

A One-Page Introduction for Each Important Feature

CAMI Research Inc.

(Developer of CAMI Research's **CableEye** continuity & hipot Cable & Harness test systems)

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What is Data Communications?

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The distance over which data moves within a computer may vary from a few thousandths of an inch, as is the case within a single IC chip, to as much as several feet along the backplane of the main circuit board. Over such small distances, digital data may be transmitted as direct, two-level electrical signals over simple copper conductors. Except for the fastest computers, circuit designers are not very concerned about the shape of the conductor or the analog characteristics of signal transmission.

Frequently, however, data must be sent beyond the local circuitry that constitutes a computer. In many cases, the distances involved may be enormous. Unfortunately, as the distance between the source of a message and its destination increases, accurate transmission becomes increasingly difficult. This results from the electrical distortion of signals traveling through long conductors, and from noise added to the signal as it propagates through a transmission medium. Although some precautions must be taken for data exchange within a computer, the biggest problems occur when data is transferred to devices outside the computer's circuitry. In this case, distortion and noise can become so severe that information is lost.

Data Communications concerns the transmission of digital messages to devices external to the message source. "External" devices are generally thought of as being independently powered circuitry that exists beyond the chassis of a computer or other digital message source. As a rule, the maximum permissible transmission rate of a message is directly proportional to signal power, and inversely proportional to channel noise. It is the aim of any communications system to provide the highest possible transmission rate at the lowest possible power and with the least possible noise.

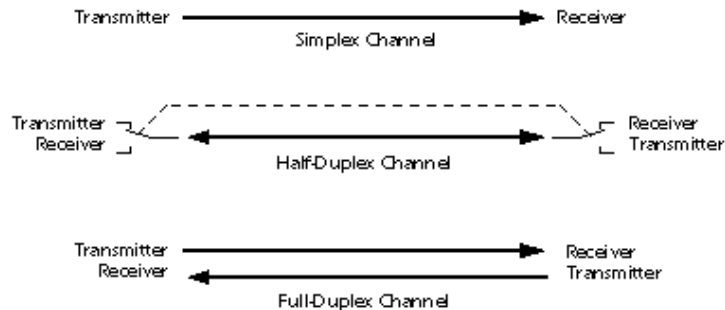
Communications Channels

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A communications channel is a pathway over which information can be conveyed. It may be defined by a physical wire that connects communicating devices, or by a radio, laser, or other radiated energy source that has no obvious physical presence. Information sent through a communications channel has a source from which the information originates, and a destination to which the information is delivered. Although information originates from a single source, there may be more than one destination, depending upon how many receive stations are linked to the channel and how much energy the transmitted signal possesses.

In a digital communications channel, the information is represented by individual data bits, which may be encapsulated into multibit message units. A byte, which consists of eight bits, is an example of a message unit that may be conveyed through a digital communications channel. A collection of bytes may itself be grouped into a frame or other higher-level message unit. Such multiple levels of encapsulation facilitate the handling of messages in a complex data communications network.

Any communications channel has a direction associated with it:

Channel Types

The message source is the transmitter, and the destination is the receiver. A channel whose direction of transmission is unchanging is referred to as a simplex channel. For example, a radio station is a simplex channel because it always transmits the signal to its listeners and never allows them to transmit back.

A half-duplex channel is a single physical channel in which the direction may be reversed. Messages may flow in two directions, but never at the same time, in a half-duplex system. In a telephone call, one party speaks while the other listens. After a pause, the other party speaks and the first party listens. Speaking simultaneously results in garbled sound that cannot be understood.

A full-duplex channel allows simultaneous message exchange in both directions. It really consists of two simplex channels, a forward channel and a reverse channel, linking the same points. The transmission rate of the reverse channel may be slower if it is used only for flow control of the forward channel.

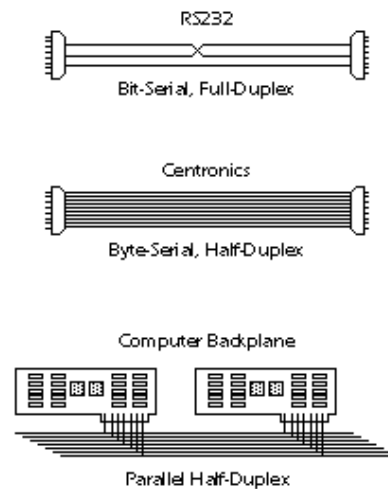
Serial Communications

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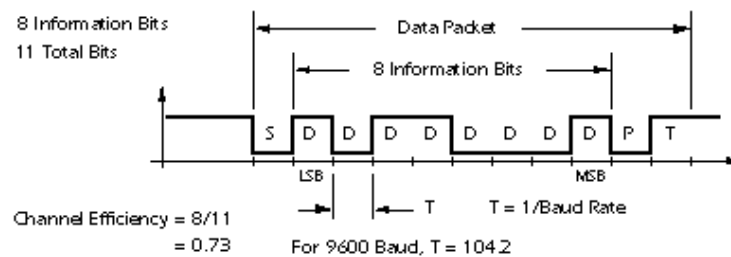
Most digital messages are vastly longer than just a few bits. Because it is neither practical nor economic to transfer all bits of a long message simultaneously, the message is broken into smaller parts and transmitted sequentially. Bit-serial transmission conveys a message one bit at a time through a channel. Each bit represents a part of the message. The individual bits are then reassembled at the destination to compose the message. In general, one channel will pass only one bit at a time. Thus, bit-serial transmission is necessary in data communications if only a single channel is available. Bit-serial transmission is normally just called serial transmission and is the chosen communications method in many computer peripherals.

Byte-serial transmission conveys eight bits at a time through eight parallel channels. Although the raw transfer rate is eight times faster than in bit-serial transmission, eight channels are needed, and the cost may be as much as eight times higher to transmit the message. When distances are short, it may nonetheless be both feasible and economic to use parallel channels in return for high data rates. The popular Centronics printer interface is a case where byte-serial transmission is used. As another

example, it is common practice to use a 16-bit-wide data bus to transfer data between a microprocessor and memory chips; this provides the equivalent of 16 parallel channels. On the other hand, when communicating with a timesharing system over a modem, only a single channel is available, and bit-serial transmission is required. This figure illustrates these ideas:



The baud rate refers to the signalling rate at which data is sent through a channel and is measured in electrical transitions per second. In the EIA232 serial interface standard, one signal transition, at most, occurs per bit, and the baud rate and bit rate are identical. In this case, a rate of 9600 baud corresponds to a transfer of 9,600 data bits per second with a bit period of 104 microseconds ($1/9600$ sec.). If two electrical transitions were required for each bit, as is the case in non-return-to-zero coding, then at a rate of 9600 baud, only 4800 bits per second could be conveyed. The channel efficiency is the number of bits of useful information passed through the channel per second. It does not include framing, formatting, and error detecting bits that may be added to the information bits before a message is transmitted, and will always be less than one.



The data rate of a channel is often specified by its bit rate (often thought erroneously to be the same as baud rate). However, an equivalent measure channel capacity is bandwidth. In general, the maximum data rate a channel can support is directly proportional to the channel's bandwidth and inversely proportional to the channel's noise level.

A communications protocol is an agreed-upon convention that defines the order and meaning of bits in a serial transmission. It may also specify a procedure for exchanging messages. A protocol will define how many data bits compose a message unit, the framing and formatting bits, any error-detecting bits that may be added, and other information that governs control of the communications hardware. Channel efficiency is determined by the protocol design rather than by digital hardware considerations.

Note that there is a tradeoff between channel efficiency and reliability - protocols that provide greater immunity to noise by adding error-detecting and -correcting codes must necessarily become less efficient.

Asynchronous vs. Synchronous Transmission

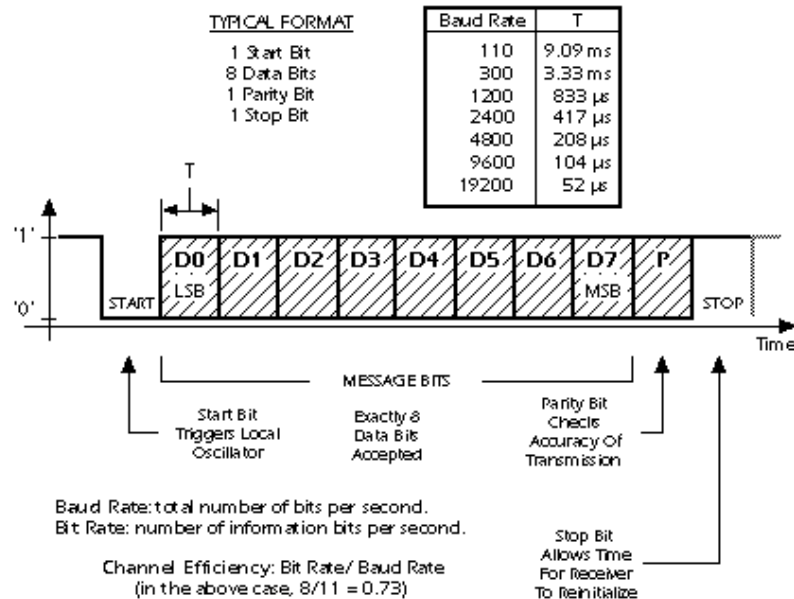
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Serialized data is not generally sent at a uniform rate through a channel. Instead, there is usually a burst of regularly spaced **binary** data bits followed by a pause, after which the data flow resumes. Packets of **binary** data are sent in this manner, possibly with variable-length pauses between packets, until the message has been fully transmitted. In order for the receiving end to know the proper moment to read individual **binary** bits from the channel, it must know exactly when a packet begins and how much time elapses between bits. When this timing information is known, the receiver is said to be synchronized with the transmitter, and accurate data transfer becomes possible. Failure to remain synchronized throughout a transmission will cause data to be corrupted or lost.

Two basic techniques are employed to ensure correct synchronization. In synchronous systems, separate channels are used to transmit data and timing information. The timing channel transmits clock pulses to the receiver. Upon receipt of a clock pulse, the receiver reads the data channel and latches the bit value found on the channel at that moment. The data channel is not read again until the next clock pulse arrives. Because the transmitter originates both the data and the timing pulses, the receiver will read the data channel only when told to do so by the transmitter (via the clock pulse), and synchronization is guaranteed.

Techniques exist to merge the timing signal with the data so that only a single channel is required. This is especially useful when synchronous transmissions are to be sent through a modem. Two methods in which a data signal is self-timed are nonreturn-to-zero and biphase Manchester coding. These both refer to methods for encoding a data stream into an electrical waveform for transmission.

In asynchronous systems, a separate timing channel is not used. The transmitter and receiver must be preset in advance to an agreed-upon baud rate. A very accurate local oscillator within the receiver will then generate an internal clock signal that is equal to the transmitter's within a fraction of a percent. For the most common serial protocol, data is sent in small packets of 10 or 11 bits, eight of which constitute message information. When the channel is idle, the signal voltage corresponds to a continuous logic '1'. A data packet always begins with a logic '0' (the start bit) to signal the receiver that a transmission is starting. The start bit triggers an internal timer in the receiver that generates the needed clock pulses. Following the start bit, eight bits of message data are sent bit by bit at the agreed upon baud rate. The packet is concluded with a parity bit and stop bit. One complete packet is illustrated below:



The packet length is short in asynchronous systems to minimize the risk that the local oscillators in the receiver and transmitter will drift apart. When high-quality crystal oscillators are used, synchronization can be guaranteed over an 11-bit period. Every time a new packet is sent, the start bit resets the synchronization, so the pause between packets can be arbitrarily long. Note that the EIA232 standard defines electrical, timing, and mechanical characteristics of a serial interface. However, it does not include the asynchronous serial protocol shown in the previous figure, or the ASCII alphabet described next.

The ASCII Character Set

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Characters sent through a serial interface generally follow the ASCII (American Standard Code for Information Interchange) character standard:

Nonprintable Control Characters		Special Symbols	Numbers, Special Symbols	Upper-Case Alphabet		Lower-Case Alphabet	
00 NUL	10 DLE	20 SP	30 0	40 @	50 P	60 .	70 p
01 SOH	11 DC1	21 !	31 1	41 A	51 Q	61 a	71 q
02 STX	12 DC2	22 "	32 2	42 B	52 R	62 b	72 r
03 ETX	13 DC3	23 =	33 3	43 C	53 S	63 c	73 s
04 EOT	14 DC4	24 \$	34 4	44 D	54 T	64 d	74 t
05 ENG	15 NAK	25 %	35 5	45 E	55 U	65 e	75 u
06 ACK	16 SYN	26 &	36 6	46 F	56 V	66 f	76 v
07 BEL	17 ETB	27 '	37 7	47 G	57 W	67 g	77 w
08 BS	18 CAN	28 (	38 8	48 H	58 X	68 h	78 x
09 HT	19 EM	29)	39 9	49 I	59 Y	69 i	79 y
0A LF	1A SUB	2A *	3A :	4A J	5A Z	6A j	7A z
0B VT	1B ESC	2B +	3B ;	4B K	5B [	6B k	7B {
0C FF	1C FS	2C ,	3C <	4C L	5C \	6C l	7C
0D CR	1D GS	2D _	3D =	4D M	5D]	6D m	7D }
0E SO	1E RS	2E .	3E >	4E N	5E ^	6E n	7E ~
0F SI	1F VS	2F /	3F ?	4F O	5F #	6F o	7F DEL

This standard relates **binary** codes to printable characters and control codes. Fully 25 percent of the ASCII character set represents nonprintable control codes, such as carriage return (CR) and line feed (LF). Most modern character-oriented peripheral equipment abides by the ASCII standard, and thus may be used interchangeably with different computers.

Parity and Checksums

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Noise and momentary electrical disturbances may cause data to be changed as it passes through a communications channel. If the receiver fails to detect this, the received message will be incorrect, resulting in possibly serious consequences. As a first line of defense against data errors, they must be detected. If an error can be flagged, it might be possible to request that the faulty packet be resent, or to at least prevent the flawed data from being taken as correct. If sufficient redundant information is sent, one- or two-bit errors may be corrected by hardware within the receiver before the corrupted data ever reaches its destination.

A parity bit is added to a data packet for the purpose of error detection. In the even-parity convention, the value of the parity bit is chosen so that the total number of '1' digits in the combined data plus parity packet is an even number. Upon receipt of the packet, the parity needed for the data is recomputed by local hardware and compared to the parity bit received with the data. If any bit has changed state, the parity will not match, and an error will have been detected. In fact, if an odd number of bits (not just one) have been altered, the parity will not match. If an even number of bits have been reversed, the parity will match even though an error has occurred. However, a statistical

analysis of data communication errors has shown that a single-bit error is much more probable than a multibit error in the presence of random noise. Thus, parity is a reliable method of error detection.

Even-Parity Computation

Data	Parity Bit
1 0 1 1 0 0 0 1	0
1 0 0 0 0 1 1 0	1

Another approach to error detection involves the computation of a checksum. In this case, the packets that constitute a message are added arithmetically. A checksum number is appended to the packet sequence so that the sum of data plus checksum is zero. When received, the packet sequence may be added, along with the checksum, by a local microprocessor. If the sum is nonzero, an error has occurred. As long as the sum is zero, it is highly unlikely (but not impossible) that any data has been corrupted during transmission.

Checksum Computation

$$\begin{array}{r}
 \begin{array}{r}
 1\ 0\ 1\ 1\ 0\ 0\ 0\ 1 \\
 1\ 0\ 0\ 0\ 0\ 1\ 1\ 0 \\
 0\ 1\ 0\ 0\ 1\ 1\ 0\ 0 \\
 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1 \\
 +\ 1\ 0\ 1\ 0\ 0\ 0\ 0\ 0 \\
 \hline
 0\ 0\ 1\ 1\ 0\ 0\ 1\ 0\ 0\ 0\ 1\ 0 \\
 \end{array}
 \begin{array}{l}
 \left. \begin{array}{c} \\ \\ \\ \\ \end{array} \right\} \text{Data} \\
 \text{Arithmetic Sum} \\
 \text{Sum Truncated to 8 Bits} \\
 \begin{array}{r}
 0\ 0\ 1\ 0\ 0\ 0\ 1\ 0 \\
 +\ 1\ 1\ 0\ 1\ 1\ 1\ 1\ 0 \\
 \hline
 \text{(mod 256)}\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0
 \end{array}
 \end{array}
 \begin{array}{l}
 \\
 \\
 \text{Checksum} \\
 \text{Sum plus Checksum Equal Zero}
 \end{array}
 \end{array}$$

Errors may not only be detected, but also corrected if additional code is added to a packet sequence. If the error probability is high or if it is not possible to request retransmission, this may be worth doing. However, including error-correcting code in a transmission lowers channel efficiency, and results in a noticeable drop in channel throughput.

Data Compression

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If a typical message were statistically analyzed, it would be found that certain characters are used much more frequently than others. By analyzing a message before it is transmitted, short **binary** codes may be assigned to frequently used characters and longer codes to rarely used characters. In doing so, it is possible to reduce the total number of characters sent without altering the information in the message. Appropriate decoding at the receiver will restore the message to its original form. This procedure, known as data compression, may result in a 50 percent or greater savings in the amount of data transmitted. Even though time is necessary to analyze the message before it is transmitted, the savings may be great enough so that the total time for compression, transmission, and decompression will still be lower than it would be when sending an uncompressed message.

Some kinds of data will compress much more than others. Data that represents images, for example, will usually compress significantly, perhaps by as much as 80 percent over its original size. Data representing a computer program, on the other hand, may be reduced only by 15 or 20 percent.

A compression method called Huffman coding is frequently used in data communications, and particularly in fax transmission. Clearly, most of the image data for a typical business letter represents white paper, and only about 5 percent of the surface represents black ink. It is possible to send a single code that, for example, represents a consecutive string of 1000 white pixels rather than a separate code for each white pixel. Consequently, data compression will significantly reduce the total message length for a faxed business letter. Were the letter made up of randomly distributed black ink covering 50 percent of the white paper surface, data compression would hold no advantages.

Data Encryption

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Privacy is a great concern in data communications. Faxed business letters can be intercepted at will through tapped phone lines or intercepted microwave transmissions without the knowledge of the sender or receiver. To increase the security of this and other data communications, including digitized telephone conversations, the **binary** codes representing data may be scrambled in such a way that unauthorized interception will produce an indecipherable sequence of characters. Authorized receive stations will be equipped with a decoder that enables the message to be restored. The process of scrambling, transmitting, and descrambling is known as encryption.

Custom integrated circuits have been designed to perform this task and are available at low cost. In some cases, they will be incorporated into the main circuitry of a data communications device and function without operator knowledge. In other cases, an external circuit is used so that the device, and its encrypting/decrypting technique, may be transported easily.

Data Storage Technology

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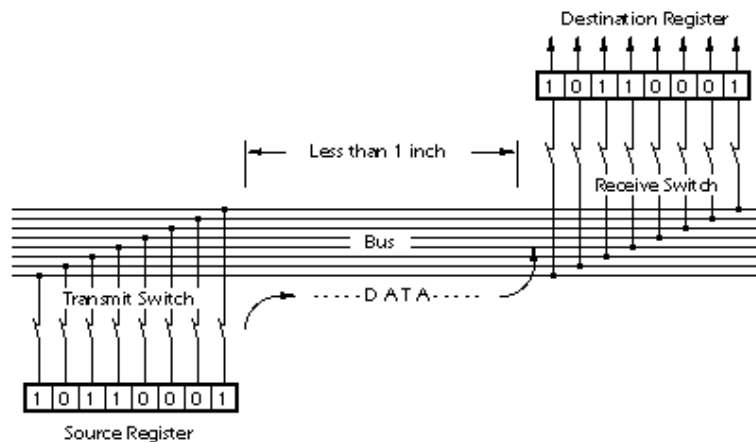
Normally, we think of communications science as dealing with the contemporaneous exchange of information between distant parties. However, many of the same techniques employed in data

communications are also applied to data storage to ensure that the retrieval of information from a storage medium is accurate. We find, for example, that similar kinds of error-correcting codes used to protect digital telephone transmissions from noise are also used to guarantee correct readback of digital data from compact audio disks, CD-ROMs, and tape backup systems.

Data Transfer in Digital Circuits

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Data is typically grouped into packets that are either 8, 16, or 32 bits long, and passed between temporary holding units called registers. Data within a register is available in parallel because each bit exits the register on a separate conductor. To transfer data from one register to another, the output conductors of one register are switched onto a channel of parallel wires referred to as a bus. The input conductors of another register, which is also connected to the bus, capture the information:



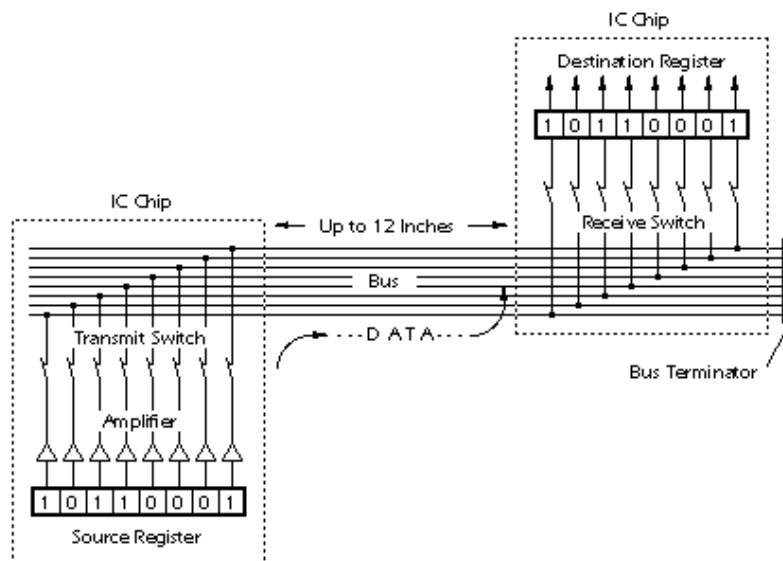
Following a data transaction, the content of the source register is reproduced in the destination register. It is important to note that after any digital data transfer, the source and destination registers are equal; the source register is not erased when the data is sent.

The transmit and receive switches shown above are electronic and operate in response to commands from a central control unit. It is possible that two or more destination registers will be switched on to receive data from a single source. However, only one source may transmit data onto the bus at any time. If multiple sources were to attempt transmission simultaneously, an electrical conflict would occur when bits of opposite value are driven onto a single bus conductor. Such a condition is referred to as a bus contention. Not only will a bus contention result in the loss of information, but it also may damage the electronic circuitry. As long as all registers in a system are linked to one central control unit, bus contentions should never occur if the circuit has been designed properly. Note that the data buses within a typical microprocessor are fundamentally half-duplex channels.

Transmission over Short Distances (< 2 feet)

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When the source and destination registers are part of an integrated circuit (within a microprocessor chip, for example), they are extremely close (thousandths of an inch). Consequently, the bus signals are at very low power levels, may traverse a distance in very little time, and are not very susceptible to external noise and distortion. This is the ideal environment for digital communications. However, it is not yet possible to integrate all the necessary circuitry for a computer (i.e., CPU, memory, disk control, video and display drivers, etc.) on a single chip. When data is sent off-chip to another integrated circuit, the bus signals must be amplified and conductors extended out of the chip through external pins. Amplifiers may be added to the source register:

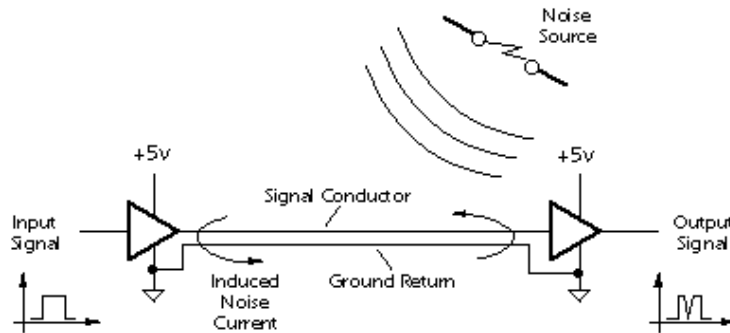


Bus signals that exit microprocessor chips and other VLSI circuitry are electrically capable of traversing about one foot of conductor on a printed circuit board, or less if many devices are connected to it. Special buffer circuits may be added to boost the bus signals sufficiently for transmission over several additional feet of conductor length, or for distribution to many other chips (such as memory chips).

Noise and Electrical Distortion

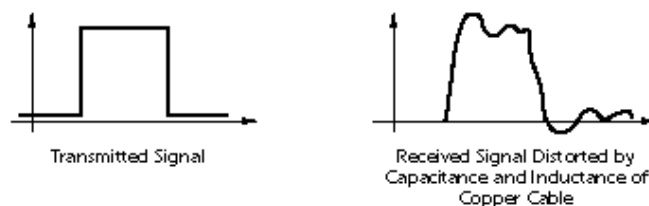
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Because of the very high switching rate and relatively low signal strength found on data, address, and other buses within a computer, direct extension of the buses beyond the confines of the main circuit board or plug-in boards would pose serious problems. First, long runs of electrical conductors, either on printed circuit boards or through cables, act like receiving antennas for electrical noise radiated by motors, switches, and electronic circuits:



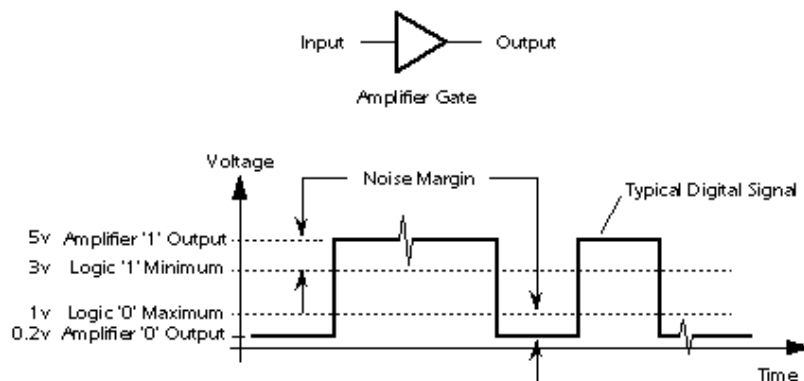
Such noise becomes progressively worse as the length increases, and may eventually impose an unacceptable error rate on the bus signals. Just a single bit error in transferring an instruction code from memory to a microprocessor chip may cause an invalid instruction to be introduced into the instruction stream, in turn causing the computer to totally cease operation.

A second problem involves the distortion of electrical signals as they pass through metallic conductors. Signals that start at the source as clean, rectangular pulses may be received as rounded pulses with ringing at the rising and falling edges:



These effects are properties of transmission through metallic conductors, and become more pronounced as the conductor length increases. To compensate for distortion, signal power must be increased or the transmission rate decreased.

Special amplifier circuits are designed for transmitting direct (unmodulated) digital signals through cables. For the relatively short distances between components on a printed circuit board or along a computer backplane, the amplifiers are in simple IC chips that operate from standard +5v power. The normal output voltage from the amplifier for logic '1' is slightly higher than the minimum needed to pass the logic '1' threshold. Correspondingly for logic '0', it is slightly lower. The difference between the actual output voltage and the threshold value is referred to as the noise margin, and represents the amount of noise voltage that can be added to the signal without creating an error:

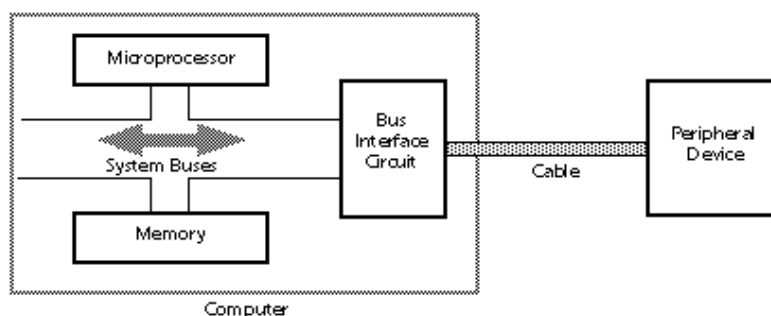


Transmission over Medium Distances (< 20 feet)

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Computer peripherals such as a printer or scanner generally include mechanisms that cannot be situated within the computer itself. Our first thought might be just to extend the computer's internal buses with a cable of sufficient length to reach the peripheral. Doing so, however, would expose all bus transactions to external noise and distortion even though only a very small percentage of these transactions concern the distant peripheral to which the bus is connected.

If a peripheral can be located within 20 feet of the computer, however, relatively simple electronics may be added to make data transfer through a cable efficient and reliable. To accomplish this, a bus interface circuit is installed in the computer:



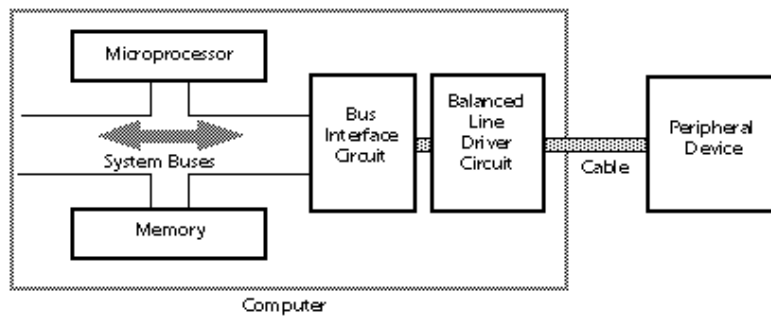
It consists of a holding register for peripheral data, timing and formatting circuitry for external data transmission, and signal amplifiers to boost the signal sufficiently for transmission through a cable. When communication with the peripheral is necessary, data is first deposited in the holding register by the microprocessor. This data will then be reformatted, sent with error-detecting codes, and transmitted at a relatively slow rate by digital hardware in the bus interface circuit. In addition, the signal power is greatly boosted before transmission through the cable. These steps ensure that the data will not be corrupted by noise or distortion during its passage through the cable. In addition, because only data destined for the peripheral is sent, the party-line transactions taking place on the computer's buses are not unnecessarily exposed to noise.

Data sent in this manner may be transmitted in byte-serial format if the cable has eight parallel channels (at least 10 conductors for half-duplex operation), or in bit-serial format if only a single channel is available.

Transmission over Long Distances (< 4000 feet)

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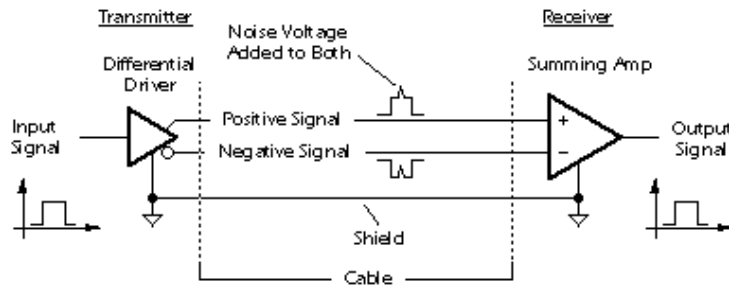
When relatively long distances are involved in reaching a peripheral device, driver circuits must be inserted after the bus interface unit to compensate for the electrical effects of long cables:



This is the only change needed if a single peripheral is used. However, if many peripherals are connected, or if other computer stations are to be linked, a local area network (LAN) is required, and it becomes necessary to drastically change both the electrical drivers and the protocol to send messages through the cable. Because multiconductor cable is expensive, bit-serial transmission is almost always used when the distance exceeds 20 feet.

In either a simple extension cable or a LAN, a balanced electrical system is used for transmitting digital data through the channel. This type of system involves at least two wires per channel, neither of which is a ground. Note that a common ground return cannot be shared by multiple channels in the same cable as would be possible in an unbalanced system.

The basic idea behind a balanced circuit is that a digital signal is sent on two wires simultaneously, one wire expressing a positive voltage image of the signal and the other a negative voltage image. When both wires reach the destination, the signals are subtracted by a summing amplifier, producing a signal swing of twice the value found on either incoming line. If the cable is exposed to radiated electrical noise, a small voltage of the same polarity is added to both wires in the cable. When the signals are subtracted by the summing amplifier, the noise cancels and the signal emerges from the cable without noise:



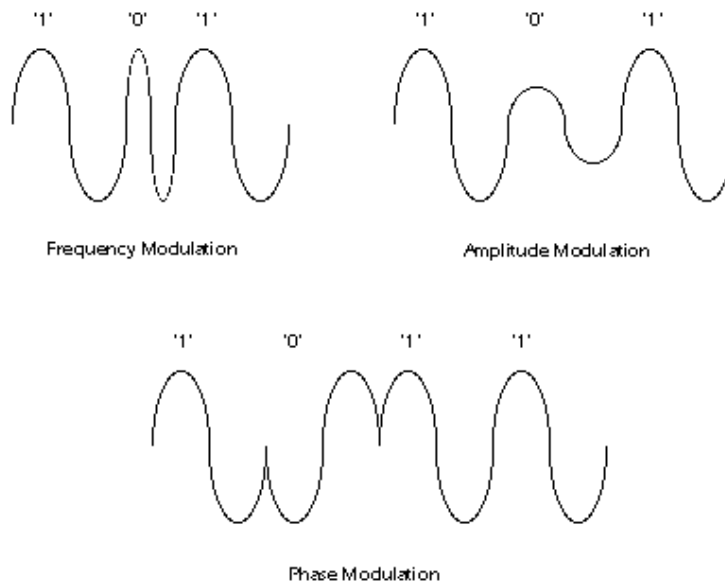
A great deal of technology has been developed for LAN systems to minimize the amount of cable required and maximize the throughput. The costs of a LAN have been concentrated in the electrical interface card that would be installed in PCs or peripherals to drive the cable, and in the communications software, not in the cable itself (whose cost has been minimized). Thus, the cost and complexity of a LAN are not particularly affected by the distance between stations.

Transmission over Very Long Distances (greater than 4000 feet)

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Data communications through the telephone network can reach any point in the world. The volume of overseas fax transmissions is increasing constantly, and computer networks that link thousands of businesses, governments, and universities are pervasive. Transmissions over such distances are not generally accomplished with a direct-wire digital link, but rather with digitally-modulated analog carrier signals. This technique makes it possible to use existing analog telephone voice channels for digital data, although at considerably reduced data rates compared to a direct digital link.

Transmission of data from your personal computer to a timesharing service over phone lines requires that data signals be converted to audible tones by a modem. An audio sine wave carrier is used, and, depending on the baud rate and protocol, will encode data by varying the frequency, phase, or amplitude of the carrier. The receiver's modem accepts the modulated sine wave and extracts the digital data from it. Several modulation techniques typically used in encoding digital data for analog transmission are shown below:



Similar techniques may be used in digital storage devices such as hard disk drives to encode data for storage using an analog medium.

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