Chapter 9: Communications systems

Learning Objectives:

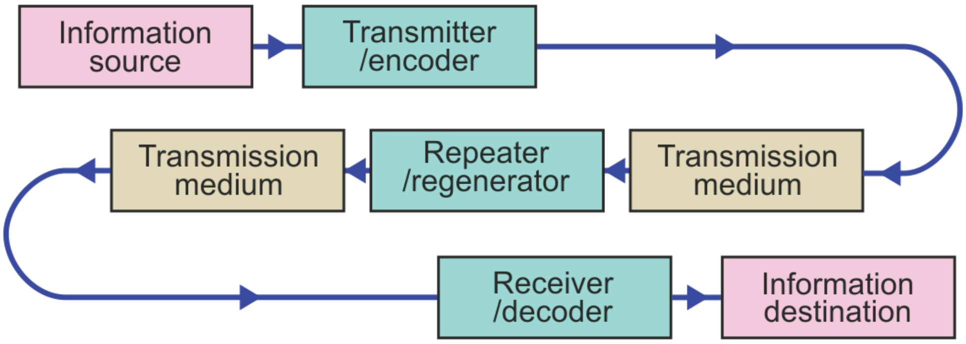
At the end of this topic you will be able to:

- recall that communication is the transfer of meaningful information from one location to another
- recall the structure of a simple communication system consisting of:
  - information source
  - transmitter/encoder
  - transmission medium
  - amplifier/regenerator
  - receiver/decoder
  - information destination
- recall and explain the relationship between:
  - bandwidth
  - data rate
  - information-carrying capacity
- select and apply the equations:
  - $N_{CH} = \frac{\text{available bandwidth}}{\text{channel bandwidth}}$
  - maximum date rate = 2 × available bandwidth
- explain the need to multiplex a number of signals onto one transmission medium and describe the principles of frequency and time division multiplexing
- describe the role of filters in communication systems
- use the decibel scale to express power gain in amplifiers and attenuation in transmission media
- select and apply the equation:
  - $G_{dB} = 10 \log_{10} = \frac{P_{OUT}}{P_{IN}}$
- differentiate between noise and distortion
- calculate the total gain in a communication system given the power gain or attenuation of its component parts
- state what is meant by signal-to-noise ratio
- select and apply the equations:
  - $SNR_{dB} = 10 \log_{10} = \frac{P_S}{P_N} = 20 \log_{10} = \frac{V_S}{V_N}$
- state what is meant by signal attenuation and describe the significance of signal attenuation (in dB) for the signal-to-noise ratio

Introduction to information transfer

Communication is defined as the transfer of meaningful information from one location to another. Over time, many ways of communicating information have evolved, allowing us to transfer information both faster and over greater distances.

The structure of a simple communication system is:



Transmission Medium
A **transmission medium** is a pathway that carries information signals from sender to receiver (plural transmission *media*). This pathway can be a solid, a liquid or a gas. Typical pathways include copper or fibre optical cables, the atmosphere or a vacuum. Information signals can be electrical, electromagnetic or optical. For example, the transmission medium for sound received by the ears is usually air. The vacuum or empty space is also a transmission medium for electromagnetic waves such as light and radio waves.

Information transfer using sound waves
Speech communication can be conveyed between people over a limited distance (about 50m). Other types of sound signals can transfer limited information (bells, sirens, guns, drums) up to several miles out in the country but over a much shorter distance in busy cities.

Information transfer using light waves
Historically, line-of-sight visual signalling systems such as flags, semaphores, lights, fires, smoke and sunlight reflected by mirrors (the heliograph) were used, effective for distances of up to about 20 km in clear weather and from high ground. Modern communication systems make use of optical fibres to carry optical signals.

Information transfer using electrical signals
The electric telegraph sent electrical currents along wires, as does the local telephone network today (but in a vastly more sophisticated form). Using amplifiers, electrical information signals can be transmitted over thousands of miles.

Information transfer using electromagnetic signals
It is possible to send signals through the air, using electromagnetic radiation in the form of radio waves. These can connect people, mobile or stationary, on board a ship, on foot or in a vehicle. Electromagnetic information signals can be transmitted over tens of thousands of miles.

Encoding / decoding
Encoding is the process of transforming information from one format into another. Both the transmitter and receiver must be aware of the code, otherwise the data cannot be retrieved.

For example, the encoder used for radio transmission is called a *modulator*. In it, a high frequency *carrier* signal is combined with the audio signal, the information. One reason for using a high frequency carrier is that these are able to propagate over large distances.

At the receiver, a *demodulator* decodes (separates) the carrier and information signal so that the audio broadcast can be heard by the listener.

Capacity of a Transmission Medium

The capacity depends on two factors:

Available Bandwidth
This depends on the medium used - copper, coaxial or fibre-optic cable, for example, and on the cable's specification. Typically, the bandwidth for copper cable is up to 1 MHz, for coaxial cable up to 100 MHz and 100 GHz for fibre optic.

The available bandwidth for radio wave transmission is from 30 kHz to 300 GHz. Frequency and bandwidth allocation is strictly controlled by national governments. FM radio stations in the UK are allocated a bandwidth of 87.5 – 108 MHz. Satellite communication systems are allocated bandwidth at frequencies above 3 GHz.

Channel Bandwidth
Earlier, it was shown how filters could be used to allow transmission of some frequencies and suppression of others. The minimum acceptable bandwidth required for transfer of meaningful information within different situations was also covered. For example, the minimum acceptable bandwidth, also known as channel bandwidth, for the UK telephone system is 3.4 kHz.

A transmission medium is divided into channels so that it can be used to send multiple streams of information simultaneously.

The formula for the capacity of a transmission medium is

$$N_{CH} = \frac{\text{available bandwidth}}{\text{channel bandwidth}}$$

Examples:

1. The available bandwidth for FM radio is 87.5 - 108 MHz. When each channel is allocated a bandwidth of 200 kHz, what is the maximum number of channels that are available?

$$N_{CH} = \frac{(108 - 87.5)}{0.2} = 102.5$$

$$N_{CH} = 102 \text{ channels}$$

2. A cable must carry 32 channels, each with a bandwidth of 12 kHz.
What is the minimum bandwidth the cable must have?

Cable bandwidth = N_{CH} × channel bandwidth

= 32 ×12
= 384 kHz

Data rate

Data rate is measured in units called *bits/s* or *bps*.

For digital signals, the maximum data rate achieved by a transmission medium depends on:

- the available bandwidth
- the number of signal levels
- the amount of noise present in the medium

Assuming that the signal is binary-encoded, (consisting of two voltage levels,) and the medium is noise free then:

$$\text{maximum date rate} = 2 \times \text{available bandwidth}$$

Example:

What is the minimum bandwidth required for a fibre optical cable to carry binary data at a rate of 30 Gbps?

$$\text{data rate} = 2 \times \text{available bandwidth}$$
$$30 = 2 \times \text{bandwidth}$$
$$\text{bandwidth} = \frac{30}{2}$$
$$= 15\text{ GHz}$$

Multiplexing

This is the process of allowing several independent users to share the same transmission medium (or link). The medium can be a cable (i.e. wire-pair, co-axial, optic fibre) or the atmosphere (or space). An information pathway within this medium is called a channel. Multiplexing allows many channels to be accommodated within one single medium.

a. Frequency division multiplexing (FDM)

Frequency-division multiplexing is a form of signal multiplexing which involves assigning non-overlapping frequency ranges to each signal or "user" of the transmission medium.
Each information signal is combined with a different high frequency carrier signal.

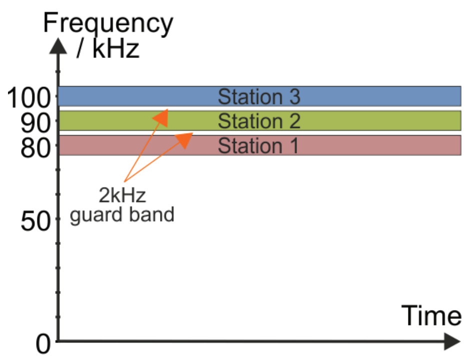
During transmission, each channel has access to a narrow range of frequencies all the time. A small frequency gap, known as a guard band, is left between channels to stop the signal interfering with one another.

Example:

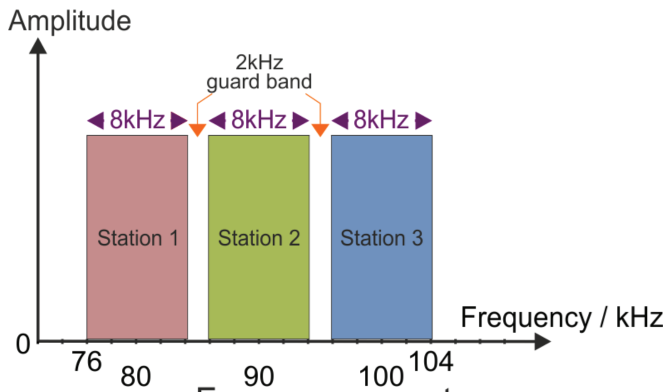
Three radio stations are each allocated a bandwidth of 8 kHz respectively. They broadcast radio waves into free space at carrier frequencies of 80, 90 and 100 kHz respectively. The guard band between each channel is 2 kHz.

(a) Determine the frequency allocation (band) for each station.
(b) Represent this information on both a time domain and a frequency spectrum graph.

(a) Station 1 occupies a frequency band of (80 ± 4) kHz (= 76 ⇒ 84) kHz.
Station 2 occupies a frequency band of (90 ± 4) kHz (= 86 ⇒ 94) kHz.
Station 3 occupies a frequency band of 100 ± 4) kHz (= 96 ⇒ 104) kHz.



Time domain



Frequency spectrum

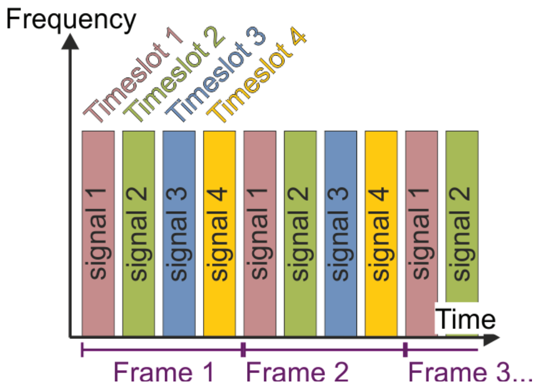
b. Time-division multiplexing (TDM)

Time division multiplexing is a type of digital (or, rarely, analogue) multiplexing in which two or more signals or bit streams take turns to access the channel. Transmission time is divided into **timeslots** of fixed length, one for each signal.

A byte of data from signal 1 is transmitted during timeslot 1, signal 2 during timeslot 2, etc.

A TDM frame consists of one timeslot from each signal. After the last of these, the cycle starts all over again with a new frame, starting with the second byte of data from signal 1, etc.

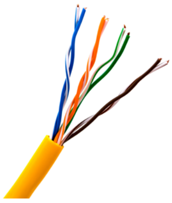
During transmission, each signal has access to the full range of frequencies available to the channel.



Bandwidth of cable communication systems

The choice of cable limits the bandwidth and data rate available.

Twisted pair copper cable:
The type of twisted pair cable used in the UK telephone network has a bandwidth of a few hundred kilohertz. Each pair of wires conducts the signals for one particular circuit. Twisting the pairs of wires reduces *crosstalk* between adjacent circuits, (when a signal in one circuit affects that in an adjacent circuit). High grade twisted pair cables used on computer networks have bandwidth in excess of 20 MHz. Twisted pair cable is suitable for use over only fairly short distances.



Internal cable;
zazameza / getty images

External underground cable;
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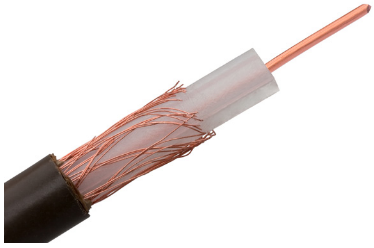
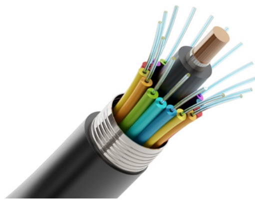
Coaxial cable:
Coaxial cables are used in the home for feeding the signal from a satellite dish to a satellite TV receiver. They are also used on computer networks and long distance telephone circuits to carry thousands of telephone signals over large distances. In the case of telephone circuits several coaxial cables will be enclosed in a polythene sheath.



oaxial cable; lucentius / getty images

Fibre optic cable
Fibre optic cable is used in local telephone networks to provide high speed broadband at data rates in excess of 100Mbps.
It is also used to carry high volumes of signals both in computer networks and in long distance telephone communication systems.



Fiber Optical Cable; Shutterstock.com

Filters

Chapter 4 introduced the design and some applications of filters. They are used extensively in communication systems.

Low-pass filters are used to:

- modify the bandwidth of information signals to match the channel bandwidth
- reconstruct audio signals that have been digitised for transmission
- prevent interference between signals, for example, between the broadband and voice signals in a domestic telephone circuit

Band-pass filters are used to:

- separate channels at the output of a FDM system
- prevent interference between radio stations in radio receivers

The use of filters in a FDM system is illustrated in the following example:

Example:

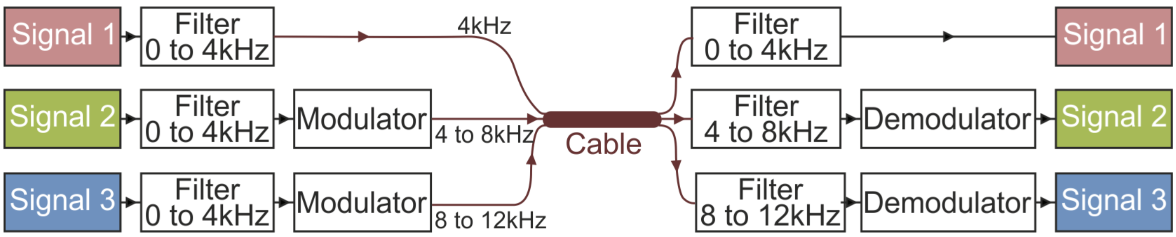
Several audio signals are transmitted simultaneously over one pair of wires in a FDM cable transmission system.

- Each signal has a bandwidth of 4 kHz (including a guard band) and is allocated its own channel
- Signal 1 is allocated the first channel. It is unmodulated, (i.e. baseband transmission,)
- The other signals cannot be transmitted in the same way since all signals would then become inseparable. Instead, signals 2, 3, etc. are each modulated onto carrier waves, having different frequencies to produce modulated signals with frequencies in the ranges of 4-8 kHz, 8-12 kHz, etc.
- At the receiver, the different frequency bands are separated, using a low pass filter for signal 1, and band-pass filters for the other signals.
- Signals 2, 3, etc. are then demodulated to recover the original signals.

(a) Draw the block diagram of the system showing the first 3 channels.

(b) Each pair of twisted cables has a bandwidth of 200kHz.
How many signal channels can be incorporated in this FDM system?

(a)



(b) Number of channels,

$$N_{CH} = \frac{200}{4}$$

$$= 50 \text{ signal channels}$$

Exercise 9.1

1. A coaxial cable has a bandwidth of 1.2 MHz. How many channels, each having a bandwidth of 8 kHz, can be accommodated on the cable?

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2. A communications medium has 150 channels. The available bandwidth of the medium is 2.4 MHz. Calculate the maximum bandwidth of each channel.

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3. What is the maximum data rate for carrying binary data on a fibre optical cable with a bandwidth of 80 GHz?

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4. Four radio stations are each allocated a bandwidth of 9 kHz respectively.
They broadcast radio waves into free space at carrier frequencies of 100,110, 120 and 130 kHz respectively. The guard band between each channel is 1 kHz.

(a) Determined the frequency band of each channel.

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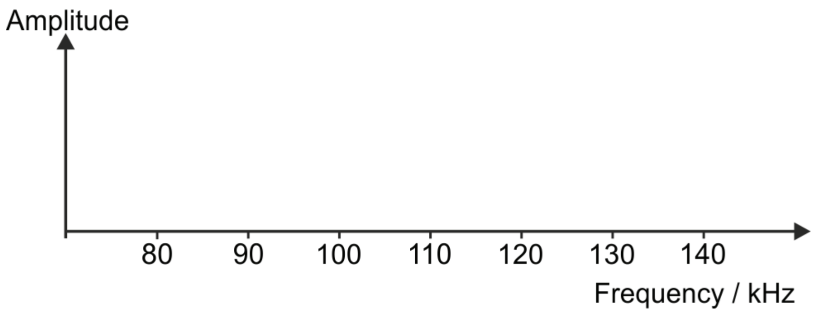
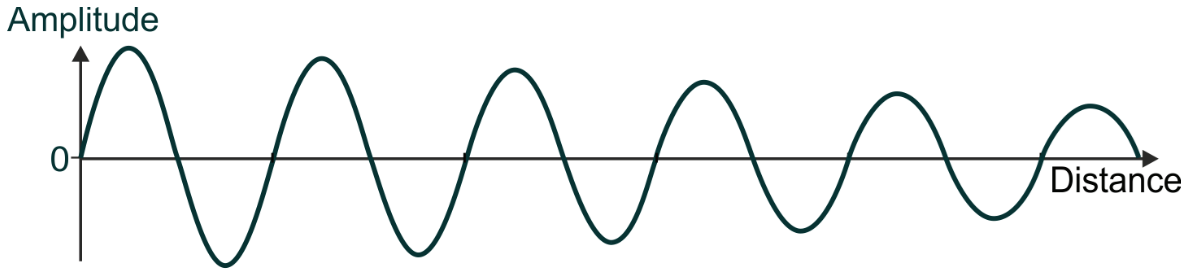
(b) Complete and label the graph below to show the frequency spectrum for each channel.



Gain and Attenuation

In electronics, **gain** is a measure of the ability of a sub-system, (often an amplifier,) to increase the voltage, current or power of a signal. It is usually defined as the ratio of the signal output of the sub-system to the signal input of the same sub-system.

Attenuation:
Occurs as signals propagate through electrical circuits, optical fibres, air (free space) etc. As the signal progresses, some of the energy is lost and its amplitude diminishes. The further it travels, the greater the loss in amplitude. This is illustrated below.



Attenuation can be thought of as a gain which is less than 1.

Power Gain:
Originally, the **decibel** (abbreviated **dB**) was created to measure the intensity of sound. In communication systems, it is used to express the power gain of an amplifier or the power attenuation (loss) of a transmission medium.

The equation to convert a power ratio into decibels is

$$G_{dB} = 10\log_{10}\frac{P_{OUT}}{P_{IN}}$$

The table gives examples of the conversion from power loss/gain as a ratio to loss/gain in decibels:

Loss / gain as a ratio	Loss / gain in decibels
$\frac{P_{OUT}}{P_{IN}}$	$10\log\frac{P_{OUT}}{P_{IN}}$
1000	30dB
100	20dB
10	10dB
1	0dB
0.1	-10dB
0.01	-20dB
0.001	-30dB

Examples:

1. An amplifier has input and output signals of 20 mW and 5W respectively.
   Calculate the power gain in dB.

$$G_{dB} = 10\log_{10}\left(\frac{5000}{20}\right)$$
$$= 10\log_{10}250$$
$$= 10 \times 2.397$$
$$= 23.97$$

2. A 4km communication link has input and output signals of 280 mW and 64 mW respectively.
   Calculate the power loss/km in dB for the link.

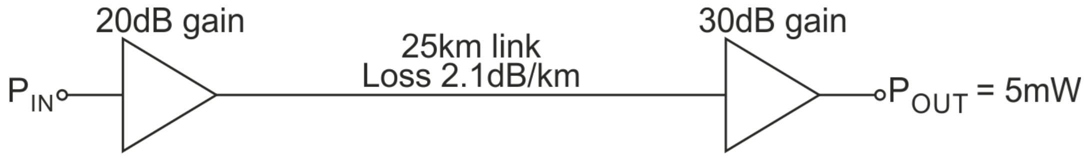
$$G_{dB} = 10\log_{10}\left(\frac{7}{300}\right)$$
$$= 10\log_{10}0.2286$$
$$= 10 \times 0.641$$
$$= -6.41$$

$$\text{loss / km} = -\frac{6.41}{4} = 1.60\ \text{dB / km}$$

3. Calculate the output power when a 20 mW signal is applied to a transmission path which has a loss of -15dB.

$$G_{dB} = -15$$
$$= 10\log_{10}\left(\frac{P_{OUT}}{20}\right)$$
$$-1.5 = \log_{10}\left(\frac{P_{OUT}}{20}\right)$$
$$10^{-1.5} = \frac{P_{OUT}}{20}$$
$$P_{OUT} = 10^{-1.5} \times 20$$
$$= 0.632\ \text{mW}$$

4. Calculate the value of P_{IN} for the following system:



Loss in link = 25 × -2.1 = -52.5 dB

Overall Gain/loss = 20 – 52.5 + 30 = -2.5 dB

$$G_{dB} = -2.5 = 10\log_{10}\left(\frac{5}{P_{IN}}\right)$$

$$-0.25 = \log_{10}\left(\frac{5}{P_{IN}}\right)$$

$$10^{-0.25} = \frac{5}{P_{IN}}$$

$$P_{IN} = \frac{5}{10^{-0.25}}$$

$$= \frac{5}{0.562} = 8.97 \text{ mW}$$

Note:
Some text books give a second equation for the gain in dB as:

$$G_{dB} = 20\log_{10}\frac{V_{OUT}}{V_{IN}}$$

This equation is for a special case where the impedance of the circuit is known to be the same at the two different points at which voltages V_{OUT} and V_{IN} are measured.

Exercise 9.2

1. An amplifier has input and output signal powers of 36 μW and 145 mW respectively. Calculate the power gain of the amplifier in dB.

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2. A 4 km communication link has input and output signal powers of 1 W and 96 mW respectively. Calculate the power loss/km in dB for the link.

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3. The output power from transmission line is 250 mW. If the overall loss is – 32 dB, calculate the input power.

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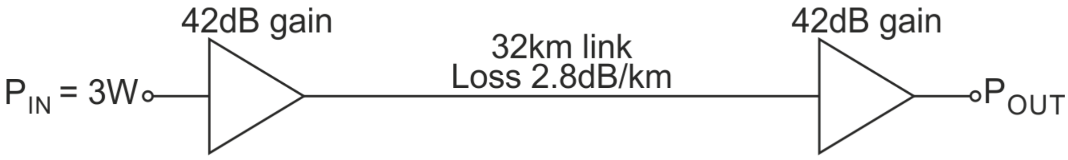
4. Calculate the value of P_{IN} for the following system:



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Noise and Distortion

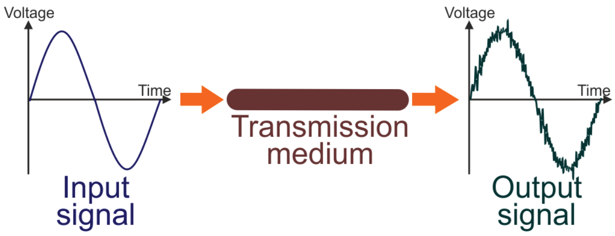
Distortion - non-linear changes introduced to the signal by the components of the circuit.
Although non-linear, the change is at least predictable and its effects can be minimised. Clipping distortion and crossover distortion have already been considered along with ways to remove them.

Electrical noise - additional external signals added to the information signal.
Noise is responsible for the familiar static heard on the radio and the "snow" seen on television screens when displaying a weak signal. In general, noise limits the range over which electrical, radio or optical signals can be transmitted and received.

Noise in electrical signals is generated in one of three main ways:

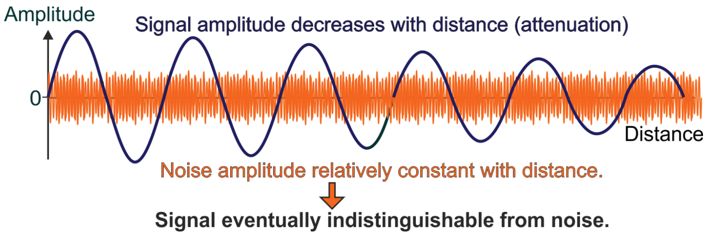
- white noise which is caused by random vibration of atoms;
- interference caused by electromagnetic radiation from lightning or electrical machinery for example;
- crosstalk picked up from nearby transmissions.

The diagram below shows the effect that noise could have on a sinusoidal signal after passing through a transmission medium. (The effect of attenuation has been ignored for clarity)



It is impossible to completely remove noise once it has been added to an analogue signal.

The effect of attenuation and noise on a signal as it travels along a transmission link is shown below:



In the diagram, noise is not shown superimposed on the sinusoidal signal in order to show more clearly that the noise amplitude remains fairly constant while the signal amplitude decreases with distance.

As a result, the ratio signal *amplitude* : noise *amplitude* also diminishes with distance.

The only way to alleviate this effect on a long distance analogue communication link is to amplify the signal at regular intervals on the link, using *repeaters*, high quality low noise amplifiers which both boost signal amplitude and filter out some of the noise.

The removal of noise from digital signals is quite straightforward and will be coved in chapter 11.

Signal to noise ratio

The ratio *signal amplitude : noise amplitude*, referred to as the signal-to-noise ratio (SNR), is expressed in dB and is calculated using a formula very similar to that for power gain in dB:

$$SNR_{dB} = 10\log_{10}\frac{P_S}{P_N} = 20\log_{10}\frac{V_S}{V_N}$$

If the signal-to-noise ratio falls below a certain level, then the information in the signal will be degraded unacceptably. A SNR of 0 dB means that the signal power is equal to the noise power and the signal is unrecoverable.

Note:
Unlike the situation with the gain formula, the second equation is readily applicable because the voltages are being measured at the same point and so across the same impedance.

The signal power or voltage can only be estimated as it cannot be separated from the noise.
It is estimated in one of two ways:

- The noise power is measured firstly with no signal present and then with the signal present. Then subtract one from the other to get the signal power.
- Use an oscilloscope to display the noisy signal and estimate the amplitude of both signal and noise.

Examples:

1. The amplitudes of the signal and noise in a transmission link are estimated at 5 V and 2 mV respectively. Estimate the signal-to-noise ratio (SNR).

$$SNR = 20\log_{10}\left(\frac{5}{0.002}\right)$$

$$SNR = 20\log_{10}250$$

$$= 47.96 \text{ dB}$$

The noise output from a coaxial cable is 0.35 mW with no signal present. What signal power is required if the minimum acceptable signal-to-noise ratio (SNR) is 25 dB?

$$SNR = 25 = 10\log_{10}\left(\frac{P_S}{0.35}\right)$$

$$2.5 = \log_{10}\left(\frac{P_S}{0.35}\right)$$

$$10^{2.5} = \frac{P_S}{0.35}$$

$$P_S = 10^{2.5} \times 0.35$$

$$= 110.7 \text{ mW}$$

3. A communications receiver requires an input signal amplitude of 3.2 V and SNR of 36 dB. What is the maximum acceptable value of the noise amplitude?

$$\text{SNR} = 36 = 20\log_{10}\left(\frac{3.2}{V_N}\right)$$

$$1.8 = \log_{10}\left(\frac{3.2}{V_N}\right)$$

$$10^{1.8} = \frac{3.2}{V_N}$$

$$P_N = \frac{3.2}{10^{1.8}}$$

$$= 0.051\text{ V}$$

4. (a) The noise power at the output of a cable link with no signal present is 43.9 μW. The combined noise and signal power is 69.8 mW. Calculate the SNR.

output signal power = 69.8 − 0.0439 = 69.796 mW

$$\text{SNR} = 10\log_{10}\left(\frac{69.756}{0.0439}\right)$$

$$= 10\log_{10}1589$$

$$= 32\text{ dB}$$

(b) A signal of power 8.5 W is applied to the input of the cable. The attenuation in the cable is 4.2 dB /km. Calculate the maximum possible length of cable that will achieve the SNR calculated in part (a) without amplification.

$$\text{Overall Gain / loss} = 10\log\left(\frac{69.756}{8500}\right)$$

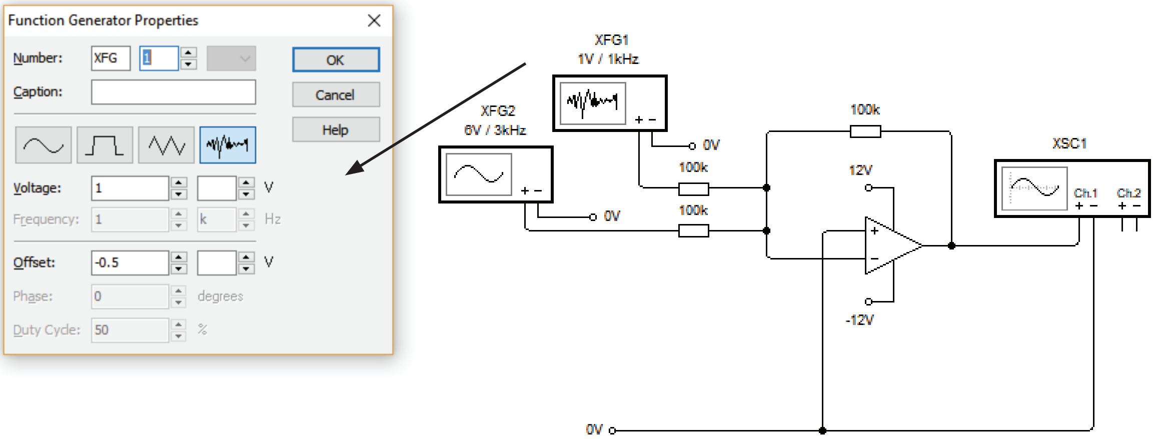
$$= -20.86\text{ dB}$$

$$\text{Maximum length of cable} = \frac{20.86}{4.2}$$

$$= 4.97\text{ km}$$

Investigation 9.1

(a) Set up the following mixer circuit on Circuit Wizard.



(b) Adjust the settings on:

- FG1 as shown in the properties insert above
- FG2 to 6 V, 3 kHz
- the oscilloscope time-base to 20 μs and the voltage scale to ±7 V

Resize the graph to show voltage steps of 1V to make the scale easier to read.

(c) Pause the graph display. Estimate the peak to peak values of both the signal and the noise. Describe the method you used in detail.

(d) Use your result to determine the SNR.

(e) How well do your estimates from the graph agree with actual settings on the function generators?

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Exercise 9.3

1. The amplitude of signal and noise in a transmission link is estimated at 3 V and 4 mV respectively. Estimate the signal-to-noise ratio (SNR).

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2. The noise output from a coaxial cable is 85 μW with no signal present. What signal power is required if the minimum SNR is 33 dB?

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3. A communications receiver requires input voltage amplitude of 5 V and SNR of 32 dB. What is the maximum acceptable value of the noise amplitude?

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4. The noise power at the output of a cable link with no signal present is 135 μW. The combined noise and signal of power is 248 mW. Calculate the SNR.

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5. A signal of power 3.5 W is applied to the input of a cable.
The attenuation in the cable is 5.1 dB /km.
The noise present is a constant 9.2 μW.
Calculate the maximum length of cable to achieve a SNR of 3 6 dB without amplification.

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