Chapter 10: Wireless transmission

Learning Objectives:

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

- recall and explain the use of the different regions of the radio spectrum for the transmission of data, including in terms of bandwidth availability and frequency channels
- describe and explain the use of amplitude modulation and frequency modulation and select and apply the equations:

depth of modulation	$m = \frac{(V_{max} - V_{min})}{(V_{max} + V_{min})} \times 100\%$
modulation index	$\beta = \frac{\Delta f_c}{f_i}$
transmitted FM bandwidth	$\text{Bandwidth} = 2(\Delta f_0 + f_i) = 2(1 + \beta)f_i$
wave speed	$c = f\lambda$

- sketch, recognise and analyse the waveforms resulting from amplitude and frequency modulation of a sinusoidal carrier by a single frequency audio signal

Radio communication

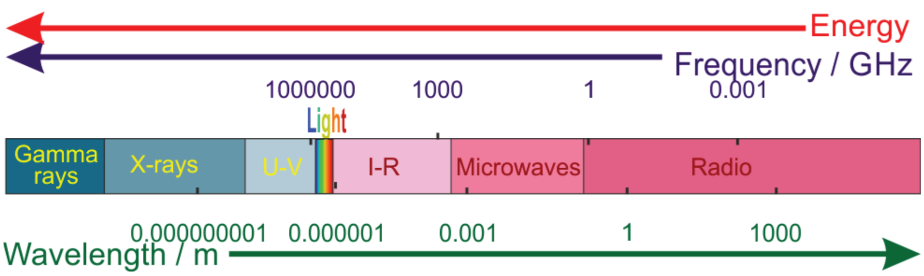
A radio transmitter converts electrical energy into electromagnetic radiation. The transmission medium for electromagnetic wave propagation is free space. Signals within the audio frequency band do not travel very far if converted directly to electromagnetic waves.

Instead, the audio signal is used to vary (modulate) some characteristics, such as amplitude or frequency, of a high frequency radio wave, known as a carrier wave. Because of its high frequency, the carrier wave is able to propagate over very large distances and therefore carry the audio signal much further without the need for repeated amplification.

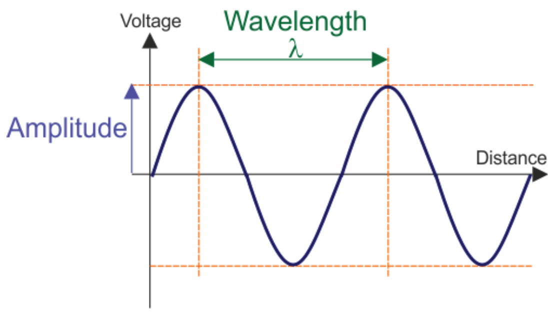
The unmodulated carrier wave conveys very little information itself. It is simply on or off.

The electromagnetic spectrum

Radio waves form part of the **electromagnetic spectrum**. The diagram below shows the position of the radio band at the low energy, long wavelength, low frequency end of the spectrum.



Frequency and wavelength



All electromagnetic waves travel through empty space at a speed of $c = 3 \times 10^8$ m s^{-1} (metres per second).

Wavelength (λ) is a measure of distance between two adjacent peaks (high points) or troughs (low points) in a repeating wave such as an electromagnetic, sound or light wave.

The unit of wavelength is the metre.

Wavespeed (**c**), frequency (**f**) and wavelength (**λ**) are linked by the formula:

$$c = f \times \lambda$$

Example:

Calculate the wavelength of an electromagnetic wave which has a frequency of 20 MHz.

Using the formula:

$$c = f \times \lambda$$

$$3 \times 10^8 = 20 \times 10^6 \times \lambda$$

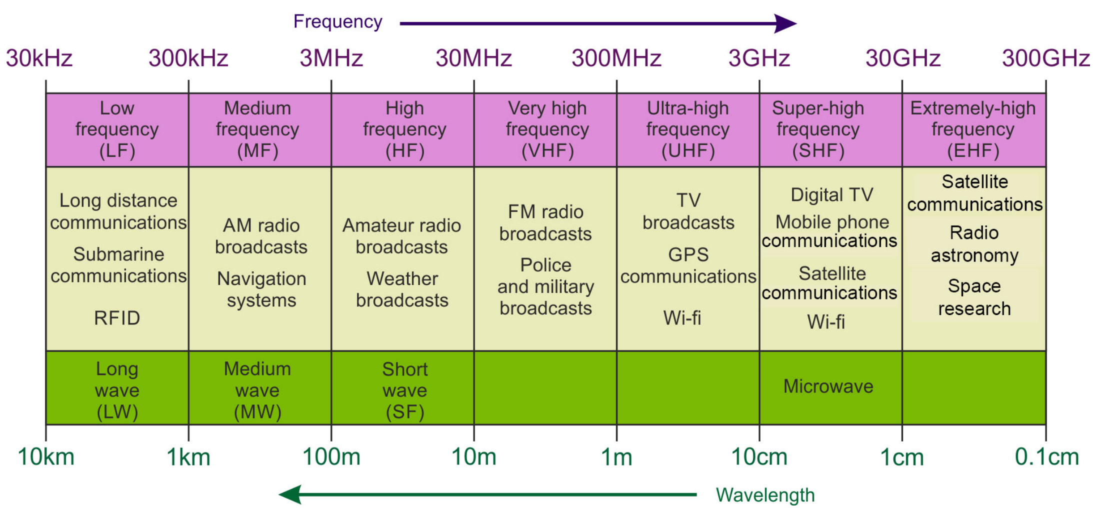
$$\lambda = \frac{3 \times 10^8}{20 \times 10^6}$$

$$= 15 \text{ m}$$

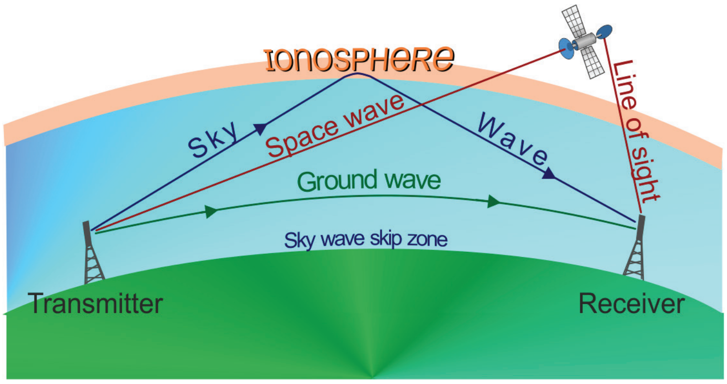
Radio bands

The frequency band allocated to a particular application is controlled in the UK by **OFCOM**. Alarm systems, cordless phones, mobile phones, baby monitors, radio-controlled model aircraft, satellites, radio and TV stations are all allocated permitted bands.

Electromagnetic waves with frequencies in the range 30 kHz to 300 GHz are used for radio TV, and satellite communication. For convenience, the range is divided up into the following bands.



Radio waves can travel from location to location in a number of ways, dependent on their frequency:



Suface (or ground) waves

At frequencies below 3 MHz, radio waves follow the contour of the earth's surface and are referred to as surface waves or *ground waves*. With sufficent transmitter power, they can travel for thousands of kilometres. This method of propagation occurs mainly in AM radio broadcasting and amateur radio.

Sky waves

At frequencies in the range 3 to 30 MHz, radio waves travel upwards, towards space, and are reflected back towards the earth by the ionosphere. In doing so, they create *dead* or *skip* zones at the Earth's surface, where the signal cannot be picked up.

Space waves

Waves with frequencies above 30 MHz travel in straight lines and are used in:

- Terrestrial 'line of sight' communication links i.e. where the receiving aerial can be 'seen' from the transmitting aerial;
- FM radio broadcasts use frequencies between 87 and 110 MHz;
- Television broadcasts use the UHF band - frequencies between 470 and 850 MHz;
- Mobile phone networks use frequencies in the range 450 to 2100 MHz;
- Line of sight microwave systems use frequencies in the range 2 to 80 GHz to carry long distance telephone traffic, television channels and data up to a distance of about 50 km. A network of repeater stations is used to give nationwide coverage;
- Satellite communication systems, using frequencies in the range 1 to 300 GHz, for global positioning systems (GPS), voice and video transmission, satellite TV, radio astronomy and space research.

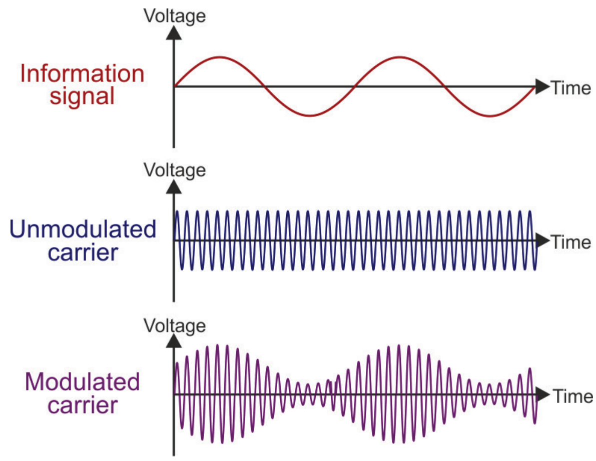
Amplitude Modulation

A modulated signal can be considered as having two parts:

1. the **information signal** - the message that needs to be sent - as speech, text, or pictures;
2. the **carrier** - the means of delivering the information signal from the transmitter to the receiver, usually a radio wave, microwave, light wave or electrical current.

In amplitude modulation, (AM), the amplitude of the carrier wave varies to reflect the instantaneous value of the information signal.

The diagram on the right illustrates this process:



Amplitude modulation has the effect of combining the information signal, f_i, and the carrier signal, f_c, in way that obeys the equation:

$$V_{AM} = A_c \sin 2\pi f_c t + \frac{1}{2} A_i [\cos(2\pi f_c - 2\pi f_i)t - \cos(2\pi f_c + 2\pi f_i)t]$$

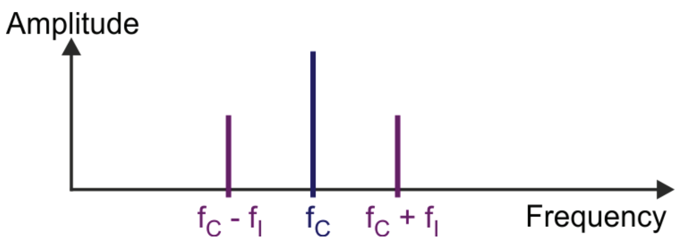
It can be seen that this equation contains three components:

- the original carrier wave, with frequency $\mathbf{f_c}$ and unmodulated amplitude $\mathbf{A_c}$;
- a wave of frequency $\mathbf{f_c - f_i}$, called the lower side frequency, with an amplitude of $\mathbf{A_i}$ / 2;
- a wave of frequency $\mathbf{f_c + f_i}$, called the upper side frequency, with an amplitude of $\mathbf{A_i}$ / 2.

It can also be seen that:

- the original signal frequency, $\mathbf{f_i}$, has disappeared;
- the carrier frequency $\mathbf{f_c}$ must be greater than the information frequency $\mathbf{f_I}$;
- The carrier amplitude $\mathbf{A_c}$ must be greater than the information amplitude $\mathbf{A_i}$.

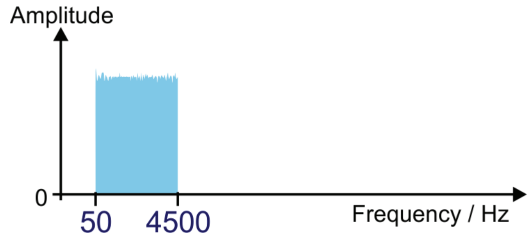
The following diagram shows the frequency spectrum of a sinusoidal carrier, with frequency $\mathbf{f_c}$, amplitude modulated by a pure sinusoidal information signal with frequency $\mathbf{f_i}$.



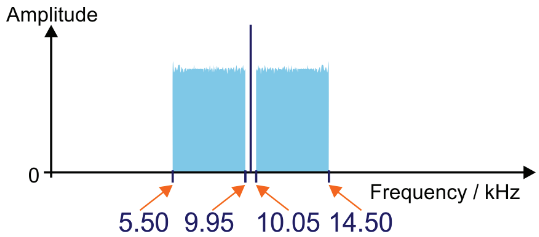
In a real communication system, the information signal is highly unlikely to be a pure sine wave with constant frequency and amplitude. Real signals will be complex waves made up of a range of frequencies as described in chapter 4, when considering filters. This range of frequencies is referred to as the *baseband* signal.

Each frequency in this baseband signal is likely to have a range of amplitudes that will be constantly changing, and any attempt to draw them would result in a very fuzzy picture.

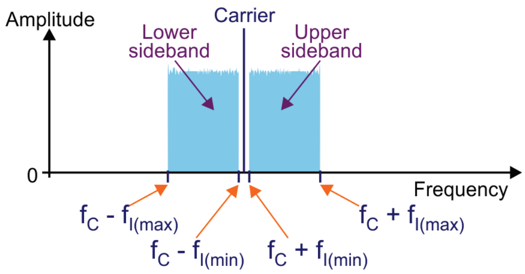
A voice signal, containing frequencies in the range 50 – 4500 Hz, would be represented by the following spectrum diagram:



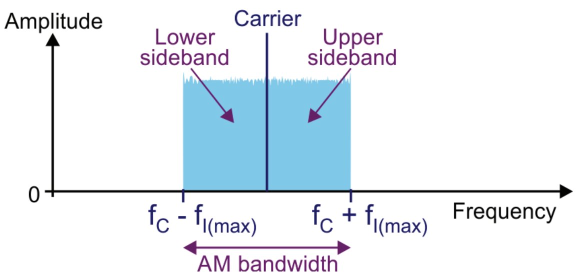
When this information signal is used to amplitude modulate a 10 kHz sinusoidal carrier signal, the resulting spectrum is as follows:



In general, when a sinusoidal carrier f_C is amplitude modulated by an information baseband from $f_{I(min)}$ to $f_{I(max)}$, then the spectrum is as shown:



Usually, the lowest frequency in the baseband signal is so small compared to the carrier frequency, that the diagram is difficult to draw accurately - the gap between the carrier frequency 'spike' and the start of the sidebands is negligibly small. It is common practice therefore to draw the spectrum as shown below:



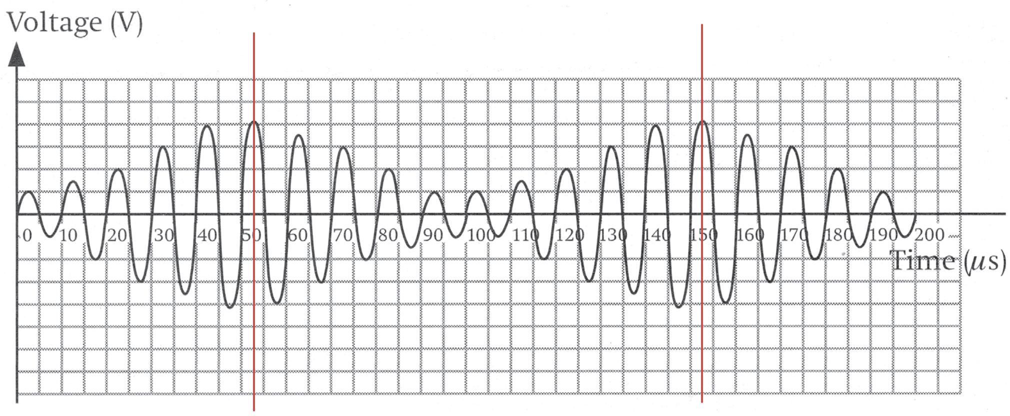
The bandwidth required for the AM waveform is twice the maximum frequency in the information signal.

Notice:

- the spectrum has three components - the carrier and the upper and lower sidebands;
- the carrier component is unchanged by the modulation process;
- the signal information is contained in the sidebands and not in the carrier;
- the signal information is duplicated in the two sidebands.

Example:

The diagram below shows an AM carrier modulated by a pure tone.



(a) Calculate the pure tone and carrier frequencies.

(b) Sketch the frequency spectrum of the AM signal.

(c) Determine the bandwidth of the transmitted signal

(a) First step - draw vertical lines at the peaks of the waveform.

Second step - take readings off the time axis for the peaks.

Pure Tone Period = (150 − 50)μs = 100 μs

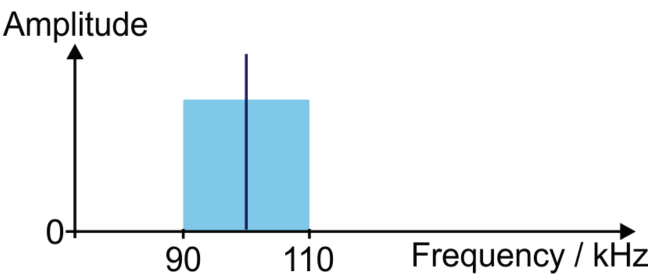
$$\text{Pure Tone Frequency} = \frac{1}{100\ \mu s} = \frac{1}{1 \times 10^{-4}} = 10\ \text{kHz}$$

As there are 10 carrier peaks between the pure tone peaks,

$$\text{Carrier Period} = \frac{100\ \mu s}{10} = 10\ \mu s$$

$$\text{Carrier Frequency} = \frac{1}{10\ \mu s} = \frac{1}{1 \times 10^{-5}} = 100\ \text{kHz}$$

(b)



Notice that the frequency spectrum is shown with constant amplitude for ease of drawing.

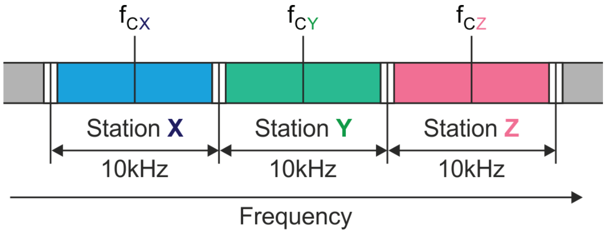
(c) Bandwidth = 110 – 90 = 20 kHz

Frequency spectrum allocation for radio stations

Reasonable quality can be obtained if the upper limit of the audio signal is kept to 5 kHz.
The total bandwidth of the AM signal is then 10 kHz.

To avoid interference, each radio station is allocated a channel in which to operate. The 10 kHz bandwidth includes a 1 kHz guard band to prevent interference between neighbouring stations.

The diagram shows three stations, **X**, **Y** and **Z**, with carrier frequencies f_{cX} , f_{cY} and f_{cZ}.



Example:

In the USA, the standard AM broadcast band starts at 535 kHz and ends at 1,605 kHz.
If each channel is allocated a bandwidth of 10 kHz, what is the maximum number of AM channels that can be broadcast in that band?

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

$$= \frac{1605-535}{10}$$

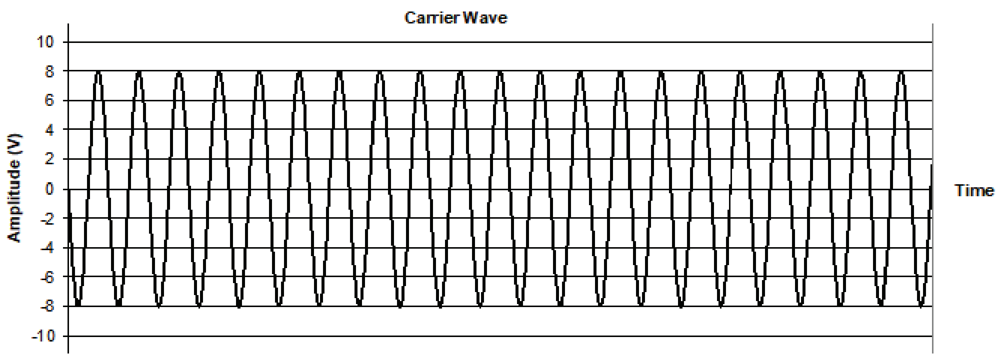
$$= \frac{1070}{10}$$

$$= 107 \text{ channels}$$

Depth of Modulation

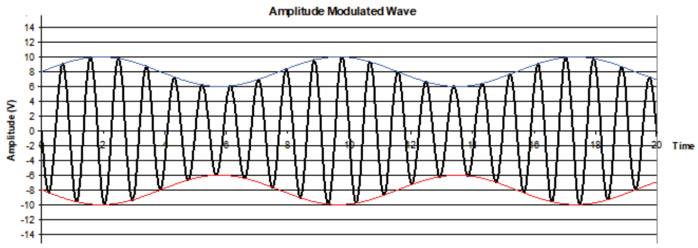
Depth of modulation is the term given to how much the amplitude of the carrier wave is affected by the information signal. This is best illustrated by considering some examples.

To demonstrate the effect the same carrier signal will be used as shown in the following diagram. The amplitude of the carrier is 8V, and is of high frequency, no units have been added to the time axis as these are illustrative diagrams only.

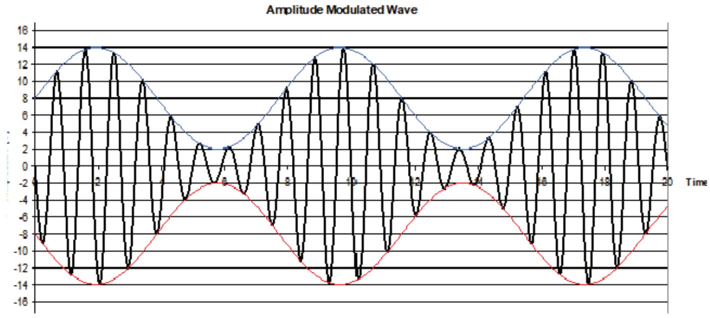


We now add four low frequency sinewave signals, with amplitudes of 2 V, 6 V, 8 V and 10 V to see the effect on the modulated signal:

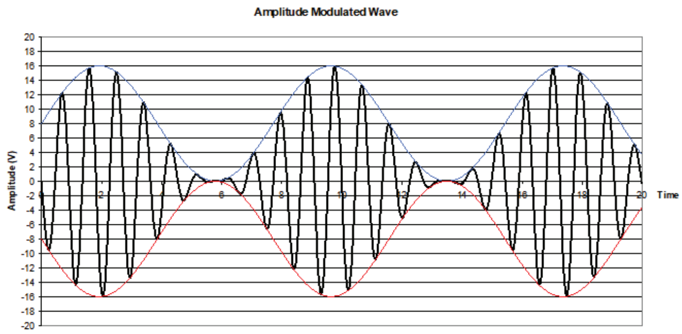
Case 1: signal amplitude = 2 V



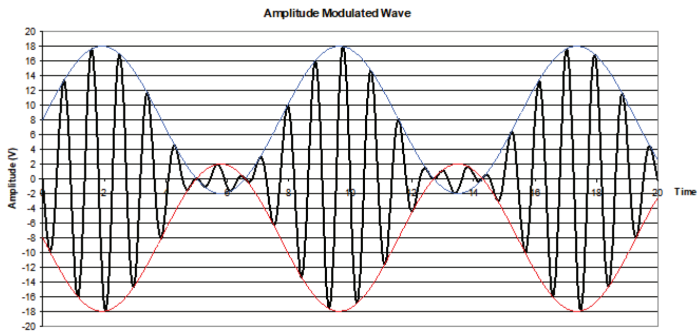
Case 2: signal amplitude = 6 V



Case 3: signal amplitude = 8 V



Case 4: signal amplitude = 10 V



The diagrams show that as the signal amplitude increases the carrier amplitude becomes significantly more varied.

When the signal amplitude and carrier amplitude are equal, as in Case 3, there is a point where the carrier amplitude actually reaches 0V. In Case 4 where the information signal amplitude is larger than that of the carrier, there are areas where the information signal overlaps the 0 V carrier amplitude. This is known as *over-modulation* and leads to distortion during transmission.

The **ratio** of the amplitude of the information signal to the amplitude of the carrier is called the *depth of modulation*, **m**, and is expressed as a percentage:

$$m = \frac{A_S}{A_C} \times 100\%$$

where A_S = information signal amplitude, and
A_C = carrier signal amplitude

Example 1:
Calculate the depth of modulation in case 1 above, where the amplitudes of the signal and carrier were given as A_S = 2 V, A_C = 8 V respectively.

Depth of modulation is given by:

$$m = \frac{A_S}{A_C} \times 100\% = \frac{2}{8} \times 100\% = 25\%$$

Where the depth of modulation is measured from a graph or an oscilloscope trace, it is not practicable to extract the signal and carrier amplitudes to use in the above formula.

In that case, the following formula can be used

$$m = \frac{(V_{max} - V_{min})}{(V_{max} + V_{min})} \times 100\%$$

where V_{max} is the maximum amplitude of the AM signal.
and V_{min} is the minimum amplitude of the AM signal.

Example 2:
Calculate the depth of modulation in case 1, using the graph, shown earlier.

From the graph:

V_{max} = 10 V;
V_{min} = 6 V.

Using:

$$m = \frac{(V_{max} - V_{min})}{(V_{max} + V_{min})} \times 100\%$$

$$= \frac{(10 - 6)}{(10 + 6)} \times 100\%$$

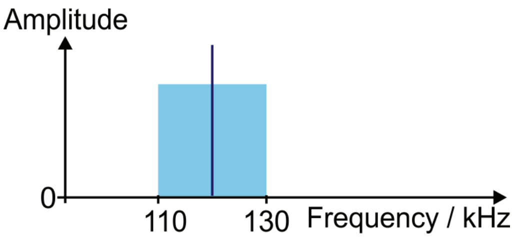
$$= 25\%$$

Note:
A depth of modulation greater than 100% results in distortion.

In practice, the depth of modulation should not exceed 80% to provide a safe margin and preserve signal clarity.

Exercise 10.1

1. The frequency spectrum of an AM radio station is shown opposite. For this radio station:



(a) (i) What is the carrier frequency;

....

(ii) What is the broadcast bandwidth?

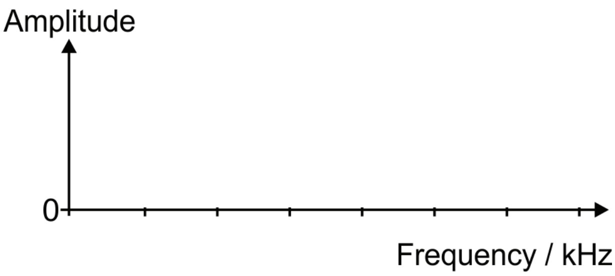
....

(b) (i) An AM broadcast frequency band is allocated a frequency range of 150 kHz to 1.6 MHz. How many radio stations, having the bandwidth calculated in (a) (ii), can be accommodated in this frequency band?

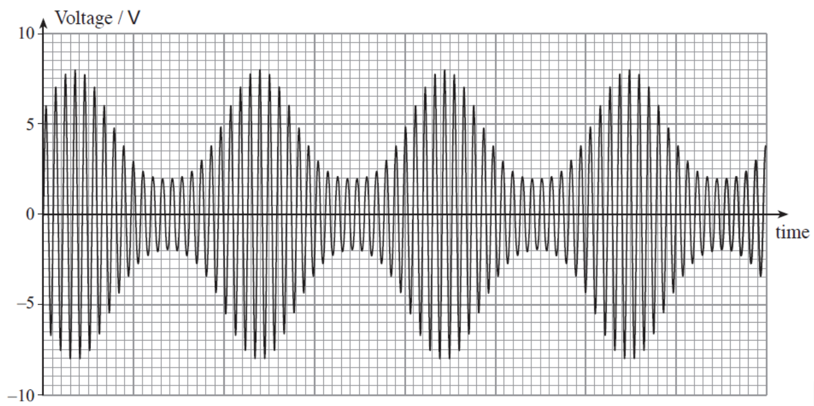
....

....

(ii) On the frequency spectrum diagram, draw the two radio stations adjacent to that in (a).



2. A carrier wave is amplitude modulated by an 8 kHz frequency test signal and broadcast by a radio station. An engineer received the following signal on the receiving circuit.



(a) Determine the frequency of the carrier signal.

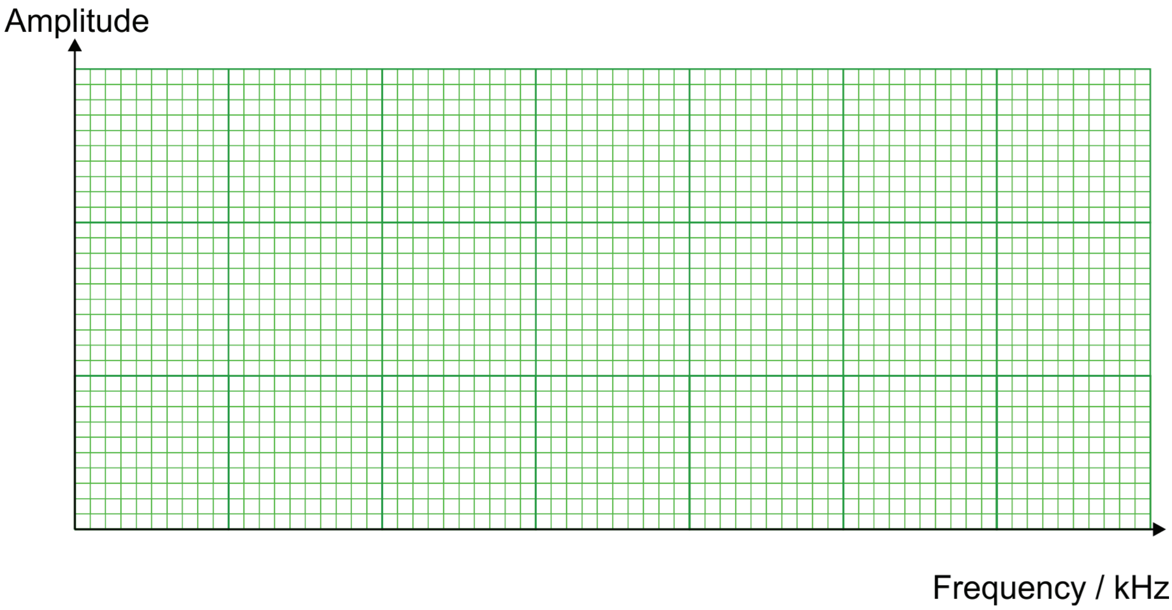
Frequency = ...

(b) Calculate the depth of modulation for this broadcast signal.

....

....

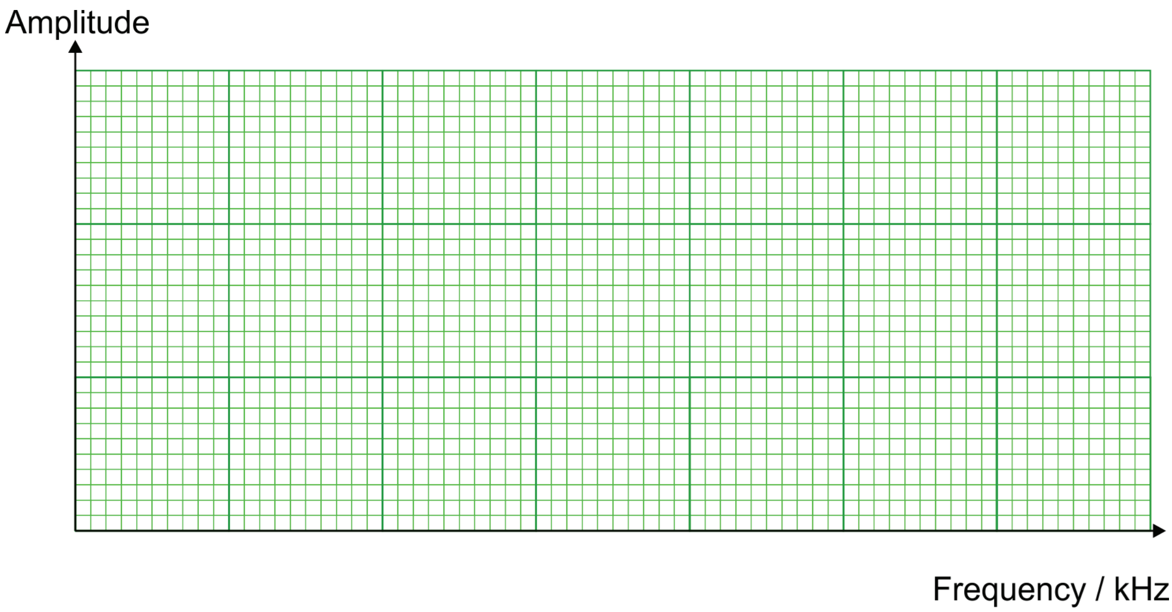
3. (a) A 15 kHz sinusoidal wave is amplitude modulated onto a 150 kHz carrier wave.



Draw the frequency spectrum of the transmitted wave. Label all significant frequencies.

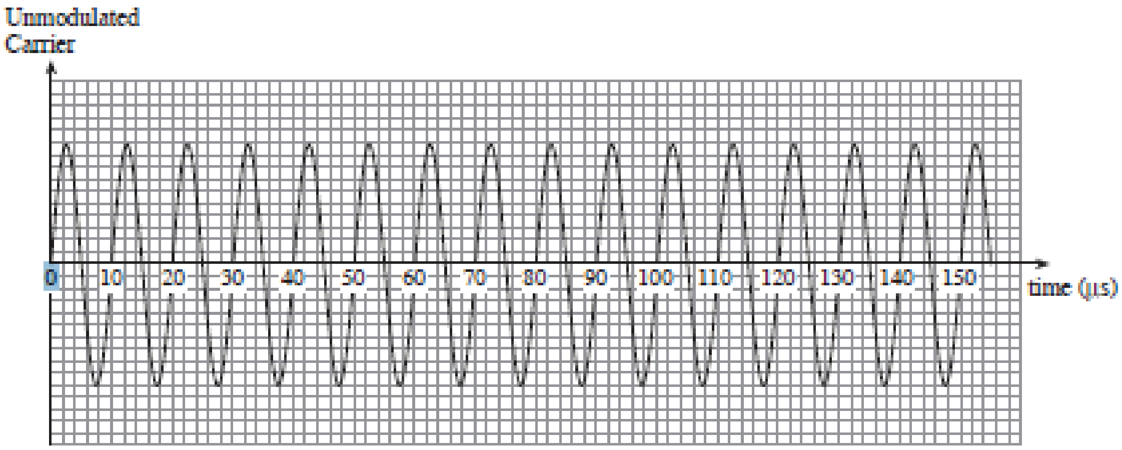
(b) The 15 kHz sinusoidal wave is now replaced with an audio signal containing frequencies in the range 300 Hz - 15 kHz.
The carrier signal frequency is not changed.

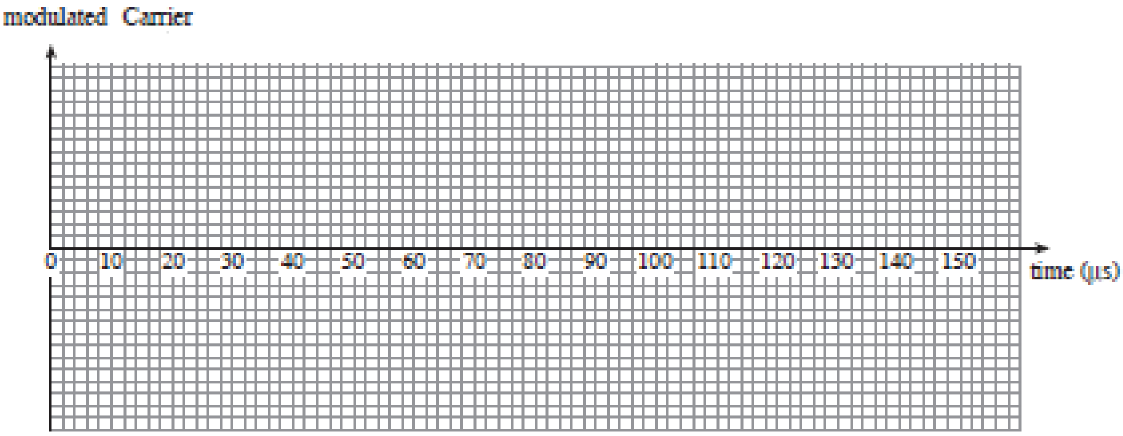
(i) Draw the frequency spectrum of the transmitted wave and the baseband audio signal.
Label all significant frequencies.



(ii) What is the broadcast bandwidth of the signal? ....

4. A 10 kHz sine wave test signal, amplitude modulated onto a 100 kHz carrier wave. Sketch the waveform of the modulated carrier if the depth of modulation is approximately 50%

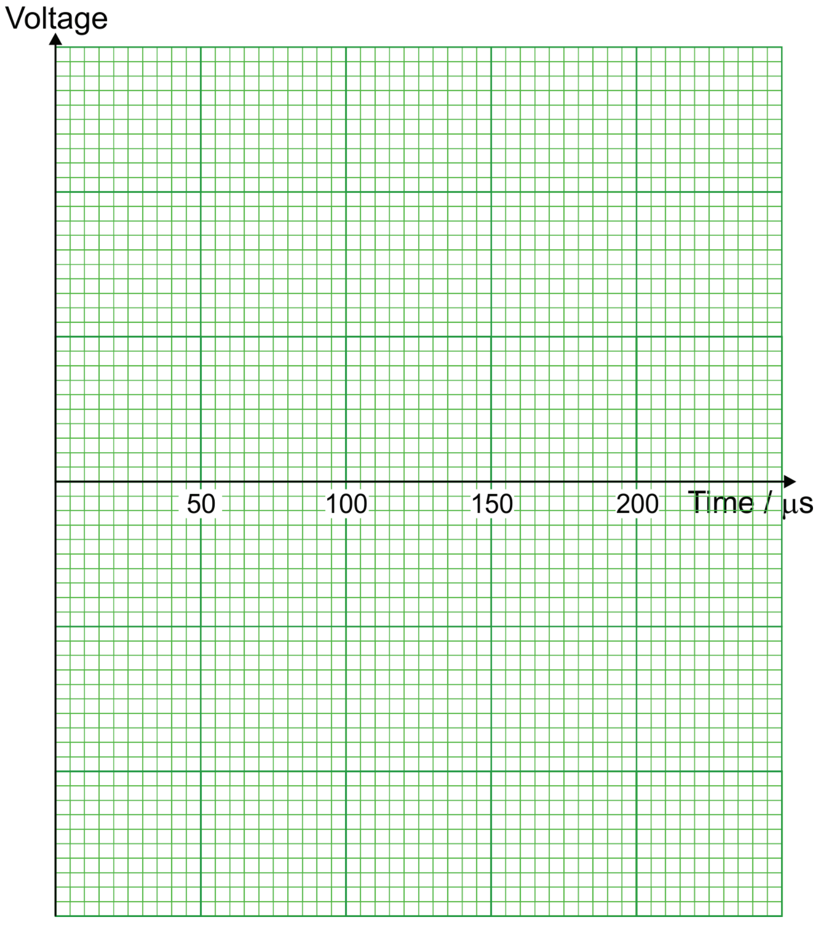




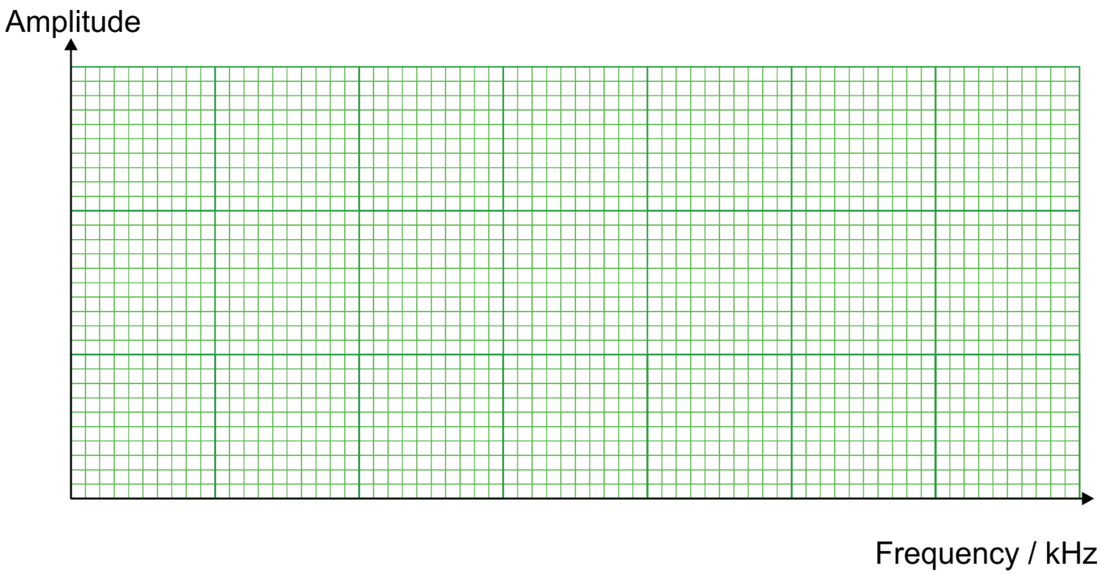
5. A radio station broadcasts for 20 hours per day on a frequency of 50 kHz, using amplitude modulation.

During the **4 hours** when the radio station is 'off-air', the station transmits its call-sign, a continuous 5 kHz single frequency with a modulation depth of 100%.

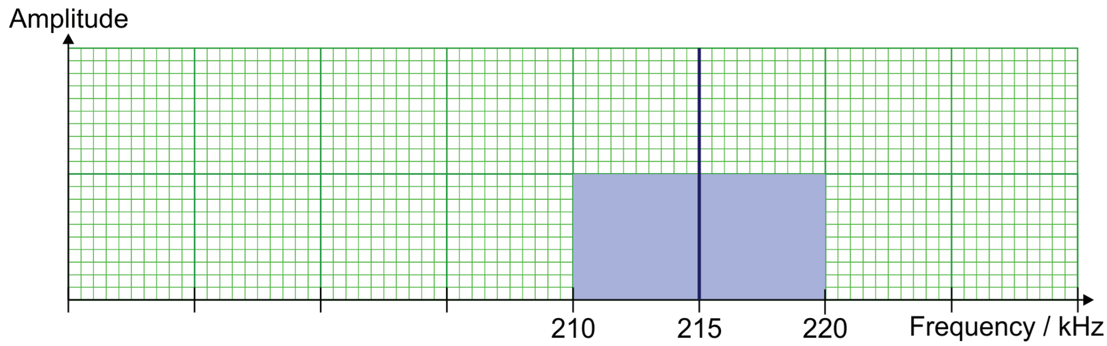
(a) Use the axes provided to sketch the amplitude modulated carrier wave envelope.



(b) Using the axes below sketch the frequency spectrum diagram for the amplitude modulated carrier of the radio station when transmitting its call-sign. Label all frequencies.



(c) The frequency spectrum of another broadcast is shown below.



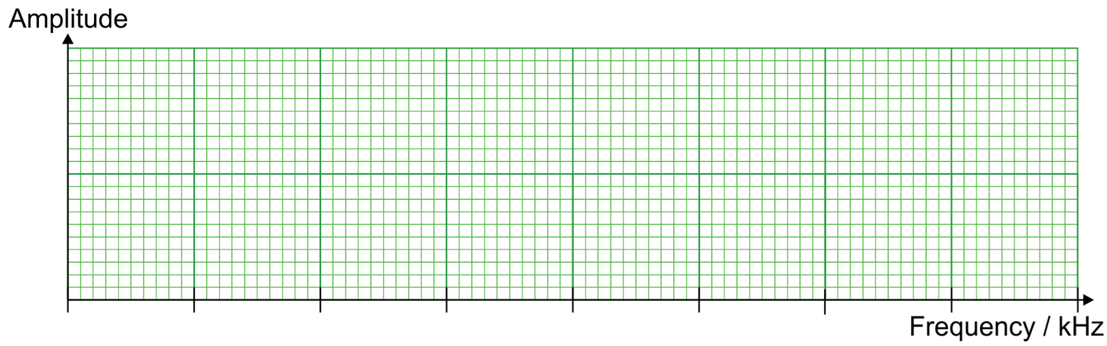
(i) What is the carrier frequency of this radio station?

....

(ii) What is the broadcast bandwidth of this transmission?

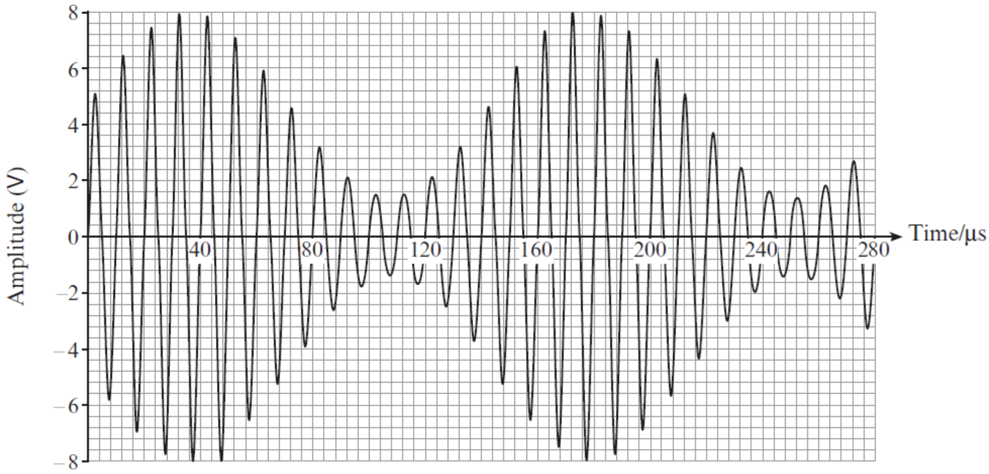
....

(iii) Use the axes provided to sketch the frequency spectrum for the baseband **audio signal** being transmitted.



6. In a radio broadcast, the audio signal from a microphone is amplitude modulated onto a carrier wave.

The graph shows part of the amplitude modulated signal:



(a) What are the period and frequency of the audio signal?

Period: ....

Frequency: ....

(b) What are the period and frequency of the carrier?

Period: ....

Frequency: ....

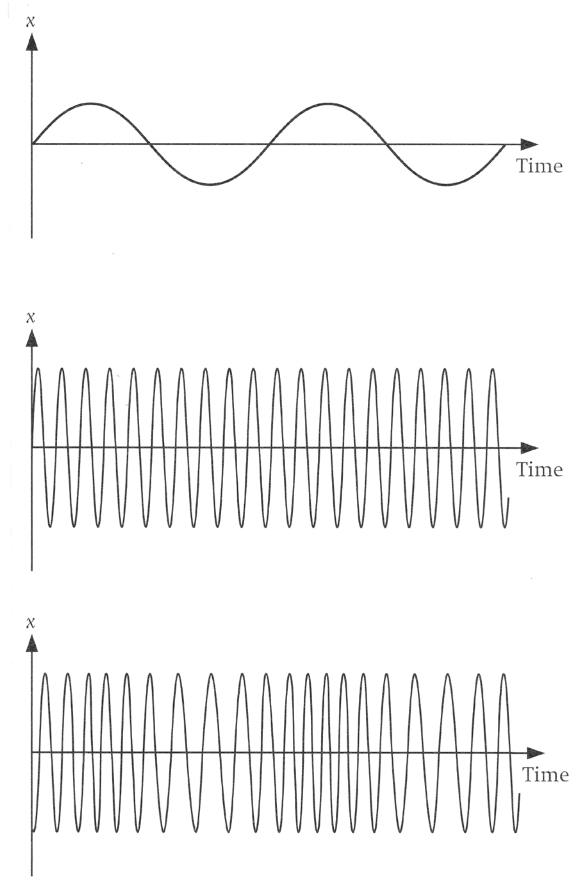
(c) Estimate the depth of modulation of the carrier wave.

....

....

Frequency Modulation

In **F**requency **M**odulation (**FM**), the instantaneous value of the information signal controls the frequency of the carrier wave as illustrated in the following diagrams.



As the information signal increases, the frequency of the carrier increases. As the information signal decreases, the frequency of the carrier decreases.

The frequency $\mathbf{f_i}$ of the information signal controls the rate at which the carrier frequency increases and decreases. As with AM, $\mathbf{f_i}$ must be less than $\mathbf{f_c}$. The amplitude of the carrier remains constant throughout this process.

When the information signal voltage reaches its maximum value, the change in frequency of the carrier also reaches its maximum deviation above the nominal value. Similarly when the information signal reaches a minimum, the carrier is at its lowest frequency below the nominal carrier frequency. When the information signal is zero, no deviation of the carrier occurs.

The maximum change in frequency from the carrier's base value $\mathbf{f_c}$ is called the **frequency deviation**, and is given the symbol $\Delta\mathbf{f_c}$.

Example:

A 400 kHz sinusoidal carrier of amplitude 5 V is frequency modulated by a 3 kHz sinusoidal information signal of amplitude 3 V.

The behaviour of the carrier is governed by the frequency deviation per volt, in this case, 25 kHz per volt. Describe how the resulting FM signal changes with time.

Solution:

The FM carrier will change in frequency from 400 kHz to 475 kHz to 400 kHz to 325 kHz and back to 400 kHz, 3000 times per second. This is because the frequency deviation Δf_c = 3 x 25 kHz = 75 kHz. The amplitude of the carrier will remain fixed at 5 V.

Modulation Index

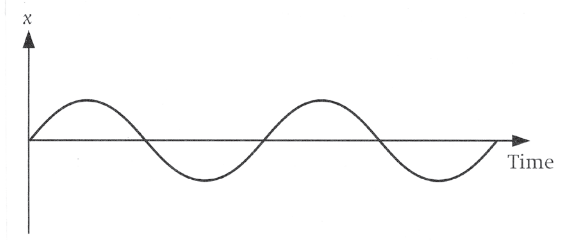
All FM transmissions are governed by the *modulation index*, β, which controls the dynamic range of the information carried in the transmission. It is defined as the ratio of the frequency deviation, Δf_c , to the maximum information frequency, $\mathbf{f_I}$, i.e.:

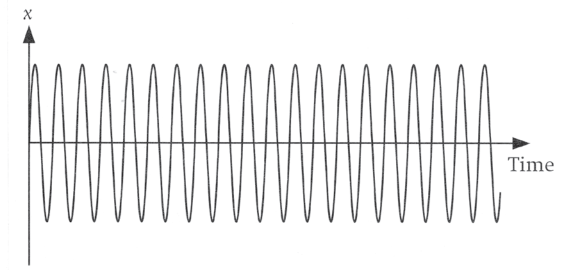
$$\beta = \frac{\Delta f_c}{f_I}$$

The diagrams show how modulation index affects the FM output, for a sinusoidal information signal of fixed frequency.

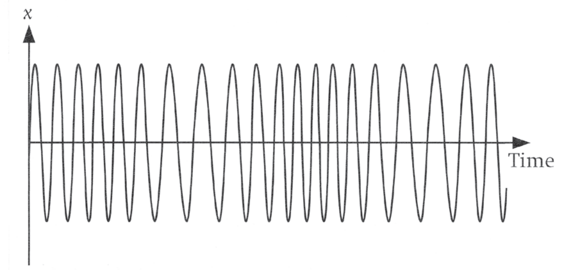
The carrier has a frequency ten times that of the information signal.

The first graph shows the information signal.
The second graph shows the unmodulated carrier.

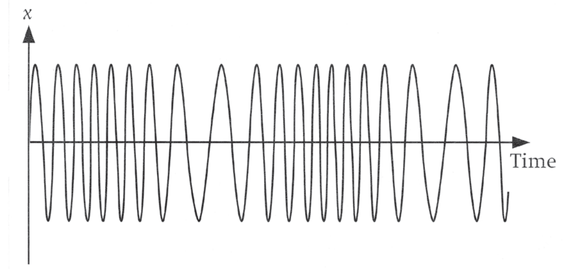




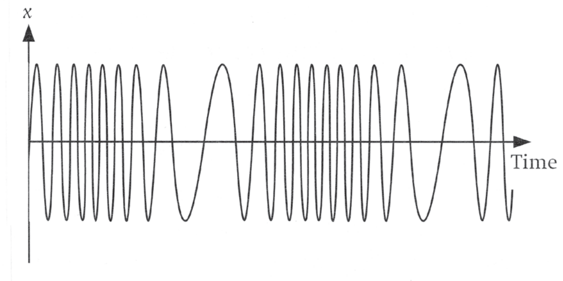
Modulation index β = 3



Modulation index β = 5



Modulation index β = 7



As the modulation index **increases**, the peaks where the information signal has a high frequency are closer together (and vice-versa). The modulated carrier, therefore, has a **higher maximum frequency** than the unmodulated carrier.

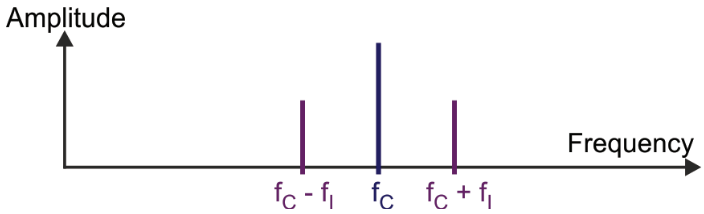
The resulting frequency spectrum is much more complicated than that of the simple AM waveform (i.e. one carrier and two sidebands) discussed earlier. This is because there are multiple frequencies present in the FM signal, even for the transfer of a simple sinusoidal information signal.

Detailed analysis of an FM waveform is complicated and beyond the scope of this course. However it is possible to get a flavour of the key features.

In theory, the FM spectrum has an infinite number of sidebands, spaced at multiples of $\mathbf{f_I}$ above and below the carrier frequency $\mathbf{f_c}$. However the size and significance of these sidebands is dependent on the modulation index, β. (As a general rule, any sidebands below 1% of the carrier amplitude can be ignored.)

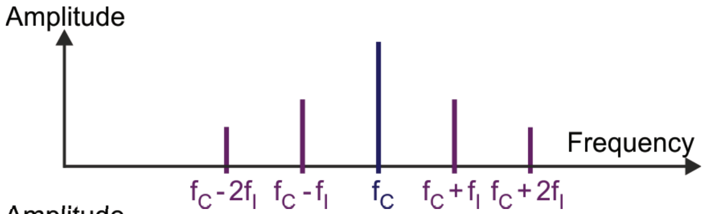
If β <1, then the spectrum looks like this:

There are only two significant sidebands. Hence, the spectrum looks very similar to that for amplitude modulation.



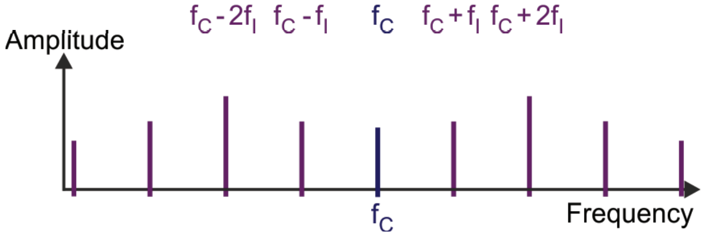
If β = 1, then the spectrum looks like this:

The number of significant sidebands has increased to four.



If β = 3, then the spectrum looks like this:

The number of significant sidebands has increased to eight.



In general, the number of significant sidebands is given by 2(β + 1).
Bandwidth implications: The bigger the value of β, the bigger the bandwidth of the FM transmission.
More precisely:

$$\text{FM Bandwidth} = 2\,(1+\beta)\,f_i$$

$$= 2\left[\,1+\left(\frac{\Delta f_c}{f_i}\right)\right]f_i$$

$$= 2\,(\Delta f_c + f_i)$$

In other words, **the bandwidth of an FM waveform is twice the sum of the frequency deviation and the maximum frequency in the information.**
Notice:

- An FM transmission is a constant power wave, regardless of the information signal or modulation index, β, because it is operated at constant amplitude with symmetrical changes in frequency.
- As β increases, the relative amplitude of the carrier component decreases and may become much smaller than the amplitudes of the individual sidebands. The effect of this is that a much greater proportion of the transmitted power is in the sidebands (rather than in the carrier), making the FM transmission more efficient than the equivalent AM.

Example 1:

Wideband FM radio uses a modulation index, β, > 1. As its name suggests, its bandwidth is much larger than an equivalent AM transmission.

In national radio broadcasts using FM, the frequency deviation of the carrier, Δf_C, is chosen to be 75 kHz, and the information baseband is the range 20 Hz to 15 kHz.

Determine the depth of modulation and transmission bandwidth of this FM radio broadcast.

Using $\beta = \frac{\Delta f_c}{f_I}$, $\beta = \frac{75}{5} = 5$

FM Bandwidth $= 2\,(\Delta f_c + f_i)$
$= 2\,(75 + 15)$
$= 180$ kHz

Example 2:

A 10 MHz carrier is frequency modulated by a pure signal tone of frequency 8 kHz.
The frequency deviation is 32 kHz.

Calculate the bandwidth of the resulting FM signal.

FM Bandwidth $= 2\,(\Delta f_c + f_i)$
$= 2\,(32 + 8)$
$= 80$ kHz

Example 3:

An audio signal has a base band from 200 Hz to 4 kHz. It modulates a carrier of frequency 50 MHz, using FM.

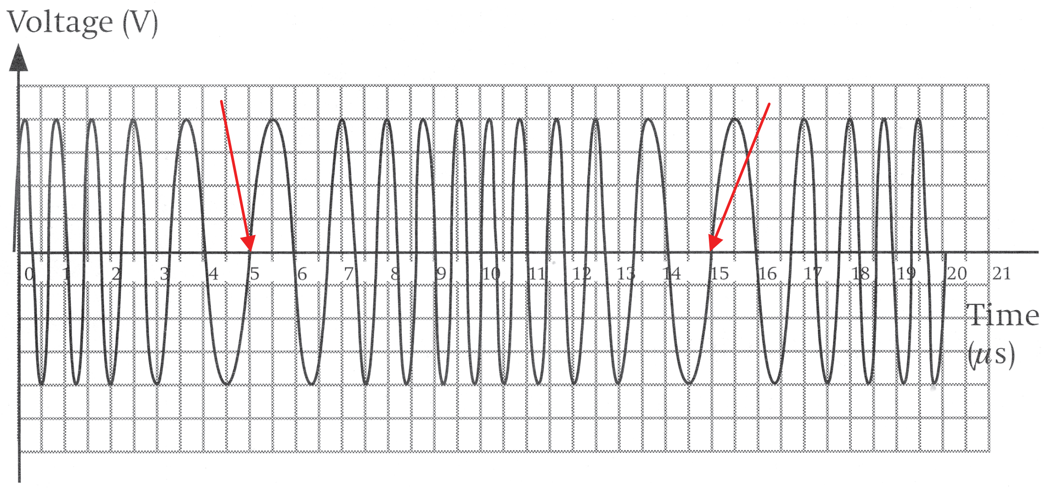
The frequency deviation per volt is 10 kHz V-1 and the maximum audio voltage that can be transmitted is 3 V.

Calculate the frequency deviation and the bandwidth of the FM signal.

Frequency deviation $\Delta f_c = 3 \times 10 = 30$ kHz
FM Bandwidth $= 2\,(\Delta f_c + f_i)$
$= 2\,(30 + 4)$
$= 68$ kHz

Example 4:

The graph shows an FM carrier modulated by a pure tone (sinusoidal signal).



Calculate:

(a) the signal frequency;
(b) the carrier frequency.

Solution:
Identify one cycle of the signal frequency, (look for the repeating widest waves as shown by the red arrows on the diagram above).
Hence:

(a) Period = 15 − 5 = 10 μs

signal frequency = $\frac{1}{\text{period}}$ = 100 kHz

(b) 10 cycles of carrier occur during 1 cycle of signal

carrier frequency = 10 x 100 kHz = 1 MHz

Example 5:

A 300 MHz carrier wave is frequency modulated by an audio signal having a maximum frequency of 16 kHz.
The instantaneous carrier frequency varies between 299.95 and 300.05 MHz.
Calculate:

(a) the modulation index;
(b) the FM bandwidth.

(a) Using $\beta = \frac{\Delta f_c}{f_i}$, $\beta = \frac{(300.05 - 299.95) \times 10^6}{16 \times 103} = 6.25$

(b) FM bandwidth $= 2(1 + \beta)f_i$
$= 2(1 + 6.25) \times 16$
$= 232$ kHz

Exercise 10.2

1. A 24 MHz carrier is frequency modulated by a pure signal tone of frequency 12 kHz. The frequency deviation is 56 kHz.

Calculate:

(a) the modulation index;

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(b) the bandwidth of the resulting FM signal.

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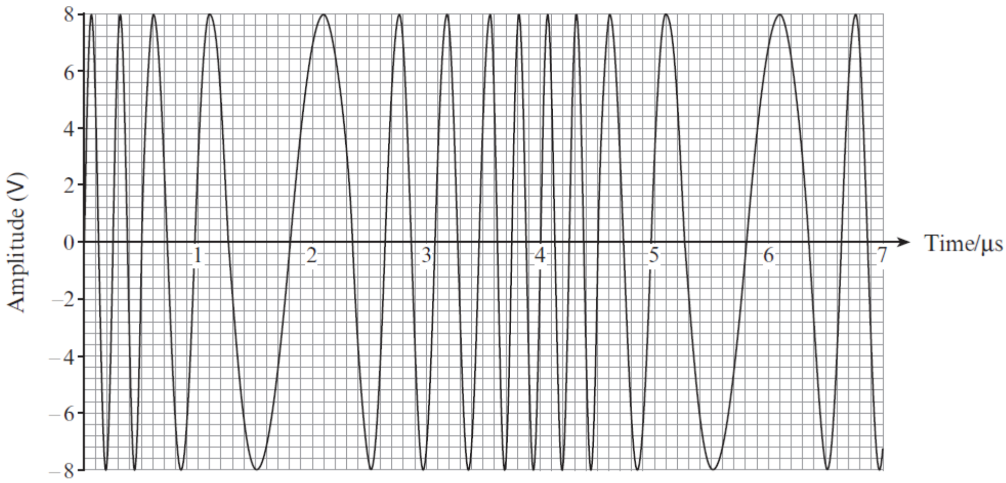
2. The graph shows an FM carrier modulated by a sinewave signal.



Calculate:

(a) the frequency of the sinusoidal signal used to modulate the carrier;

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(b) the carrier frequency.

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3. A 100MHz carrier wave is frequency modulated by a signal with a maximum frequency of 8 kHz. The instantaneous carrier frequency varies between 99.96 and 100.04 MHz.

Calculate:

(a) the modulation index;

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(b) the FM bandwidth.

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4. An audio signal, with a base band of 200 Hz to 12 kHz, is used to frequency modulate a carrier of frequency 50 MHz.

The frequency deviation per volt is 15 kHz V^{-1} and the maximum audio voltage that can be transmitted is 7 V.

Calculate the frequency deviation and the bandwidth of the FM signal.

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