Electrical Engineering

Communication Systems

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Communication Systems

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CHAPTER 1

Introduction to Communication Systems

1.1 What is Communication

In the most fundamental sense, communication involves implicitly the transmission of information from one point to another through a succession of processes, as described here:

1. The generation of a message signal: voice, music, picture, or computer data.
2. The description of that message signal with a certain measure of precisions, by a set of symbols: electrical, aural, or visual.
3. The encoding of these symbols in a form that is suitable for transmission over a physical medium of interest.
4. The transmission of the encoded symbols to the desired destination.
5. The decoding of the reproduction of the original symbols.
6. The re-creation of the original message signal, with a definable degradation in quality; the degradation is caused by imperfections in the system.

There are, of course, many other forms of communication that do not directly involve the human mind in real time. For example, in computer communications involving communication between two or more computers, human decisions may enter only in setting up the programs or commands for the computer, or in monitoring the results.

1.2 Communication Model

The study of communication becomes easier, if we break the whole subject of communication in parts and then study it part by part. The whole idea of presenting the model of communication is to analyse the key concepts used in communication, in isolated parts and then combining them to form the complete picture.

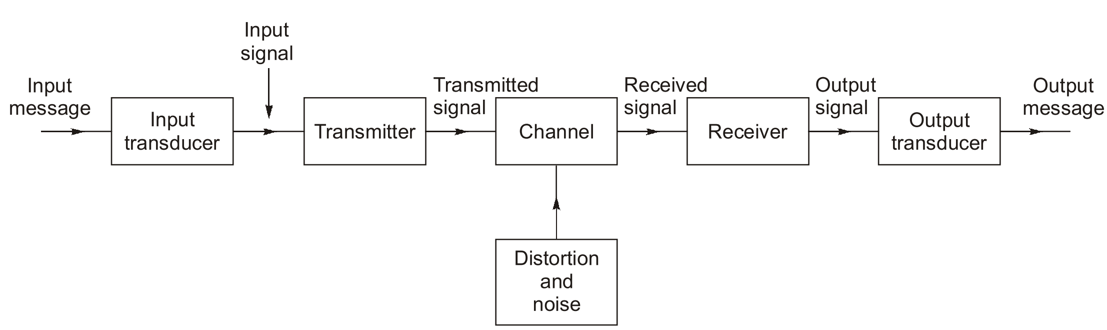


Figure-1.1 : *Model of communication system*

Source

The source originates a message, such as a human voice, a television picture, an e-mail message, or data. If the data is non-electric (e.g., human voice, e-mail text, television video), it must be converted by an **input transducer** into an electric waveform referred to as the **baseband signal** or **message signal** through physical devices such as a microphone, a computer keyboard or a CCD camera.

Transmitter

The transmitter modifies the baseband signal for efficient transmission. The transmitter may consist of one or more subsystems: an A/D converter, an encoder and a modulator. Similarly, the receiver may consist of a demodulator, a decoder and a D/A converter.

Channel

The channel is a medium of choice that can convey the electric signals at the transmitter output over a distance. A typical channel can be a pair of twisted copper wires (telephone and DSL), coaxial cable (television and internet), an optical fiber or a radio link. Channel may be of two types.

1. **Physical channel:** When there is a physical connection between the transmitter and receiver through wires. eg. coaxial cable.
2. **Wireless channel:** When no physical channel is present and transmission is through air. e.g. mobile communication.

It is inevitable that the signal will deteriorate during the process of transmission and reception as a result of some distortion in the system, or because of the introduction of noise, which is unwanted energy, usually of random character, present in a transmission system, due to a variety of causes. Since noise will be received together with the signal, it places a limitation on the transmission system as a whole. When noise is severe, it may mask a given signal so much that the signal becomes undetectable and therefore useless. Noise may interfere with signal at any point in a communications system, but it will have its greatest effect when the signal is weakest. This means that noise in the channel or at the input to the receiver is the most noticeable.

Receiver

The receiver reprocesses the signal received from the channel by reversing the signal modifications made at the transmitter and removing the distortions made by the channel. The receiver output is fed to the output transducer, which converts the electric signal to its original form i.e. the message signal.

Destination

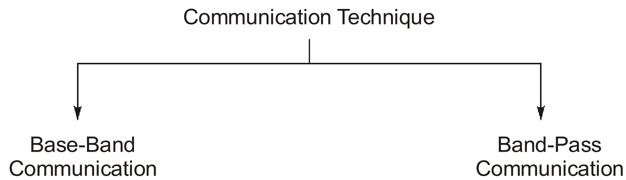
The destination is the unit to which the message is communicated.

1.3 Modes of Communication

There are two basic modes of communication:

1. **Broadcasting**, which involves the use of a single powerful transmitter and numerous receivers that are relatively inexpensive to build. Here information-bearing signals flow only in one direction.
2. **Point-to-point communication**, in which the communication process takes place over a link between a single transmitter and a receiver. In this case, there is usually a bidirectional flow of information-bearing signals, which requires the use of a transmitter and receiver at each end of the link.

1.3.1 Communication Technique



1. Base Band Communication:

It is generally used for short distance communication. In this type of communication message is directly sent to the receiver without altering its frequency.

2. Band Pass Communication:

It is used for long distance communication. In this type of communication, the message signal is mixed with another signal called as the carrier signal for the process of transmission. This process of adding a carrier to a signal is called as modulation.

1.3.2 Need of Modulation

1. To avoid the mixing of signals

   All messages lies within the range of 20 Hz - 20 kHz for speech and music, few MHz for video so all signals from the different sources would be inseparable and mixed up. In order to avoid mixing of various signals, it is necessary to translate them all to different portions of the electromagnetic spectrum.

2. To decrease the length of transmitting and receiving antenna

   For a message at 10 kHz, the antenna length 'l' for practical purposes is equal to $\lambda/4$ (from antenna theory) i.e.,

$$\lambda = \frac{3\times10^8}{10\times10^3} = 3\times10^4 \text{ m}$$

   and $$l = \frac{\lambda}{4} = \frac{3\times10^4}{4} = 7500 \text{ m}$$

   An antenna of this size is impractical and for a message signal at 1 MHz

$$\lambda = \frac{3\times10^8}{10^6} = 300 \text{ m}$$

   and $$l = \frac{\lambda}{4} = 75 \text{ m (practicable)}$$

3. To allow the multiplexing of signals

   By translating all signals from different sources to different carrier frequency, we can multiplex the signals and able to send all signals through a single channel.

4. To remove the interference
5. To improve the quality of reception i.e. increasing the value of S/N ratio
6. To increase the range of communication

1.4 Types of Modulation

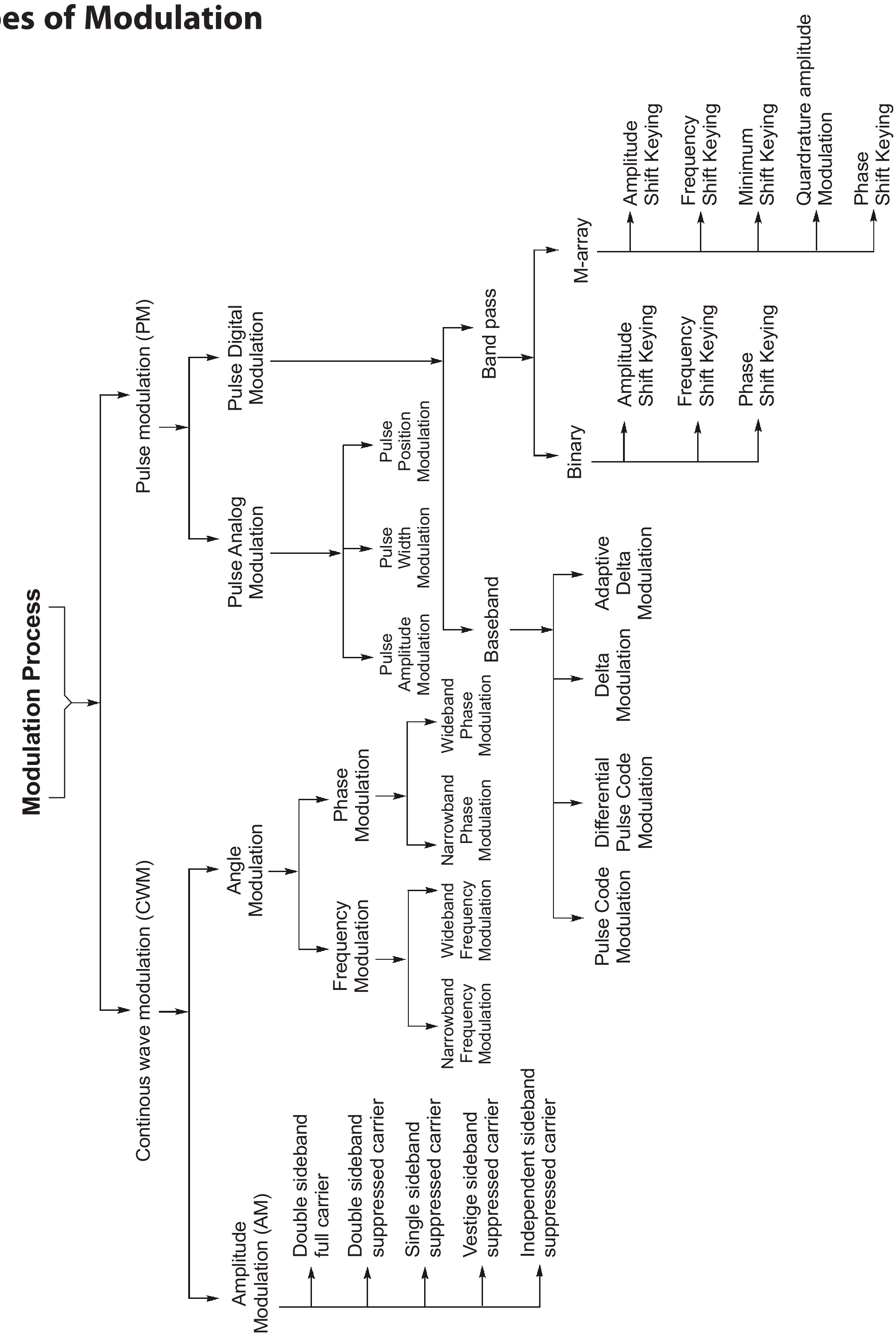


Figure-1.2

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CHAPTER 2

Amplitude Modulation

Introduction

In analog communication, message is analog and the carrier is a sine wave, which is also analog in nature. The modulation techniques in analog communication can be classified into amplitude modulation (AM) and angle modulation techniques. The amplitude of the carrier signal is varied in accordance with the message to obtain modulated signal in case of amplitude modulation. The angle modulation employs variation of angle of the carrier signal in proportion to the message. This chapter deals with the amplitude modulation techniques employed in analog communication. The next chapter deals with angle modulation techniques.

After studying the theory of amplitude modulation techniques, one will be able to know that an AM wave is made of a number of frequency components having a specific relation to one another. Based on this observation, AM can be further classified as double sideband full carrier (DSBFC), double sideband suppressed carrier (DSBSC), single sideband (SSB) and vestigial sideband (VSB) modulation techniques. This is based on how many components of the basic amplitude modulated signal are chosen for transmission. This is followed by a description of different methods for the generation of AM, DSBSC, SSB and VSB signals. To summarize, this chapter describes the basic essence of all the amplitude modulation techniques. In this chapter AM and its variants, their differences, merits and demerits are discussed. The students will also be able to calculate the frequencies present, plot the spectrum, the power or current associated with different frequency components and finally bandwidth requirements.

2.1 Amplitude Modulation

Consider a sinusoidal carrier wave $c(t)$ defined by

$$c(t) = A_c \cos(2\pi f_c t)$$

where the peak value A_c, is called the *carrier amplitude* and f_c is called the *carrier frequency*. For convenience, we have assumed that the phase of the carrier wave is zero. It is justified to make this assumption since the carrier source is always independent of the message source. We refer to $m(t)$ as the message signal which is baseband in nature. **Amplitude modulation is defined as a process in which the amplitude of the carrier wave $c(t)$ is varied linearly with the message signal $m(t)$ keeping other parameters constant.** This definition is general enough to permit different interpretations of the linearity. Correspondingly, amplitude modulation may take on different forms, depending on the frequency content of the modulated wave. In the following section, we consider the standard form of amplitude modulation.

2.1.1 Time-Domain Description

The standard form of an amplitude-modulated (AM) wave is defined by

$$x(t) = A_c[1 + k_a m(t)] \cos(2\pi f_c t)$$

where k_a is a constant called the *amplitude sensitivity* of the modulator. The modulated wave so defined is said to be a "standard" AM wave, because its frequency content is *fully* representative of amplitude modulation.

- The amplitude of the time function, multiplying $\cos(2\pi f_c t)$ is called the *envelope* of the AM wave $x(t)$. Using $a(t)$ to denote this envelope, we may thus write

$$a(t) = A_c|1 + k_a m(t)|$$

- Here, two cases of particular interest arise, depending on the magnitude of $k_a m(t)$, compared to unity.
- For case 1, we have

$$|k_a m(t)| \leq 1, \text{ for all } t$$

Under this condition, the term $1 + k_a m(t)$ is always non-negative. We may therefore simplify the expression for the envelope of the AM wave by writing

$$a(t) = A_c[1 + k_a m(t)], \quad \text{for all } t$$

- For case 2, on the other hand, we have

$$|k_a m(t)| > 1, \text{ for all } t$$

The maximum absolute value of $k_a m(t)$ multiplied by 100 is referred as the percentage modulation. Accordingly, case 1 corresponds to a percentage modulation less than or equal to 100%, whereas case 2 corresponds to a percentage modulation in excess of 100%.

NOTE

The envelope of the AM wave has a waveform that bears a *one-to-one correspondence* with that of the message signal if and only if the percentage modulation is less than or equal to 100%. This correspondence is destroyed if the percentage modulation exceeds 100%. In the later case, the modulated wave is said to suffer from **envelope distortion**, and the wave is said to be **over modulated**.

The complexity of the detector is greatly simplified if the transmitter is designed to produce an envelope $a(t)$ that has the same shape as the message signal $m(t)$. For this, two conditions are need to be satisfied.

1. The percentage modulation should be less than 100%, so as to avoid envelope distortion.
2. The message bandwidth, W, should be small as compared to the carrier frequency f_c, so that the envelope $a(t)$ may be visualized satisfactorily. Here, it is assumed that the spectral content of the message signal is negligible for frequencies outside the interval $-W \leq f \leq W$.

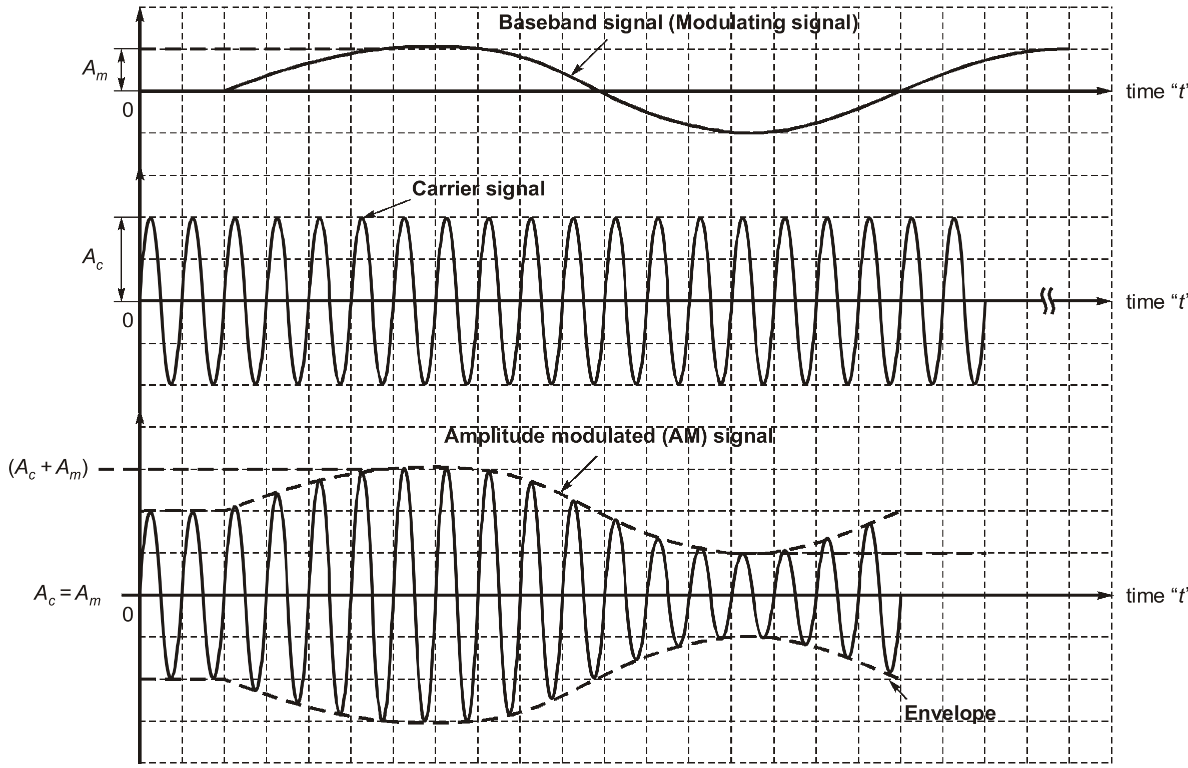


Figure-2.1 : *AM waveform for sinusoidal modulating signal*

2.1.2 Observations

1. The frequency of the sinusoidal carrier is much higher than that of the modulating signal.
2. In AM, the instantaneous amplitude of the sinusoidal high frequency carrier is changed in proportion to the instantaneous amplitude of the modulating signal. This is the principle of AM.
3. The time domain display of AM signal is as shown in Figure (2.1). This AM signal is transmitted by a transmitter. The information in the AM signal is contained in the amplitude variations of the carrier of the envelope shown by dotted lines.
4. Note that the frequency and phase of the carrier remain constant.
5. AM is used in the applications such as radio transmission, TV transmission

Example 2.1 The amplitude modulated wave form $s(t) = A_C\left[1+K_a m(t)\right]\cos\omega_C t$ is fed to an ideal envelope detector. The maximum magnitude of $K_a m(t)$ is greater than 1. Which of the following could be the detector output?

(a) $A_c m(t)$ (b) $A_c^2[1+K_a m(t)]^2$ (c) $\left[A_c\left|1+K_a m(t)\right|\right]$ (d) $A_c\left|1+K_a m(t)\right|^2$

Solution: (c)

When the modulation index of AM wave is less than unity the output of the envelope detector is envelope of the AM wave but when the modulation index is greater than unity then the output of the envelope detector is not envelope but modulus of the envelope of the AM wave. Thus the detector output in given case would be $A_c\left|1+k_a m(t)\right|$.

2.1.3 Frequency Domain Description

To develop the frequency description of the AM wave, we take the Fourier transform of both sides. Let $S(f)$ denote the Fourier transform of $s(t)$, and $M(f)$ denote the Fourier transform of the message signal $m(t)$; we refer to $M(f)$ as the message spectrum. Accordingly, using the Fourier transform of the cosine function $A_c \cos(2\pi f_c t)$ and the frequency-shifting property of the Fourier transform, we may write

$$S(f) = \frac{A_c}{2}[\delta(f - f_c) + \delta(f + f_c)] + \frac{k_a A_c}{2}[M(f - f_c) + M(f + f_c)]$$

Let the message signal $m(t)$ be band-limited to the interval $-W \le f \le W$, (the shape of the spectrum shown in this figure is intended for the purpose of illustration only).

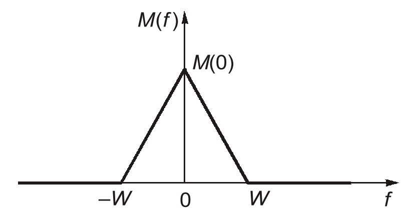


Figure-2.2

1. For positive frequencies, the portion of the spectrum of the modulated wave lying above the carrier frequency f_c is called the upper sideband, whereas the symmetric portion below f_c is called the lower sideband. For negative frequencies, the image of the upper sideband is represented by the portion of the spectrum below $-f_c$ and the image of the lower sideband by the portion above $-f_c$. The condition $f_c > W$ ensures that the sidebands do not overlap. Otherwise, the modulated wave exhibits spectral overlap and therefore frequency distortion.
2. For positive frequencies, the highest frequency component of the AM wave is $f_c + W$, and the lowest frequency component is $f_c - W$. The difference between these two frequency defines the transmission bandwidth B for an AM wave, which is exactly twice the message bandwidth W; that is

$$B = 2W$$

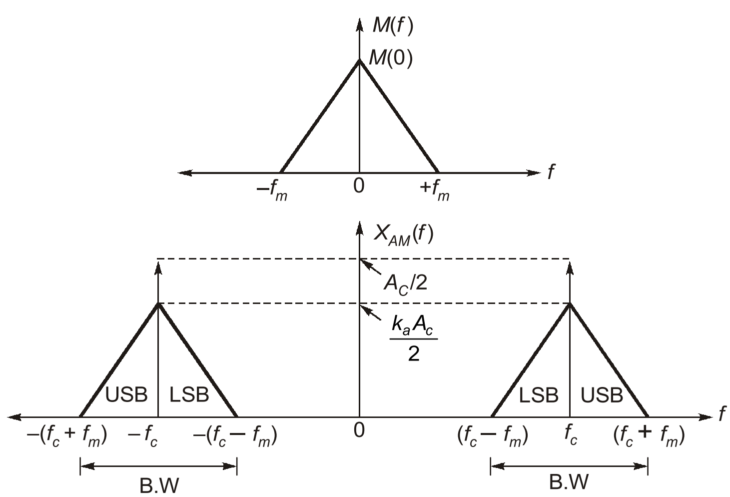


Figure-2.3

$$\text{B.W} = (f_c + f_m) - (f_c - f_m)$$
$$\text{B.W} \approx 2 f_m \text{ Hz or kHz}$$
$$\text{B.W} = 2\omega_m \text{ rad/sec}$$

2.2 Single Tone Amplitude Modulation

$$x(t) = A_C \cos \omega_c t \text{ ....carrier signal}$$
$$m(t) = A_m \cos \omega_m t \text{ .... modulating signal}$$

then after modulation, we get

$$\therefore \quad X_{AM}(t) = [A_c + A_m \cos \omega_m t] \cos \omega_c t$$

$$X_{AM}(t) = A_c\left[1+\frac{A_m}{A_c}\cos\omega_m t\right]\cos\omega_c t$$

$$X_{AM}(t) = A_c[1 + m_a \cos \omega_m t] \cos \omega_c t$$

where, $m_a = \dfrac{A_m}{A_c}$ = Modulation Index or Depth of modulation.

The above equation can also be written as

$$X_{AM}(t) = \underbrace{A_c\cos\omega_c t}_{\text{Full carrier}} + \frac{1}{2}m_a A_c \underbrace{\cos(\omega_c+\omega_m)t}_{\text{USB}} + \frac{1}{2}m_a A_c\underbrace{\cos(\omega_c-\omega_m)t}_{\text{LSB}}$$

2.2.1 Spectrum of Sinusoidal AM signal

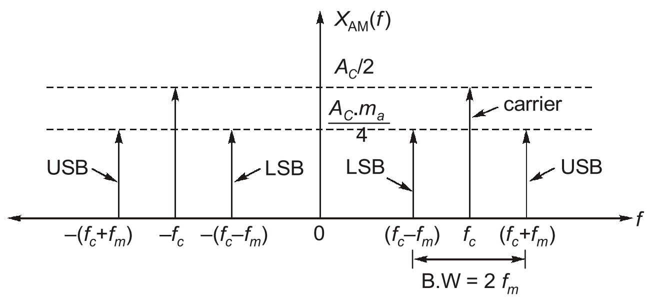


Figure-2.4

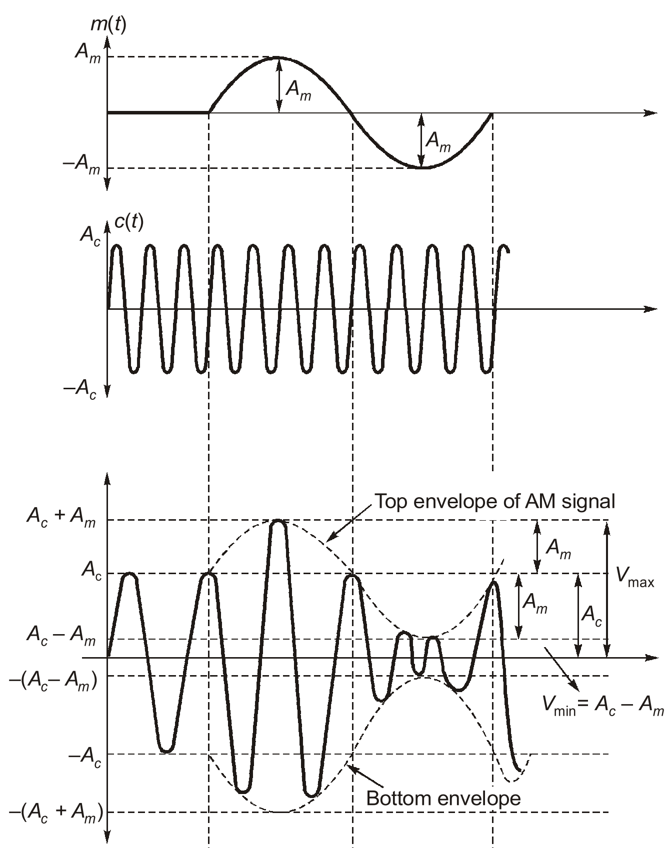


Figure-2.5

$$2A_m = V_{max} - V_{min}$$

$$\Rightarrow \quad A_m = \frac{V_{max} - V_{min}}{2}$$

$$A_c = V_{max} - A_m = V_{max} - \frac{V_{max} - V_{min}}{2}$$

$$\Rightarrow \quad A_c = \frac{V_{max} + V_{min}}{2}$$

Finally, we get

$$m_a = \frac{A_m}{A_C} = \frac{V_{max} - V_{min}}{V_{max} + V_{min}} \rightarrow \text{modulation index}$$

- % modulation = $m_a \times 100$
- Modulation index gives the depth to which the carrier signal is modulated.
- For $m(t)$ to be preserved in the envelope of AM signal, $m_a \leq 1$
  i.e. $A_m \leq A_c$
  so, range of m_a is, $0 \leq m_a \leq 1$

2.2.2 Over modulation

When $m_a > 1$ i.e. $A_m > A_C$, over modulation takes place and the signal gets distorted. Since, the negative part of waveform gets cut from the waveform leaving behind a "square wave type" of signal, which generates infinite number of harmonics. This type of distortion is known as "Non-linear distortion" or "Envelope distortion".

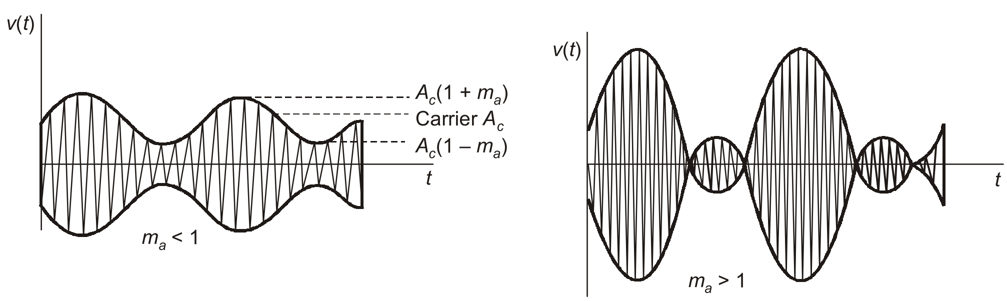


***Figure-2.6 :** (a) Undermodulated AM wave (b) Over modulated AM wave*

2.3 Power Relations in AM

- In practice, the AM wave is a voltage or current wave.
- An AM wave consists of carrier and two sidebands. Hence the AM wave will contain more power than the power-contained by an unmodulated carrier.
- The amplitudes of the two sidebands are dependent on the modulation index "*m*". Hence the power contained in the sidebands depends on the value of *m*. Hence the total power in an AM wave is a function of the value of modulation index *m*.

2.3.1 The Total Power in AM

The total power in an AM wave is given by,

$$P_t = \text{[Carrier Power]} + \text{[Power in USB]} + \text{[Power in LSB]}$$

$$\therefore \quad P_t = \frac{E^2}{R} + \frac{E_{USB}^2}{R} + \frac{E_{LSB}^2}{R}$$

Where E, E_{USB} and E_{LSB} are the RMS values of the carrier and sideband amplitudes and R is the characteristic resistance of antenna through which the total power is dissipated.

After passing from LPF with $f_c = 1$ Hz

$$\therefore \quad y(t) = \frac{1}{2t}[\sin 2\pi t + \sin 2\pi t - \sin \pi t]$$

$$\Rightarrow \quad y(t) = \frac{\sin 2\pi t}{2t} + \frac{1}{2t}[2\sin 0.5\pi t \cdot \cos 1.5\pi t]$$

$$\Rightarrow \quad y(t) = \frac{\sin 2\pi t}{2t} + \frac{\sin 0.5\pi t \cos 1.5\pi t}{t}$$

Sl. No.	Parameter	DSBFC	DSBSC	SSB	VSB
1.	Carrier suppression	N.A.	Fully	Fully	Fully
2.	Sideband suppression	N.A.	N.A.	One S.B. completely	One S.B. suppressed partially
3.	Bandwidth	$2 f_m$	$2 f_m$	f_m	$f_m < BW < 2f_m$
4.	Transmission efficiency	Minimum	Moderate	Maximum	Moderate
5.	No. of modulating inputs	1	1	1	2
6.	Application	Radio broadcasting	Radio broadcasting	Point to point mobile communication	T.V. Video transmission
7.	Power requirement to cover same area	High	Medium	Very small	Moderate
8.	Complexity	Simple	Simple	Complex	Simpler than SSB

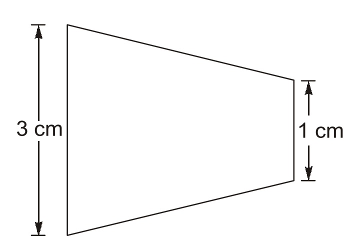
Table-2.1

Student's Assignments 1

Q.1 Total power saving when carrier and one of the sidebands are suppressed in an AM wave modulated to a depth of 50% is

(a) 66.67% (b) 83.33%
(c) 94.44% (d) 100%

Q.2 Consider the Trapezoidal pattern for AM wave shown below. Modulation index is given by



(a) 33% (b) 50%
(c) 75% (d) 100%

Q.3 For a message signal $m(t)$ = 10 cos 100 t with 60% modulation, the maximum envelope time will be

(a) 10.3 ms (b) 13.3 ms
(c) 33.3 ms (d) 10 ms

Q.4 The modulation index of an AM wave is changed from 0 to 1. The transmitted power is

(a) unchanged
(b) halved
(c) doubled
(d) increased by 50 percent

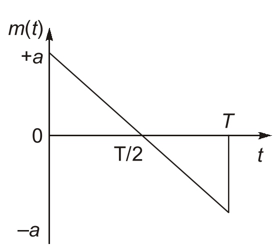
Q.5 The most commonly used filters in SSB generation are

(a) mechanical (b) RC
(c) LC (d) low-pass

Q.6 The amplitude modulated waveform $s(t) = A_C[1 + k_a m(t)] \cos\omega_C t$ is fed to an ideal envelope detector. The maximum magnitude of $k_a m(t)$ is greater than 1. Which of the following could be the detector output?

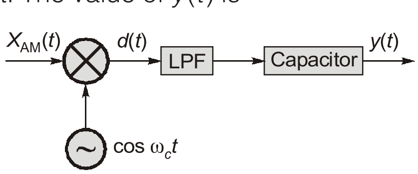
(a) $A_C m(t)$ (b) $A_C^2[1+k_a m(t)]^2$
(c) $|A_C[1+k_a m(t)]|$ (d) $A_C[1 + k_a m(t)]^2$

Q.7 A message signal periodic with T is applied to an AM modulator with m = 0.5. The modulation efficiency will be



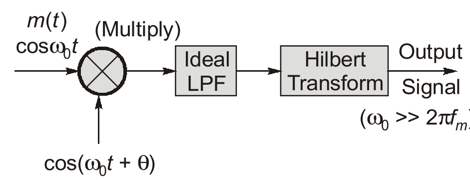
(a) 5.1% (b) 7.7%
(c) 10.2% (d) 15.4%

Q.8 For given synchronous demodulator can demodulate AM signal $X_{AM}(t) = [A + m(t)] \cos \omega_c t$. The value of $y(t)$ is



(a) $m(t)$ (b) $\frac{m(t)}{2}$
(c) $\frac{m(t)}{4}$ (d) zero

Q.9 A message $m(t)$ band limited to the frequency f_m has a power of P_m. The power of output signal is



(a) $\frac{P_m \cos\theta}{2}$ (b) $\frac{P_m}{4}$
(c) $\frac{P_m \sin^2\theta}{4}$ (d) $\frac{P_m \cos^2\theta}{4}$

■ ANSWERS

1. (c)	2. (b)	3. (b)	4. (d)	5. (a)
6. (c)	7. (b)	8. (b)	9. (c)	

Student's Assignments 2

Q.1 The input to an envelope detector is a single-tone AM signal

$x_{AM}(t) = A[1 + m_a \cos(\omega_m t)]\cos(\omega_c t)$

where m_a is constant, $0 < m_a < 1$, and $\omega_c >> \omega_m$.

(i) Show that if the detector output is to follow the envelope of $x_{AM}(t)$, it requires that at any time to

$$\frac{1}{RC} \geq \omega_m\left(\frac{m_a \sin\omega_m t_o}{1 + m_o \cos\omega_m t_o}\right)$$

(ii) Also prove if the detector output is to follow the envelope at all times, it is required that

$$RC \leq \frac{1}{\omega_m}\frac{\sqrt{1-m_a^2}}{m_a}$$

Q.2 Given the SSB wave

$$s(t) = m(t)\cos(2\pi f_c t) - \hat{m}(t)\sin(2\pi f_c t)$$

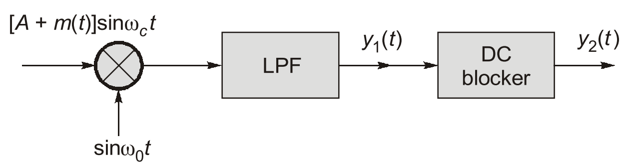
where f_c is carrier frequency, $m(t)$ is the message signal and $\hat{m}(t)$ is its Hilbert transformer.

The modulated wave is applied to a square-law device characterized by

$$y(t) = s^2(t)$$

Prove that the output has a time varying phase which make it impractical for detection.

Q.3 Coherent demodulation of AM signal is shown below. The LPF and message signal $m(t)$ have the same bandwidths.



Find the expression for signal at $y_1(t)$.

Q.4 The antenna current of an AM broadcast transmitter, modulated to a depth of 40 percent by an audio sine wave, is 11 amperes. It increases to 12 amperes as a result of simultaneous modulation by another audio sine wave. What is the modulation index due to this second wave?

■ ANSWERS

3. $y_1(t) = \dfrac{A + m(t)}{2}$

4. 0.64

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