ELECTRICAL ENGINEERING

Communication Systems

Comprehensive Theory
with Solved Examples *and* Practice Questions

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Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016 | **Ph. :** 9021300500

Email : infomep@madeeasy.in | **Web :** www.madeeasypublications.org

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1

Introduction to Communication Systems

1.1 HISTORICAL SKETCH

The development of communication technology has proceeded in step with the development of electronic technology as a whole. For example, the demonstration of telegraphy by Joseph Henry in 1832 and by Samuel F.B. Morse in 1838 followed hard on the discovery of electromagnetism by Oersted and Ampere early in 1820's. Similarly, Hertz's verification late in the 1880's of Maxwell's postulation (1873) predicting the wireless propagation of electromagnetic energy led within 10 years of the radio-telegraph experiments of Marconi and Popov. The invention of diode by Flaming in 1904 and of triode by deforest in 1906 made possible the rapid development of long distance telephony, both by radio and wireless.

1.2 WHY STUDY COMMUNICATION

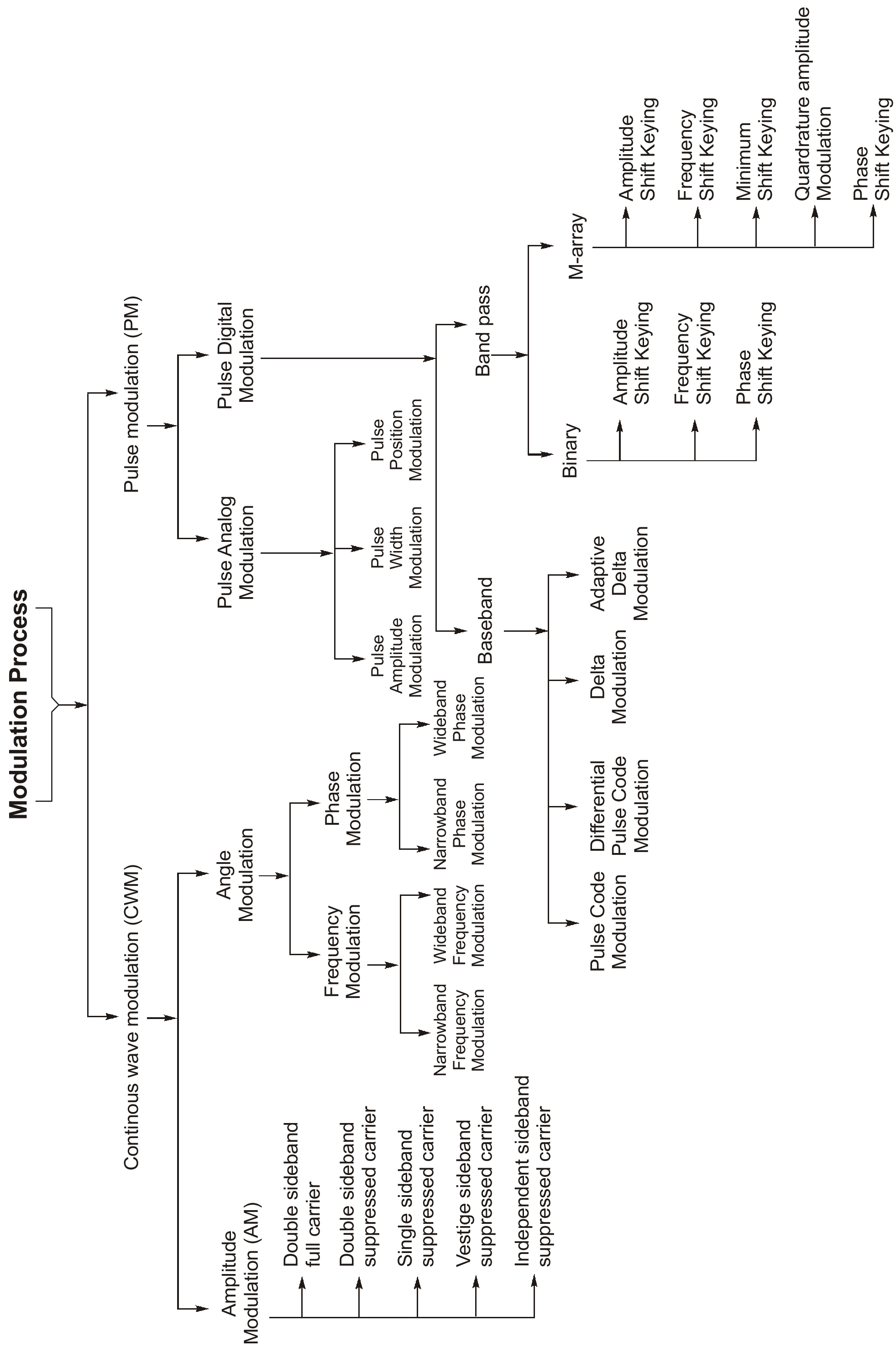
The rapidly changing face of technology necessitates learning of new technology. Today the question is no longer in the field of invention but of innovation. The question today in the twenty first century in not how to transmit data from point A to point B but how efficiently can we do it. To be able to answer this question, first we should be able to diagnose the problem. This can be done only by studying communication from the beginning to its modern form.

1.3 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, audio, 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.

1.6 TYPES OF MODULATION



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CHAPTER

2

Amplitude Modulation

INTRODUCTION

In analog communication, message is analog and the carrier is 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.

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

Amplitude modulation is the process of changing the amplitude of a relatively high frequency carrier signal in proportion with the instantaneous value of the modulating signal (information).

Amplitude modulation is a relatively inexpensive, low quality form of modulation that is used for commercial broadcasting of both audio and video signals.

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 in making 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.**

Amplitude modulation is linear process but AM modulators are non-linear devices.

2.1.1 Time-Domain Description

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

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

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 $s(t)$. Using $a(t)$ to denote this envelope, we may thus write

$$a(t) = A_c\left|1 + k_a m(t)\right| \quad \text{...(i)}$$

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

$$\left|k_a m(t)\right| \le 1, \text{ for all } t$$

Under this condition, the term $1 + k_a m(t)$ is always nonnegative. 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

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

Under this condition, we must use equation (i) for evaluating the envelope of AM wave.

The maximum absolute value of $k_a m(t)$ multiplied by 100 is referred to as the percentage modulation.

> **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 (i.e., the demodulation circuit used to recover the message signal from the incoming AM wave at the receiver) 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, f_m, 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 $-f_m \le f \le f_m$, i.e., message signal is basedband in nature.

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. 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.

$$= \left[A_c^2 + \left(\frac{1}{1+t^2}\right)^2 + \frac{2A_c}{1+t^2} + \frac{t^2}{(1+t^2)^2}\right]^{1/2}$$

$$= \left[A_c^2 + \frac{1}{1+t^2} + \frac{2A_c}{1+t^2}\right]^{1/2}$$

$$= A_c\left[1 + \frac{2}{A_c(1+t^2)} + \frac{1}{A_c^2(1+t^2)}\right]^{1/2}$$

↓ neglect (last term)

$$[x(t)]_{env} = A_c\left[1 + \frac{2}{A_c(1+t^2)}\right]^{1/2}$$

Using exp.

$$[x(t)]_{env} = A_c\left[1 + \frac{1}{2}\frac{2}{A_c(1+t^2)}\right] = A_c + \frac{1}{1+t^2}$$

OBJECTIVE BRAIN TEASERS

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%

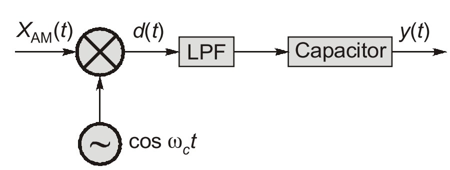
Q.2 For a message signal $m(t) = 10 \cos 100\, t$ with 60% modulation, the maximum envelope time will be

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

Q.3 The modulation index of an AM wave is changed from 0 to 1. The transmitted power is

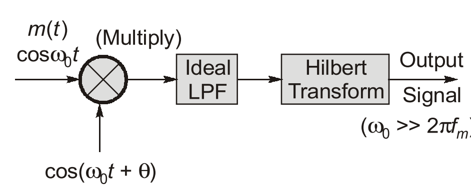
(a) unchanged
(b) halved
(c) doubled
(d) increased by 50 percent

Q.4 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.5 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 KEY

1. (c) 2. (b) 3. (d) 4. (b) 5. (c)

HINTS & EXPLANATIONS

1. (c)

$$\% \text{ Power saving} = \frac{P_C + P_{USB}}{P_t} \times 100\%$$

$$= \frac{P_C + \frac{P_C \mu^2}{4}}{P_C\left(1+\frac{\mu^2}{2}\right)} \times 100\% = \frac{\mu^2 + 4}{2(2+\mu^2)} \times 100\%$$

$$= \frac{4+0.25}{2(2+0.25)} \times 100\% = 94.44\%$$

2. (b)

For the envelope detector output to follow the envelope of AM signals,

$$RC \le \frac{1}{\omega_m} \cdot \frac{\sqrt{1-\mu^2}}{\mu}$$

For $m(t) = 10\cos 100t$, $\omega_m = 100$ rad/sec

$$\therefore \quad RC \le \frac{1}{100} \times \frac{\sqrt{1-(0.6)^2}}{0.6}$$

$$RC \le \frac{1}{100} \times \frac{0.8}{0.6}$$

$$RC \le 13.33 \text{ ms}$$

3. (d)

For AM wave, transmitted power is

$$P_t = P_C\left(1+\frac{\mu^2}{2}\right)$$

For $\mu = 0$, $P_{t_1} = P_C$

For $\mu = 1$, $P_{t_2} = \frac{3P_C}{2}$

The percentage change in transmitted power,

$$= \frac{P_{t_2} - P_{t_1}}{P_{t_1}} \times 100\% = \frac{\frac{3}{2}P_C - P_C}{P_C} \times 100\% = 50\%$$

Hence, the transmitted power is increased by 50 percent when μ is changed from 0 t to 1.

4. (b)

We have,

$$d(t) = [A + m(t)]\cos\omega_c t \cdot \cos\omega_c t$$

$$d(t) = [A + m(t)]\cos^2 \omega_c t$$

$$d(t) = [A + m(t)]\frac{(1+\cos 2\omega_c t)}{2}$$

$$d(t) = \frac{A}{2} + \frac{A}{2}\cos 2\omega_c t + \frac{m(t)}{2} + \frac{m(t)\cdot\cos 2\omega_c t}{2}$$

On passing through low pass filter,

$$y'(t) = \frac{A}{2} + \frac{m(t)}{2}$$

The capacitor blocks the DC component

Hence, $y(t) = \frac{m(t)}{2}$

5. (c)

The input to the low pass filter,

$s(t) = m(t)\cos\omega_o t \cdot \cos(\omega_o t + \theta)$

$$s(t) = \frac{m(t)}{2}[\cos(2\omega_o t + \theta)\cos\theta]$$

$$s(t) = \underbrace{\frac{m(t)\cdot\cos(2\omega_o t+\theta)}{2}}_{\substack{\text{Frequency range from} \\ 2f_o - f_m \text{ to } 2f_o + f_m \\ \text{where } f_o = \omega_o/2\pi}} + \underbrace{\frac{m(t)\cos\theta}{2}}_{\substack{\text{Frequency} \\ \text{range from} \\ 0 \text{ to } f_m}}$$

Hence, the output of LPF,

$$y'(t) = \frac{m(t)\cdot\cos\theta}{2}$$

The Hilbert transform of $y'(t)$ gives the output signal as

$$y(t) = \frac{m(t)\cdot\sin\theta}{2}$$

(Hilbert transform is a 90° phase shifter).

Hence, the power of output signal is

$$P_o = \frac{P_m \sin^2\theta}{4}$$

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CONVENTIONAL BRAIN TEASERS

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 t_o

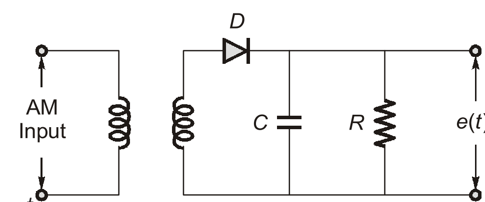
$$\frac{1}{RC} \geq \omega_m \left(\frac{m_a \sin\omega_m t_o}{1 + m_o \cos\omega_m t_o}\right)$$

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

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

1. (Sol.)

(i) The input to an envelope detector is given as

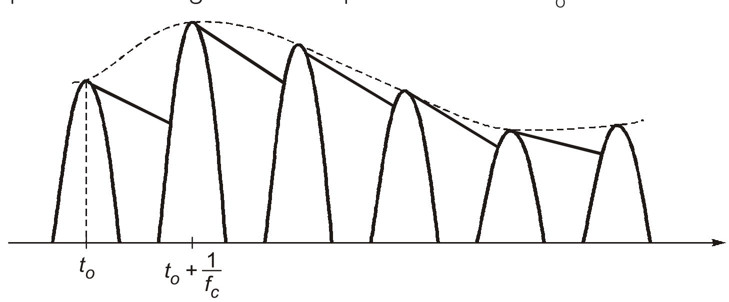


$$x_{AM}(t) = A[1 + m_a \cos(\omega_m t)] \cdot \cos(\omega_c t)$$

The maximum amplitude of the signal, at $t = t_o$

$$V_o = A + m_a A \cos(\omega_m t_o)$$

Assume the capacitor discharges from the peak value at $t = t_o$.



The voltage $v_c(t)$ across the capacitor,

$$V_c(t) = V_o\, e^{-(t-t_o)/Rc}$$

Rate of discharge, $$\frac{-dV_c(t)}{dt} = \frac{V_o}{RC} e^{-(t-t_o)/RC}$$

Rate of change at $t = t_o$,

$$\left(-\frac{dV_c(t)}{dt}\right)_{t=t_o} = \frac{V_o}{RC} = \frac{A}{RC}(1 + m_a \cos\omega_m t_o) \quad \text{...(i)}$$

Now, the rate of change of envelope of AM signal,

$$-\frac{de(t)}{dt} = -\frac{d}{dt}[A(1 + m_a \cos\omega_m t)]$$

$$-\frac{de(t)}{dt} = \omega_m m_a A \sin\omega_m t$$

At $t = t_o$, $$\left(-\frac{de(t)}{dt}\right)_{t=t_o} = \omega_m \cdot m_a \cdot A \sin\omega_m t_o \quad \text{...(ii)}$$

Thus, to preserve the value of envelope, at any time t_o.

Rate of change of capacitor voltage ≥ Rate of change of AM signal.

Using equation (i) and (ii),

$$\frac{A}{RC}[1+m_a\cos\omega_m t_o] \geq \omega_m \cdot m_a A\sin\omega_m t_o$$

$$\Rightarrow \quad \frac{1}{RC} \geq \omega_m\left[\frac{m_a\sin\omega_m t_o}{1+m_a(\cos\omega_m t_o)}\right]$$

(ii) From result obtained in part (i), to get maximum value

$$\frac{d}{dt_o}\left[\frac{m_a\omega_m\sin\omega_m t_o}{1+m_a\cos\omega_m t_o}\right] = 0$$

$$\Rightarrow \quad (1+m_a\cos\omega_m t_o)\cdot m_a\omega_m^2\cos\omega_m t_o + m_a^2\omega_m^2\sin^2\omega_m t_o = 0$$

$$\Rightarrow \quad m_a\omega_m^2\cos\omega_m t_o + m_a^2\omega_m^2\left[\cos^2\omega_m t_o + \sin^2\omega_m t_o\right] = 0$$

$$\Rightarrow \quad \cos\omega_m t_o = -m_a$$

Hence,

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

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

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.

2. (Sol.)

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

The output of the square-law device is

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

$$\Rightarrow \quad y(t) = [m(t)\cos(2\pi f_c t) - \hat{m}(t)\sin(2\pi f_c t)]^2$$

$$y(t) = \left[\frac{m(t)}{\sqrt{m^2(t)+\hat{m}^2(t)}}\cdot\cos 2\pi f_c t - \frac{\hat{m}(t)}{\sqrt{m^2(t)+\hat{m}^2(t)}}\cdot\sin 2\pi f_c t\right]^2\left[m^2(t)+\hat{m}^2(t)\right]$$

$$y(t) = \left[\hat{m}^2(t)+m^2(t)\right]\cos^2\left[2\pi f_c t + \tan^{-1}\left(\frac{\hat{m}(t)}{m(t)}\right)\right]$$

$$y(t) = \frac{\left[\hat{m}^2(t)+m^2(t)\right]}{2}\left[1+\cos\left[4\pi f_c t + 2\tan^{-1}\left(\frac{\hat{m}(t)}{m(t)}\right)\right]\right]$$

Thus, the output has a time-varying phase which makes it impractical for detection.