OPTION T

Telecommunications

T1. Communication Principles

1 (a) *Candidates should be able to recall that any waveform can be resolved into or synthesised from sinusoidal components.*

The mathematician Fourier was the first person to prove that a sine wave is the simplest possible repeating waveform. Furthermore, he showed that any repetitive waveform of frequency f can be created by adding together a sine wave of the same fundamental frequency f and a number of its harmonics. (A harmonic is a sine wave of frequency $2f$, $3f$, $4f$, $5f$, etc.) The classic example is a perfect square wave of amplitude A and frequency f. This is composed of an infinite sum of odd numbered harmonics with amplitudes in the ratios

$$1 : \frac{1}{3} : \frac{1}{5} : \frac{1}{7} : \frac{1}{9} : \frac{1}{11} \text{ etc.}$$

Thus, the square wave of frequency f and amplitude A may be represented as

$$A\sin 2\pi ft + \frac{A}{3}\sin 2\pi 3ft + \frac{A}{5}\sin 2\pi 5ft + \ldots\ldots$$

This is illustrated in Fig. 1.1 where, even with only two harmonics added to the fundamental, the sum is becoming square-shaped. If all the odd harmonics were added, then a true square wave would result.

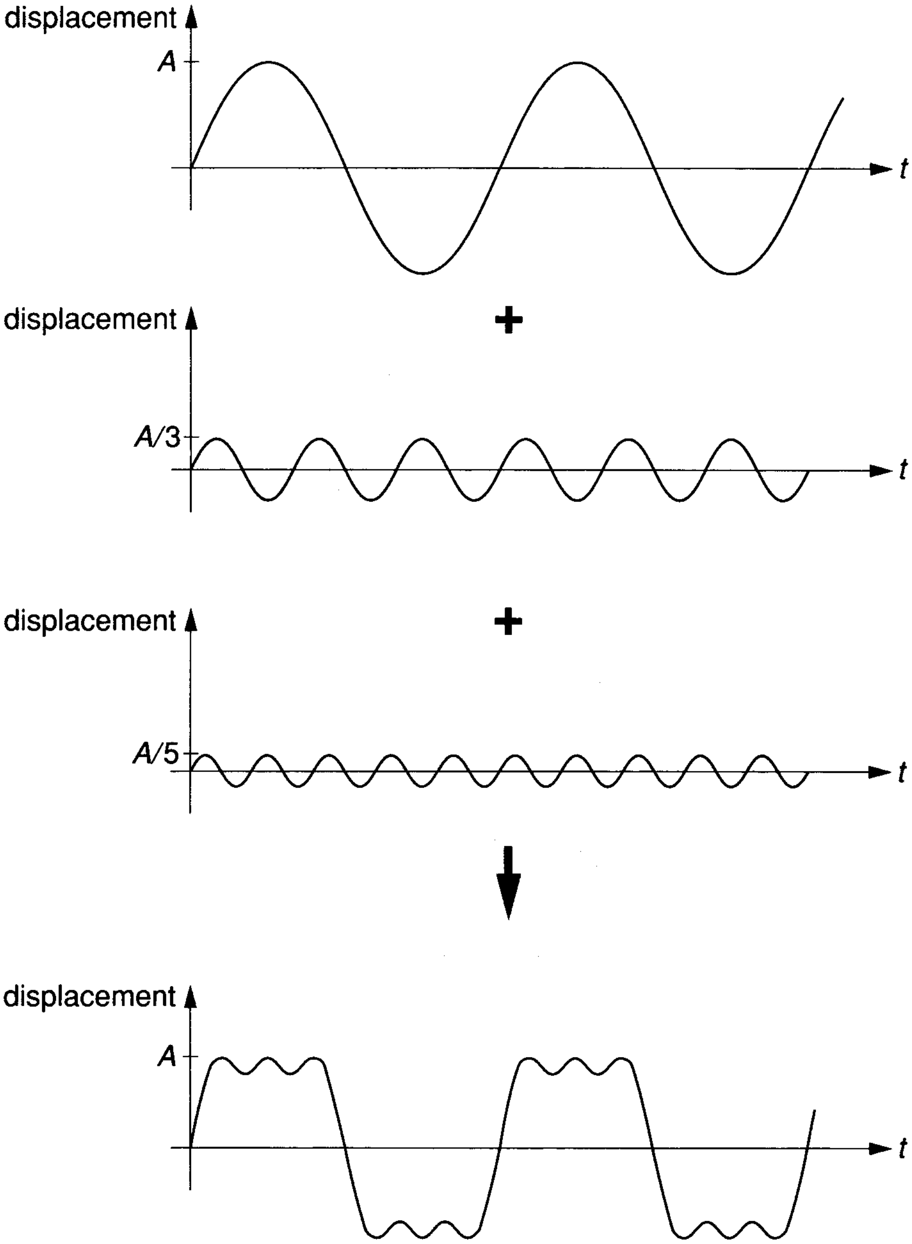


Fig. 1.1

Normally, when waveforms from signal generators or microphones are examined in school laboratories, they are viewed on an oscilloscope (c.r.o.) and this provides a view of the waveform as a function of time. It is usually easy to “see” and estimate the fundamental frequency of such a repetitive waveform but it is much more difficult to make any measurements of the harmonic frequencies present. In other words, an oscilloscope does not analyse the harmonic content of a waveform. An instrument which allows such an analysis is called a *spectrum analyser* and this provides a view of the waveform as a function of frequency. The spectrum of a waveform is simply a graphical presentation of the relative magnitudes of the various frequencies of which it is composed. This is illustrated in Fig. 1.2.

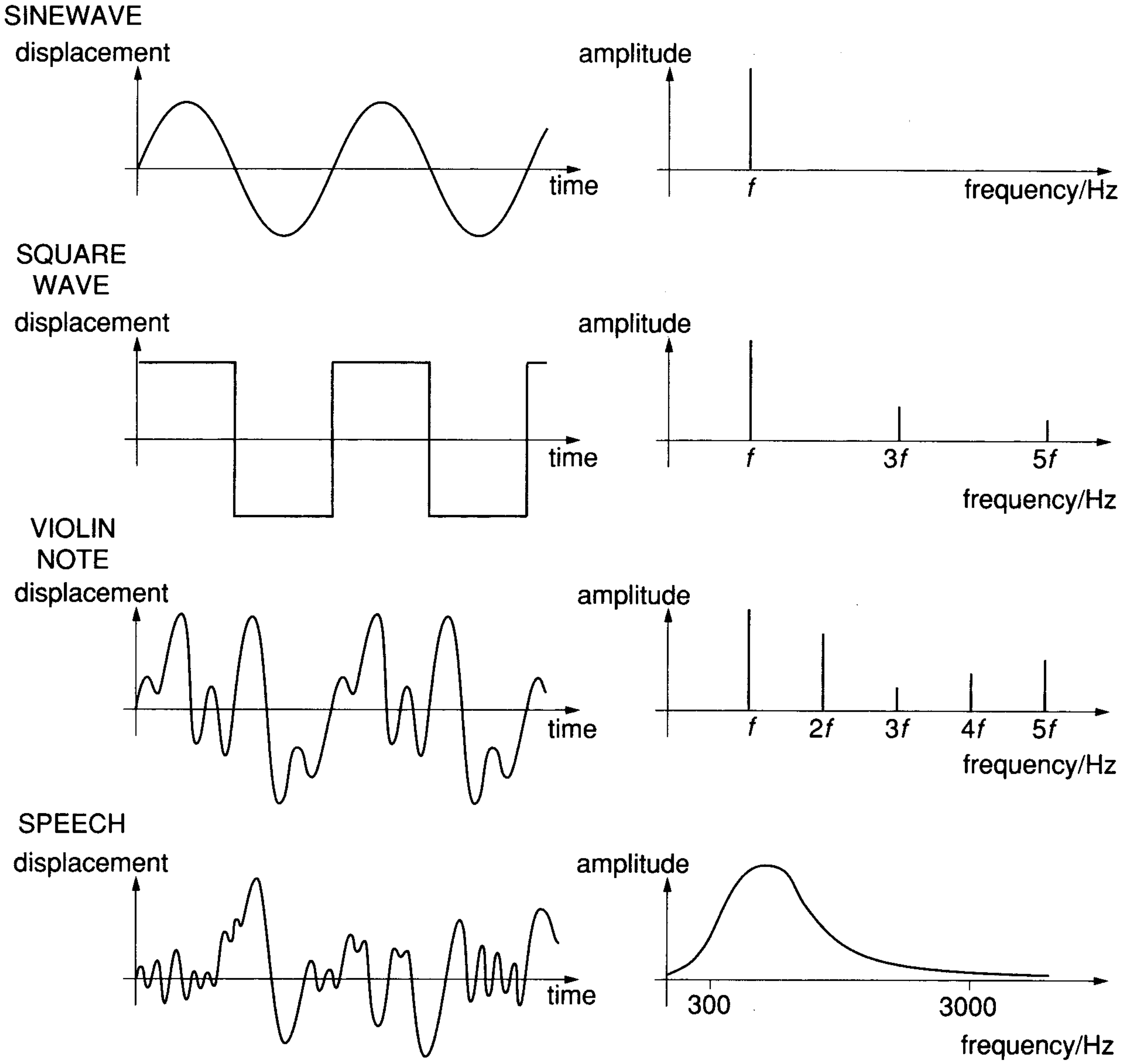


Fig. 1.2

Note the difference in spectra created by a repeating note such as a square wave or a single note on a violin with that of the highly complex waveform of ordinary speech in which frequencies and amplitudes continually change with time.

The range of frequencies which make up a signal waveform is called the *bandwidth* of the signal, see section *1(c)*.

1 (b) *Candidates should be able to understand the term modulation and distinguish between amplitude modulation (AM) and frequency modulation (FM).*

All communication systems require a source and a receiver. Three such systems are illustrated in Fig. 1.3.

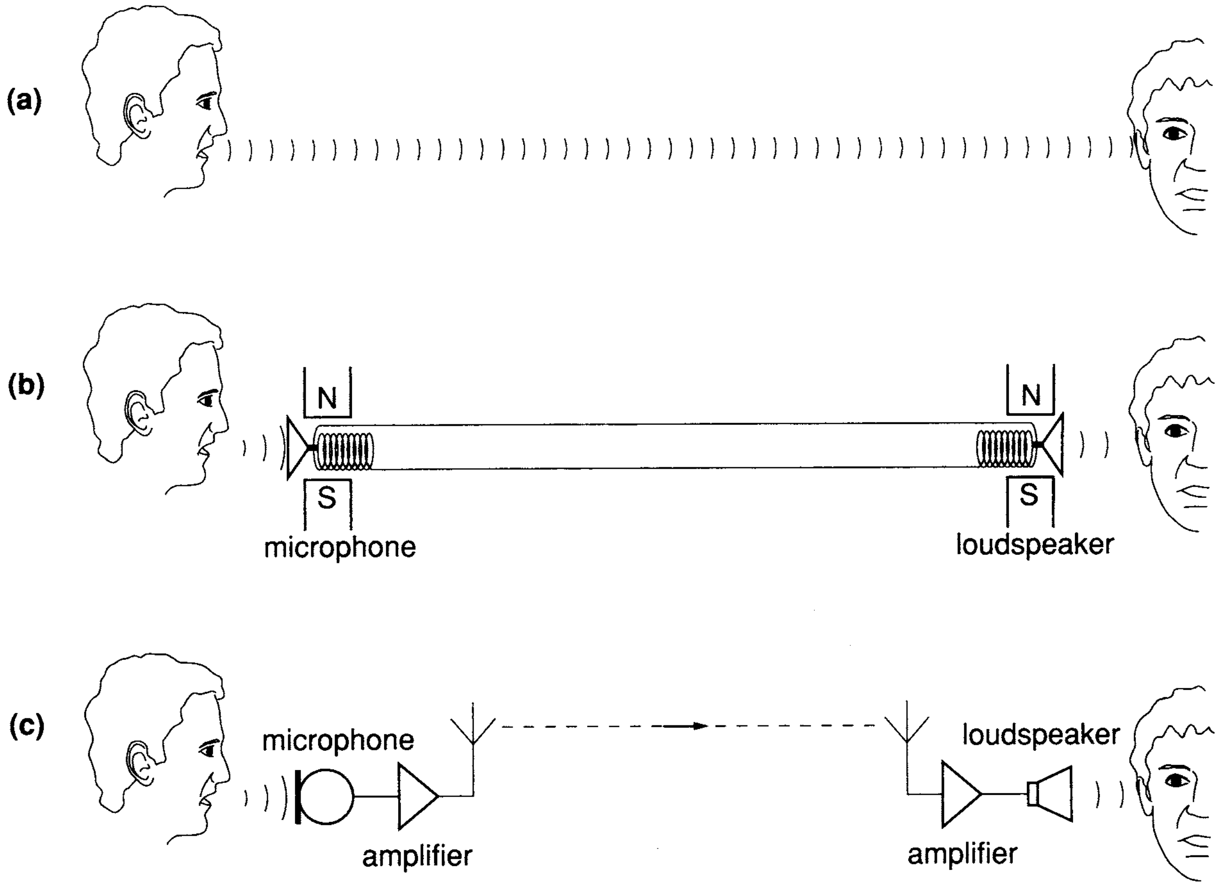


Fig. 1.3

Sound can be transmitted either directly as in (a) or via the alternating currents induced in a moving-coil microphone and received by a moving coil speaker as illustrated in (b). It is also possible to communicate using radio waves by simply amplifying the audio signal and applying it to a suitable aerial as illustrated in (c). However, this causes two fundamental problems:

(i) only one radio station could operate in the region because the wave from a second station operating would interfere with the first,

(ii) the aerial required to transmit frequencies in the audio range (20 Hz to 20 kHz) would be both very long and inefficient (the radio waves would not travel very far unless huge powers were used).

Both of these problems are solved by the process of *modulation*, the principle of which is illustrated in Fig. 1.4 where a high frequency wave known as the *carrier wave* has either its amplitude or frequency altered by the information signal in order to carry the information.

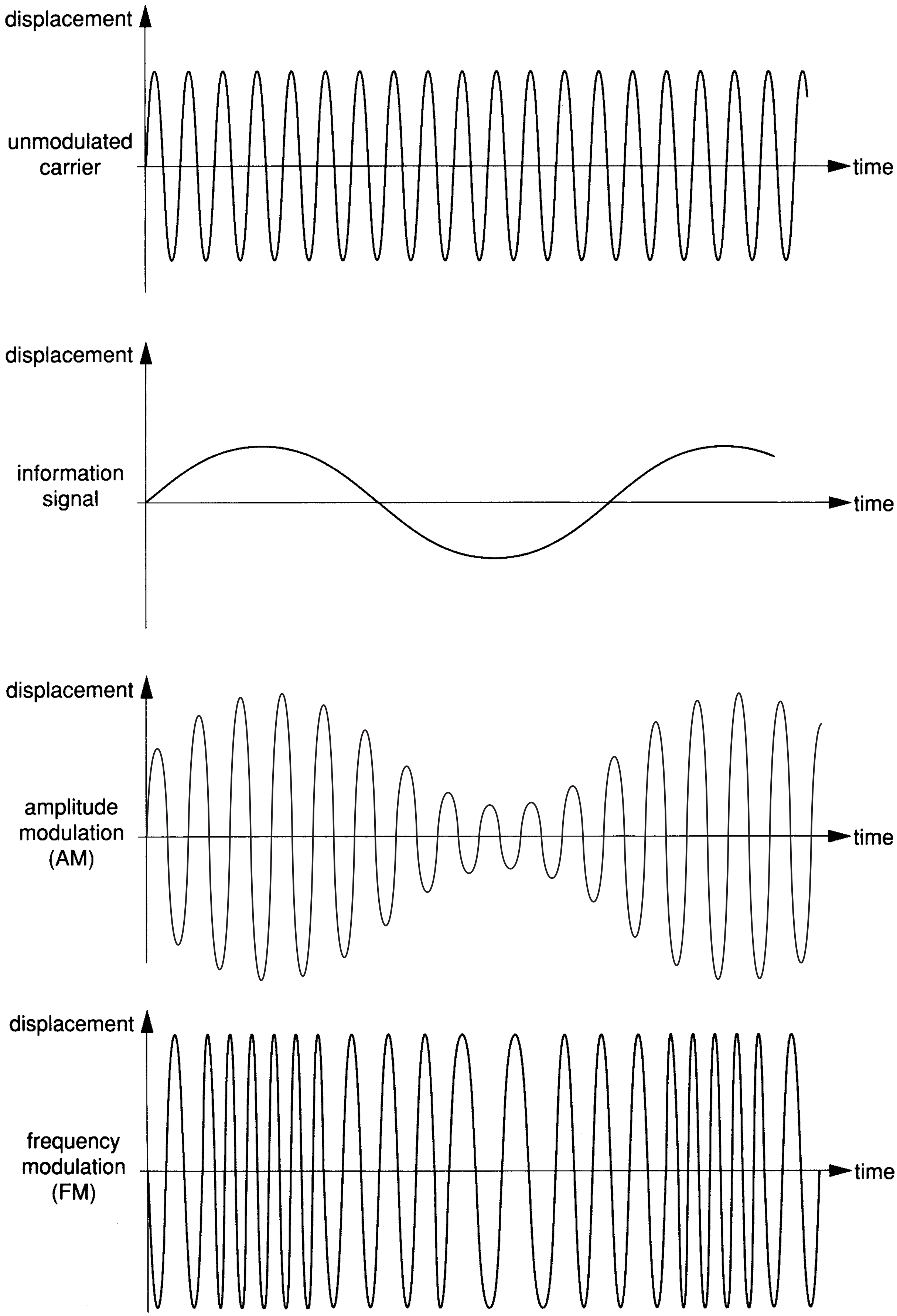

displacement
unmodulated carrier
time
displacement
information signal
time
displacement
amplitude modulation (AM)
time
displacement
frequency modulation (FM)
time

Fig. 1.4

For *amplitude modulation* (AM), the amplitude of the carrier wave is made to vary in synchrony with the displacement of the information signal. The variation in the amplitude of the carrier wave is a measure of the displacement of the information signal and the rate at which the carrier amplitude varies is equal to the frequency of the information signal.

For *frequency modulation* (FM), the frequency of the carrier wave is made to vary in synchrony with the amplitude of the information signal. The change in frequency of the carrier wave is a measure of the displacement of the information signal and the rate at which the carrier wave frequency is made to vary is equal to the (instantaneous) frequency of the information signal.

Note: The use of a carrier wave allows different radio stations in the same location to transmit simultaneously. Each station transmits on a different carrier frequency and consequently the carrier waves do not interfere, in effect, with one another. This is because any one receiver is tuned to the frequency of a particular carrier wave. The receiver then responds to, and gives and output based on, the differences in displacement, or frequency, between the actual waveform and the 'underlying' carrier wave. In other words, the receiver recognises the information signal.

1 (c) *Candidates should be able to recall that a carrier wave, amplitude modulated by a single audio frequency, is equivalent to the carrier wave frequency together with two sideband frequencies, leading to an understanding of the term bandwidth.*

Fig. 1.5 shows the waveform resulting from the amplitude modulation of a high frequency carrier wave by a signal that consists of a single audio frequency. If this waveform is analysed, it will be seen to be composed of the sum of three separate frequencies. The central frequency is that of the high frequency carrier wave (i.e. f_c) while the other two are known as *sidebands*. Note that the relative amplitude of the sidebands depends on the relative amplitudes of the audio and the carrier waveforms. (If there is no audio frequency signal, there are no sidebands.)

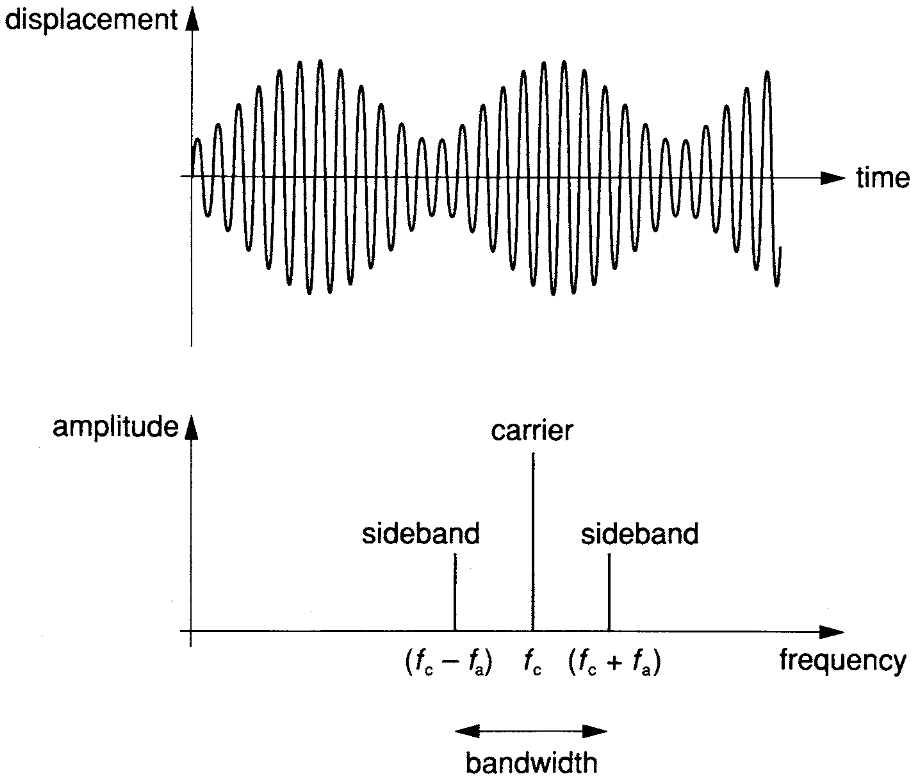


Fig. 1.5

The sidebands of the AM waveform occur at frequencies given by $f_c \pm f_a$ where f_a is the frequency of the audio signal.

The bandwidth is the frequency range occupied by the AM waveform and is equal to $2f_a$.

Fig. 1.6 shows the AM waveform and corresponding spectrum for a voice signal where many audio frequencies are involved. Again, it can be seen that the bandwidth is the range of frequencies from the lowest to the highest component of the AM waveform.

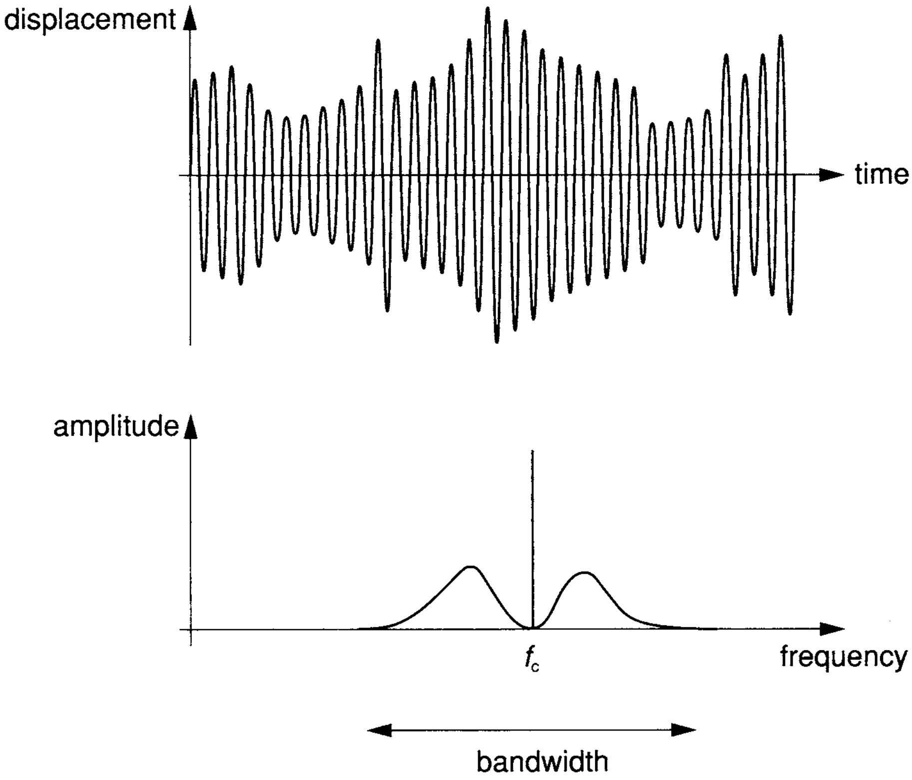


Fig. 1.6

1 (d) *Candidates should be able to demonstrate awareness of the relative advantages of FM and AM transmissions.*

An aerial receiving electromagnetic waves cannot distinguish between a genuine radio signal and, say, the interfering radiation from a passing unsuppressed motorbike engine. If the radio signal is AM, the interference is considered to be part of the modulation and becomes audible in the output produced by the receiver. If, however, the radio signal is FM, the interference will be ignored by the receiver because it is only variations in frequency which are important, not variations in amplitude. Thus, the quality of AM reception is generally poorer than that of FM, in terms of interference.

On the LW and MW wavebands, the bandwidth of an AM radio station is 9 kHz and consequently, the maximum audio frequency which can be broadcast is 4.5 kHz (i.e. 9 ÷ 2). (This is fairly close to the highest frequency typically audible to the human ear.)

On the VHF waveband, the bandwidth of an FM radio station is about 200 kHz, and the maximum audio frequency broadcast is 15 kHz. Thus, the quality of music received on AM is also poorer than that of FM, this time in terms of bandwidth.

Note: The power spectrum of an FM waveform is not the same as that of an AM waveform because further side frequencies which are multiples of the audio frequencies are produced.

The LW waveband occupies a region of the electromagnetic spectrum from 30 kHz to 300 kHz. The number of separate AM radio stations which could share this waveband is (theoretically) 270 ÷ 9 = 30, but the number of separate FM stations would only be 270 ÷ 200, i.e. 1. Thus, more AM radio stations than FM stations can share any waveband. (Indeed, FM is only used at frequencies in excess of 1 MHz.)

The AM transmissions on the LW, MW and SW wavebands are propagated through very large distances (see section *3(a)*) so that broadcasts can be made to a very large area from only one transmitter. FM transmissions have a range of only about 30 km by line-of-sight. To broadcast to a large area, many FM transmitters are required. It is, accordingly, much cheaper and simpler to broadcast by AM than by FM.

AM transmitters and receivers are electronically simpler and cheaper and occupy a much smaller bandwidth than those of FM. Indeed, it should be noted that television video signals broadcast terrestrially on the UHF waveband are AM signals.

1 (e) *Candidates should be able to recall the advantages of transmission of data in digital form.*

Much of the information which is to be communicated in the real world is analogue information (e.g. a microphone waveform which varies in time in an analogous manner to the sound waveform which caused it). If this analogue signal – which can be regarded as a variable voltage *V* – is to be transmitted over a large distance (either by radio or cable), it will be attenuated (its power will become smaller) and random noise will be picked up (see section *2(c)*). Eventually, the signal will have to be amplified (otherwise it could not be distinguished from the noise) by a repeater amplifier before being passed further on. The amplifier, however, will amplify the noise as well as the original signal. After several of these repeater amplifications (required for transmission over a long distance), the signal will be very noisy indeed. This is illustrated in Fig. 1.7.

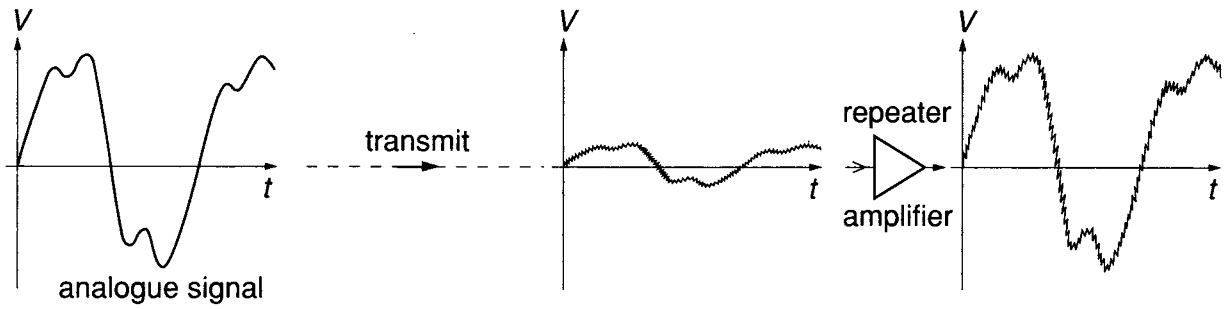


Fig. 1.7

If the information to be transmitted is in digital form, then it too suffers from attenuation and the addition of noise. However, the amplifiers which are used with digital signals are required only to produce a high voltage or a low voltage and are not required to amplify small fluctuations in amplitude. Since noise typically consists of such small fluctuations, the amplification of a digital signal does not also amplify the noise. These amplifiers are called *regenerator amplifiers* and are able to reproduce the original digital signal and 'filter out' the noise. Thus a digital signal can be transmitted through very long distances with regular regenerations without becoming increasingly noisy as happens to analogue signals. This is illustrated in Fig. 1.8.

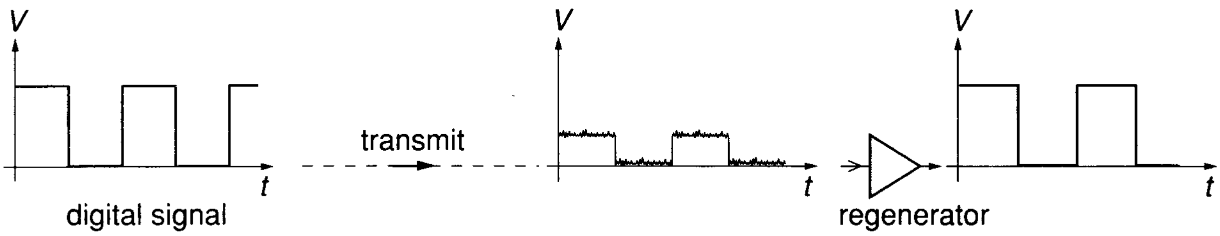


Fig. 1.8

A further advantage of digital transmissions is that they can have extra bits of data added by the transmitting system. These extra data are a code to be used by the receiving system to check for errors and to correct them before passing the information on to the user.

Nowadays, digital circuits are generally more reliable and cheaper to produce than analogue circuits. This is perhaps the main reason why, in the near future, almost all communication systems will be digitally based.

1 (f) Candidates should be able to understand that the digital transmission of speech or music involves analogue-to-digital conversion on transmission and digital-to-analogue conversion on reception.

The electrical signals derived from speech or music are analogue audio-frequency signals. The voltage generated varies continuously between two limits. To convert an analogue signal into a digital signal involves taking samples of the analogue waveform (i.e. measuring its instantaneous voltage) at regular intervals of time. The instantaneous or sample voltage is converted into a binary number which represents its value.

e.g. If the instantaneous voltage is 6 V, the binary number could be 0110.
If the instantaneous voltage is 13 V, the binary number could be 1101.

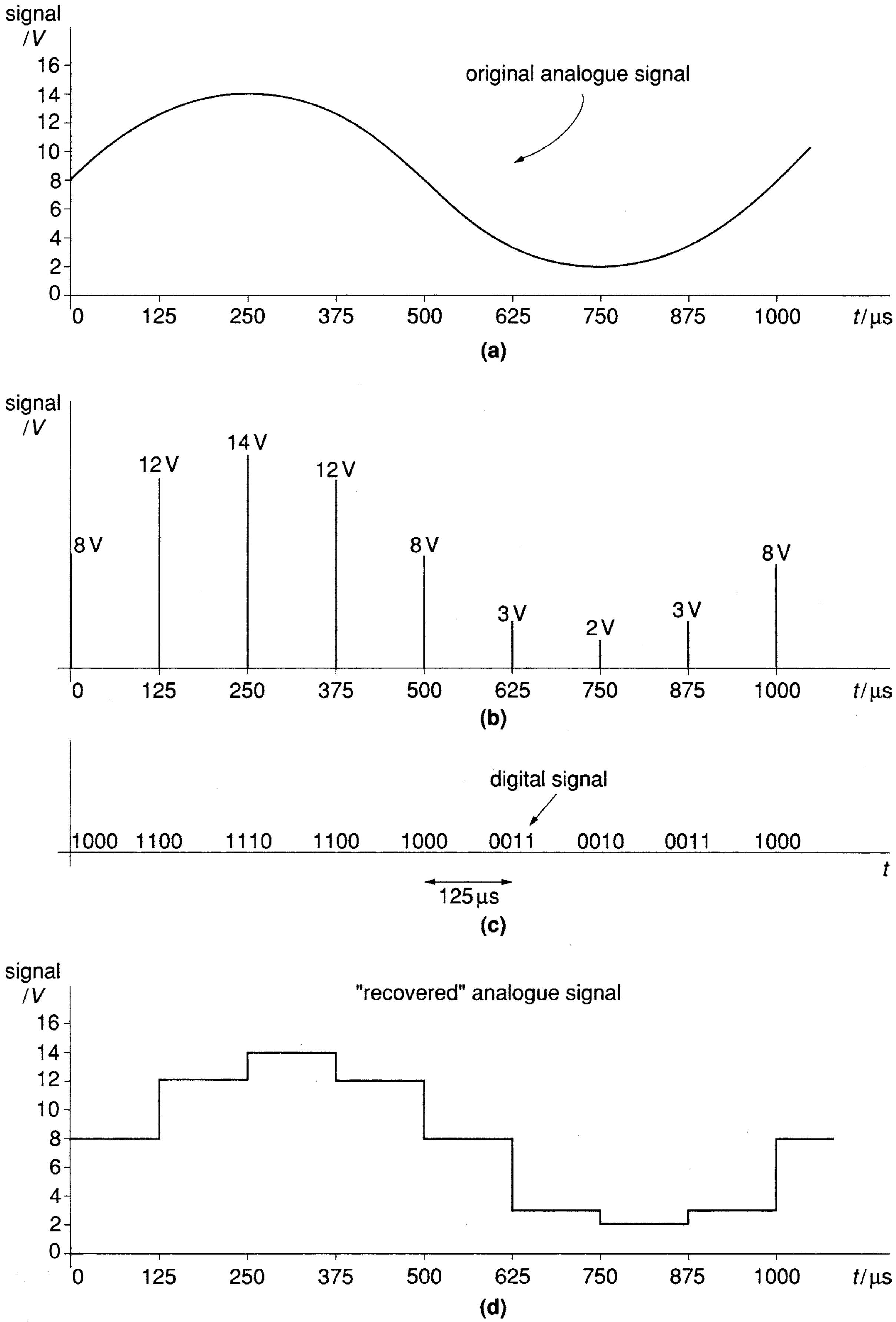
It should be remembered that the most significant bit (the bit representing the largest decimal number) is written first.

Note (i) A bit is a binary digit and is represented by a 1 or a 0.

(ii) A 1 is represented by a high voltage and a 0 by a low voltage.

(iii) A 4-bit system is used in the examples below although, in reality, 8 or more bits would be used.

Fig. 1.9(a) shows an analogue signal of frequency 1 kHz. This signal is sampled every 125 μs (a sampling frequency of 8 kHz) and the sample voltages are shown in Fig. 1.9(b). Note that the value given to the sampled voltage is always the value of the nearest increment *below* the actual sample voltage. In this particular example, an analogue signal of 14.3 V would be sampled as 14 V, an analogue signal of 3.8 V would be sampled as 3 V. The resulting digital signal is shown as a regular series of groups of 4 bits with each group separated in time by 125 μs.



signal /V
16
14
12
10
8
6
4
2
0
original analogue signal
0
125
250
375
500
625
750
875
1000
t/μs
(a)
signal /V
8 V
12 V
14 V
12 V
8 V
3 V
2 V
3 V
8 V
0
125
250
375
500
625
750
875
1000
t/μs
(b)
digital signal
1000
1100
1110
1100
1000
0011
0010
0011
1000
t
125 μs
(c)
signal /V
"recovered" analogue signal
16
14
12
10
8
6
4
2
0
0
125
250
375
500
625
750
875
1000
t/μs
(d)

Fig. 1.9

Note: Over 50 years ago, it was shown by Harry Nyquist that in order to be able to recover the analogue signal from its digital conversion, the sampling has to occur at a frequency greater than twice the highest frequency component in the original signal. Thus, in the telephone system, the highest frequency is restricted to be 3.4 kHz and therefore the sampling frequency is 8000 Hz. In the manufacture of compact discs, the highest frequency is 20 kHz and the sampling frequency is 44.1 kHz.

After the analogue signal has been converted to a 4-bit digital signal by the analogue-to-digital converter (ADC), the original signal can be recreated by passing the 4-bits into a digital-to-analogue converter (DAC). The output of the DAC is necessarily "grainy" and is not smooth because the number of bits limits the number of possible voltages levels (with 4-bits there are $2^4 = 16$ levels). This is illustrated in Fig. 1.9(d) where the original analogue signal of Fig. 1.9(a) has been recreated.

In practice, digital systems make use of filters to remove this "grainy" effect and make the final output look much more like the original.

1 (g) *Candidates should be able to demonstrate an awareness of how waveforms are encoded by digital sampling.*

After the analogue voltage has been sampled and converted by the ADC, the 4-bit digital signal could be transmitted in parallel form down four separate wires. This form of transmission, as illustrated in Fig. 1.10, is the fastest method of transmitting digital data.

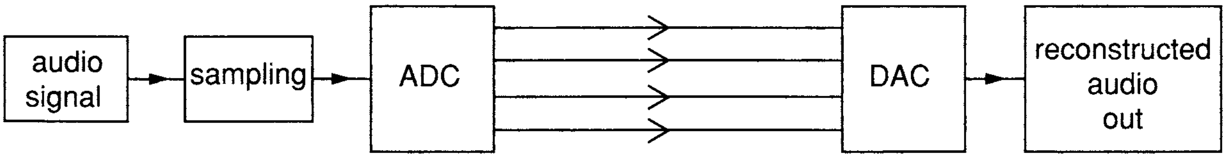


Fig. 1.10

Computers which have to communicate with each other over short distances are often linked this way. However, if the transmission distance is very large, it becomes uneconomic or impossible to have 4 (or more) separate channels of communication.

The solution is to pass the 4-bit signal into a *parallel to serial data converter*. This circuit accepts the 4-bit word as a whole and then emits it, one bit at a time. Each individual bit is passed in series along a single communication channel (a cable or radio link), at the end of which is a *serial to parallel converter*. This circuit accepts the 4 bits, one after the other and then presents them in parallel to the DAC. This is illustrated in Fig. 1.11.

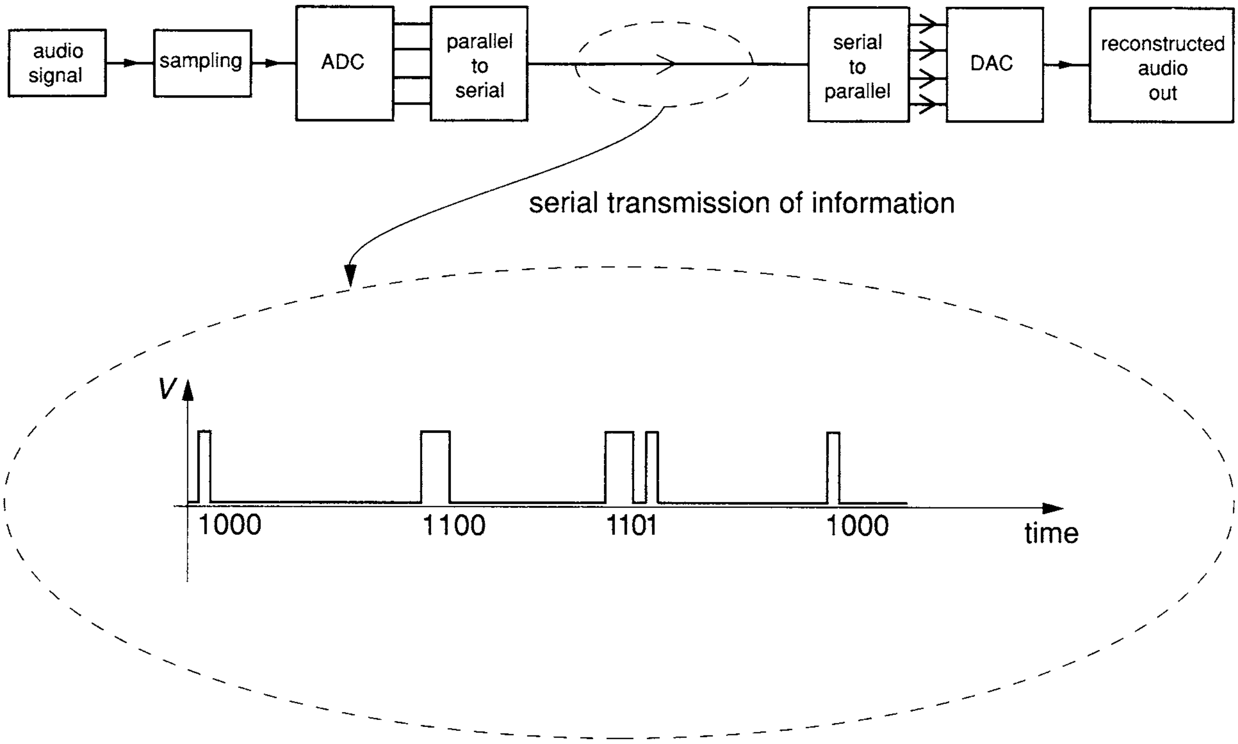


Fig. 1.11

It is essential in a serial transmission system that data conversion and transfer are carefully synchronised. Fig. 1.11 also shows a "snapshot" of the digital signal passing serially through the channel.

If the channel were an optic fibre, then the 1 would be represented by light and the 0 would be represented by no light.

If the actual time required for one bit can be made very short (e.g. 1 µs), then the time required to transmit four bits is short (4 µs). This means that the channel would be unused for most of the time between samples (in this case, 125 – 4 = 121 µs). In this period of time, other users can share the transmission link and transmit their digitally encoded signals. This process is known as *time division multiplexing*.

1 (h) *Candidates should be able to appreciate the scientific and economic advantages of fibre optic transmission, compared with metal cable and radio transmission.*

The following example should illustrate one of the scientific advantages.

The audio signal of a single telephone call is sampled 8000 times per second and each sample consists of 8 bits. Thus, any one telephone call generates 8000 x 8 or 64 000 bits per second.

If a bit lasted for $1\,\mu s$, then any one call would only occupy the telephone line for $64\,000\,\mu s = 0.064\,s$ within any one second. Thus, (theoretically) a total of

$$\frac{(1-0.064)}{0.064} \approx 15$$

other calls could share the same line by time division multiplexing.

Now, if a bit lasted for $0.1\,\mu s$ then any one call would only occupy the telephone line for $6400\,\mu s = 0.0064\,s$ within any one second. Thus, (again theoretically) a total of about 150 other calls could share the same line by time division multiplexing.

Clearly, as the time for the system to generate 1 bit decreases, the number of separate telephone calls which can share the same line increases. This has financial implications in that the cost of calls could be reduced.

The minimum time for one bit is approximately equal to the reciprocal of the maximum frequency which the telephone line can transmit over long distances.

Metal cable
This has a maximum transmission frequency of a few MHz and can support only a few separate telephone calls.

Microwave Radio
This has a maximum transmission frequency of a few 1000 MHz and can support about a thousand separate telephone calls.

Optic Fibre
This uses light waves which have a frequency of the order of 10^8 MHz: thus, (in theory) a bit (or individual light wave) could last for only 10^{-14} second and this would allow hundreds of thousands of separate telephone calls to share the same fibre. However, the present state of technology does not allow control at such high frequencies and the "bit" in an optic fibre is a pulse or a chain of light waves. The duration of the bit is governed by how fast the laser providing light to the fibre can be switched on and off. This is presently of the order of GHz but is increasing as technology develops.

The advantages of optic fibres are summarised below.

(i) Optic fibres have a wide bandwidth which creates a large transmission capacity (more information can be carried down a single link).

(ii) Signal power losses in optic fibres are relatively small, thus allowing longer uninterrupted distances between regenerator amplifiers. This reduces the cost of installation.

(iii) The cost of fibre optic cable is very much lower than that of metal cable.

(iv) The diameter and weight of fibre optic cables is much smaller than metal cables. This implies easier handling and storage.

(v) Optic fibres have very high security since they do not radiate energy and thus there is negligible "crosstalk" between fibres.

(vi) Optic fibres do not pick up electromagnetic interference. Hence they can be used in electromagnetically "noisy" environments, e.g. alongside electric railway lines. In fact, optic fibres are being installed along the routes of the electricity distribution networks.

(vii) Optic fibre is ideal for digital transmissions since the light is obtained from a laser which can be switched on and off very rapidly.

1 (i) Candidates should be able to demonstrate an awareness of social, economic and technological changes arising from modern communication methods.

1. With mass production and ever developing integration of more and more complex circuits, the cost of electronics is steadily falling. In the early 1960's, a "transistor radio" cost about £25. Nowadays, a comparable receiver costs £15, in spite of inflation.

2. The cost of national and international telephone calls has fallen so much that greater use is now made of this system by domestic consumers. In many instances, it is now cheaper to phone than to write a letter, and there is a saving on time.

3. The telephone system now allows fax machines, itemised billing, three-way calls, call diversions, answer machines etc, again for use in the home as well as commerce. Until the 1980's, telephones were available for conversations only.

4. Much greater use is now made of the huge bandwidth potential of the high frequency end of the electromagnetic spectrum. This has enabled the transmission of TV signals in optic fibre cable and via satellites, resulting in a wider choice of TV channels.

5. Communication satellites now allow the broadcast and reception of TV programmes, telephone messages etc. from and to anywhere in the world. Whereas in the past, facilities were limited, these are now readily available with no pre-booking of, for example, calls to and from the US.

6. A possible national grid of optic fibre cable will eventually allow two-way domestic communication for:

   electronic mail,
   electronic banking,
   electronic shopping,
   electronic voting.

T2. Communication Channels

2 (a) *Candidates should be able to appreciate that information may be carried by a number of different channels, including wire-pairs, coaxial cables, radio and microwave links, and optic fibres.*

2 (b) *Candidates should be able to discuss the relative advantages and disadvantages of channels of communication in terms of available bandwidth, noise, cross-linking, security, signal attenuation, repeaters and regeneration, cost and convenience.*

Wire-pairs

In the early days of electrical communication, a transmitter was connected to a receiver by a pair of wires. Fig. 2.1 shows an arrangement for transmitting information in digital code (e.g. Morse code) in this way. This is a very simple link. Nowadays, wire pairs are used only for very short distances with low frequency signals.

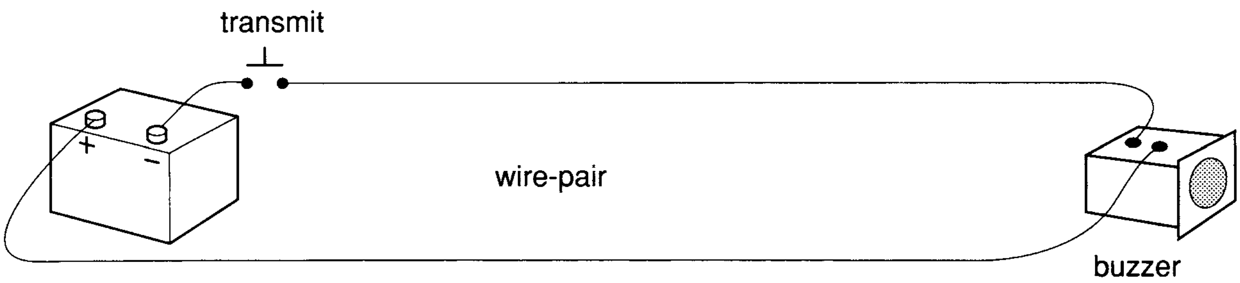


Fig. 2.1

If high frequency signals are to be sent along a pair of wires over an appreciable distance, it is necessary to arrange repeated amplification at regular intervals. This is due to the relatively high attenuation of the signal. Energy is lost as heat in the resistance of the wires and also as radiation since the wires act as aerials. A further problem is that the wires easily pick up external interference which degrades the original signal so much that if several wire-pairs are arranged next to each other, they will pick up each other's signals. This effect is known as cross-talk or cross-linking and gives very poor security as it is easy to "tap" a telephone conversation.

The bandwidth of a pair of wires is only about 500 kHz. Consequently, as a means of carrying a large quantity of information, it is extremely limited.

Coaxial cable

Coaxial cable is essentially a pair of wires arranged so that one wire is shrouded by the other. This is shown in Fig. 2.2. The signal is passed down the inner conductor while the outer conductor acts as the return wire and shields the inner one from external interference. The outer conductor is usually connected to earth.

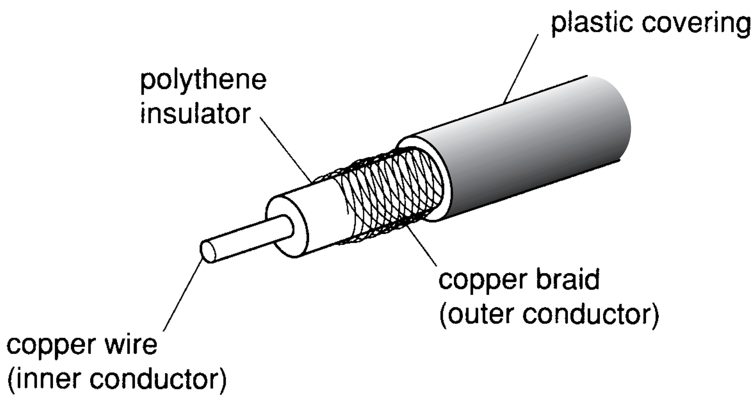


Fig. 2.2

Coaxial cable is more expensive than wire-pairs but causes less attenuation of the signal so that in long distance communication, repeater amplifiers can be arranged further apart. It is also less prone to external interference, though not immune to it, so offers slightly more security.

The bandwidth of coaxial cable is about 50 MHz. It is able to carry much more information than a wire-pair.

Radio link
When radio was first developed, an electrical oscillation of a few kHz (the carrier wave) was linked to a long wire (the aerial). The oscillations were switched on and off. In this way, information was transmitted from the aerial in digital form (by Morse code). It soon became possible to modulate the carrier wave (by AM or by FM) so that information could be sent at a much faster rate. Different carrier frequencies allowed different radio stations to share the same air space (frequency multiplexing).

Energy which is radiated from an aerial is in the form of electromagnetic waves and is propagated at the speed of light. If the frequency of the radiation lies somewhere in the range from 30 kHz to 3 GHz, then the waves are known as radio waves.

The electromagnetic radiation which is emitted from a transmitting aerial can be arranged (by suitable choice of the aerial) to radiate in all directions (e.g. for national broadcasting). For point-to-point communications, the aerial can be arranged to radiate predominantly in one direction. No matter what aerial is used there is always energy loss and the power of the signal picked up by a receiving aerial is reduced as the distance between the transmitter and receiver is increased. The actual distance that any particular waves propagate is very much a function of frequency. This is discussed in section *3(a)*.

As a means of communicating from a single transmitter over a large area, the AM broadcasts on the LW and MW wavebands are relatively cheap and technically simple, as explained in section *1(d)*.

In modern communication, considerable use is made of the VHF and UHF wavebands for mobile phones, walkie-talkie radio etc. (This is due to the fact that, at these frequencies, the wavelength is relatively small and hence the aerial can be made conveniently short.)

The bandwidth of a radio link increases as the frequency of the carrier wave increases.

Microwave link

Microwaves are radio waves in the SHF waveband from 3 GHz to 30 GHz with wavelengths of only a few centimetres. They are generally used for point-to-point communication, as illustrated in Fig. 2.3.

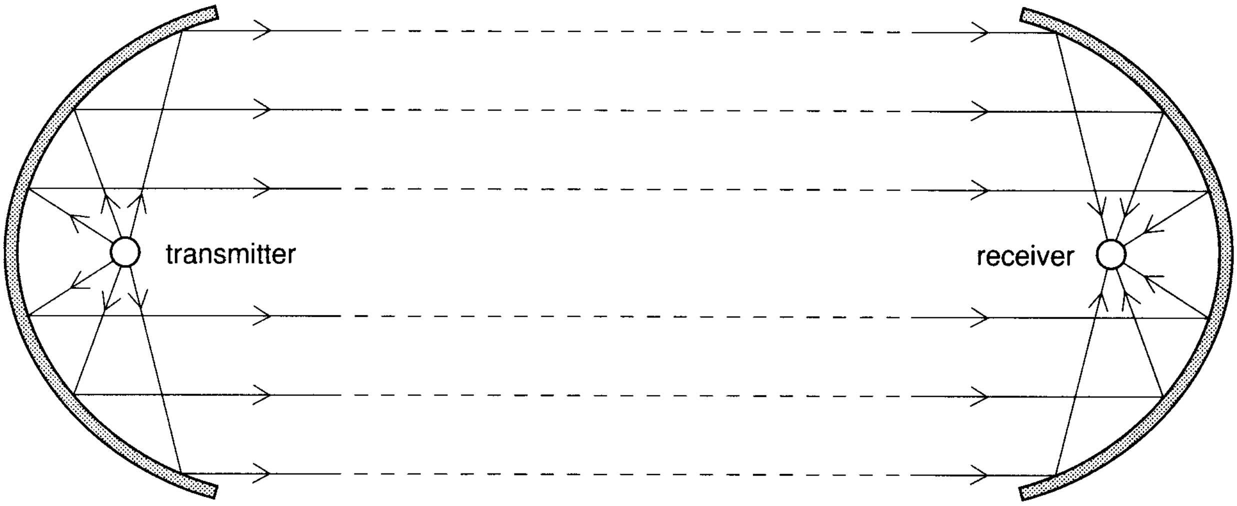


Fig. 2.3

Here the transmitting element is placed at the focus of a parabolic reflector which causes the power to be radiated in a parallel beam. A parabolic reflector, placed in the path of this beam reflects and focuses the power on to a receiving element.

Note: The reflecting parabolic dish is not an aerial as such; it is simply a means of directing as much power as possible into a parallel beam. It is most useful with short wavelengths where the spread of waves due to diffraction is less pronounced.

The bandwidth of a microwave link is of the order of GHz. Consequently, microwave links have a huge information carrying capacity. However, for terrestrial transmissions, the range is limited to line of sight. Many repeater stations are required to transmit over long distances.

Optic Fibres

These carry digital information in the form of pulses of light from lasers which are switched on and off at extremely high frequencies. Because the glass is so pure, the signal can travel very large distances before regeneration becomes necessary.

Optic fibres are discussed in section *1(h)*.

2 (c) *Candidates should be able to understand and use signal attenuation expressed in* dB *per unit length, including recall and use of the expression number of decibels (dB) = 10 lg (P_1/P_2) for the ratio of two powers.*

Attenuation
An electrical signal travelling along a metal wire gradually loses power (mostly as thermal energy in heating the wire).

A light pulse travelling along an optic fibre also loses power (mostly by absorption due to impurities in the glass and scattering by imperfections in the fibre).

Electromagnetic waves radiating from a transmitter also lose power by absorption and dispersion.

The reduction in signal power is known as *attenuation*.

Noise
In all electrically operated systems, there is always unwanted power present which adds itself in a random manner to any signal. There are several sources of this additional power. One of them arises from the thermal vibrations of the atoms of the material through which the signal is passing. As a result, this additional power can never be totally removed.

This unwanted power is known as *noise* and it is seen as a distortion of the signal.

The decibel
In order that a signal may be detected adequately, its power must be a minimum number of times greater than the power associated with the noise. Typically, this signal-to-noise ratio could be 100. Repeater amplifiers may be required to increase the power of the signal being transmitted along a transmission line. The gain of such an amplifier (i.e. the ratio of the signal output power to the input power) would be 100 000. For a radio link between Earth and a geostationary satellite, the power received by the satellite may be 10^{19} times less than that transmitted from Earth.

It can be seen that the ratio of the two powers may be very large. Consequently, an extremely convenient unit by which power levels (or, in fact, any other quantities) may be compared is the bel (B). In practice, these ratios are usually expressed in decibels (dB) where

10 decibels (10 dB) = 1 bel (1 B).

The number of decibels is related to the ratio of the two powers P_1 and P_2 by the expression

$$\text{number of decibels} = 10\,\lg \frac{P_1}{P_2}.$$

Example

The gain of an amplifier is 45 dB. Calculate the output power P_{out} of the amplifier for an input power P_{in} of 2.0×10^{-6} W.

$$\text{number of decibels} = 10 \lg \frac{P_{out}}{P_{in}}$$

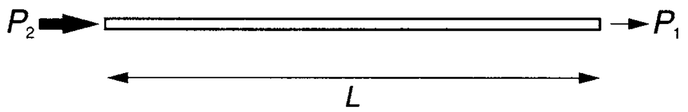
$$45 = 10 \lg \frac{P_{out}}{2.0 \times 10^{-6}}$$

$$4.5 = \lg \frac{P_{out}}{2.0 \times 10^{-6}}$$

$$P_{out} = 10^{4.5} \times 2.0 \times 10^{-6}$$

$$P_{out} = 6.3 \times 10^{-2}\,\text{W} = 63\,\text{mW}$$

If the power P_1 at any point along a transmission line is known and the input power P_2 to the line is also known, then the loss, or attenuation, can be calculated.



$$\text{Attenuation in line} = 10 \lg \frac{P_2}{P_1}.$$

Now if the length L of the line is known, then it is possible to determine an important characteristic of the line which is the loss per unit length.

$$\text{Attenuation per unit length} = \frac{1}{L}\, 10 \lg \frac{P_2}{P_1}.$$

Example

The input power to a cable of length 25 km is 500 mW. The attenuation per unit length of the cable is 2 dB km^{-1}. Calculate the power of the signal which emerges from the output end of the cable.

$$\text{Total signal loss in cable} = 2 \times 25\,\text{dB} = 50\,\text{dB}.$$

$$50 = 10 \lg \frac{500 \times 10^{-3}\,\text{W}}{P_{out}},$$

where P_{out} is the output power.

$$P_{out} = 500 \times 10^{-3}\,\text{W} \div 10^{5} = 5 \times 10^{-6}\,\text{W}.$$

The signal cannot be allowed to travel indefinitely in the cable because eventually it will become so small that it cannot be distinguished from background noise. An important factor is the minimum *signal-to-noise ratio* which effectively provides a value of the lowest signal power allowed in the cable.

In the above example, the background noise is 5×10^{-13} W and the minimum signal-to-noise ratio permissible is 20 dB.

Then, if P_m is the minimum signal power,

$$20 = 10 \lg \frac{P_m}{5 \times 10^{-13}}.$$

$$P_m = 5 \times 10^{-13} \times 10^2 \text{ W} = 5 \times 10^{-11} \text{ W}.$$

This enables the maximum uninterrupted length of cable down which the signal can be transmitted to be determined.

Maximum loss in cable $= 10 \lg \dfrac{500 \times 10^{-3}}{5 \times 10^{-11}}$ dB $=$ 100 dB

Maximum distance $=$ 100 dB $\div$ 2 dB km^{-1} $=$ 50 km.

2 (d) *Candidates should be able to understand and use repeater gain in dB.*

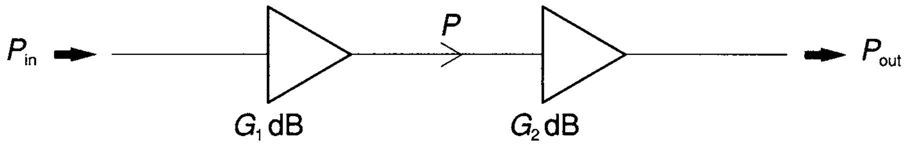
The power gain of an amplifier is defined to be the ratio of the power output to the power input. This could be expressed as a simple number. For example, if the power gain of an amplifier is 10^4, then the output signal power P_{out} is ten thousand times greater than the input signal power P_{in}.

However, this is another factor which is better expressed in dB.

$$\text{Amplifier power gain} = 10 \lg \frac{P_2}{P_1} \text{ dB}$$

Thus, the above amplifier can either be stated to have a power gain of 10^4 or a power gain of 40 dB.

The advantage of using amplifier gains in dB becomes clear when there are several repeater amplifiers along a transmission line. *In order to calculate the total gain of a number of amplifiers, it is only necessary to add the gains in dB* (instead of having to multiply each gain if expressed as a simple ratio). Consider the case of two amplifiers of gains G_1 dB and G_2 dB



Let the input power to the amplifier of gain G_1 dB be P_{in} and the output power be P. Then,

$$G_1 = 10\lg \frac{P}{P_{in}}.$$

Similarly, for the amplifier of gain G_2 dB with output power P_{out},

$$G_2 = 10\lg \frac{P_{out}}{P}.$$

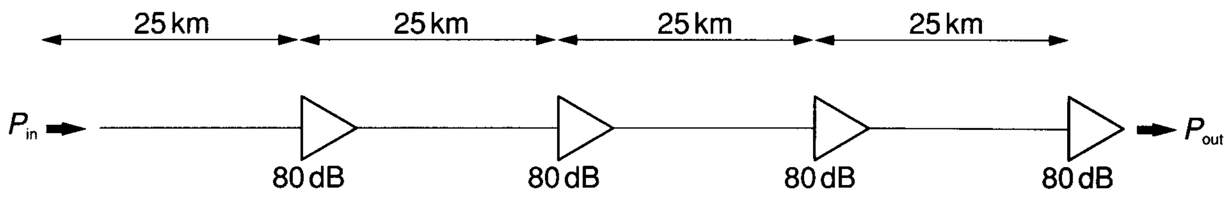
The overall gain of the two amplifiers is given by

$$\frac{P_{out}}{P_{in}} = \frac{P}{P_{in}} \times \frac{P_{out}}{P}.$$

$$\begin{aligned} \text{Total gain in dB} &= 10\lg \left(\frac{P}{P_{in}} \times \frac{P_{out}}{P} \right) \\ &= 10\lg \frac{P}{P_{in}} + 10\lg \frac{P_{out}}{P}. \\ \text{Total gain in dB} &= G_1 + G_2 \end{aligned}$$

Example

A cable of length 100 km has an attenuation of 3 dB km^{-1}. Every 25 km along its length, there is a repeater amplifier with a gain of 80 dB, as shown below. Calculate the overall gain or loss in this system.



Total amplifier gain = 4 x 80 = 320 dB

Total cable loss = 100 x 3 = 300 dB

Overall gain in system = + 320 – 300 = +20 dB.

2 (e) *Candidates should be able to estimate and use typical power levels and attenuations associated with different channels of communication.*

Some typical power levels and attenuations associated with optic fibres and metal cables are given in the table below.

	power input / W	attenuation loss / dB km^{-1}	background noise / W
optic fibre	$\simeq 10^{-3}$	$\simeq 1$	$\simeq 10^{-20}$
metal cable	$\simeq 10^{-1}$	$\simeq 5$	$\simeq 10^{-12}$

T3. Radio Communication

3 (a) *Candidates should be able to appreciate the effect of the Earth's surface on the propagation of radio waves over long distances, and the use of the ionosphere as a reflector if the waves are to be propagated over long distances.*

There are three important means by which the electromagnetic waves, generated by a transmitting aerial, find their way to a receiving aerial.

(i) *Surface wave*

For frequencies below about 3 MHz (relatively long wavelengths), a vertically polarised wave travelling near the Earth's surface will be affected by the conductivity of the Earth. This causes the wave to tilt forward and, in combination with some diffraction, increases the effective range well beyond the horizon. This is illustrated in Fig. 3.1. The maximum distance for this method of propagation is about 1000 km.

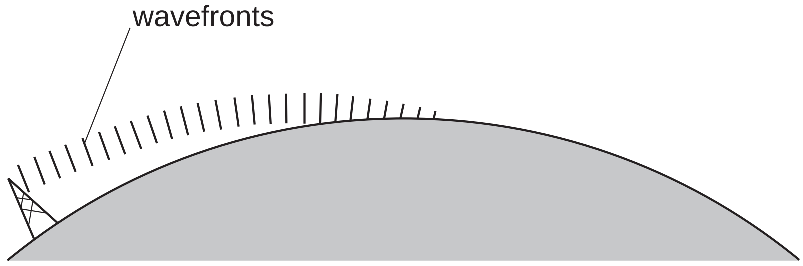


Fig. 3.1

(ii) *Sky wave*

Waves having frequencies between 3 MHz and 30 MHz (the short-wave waveband), are sometimes known as *sky waves*. These waves are found to reflect off the ionosphere. The ionosphere is essentially a complex series of layers of charged particles high up in the Earth's atmosphere. If the frequency is too low or too high, the wave simply passes through these layers. After a wave of the appropriate frequency has reflected off the ionosphere, it can then reflect off the surface of the Earth (also a conducting layer). In this way, the wave can make multiple reflections and travel round the entire Earth. This is illustrated in Fig. 3.2.

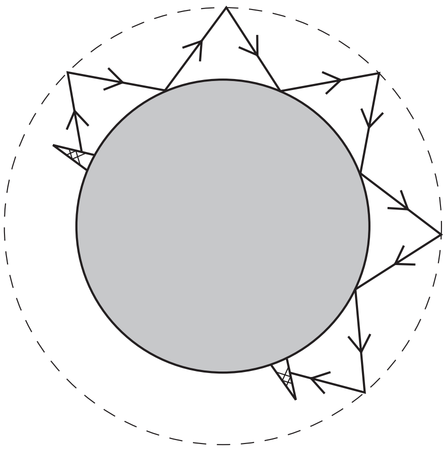


Fig. 3.2

(iii) *Space wave*

At frequencies greater than 30 MHz, the waves have relatively short wavelengths and are known as *space waves*. These waves tend to travel by line-of-sight and hence the maximum range is limited by the horizon from the top of a transmitting tower. This is illustrated in Fig. 3.3.

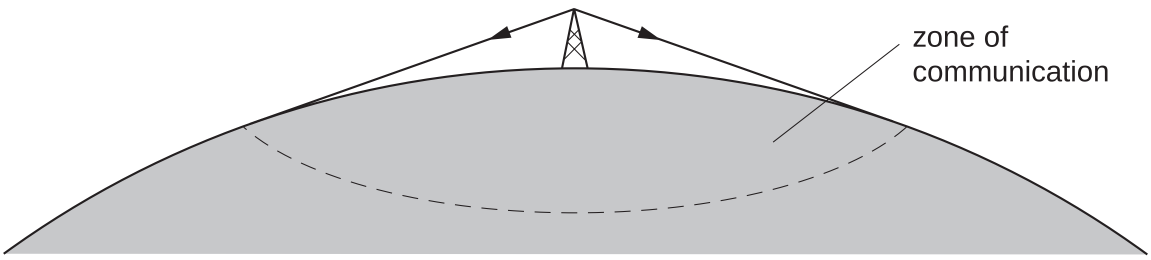


Fig. 3.3

3 (b) *Candidates should be able to describe the use of satellites in radio communication and appreciate the importance of geostationary satellites.*

Fig. 3.4 shows the basic principle of satellite communication. A transmitting station T directs a carrier wave of frequency f_{up} towards the satellite. The satellite receives this signal, amplifies it and changes the carrier frequency to a lower value f_{down}, before directing it towards a receiver R back on Earth. Typically, the uplink would have a frequency of 6 GHz and the downlink 4 GHz (the 6/4 GHz band). Alternatives are the 14/11 GHz band and the 30/20 GHz band. The two carrier frequencies are different to prevent the satellite's high power transmitted signal swamping its reception of the very low power signal which it receives. There is no interference of the actual information being carried by the waves because this is stored as a modulation of the carrier waves.

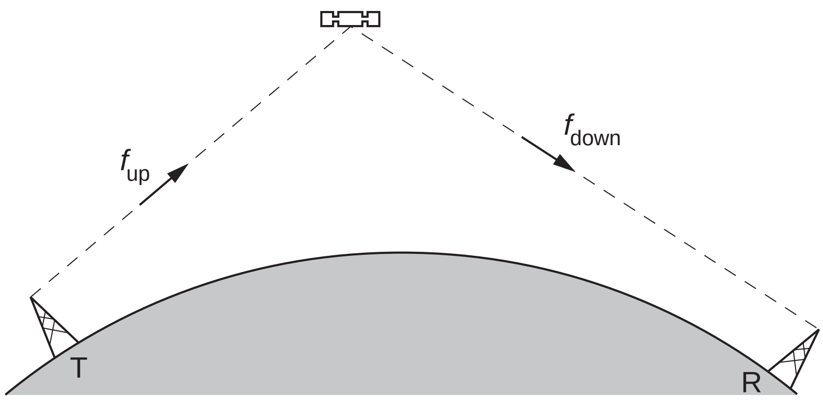


Fig. 3.4

Although the transmitter of Fig. 3.4 could transmit more or less directly to the receiver without the use of a satellite, it could only do so on the SW or MW wavebands (see section *3(a)*). However, in modern communication systems, this is not done for three reasons.

(i) Long-distance communication on these wavebands is unreliable. Sky waves rely on reflection from layers of ions in the atmosphere. These layers vary in height and density according to the time of day. In hilly areas, surface waves give rise to regions of poor reception where there are shadows.

(ii) The bands are already filled by existing broadcasts (see section *1(d)*).

(iii) The available bandwidths are too narrow to carry the required amount of information.

Fig. 3.5 shows a satellite in a relatively low polar orbit with a period of rotation of the order of 90 minutes. This type of satellite is often used for monitoring the state of the Earth's surface because at some time or other during the day, the satellite will be above every point on the Earth. As the satellite orbits, the Earth is rotating below it. For a satellite having an orbital period of 90 minutes, each orbit crosses the equator 23° to the west of the previous orbit. It is not possible to have continuous communication links with such a satellite because, from Earth, the satellite appears to move quickly across the sky.

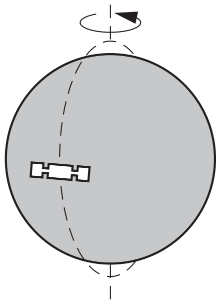


Fig. 3.5

Fig. 3.6 illustrates a satellite in a geostationary orbit (see section *8(j)*).

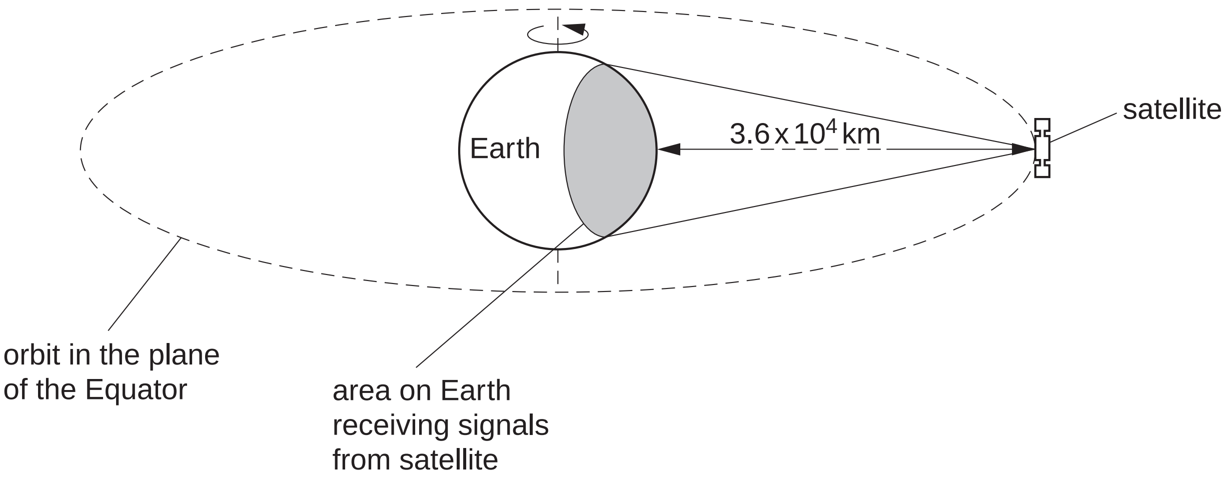


Fig. 3.6

Such a satellite orbits the Earth with a period of rotation of 24 hours at a distance of 3.6×10^4 km above the Earth's surface. If the satellite is placed in orbit directly above the Equator, then, for an observer on the Earth, the satellite will always appear to be above a fixed position on the Earth. The satellite can support continuous communication between a ground station and anywhere on the surface of the Earth which receives the signal from the satellite (see Fig. 3.6). A number of such satellites with over-lapping areas of communication are used for trans-oceanic telephone calls (thus removing the need for long-distance submarine cables) and for intercontinental television broadcasts, enabling viewers in one country to watch television programmes from another.

It should be remembered that the geostationary satellites must be in equatorial orbit. Thus, communication to and from polar regions presents difficulties in that the region may not be in line-of-sight with a satellite (see Fig. 3.6).

3 *(c) Candidates should be able to recall the wavelengths used in different modes of radio communication.*

That part of the electromagnetic spectrum which is used for radio communication is illustrated in Fig. 3.7.

frequency	30 kHz – 300 kHz	300 kHz – 3 MHz	3 MHz – 30 MHz	30 MHz – 300 MHz	300 MHz – 3 GHz	3 GHz – 30 GHz	30 GHz – 300 GHz
	low frequencies LF	medium frequencies MF	high frequencies HF	very high frequencies VHF	ultra–high frequencies UHF	super–high frequencies SHF	extra–high frequencies EHF
wavelength in vacuum	10 km – 1 km	1 km – 100 m	100 m – 10 m	10 m – 1 m	1 m – 10 cm	10 cm – 1 cm	1 cm – 1 mm
	LW radio	MW radio	SW radio	FM radio	TV broadcast	microwave/satelite	

Fig. 3.7

It should be remembered that, although different regions of the spectrum are named, the boundaries between regions are not clearly defined.