3 Modulation, Multiplexing and Digitization

3.1 Introduction

Within shared transmission media, the transmission of signals often involves creating a carrier signal which identifies the sender, and where the receiver must ‘tune-into’ the signal. This chapter outlines some of the methods used to carry signals.

3.2 Modulation

Modulation allows the transmission of a signal through a transmission medium by carrying it on a carrier wave (which can propagate through a given media). It also adds extra information that allows the receiver to pick-up the signal (allowing the modulated signal to be ‘tuned-into’). For example, audio signals do not propagate well through air for any great distances. If they are added onto radio waves, the waves can propagate for vast distances. With long waves they can actually even transverse the planet. The other advantage of using a radio wave to carry the audio signal is that each audio signal can be transmitted using a different radio frequency. This then allows for many audio signals to be transmitted at the same time. This is known as frequency division multiplexing (FTM). Anyone who tunes to the correct carrier frequency can receive the signal, thus there can be one transmitter of the signal and many receivers. This is similar to the transmission of radio signals, where each radio station has its own carrier frequency, and receivers are tuned into these. This is also known as broadband communications, where a wide band is used to transmit the signals.

There are three main methods used to modulate: amplitude, frequency and phase modulation. With amplitude modulation (AM) the information signal varies the amplitude of a carrier wave. In frequency modulation (FM) it varies the frequency of the wave and with phase modulation (PM) it varies the phase.

3.2.1 Amplitude modulation (AM)

AM is the simplest form of modulation where the information signal modulates a higher frequency carrier. The modulation index, *m*, is the ratio of the signal amplitude to the carrier amplitude, and is always less than or equal to unity. It is given by:

$$m = \frac{V_{signal}}{V_{carrier}}$$

Figure 3.1 shows three differing modulation indices. In Figure 3.1 (a) the information signal has a relatively small amplitude compared with the carrier signal, giving a relatively small modulation index. In Figure 3.1 (b) the signal amplitude is approximately half of the carrier amplitude, and in Figure 3.1 (c) the signal amplitude is almost equal to the carrier’s amplitude (giving a modulation index of near unity).

AM is generally susceptible to noise and fading as it is dependent on the amplitude of the modulated wave. Binary information can be transmitted by assigning discrete amplitudes to bit patterns.

3.2.2 Frequency modulation (FM)

Frequency modulation involves the modulation of the frequency of a carrier. FM is preferable to AM as it is less affected by noise as the information is contained in the change of frequency and not the amplitude. Thus, the only noise that affects the signal is limited to a small band of frequencies contained in the carrier. The information in an AM waveform is contained in its amplitude which can be easily affected by noise.

Figure 3.2 shows a modulator/demodulator FM system. A typical device used in FM is a Phased-Locked Loop (PLL) which converts the received frequency-modulated signal into a signal voltage. It locks onto frequencies within a certain range (named the capture range) and follows the modulated signal within a given frequency band (named the lock range). Typically, binary information can be sent by using two frequencies, the upper frequency representing a zero, and the lower frequency representing a one. Modems can transmit binary information by using different frequencies to represent bit patterns.

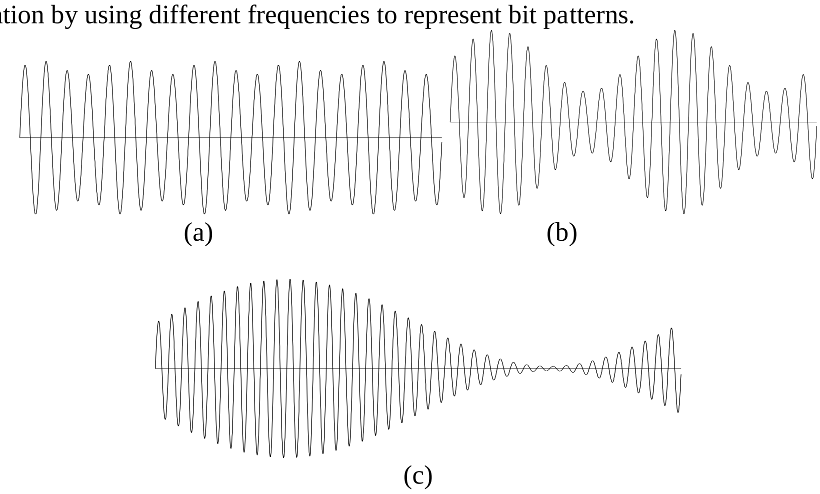

Figure 3.1 AM waveform

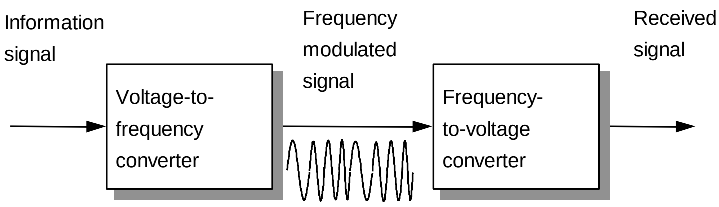

Figure 3.2 Frequency modulation

3.2.3 Phase modulation (PM)

Phase modulation involves modulating the phase of the carrier. PM is less affected by noise than AM because the information is contained in the change of phase and, like FM, not in its amplitude. As with FM, binary information can be transmitted by assigning discrete phases to bit sequences. For example, a zero phase could represent a zero, and a 180° phase shift could represent a one.

3.3 Digital modulation

Digital modulation changes the characteristic of a carrier according to binary information. With a sine wave carrier, the amplitude, frequency or phase can be varied. Figure 3.3 illustrates the three basic types: amplitude-shift keying (ASK), frequency-shift keying (FSK) and phase-shift keying (PSK).

3.3.1 Frequency-shift keying (FSK)

FSK, in the most basic case, represents a 1 (a mark) by one frequency and a 0 (a space) by another. These frequencies lie within the bandwidth of the transmission channel. On a V.21, 300 bps, full-duplex modem the originator modem uses the frequency 980 Hz to represent a mark and 1180 Hz a space. The answering modem transmits with 1650 Hz for a mark and 1850 Hz for a space. These four frequencies allow the caller originator and the answering modem to communicate at the same time; that is, full-duplex communication.

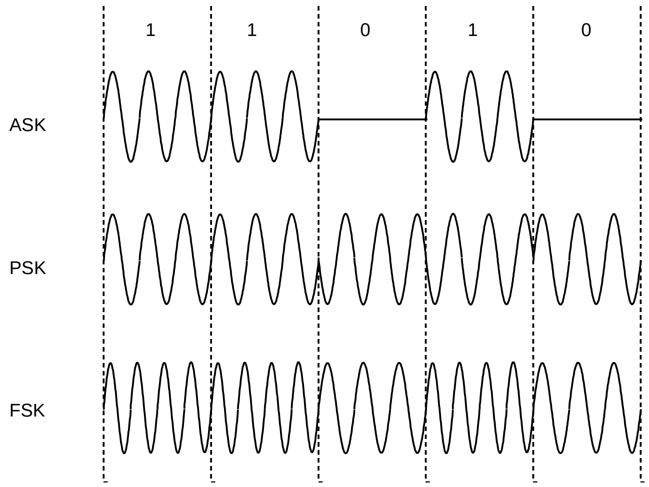

Figure 3.3 Waveforms for ASK, PSK and FSK

FSK modems are inefficient in their use of bandwidth, with the result that the maximum data rate over normal telephone lines is 1800 bps. Typically, for rates over 1200 bps, other modulation schemes are used.

3.3.2 Phase-shift keying (PSK)

In coherent PSK a carrier gets no phase shift for a 0 and a 180° phase shift for a 1, such as:

$$0 \Rightarrow 0^\circ \qquad 1 \Rightarrow 180^\circ$$

Its main advantage over FSK is that, as it uses a single frequency, it uses much less bandwidth. It is thus less affected by noise, and has an advantage over ASK that its information is not contained in the amplitude of the carrier, thus again it is less affected by noise.

3.3.3 *M*-ary modulation

With *M*-ary modulation a change in amplitude, phase or frequency represents one of *M* possible signals. It is possible to have *M*-ary FSK, *M*-ary PSK and *M*-ary ASK modulation schemes. This is where the baud rate differs from the bit rate. The bit rate is the true measure of the rate of the line, whereas the baud rate only indicates the signalling element rate, which might be a half or a quarter of the bit rate.

For four-phase differential phase-shift keying (DPSK) the bits are grouped into two and each group is assigned a certain phase shift. For two bits, there are four combinations: a 00 is coded as 0°, 01 coded as 90°, and so on:

$$\begin{array}{llll} 00 \Rightarrow & 0^\circ & 01 \Rightarrow & 90^\circ \\ 11 \Rightarrow & 180^\circ & 10 \Rightarrow & 270^\circ \end{array}$$

It is also possible to change a mixture of amplitude, phase or frequency. *M*-ary amplitude-phase keying (APK) varies both the amplitude and phase of a carrier to represent *M* possible bit patterns.

M-ary quadrature amplitude modulation (QAM) changes the amplitude and phase of the carrier. 16-QAM uses four amplitudes and four phase shifts, allowing it to code four bits at a time. In this case, the baud rate will be a quarter of the bit rate.

Typical technologies for modems are:

FSK – used up to 1200 bps
Four-phase DPSK – used at 2400 bps
Eight-phase DPSK – used at 4800 bps
16-QAM – used at 9600 bps

Most modern modems operate with V.90 (56 kbps), V.22bis (2400 bps), V.32 (9600 bps), V.32bis (14 400 bps); such as those outlined in Table 1.3. The V.32 and V.32bis modems can be enhanced with echo cancellation. They also typically have built-in compression using either the V.42bis standard or MNP level 5.

Table 1.1 Example modems

Type	*Bit rate (bps)*	*Modulation*
V.21	300	FSK
V.22	1,200	PSK
V.22bis	2,400	ASK/PSK
V.27ter	4,800	PSK
V.29	9,600	PSK
V.32	9,600	ASK/PSK
V.32bis	14,400	ASK/PSK
V.34	28,800	ASK/PSK

3.3.4 V.22bis modems

V.22bis modems allow transmission at up to 2400 bps. It uses four amplitudes and four phases. Figure 3.4 shows the 16 combinations of phase and amplitude for a V.22b is modem. It can be seen that there are 12 different phase shifts and four different amplitudes. Each transmission is known as a symbol, thus each transmitted symbol contains 4 bits. The transmission rate for a symbol is 600 symbols per second (or 600 baud), thus the bit rate will be 2,400 bps.

Trellis coding tries to ensure that consecutive symbols differ as much as possible.

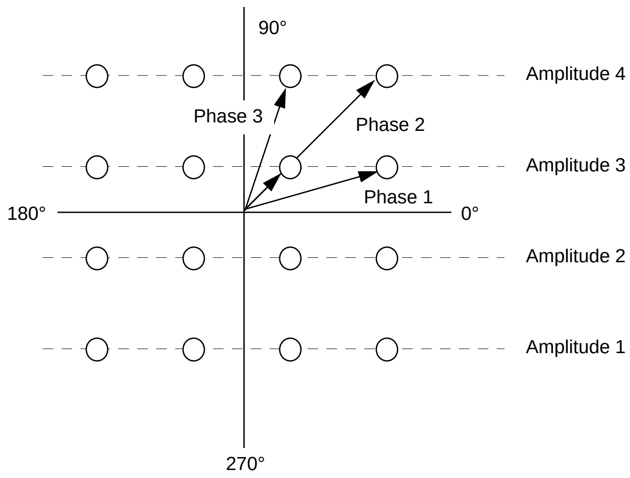

Figure 3.4 Phase and amplitude coding for V.32

3.4 Multiplexing

Multiplexing is a method of sending information from many sources over a single transmission media. For example, satellite communications and optical fibers allow many information channels to be transmitted simultaneously. There are two main methods of achieving this, either by separation in time with time-division multiplexing (TDM) or separation in frequency with frequency-division multiplexing (FDM).

3.4.1 Frequency-division multiplexing (FDM)

With FDM each channel uses a different frequency band. Examples of this are FM radio and satellite communications. With FM radio, many channels share the same transmission media but are separated into different carrier frequencies. Satellite communication normally involves an Earth station transmitting on one frequency (the up-link frequency) and the satellite relays this signal at a lower frequency (the down-link frequency).

Figure 3.5 shows an FDM radio system where each radio station is assigned a range of frequencies for their transmission. The receiver then tunes into the required carrier frequency.

3.4.2 Time-division multiplexing (TDM)

With TDM different sources have a time slot in which their information is transmitted. The most common type of modulation in TDM systems is pulsed code modulation (PCM). With PCM, analogue signals are sampled and converted into digital codes. These are then transmitted as binary digits.

In a PCM-TDM system, several voice-band channels are sampled and converted into PCM codes. Each channel gets a time slot and each time slot is built up into a frame. The complete frame has extra data added to it to allow synchronization. Figure 3.6 shows a PCM-TDM system with three sources.

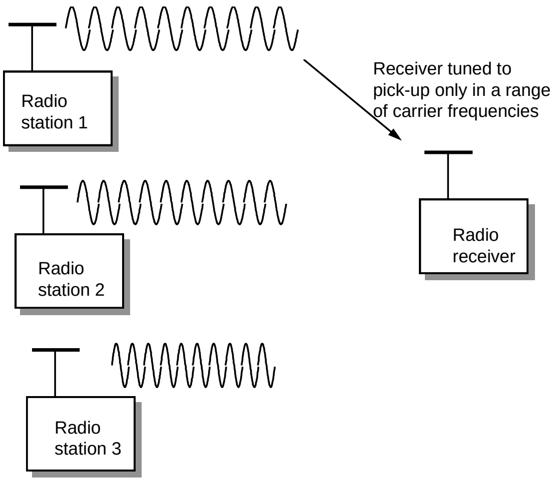

Figure 3.5 FDM radio system

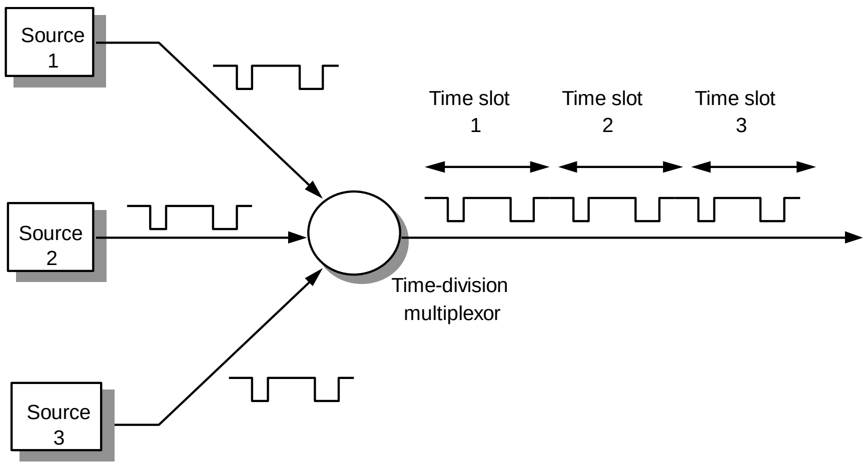

Figure 3.6 TDM system

3.5 Frequency carrier

Often a digital signal cannot be transmitted over a channel without it being carried on a carrier frequency. The frequency carrier of a signal is important and is chosen for several reasons, such as the:

- Signal bandwidth.
- Signal frequency spectrum.
- Transmission channel characteristics.

Figure 3.7 shows the frequency spectrum of electromagnetic (EM) waves. The microwave spectrum is sometimes split into millimetre wave and microwaves and the radio spectrum splits into seven main bands from ELF (used for very long distance communications) to VHF (used for FM radio).

Normally, radio and lower frequency microwaves are specified as frequencies. Whereas, EM waves from high frequency (millimeter wavelength) microwaves upwards are specified as a wavelength. The wavelength of a signal is the ratio of its speed of propagation (u) to its frequency (f). It is thus given by:

$$\lambda = \frac{u}{f}$$

In free space, an electromagnetic wave propagates at the speed of light (300,000,000 ms^{-1} or 186,000 miles s^{-1}). For example, if the carrier frequency of an FM radio station is 97.3 MHz then its transmitted wavelength is 3.08 m, and if an AM radio station transmits at 909 kHz then the carrier wavelength is 330 m. Typically, the length of radio antenna is designed to be half the wavelength of the received wavelength. This is the reason why FM aerials are normally between 1 and 2 m, in length, whereas in AM and LW aerials have a long coil of wire wrapped round a magnetic core. Note that a 50 Hz mains frequency propagates through space with a wavelength of 6,000,000 m.

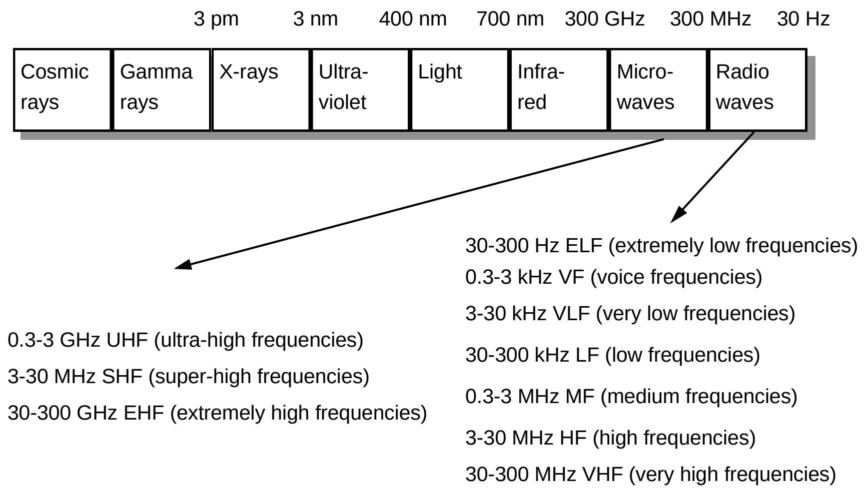

Figure 3.7 EM frequency spectrum

If an EM wave propagates through a dense material, its speed reduces. In terms of the dielectric constant, ε_r, of a material (which is related to density) then the speed of propagation is:

$$u = \frac{c}{\sqrt{\varepsilon_r}}$$

Each classification of EM waves has its own characteristics. The main classifications of EM waves used for communication are:

- **Radio waves.** The lower the frequency of a radio wave the more able it is to bend around objects. Defence applications use low frequency communications, as they can be transmitted over large distances, and over and round solid objects. The trade-off is that the lower the frequency, the less the information that can be carried. LW (MF) and AM (HF) signals can propagate over large distances, but FM (VHF) requires repeaters as they cannot bend round and over solid objects, such as trees and hills. Long wave radio (LW) transmitters operate from approximately 100 to 300 kHz, medium wave (AM) from 0.5 to 2 MHz and VHF radio (FM) from 87 to 108 MHz.
- **Microwaves.** Microwaves have an advantage over optical waves (light, infrared and ultraviolet) in that they can propagate well through water and thus can be transmitted through clouds, rain, and so on. If they are of a high enough frequency, they can propagate through the ionosphere and out into outer space. This property is used in satellite communications where the transmitter bounces microwave energy off a satellite, which is then picked up at a receiving station. Radar and mobile radio applications also use these properties. Their main disadvantage is that they will not bend round large objects, as their wavelength is too small. Included in this classification is UHF (used to transmit TV signals), SHF (satellite communications) and EHF waves (used in line-of-sight communications).
- **Infrared.** Infrared is used in optical communications. When it is used as a carrier frequency the transmitted signal can have a very large bandwidth as the carrier frequency is high. It is extensively used in fiber optic communications and for line-of-site communications, especially in remote control applications. Infrared radiation is basically the propagation of heat, and heat received from the sun propagates as infrared radiation.
- **Light.** Light is the only part of the spectrum that humans can 'see'. It is a very small part of the spectrum and ranges from 300 to 900 nm. Colors visible are red, orange, yellow, green, blue, indigo and violet.
- **Ultraviolet.** As with infrared it is used in optical communications. In high enough exposures it can cause skin cancer. Luckily, the ozone layer around the Earth blocks much of the ultraviolet radiation from the sun.

3.6 Routing of data

Data communications involves the transmission of data from a transmitter to a receiver, over some physical distances. This could involve short distances, such as within a computer system, or a building, or could involve large distances, such as countrywide or even worldwide (or in the extreme case, planet-wide). In order for data to be delivered to a recipient, a path must exist for it. Normally this path is setup by either mechanical switching, electronic switching (where the mechanical switch is replaced by an electronic switch) or virtual switching (where no physical or electronic connection exists between the sender and the receiver, but data is routed over virtual paths). The different types of switching include:

- **Circuit switching.** This type of switching uses a dedicated line to make the connection between the source and destination, just as a telephone line makes a connection between the caller and the recipient. As the connection is dedicated to the connection, the bit rate can vary as required, and possibly underutilized, but there tends to very little delay in transmitting the data.
- **Packet switching.** This type of switching involves splitting data into data packets. Each packet contains the data and a packet header which has the information that is used to route the packet through the network. Typical information contained in the packet header are source and destination addresses. These addresses may only have local significance (such as the address of the next switching device) or could have global significance (such as the Internet address of the source and destination devices). If the addresses have local significance it is likely that they will change as the data packet is passed from place to place, whereas global addresses will stay fixed. With packet switching each switching device on the path reads the data packet and sends it onto the next in the path. The transport can either be:

  - **Datagram**. This is where the data packets travel from the source to the destination, and can take any path through the interconnected network. This technique has an advantage, over setting up a fixed path, that data packets can take alternative paths. This is important when there is heavy traffic on parts of the network, or when links become unavailable. It also does not require a call setup.
  - **Virtual circuit**. This is where all the data packets are routed along the same path. It differs from circuit switching in that there is no dedicated path for the data. Virtual circuits must be setup before any data can be transmitted, and normally the route taken by the data can be chosen so that it gives the required link quality. This quality typically relates to propagation delay (latency), error rate and bandwidth limitations. Data packets in a virtual circuit also normally have some information in the header which identifies the virtual circuit, and this is likely only to have significance to the actual circuit setup.
- **Multirate circuit switching.** Traditionally TDM (time division multiplexing) is used to transmit data over a PSN (public switched network). This uses a circuit switching technology with a fixed data rate, and has fixed channels for the data. Multirate rates allow transmitters to transmit to different destinations over a single physical connection. For example, in ISDN a node can transmit to two different destinations with a single connection (each of 64 kbps). The bit rate, though, is fixed at 64 kbps, and it is difficult to achieve a variable bit rate (VBR).
- **Frame relay.** This method is similar to packet switching, but the data packets (typically known as data frames in frame relays) have a variable length and are not fixed in length. This allows for variable bit rates. As the data packets are of variable length there must be some way of defining the start and end of the data packet. For this, the special bit sequence of 01111110 is typically used at the start and the end of the frame. A special technique, known as bit stuffing, is then used to stop the start and end sequence from occurring at any other place, apart from at the start and the end of the data frame.
- **Cell relay.** This method uses fixed packets (cells), and is a progression of the frame relay and multirate circuit switching. Cell relay allows for the definition of virtual

channels with data rates dynamically defined. Using a small cell size allows almost constant data rate even though it uses packets.

Local connections are typically either made with a direct connection, or over a local area network (LAN). For a connection over a large area, the connection is typically made over a wide area network (WAN) which connects one node to another over relatively large distances via an arbitrary connection of switching nodes. Typically the WAN can use the public data network (PDN) or through dedicated company connections. Figure 3.9 illustrates the two main types of connection over the public telephone network: circuit switching and packet switching.

With circuit switching, a physical, or a reserved multiplexed, connection exists between two nodes. This type of connection is typical in a public-switched telephone network (PSTN), as telephone connections have been made, in the past, with this method. As with a telephone call, the connection must be made before transferring any data. Until recently this connection took a relatively long time to setup (typically over 10 seconds), but with the increase in digital switching it has reduced to less than a second. The usage of digital switching has also allowed the transmission of digital data, over PSTNs, at rates of 64 kbps and greater. This type of network is known as a circuit-switched digital network (CSDN). Its main disadvantage is that a permanent connection is setup between the nodes, which is wasteful in time and can be costly. Another disadvantage is that the transmitting and receiving nodes must be operating at the same speed. A CSDN, also, does not perform any error detection or flow control.

Packet switching involves segmenting data into packets that propagate within a digital network. They either follow a predetermined route or are routed individually to the receiving node via packet-switched exchanges (PSE) or routers. These examine the destination addresses and based on an internal routing directory pass, it to the next PSE on the route. As with circuit switching, data can propagate over a fixed route. This differs from circuit switching in that the path is not an actual physical circuit (or a reserved multiplexed channel). As it is not a physical circuit, it is normally defined as a virtual circuit. This virtual circuit is less wasteful on channel resources as other data can be sent when there are gaps in the data flow. Table 1.2 gives a comparison of the two types.

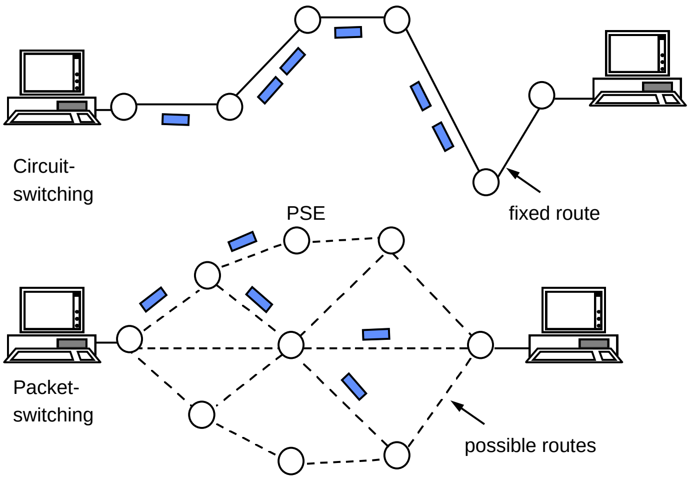

Figure 3.8 Circuit and packet switching

Table 1.2 Comparison of switching techniques

	Circuit-switching	*Packet-switching*
Investment in equipment	Minimal as it uses existing connections	Expensive for initial investment
Error and flow control	None, this must be supplied by the end users.	Yes, using the FCS in the data link layer
Simultaneous transmissions and connections	No	Yes, nodes can communicate with many nodes at the same time and over many different routes
Allows for data to be sent without first setting up a connection	No	Yes, using datagrams
Response time	Once the link is setup it provides a good reliable connection with little propagation delay	Response time depends on the size of the data packets and the traffic within the network

Telephones were initially connected using a party-line connection, where a number of phones are connected to the same connection. Unfortunately other users cannot use the shared media when it is being used by another connection. A great improvement occurred with the cross-bar switch which allowed multiple connections (Figure 3.10).

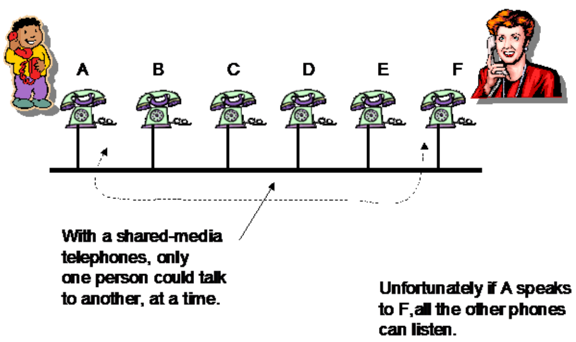

Figure 3.9 Party-line connection

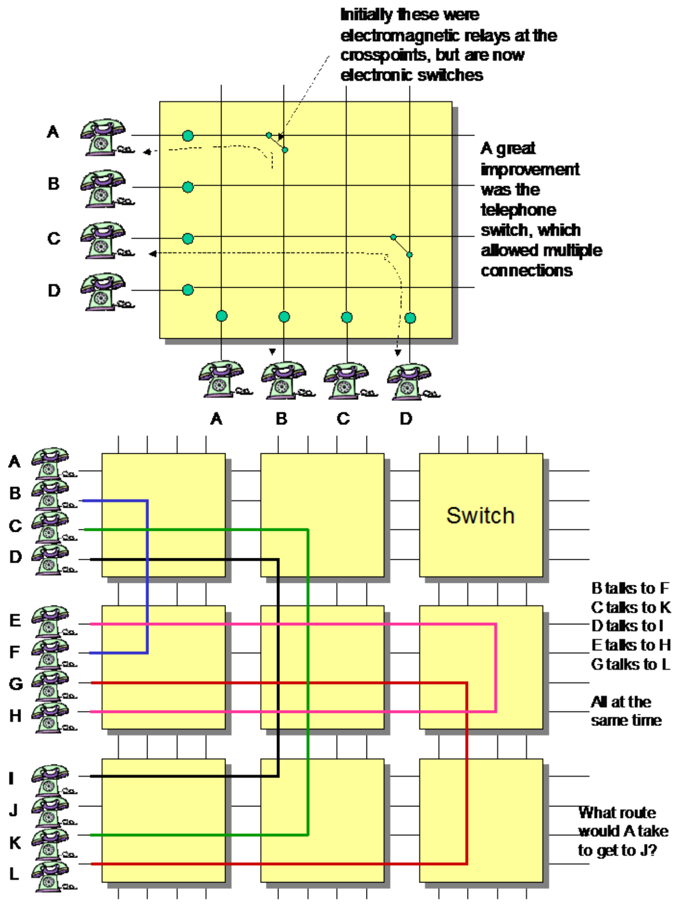

Figure 3.10 Telephone switch