or displacement) and electrical signals spanning a wide range, by means of limited technical resources. The measurement performance of such a system depends not only on the specifications of the boards used, but also on the characteristics of the system's application software. By using signal filtration and averaging, statistical calculations, and other procedures, the quality of final measurement results may be significantly improved.

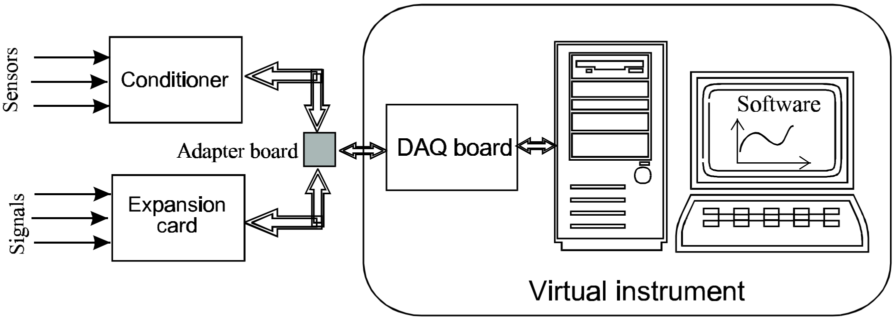

Figure 11.6 A virtual instrument–based measurement system.

11.3 PROGRAMMING OF MEASUREMENT SYSTEMS AND VIRTUAL INSTRUMENTS

Software is an indispensable part of a computer-based measurement system and of a virtual instrument. High-level graphical programming languages, known as measurement system development environments, provide extensive software development capabilities and make it easy to program a measurement system or a virtual instrument. Furthermore, the major instrumentation manufacturers offer proprietary programming languages (environments), such as LabVIEW or LabWindows from National Instruments, VEE (formerly HP VEE) from Agilent Technologies, and TestPoint from Keithley. All these languages have a number of advantages but they are rather expensive. The price is several thousand dollars for a basic version.

Graphically rich general-purpose programming languages, such as Visual C++ or Visual Basic, and commands from the list of Standard Commands for Programmable Instruments (SCPI) [7], can also be used to develop virtual instrument software.

LabVIEW, LabWindows, VEE, and TestPoint all come with libraries of drivers for specific instruments, such as multimeters, digital oscilloscopes, analyzers, DAQ boards, and generators. Instrumentation manufacturers ensure that the drivers for their instruments are available in the libraries of most popular development environments. The development issues are so elaborate that each package comes with a two-volume documentation and requires a comprehensive manual.

11.3.1 Software Development in the LabVIEW Environment

The principles of developing measurement system (or virtual instrument) software in a development environment are described briefly in the example of using LabVIEW to build a virtual instrument (a spectrum analyzer) with a DAQ board [5]. Each software developed in LabVIEW consists of two main parts:

- The Graphical User Interface (GUI), which provides an integrated front panel of the instruments making up the measurement system or virtual instrument. Figure 11.7 shows a sample front panel of a virtual spectrum analyzer in LabVIEW 7.
- The functional diagram (block diagram), which maps the function block icons and relations between these function blocks of the virtual instrument. See Figure 11.8 for a block diagram of a spectrum analyzer. This block diagram is the source code of the virtual instrument control program.

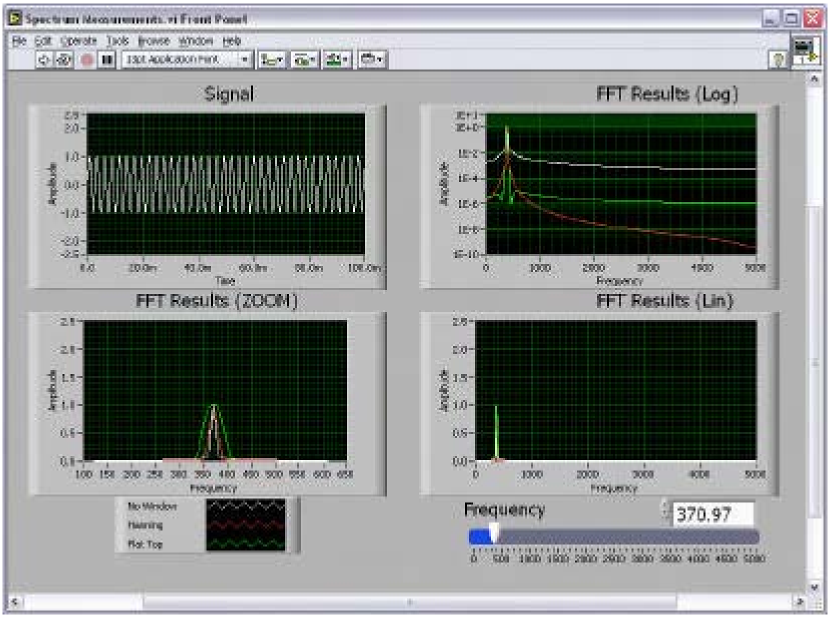

Figure 11.7 Graphical User Interface of the Virtual Instrument spectrum analyzer in LabVIEW 7. (Courtesy of National Instruments.)

To write a program in LabVIEW, a block diagram is created by dragging and dropping object icons or function icons from the *All Functions* palette, as shown in Figure 11.9, and the *All Controls* palette, as shown in Figure 11.10, onto the panel.

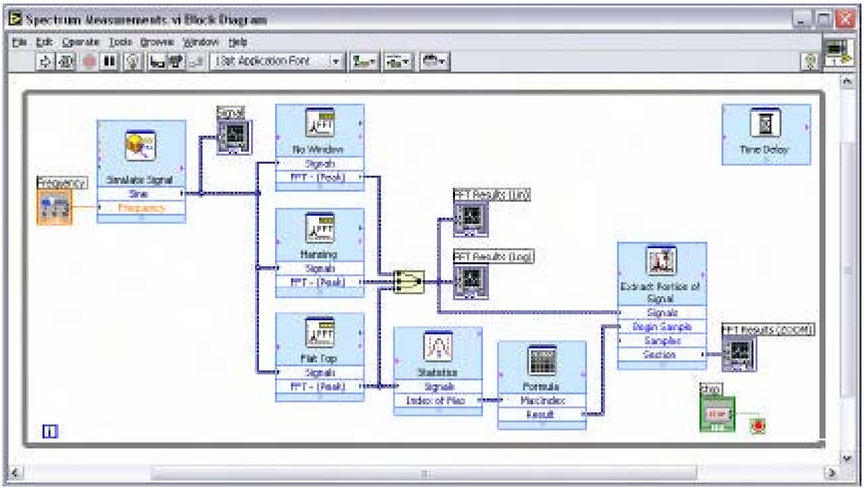

Figure 11.8 Block diagram of a virtual spectrum analyzer in LabVIEW 7. (Courtesy of National Instruments.)

Figure 11.9 *All Functions* palette in LabVIEW 7. (Courtesy of National Instruments.)

Many of these functions in the diagram can be expanded on multiple levels to set their required properties. Surrounding the selected objects with a loop forces a conditional execution or repetition of the selected operations, corresponding to the effect of *if* or *while* instructions known from other programming languages [5].

Instrument drivers which are necessary for the program to run should be stored in the LabVIEW driver library. Once the icon of a specific instrument is placed on the system diagram, as shown in Figure 11.8, the program will use that instrument's driver at runtime. Figure 11.11 shows the expanded view of program menus that must be invoked to insert the HP34401A digital multimeter driver from Hewlett-Packard into the system.

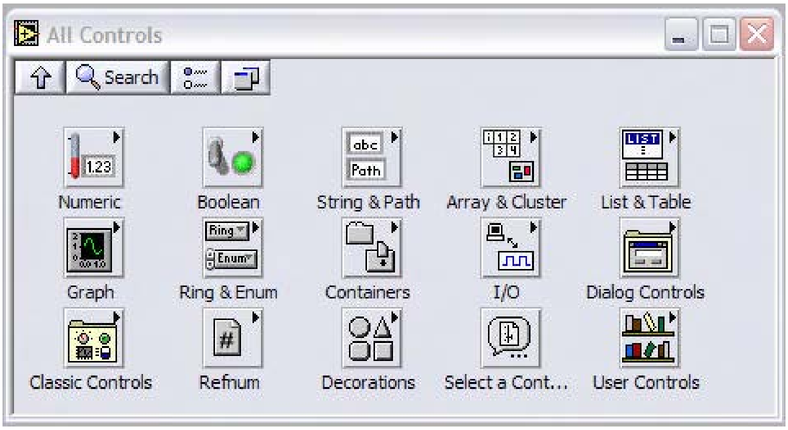

Figure 11.10 *All Controls* palette in LabVIEW 7. (Courtesy of National Instruments.)

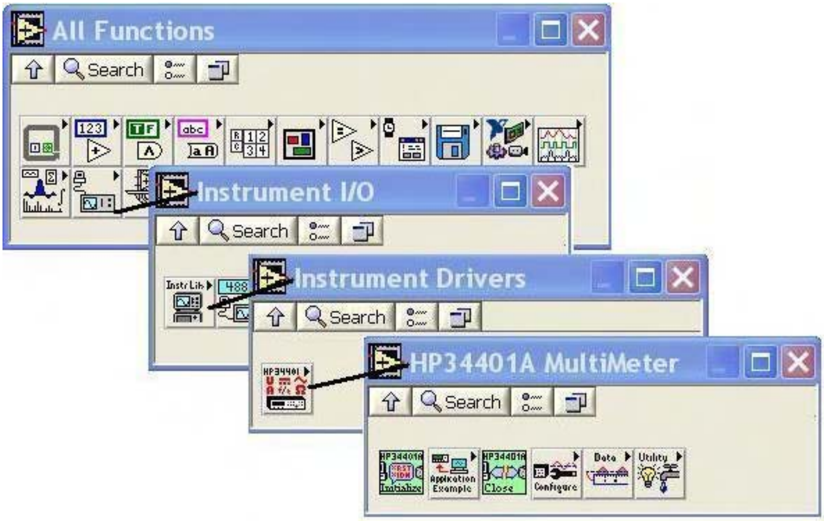

Figure 11.11 Inserting instrument drivers in LabVIEW 7. (Courtesy of National Instruments.)

Creating control programs in *VEE* or *TestPoint* is similar to the technique described earlier.

11.3.2 Programming of LAN-Based and Internet-Based Measurement Systems

DataSocket

Special communication technologies are used in the programming of measurement systems that use data communication over a LAN or the Internet. The most common include DataSocket, ActiveX, and LabVIEW Web Server. To use these functions, choose: All Functions ⇒ Communication ⇒ ActiveX, DataSocket, as shown in Figure 11.12.

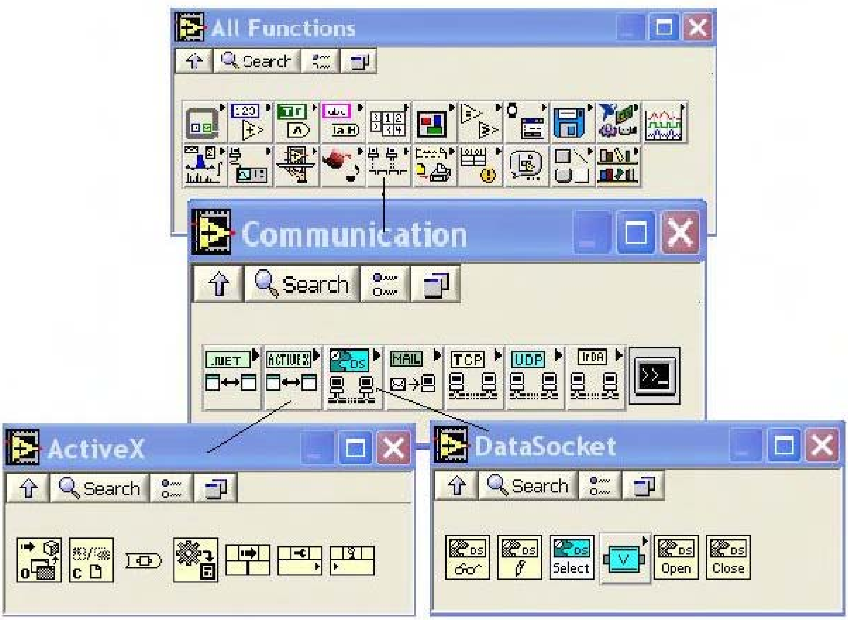

Figure 11.12 *ActiveX* and *DataSocket* functions in LabVIEW 7. (Courtesy of National Instruments.)

DataSocket supports the following functions in a network-based measurement system:

- Data acquisition from multiple measurement servers/nodes (PC + DAQ) by a single host;
- Data publishing from a single node to multiple network users;
- Data publishing from multiple nodes to multiple users;
- DataSocket uses TCP (Transmission Control Protocol), however the programmer need not learn the TCP, as Data Socket is just a component used during high level language programming.

ActiveX

ActiveX controls can be used to program network communication with instruments, to process measurement data, and to display the results. ActiveX functions are available in the LabVIEW and VEE environments. On the client end in a network-based measurement system (see Section 10.4), ActiveX controls can be used to create graphical images of actual instrument or system panels, and to program their functions. The measurement node computer, which is a network server, receives requests from the system clients, executes them, and returns the results. ActiveX controls can be created as new programs (user-drawn controls), as an extension of the programs already existing on the server (by adding new properties, operations, or functions), or by compiling off-the-shelf control components delivered with the development environment compiler. ActiveX controls provide significantly more capabilities than merely viewing the measurement results from a remote instrument.

LabVIEW Web Server

One of the features of the LabVIEW development environment is that the Web server can be used to convert the measurement system or virtual instrument GUI into an HTML file and share it in the network, where it can be viewed from a standard Web browser. To use the LabVIEW Web Server, choose: Edit ⇒ Preferences ⇒ Web Server. The Web Publishing Tool in LabVIEW 7 is shown in Figure 11.13.

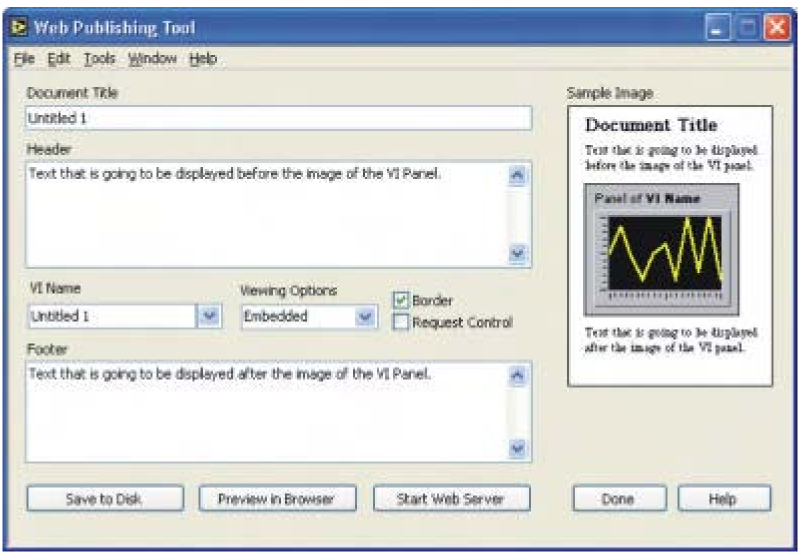

Figure 11.13 *Web Publishing Tool* in LabVIEW 7. (Courtesy of National Instruments.)

The Web Server provides three windows for the user:

- Configuration (basic configuration settings);
- Browser Access (the list of machines and domains that have access to the data server);
- Visible VIs (the list of virtual instruments available on the server).

There are three options to make a virtual instrument on the server available to any browser: as a front panel image (GUI), as a panel animation, or as an HTML document with the panel image.

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[7] http://www.scpiconsortium.org/scpistandard.htm.

Acronyms and Abbreviations

AD	Analog Devices Company
A/D	Analog-to-digital conversion
ADC	Analog-to-digital converter
ARQ	Automatic Repeat reQuest
ASK	Amplitude Shift Keying
B-ISDN	Broadband Integrated Services Digital Network
CAMAC	Computer Aided Measurement And Control
CAN	Controller Area Network, the standard of a serial interface for automotive and industrial applications
CMOS	Complementary Metal-Oxide-Semiconductor field effect transistor, technology for semiconductor devices
CMRR	Common Mode Rejection Ratio coefficient
CRC	Cyclic Redundancy Check
DAC	Digital-to-analog converter
D/A	Digital-to-analog conversion
DAQ	Data Acquisition Board or Data Acquisition Card
DCE	Data Communication Equipment
DIO	Data Input Output signals and lines
DMA	Direct Memory Access
DTE	Data Terminal Equipment
EDGE	Enhanced Data rates for GSM Evolution, transmission mode in GSM
EMF	ElectroMotive Force
Ethernet	Standard of a local computer network
FSK	Frequency Shift Keying
GPIB	General Purpose Interface Bus, the generic name for the IEEE-488 interface standard
GPRS	General Packet Radio Service
GSM	Global System of Mobile Communications
HDLC	High-level Data Link Control protocol
HP	Hewlett-Packard company
HSCSD	High-Speed Circuit Switched Data

IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IrDA	Infrared Data Association
ISA	Industry Standard Architecture bus
ISDN	Integrated Services Digital Network
ISM	Industry, Science, and Medicine, license-free frequency band for transmission
ITS-90	International Temperature Scale of 1990
LabVIEW	High level programming language
LAN	Local Area Network, computer network
LSB	Least Significant Bit
MAN	Metropolitan Area Network, computer network
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
MSB	Most Significant Bit
MXI	Multisystem eXtension Interface
NI	National Instruments
NS	National Semiconductor
PCI	Peripheral Component Interconnect bus
PCMCIA	Personal Computer Memory Card International Association
PDM	Pulse Duration Modulation
PLC	Power Line Communication
PROFIBUS	PROcess FIeld BUS, family of standards for data control and data exchange in industrial distributed systems
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
PXI	PCI eXtension for Instrumentation, standard for crate systems
PUT	Poznan University of Technology, Poland
QAM	Quadrature Amplitude Modulation
RS	Recommended Standard, serial interface standards
SAR	Successive Approximation Register, analog-to-digital conversion mode
SCPI	Standard Commands for Programmable Instruments
S&H	Sample and Hold circuit
S&T	Sample and Trace circuit
TCP/IP	Transmission Control Protocol/Internet Protocol
UART	Universal Asynchronous Receiver Transmitter
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
VEE	Visual Environment Engineering, high level programming language
VXI	VME eXtension for Instrumentation, standard for modular systems

About the Author

Waldemar Nawrocki is a professor of electronics at the Institute of Electronics and Telecommunications, Poznan University of Technology, in Poznan, Poland, where he earned a Ph.D. in technical sciences. Dr. Nawrocki also holds a D.Sc. in physics from Friedrich Schiller University in Jena, Germany.

He is an expert in computer-based measurement systems, in quantum metrology, and in thermometry. He has published six books, all in Polish: *Electronic Measurement Systems* (1983, coauthor D. Bartkiewicz), *Noise Thermometry* (1995), *Electronic Circuits* (1999, coauthors K. Arnold and K. Lange), *Sensors and Measurement Systems* (2001), *Computer-Based Measurement Systems* (2002), and *Quantum Effects in Electric Metrology* (2003, coauthor M. Wawrzyniak).

For short periods he was a visiting professor at Istituto di Metrologia in Torino, Italy, and at the Polish-French High School for Computer Sciences and Telecommunications in Poznan.

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