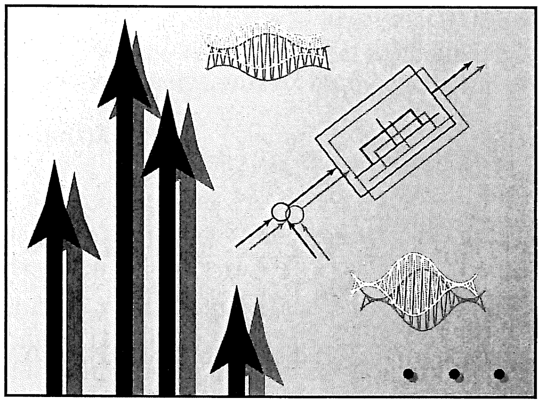
8

COMMUNICATION SYSTEMS



8.0 INTRODUCTION

Communication systems play a key role in our modern world in transmitting information between people, systems, and computers. In general terms, in all communication systems the information at the source is first processed by a transmitter or modulator to change it into a form suitable for transmission over the communication channel. At the receiver, the signal is then recovered through appropriate processing. This processing is required for a variety of reasons. In particular, quite typically, any specific communication channel has associated with it a frequency range over which it is best suited for transmitting a signal and outside of which communication is severely degraded or impossible. For example, the atmosphere will rapidly attenuate signals in the audible frequency range (10 Hz to 20 kHz), whereas it will propagate signals at a higher frequency range over longer distances. Thus, in transmitting audio signals such as speech or music over a communication channel that relies on propagation through the atmosphere, the transmitter first embeds the signal through an appropriate process into another, higher frequency signal.

Many of the concepts and techniques we have developed in the earlier chapters of this text play a central role in the analysis and design of communication systems. As with any concept that is closely tied to a wide variety of important applications, there are a large number of detailed issues to be considered, and, as indicated in the bibliography, there are many excellent texts on the subject. While a full and detailed analysis of communication systems is well beyond the scope of our discussions here, with the background of the previous chapters we are now in a position to introduce some of the basic principles and issues encountered in the design and analysis of these systems.

The general process of embedding an information-bearing signal into a second signal is typically referred to as *modulation*. Extracting the information-bearing signal is known as *demodulation.* As we will see, modulation techniques not only allow us to embed information into signals that can be transmitted effectively, but also make possible the simultaneous transmission of more than one signal with overlapping spectra over the same channel, through a concept referred to as *multiplexing.*

There are a wide variety of modulation methods used in practice, and in this chapter we examine several of the most important of these. One large class of modulation methods relies on the concept of *amplitude modulation* or AM in which the signal we wish to transmit is used to modulate the amplitude of another signal. A very common form of amplitude modulation is *sinusoidal amplitude modulation,* which we explore in some detail in Sections 8.1–8.4 together with the related concepts of frequency-division multiplexing. Another important class of AM systems involves the modulation of the amplitude of a pulsed signal, and in Sections 8.5 and 8.6 we examine this form of modulation as well as the concept of time-division multiplexing. In Section 8.7 we then examine a different form of modulation, namely *sinusoidal frequency modulation* in which the information-bearing signal is used to vary the frequency of a sinusoidal signal.

All of the discussion up through Section 8.7 focuses attention on continuous-time signals, since most transmission media, such as the atmosphere, are best thought of as continuous-time phenomena. Nevertheless, not only is it possible to develop analogous techniques for discrete-time signals, but it is of considerable practical importance to consider modulation concepts involving such signals, and in Section 8.8 we examine some of the basic ideas behind the communication of discrete-time signals.

PLEX EXPONENTIAL AND SINUSOIDAL AMPLITUDE MODULATION

Many communication systems rely on the concept of sinusoidal amplitude modulation, in which a complex exponential or sinusoidal signal $c(t)$ has its amplitude multiplied (modulated) by the information-bearing signal $x(t)$. The signal $x(t)$ is typically referred to as the *modulating signal* and the signal $c(t)$ as the *carrier signal.* The modulated signal $y(t)$ is then the product of these two signals:

$$y(t) = x(t)c(t)$$

As we discussed in Section 8.0, an important objective in modulation is to produce a signal whose frequency range is suitable for transmission over the communication channel to be used. In telephone transmission systems, for example, long-distance transmission is often accomplished over microwave or satellite links. The individual voice signals are in the frequency range 200 Hz to 4 kHz, whereas a microwave link requires signals in the range 300 megahertz (MHz) to 300 gigahertz (GHz), and communication satellite links operate in the frequency range from a few hundred MHz to over 40 GHz. Thus, for transmission over these channels, the information in a voice signal must be shifted into these higher ranges of frequency. As we will see in this section, sinusoidal amplitude modulation achieves such a shift in frequency in a very simple manner.

8.1.1 Amplitude Modulation with a Complex Exponential Carrier

There are two common forms of sinusoidal amplitude modulation, one in which the carrier signal is a complex exponential of the form

$$c(t) = e^{j(\omega_c t + \theta_c)} \tag{8.1}$$

and the second in which the carrier signal is sinusoidal and of the forn.

$$c(t) = \cos(\omega_c t + \theta_c).$$

In both cases, the frequency ω_c is referred to as the *carrier frequency.* Let u
the case of a complex exponential carrier, and for convenience, let us cho
that the modulated signal is

$$y(t) = x(t)e^{j\omega_c t}.$$

From the multiplication property (Section 4.5), and with $X(j\omega)$, $Y(j$
denoting the Fourier transforms of $x(t)$, $y(t)$, and $c(t)$, respectively,

$$Y(j\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} X(j\theta)C(j(\omega - \theta))d\theta.$$

For $c(t)$ a complex exponential as given in eq. (8.1),

$$C(j\omega) = 2\pi\delta(\omega - \omega_c),$$

and hence,

$$Y(j\omega) = X(j\omega - j\omega_c).$$

Thus, the spectrum of the modulated output $y(t)$ is simply that of the in
frequency by an amount equal to the carrier frequency ω_c. For example, wi
limited with highest frequency ω_M (and bandwidth $2\omega_M$), as depicted in
the output spectrum $Y(j\omega)$ is that shown in Figure 8.1(c).

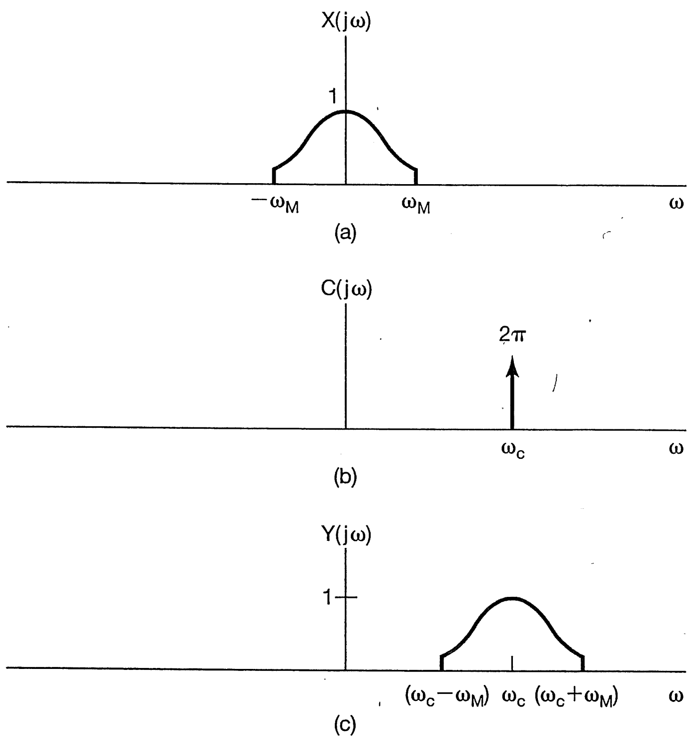


Figure 8.1 Effect in
domain of amplitude m
complex exponential ca
trum of modulating sig
spectrum of carrier $c(t)$
spectrum of amplitude-
nal $y(t) = x(t)e^{j\omega_c t}$.

From eq. (8.3), it is clear that $x(t)$ can be recovered from the modulated signal $y(t)$ by multiplying by the complex exponential $e^{-j\omega_c t}$; that is,

$$x(t) = y(t)e^{-j\omega_c t}. \tag{8.7}$$

In the frequency domain, this has the effect of shifting the spectrum of the modulated signal back to its original position on the frequency axis. The process of recovering the original signal from the modulated signal is referred to as *demodulation,* a topic we discuss at more length in Section 8.2.

Since $e^{j\omega_c t}$ is a complex signal, eq. (8.3) can be rewritten as

$$y(t) = x(t)\cos\omega_c t + jx(t)\sin\omega_c t. \tag{8.8}$$

Implementation of eq. (8.7) or (8.8) with $x(t)$ real utilizes two separate multipliers and two sinusoidal carrier signals that have a phase difference of $\pi/2$, as depicted in Figure 8.2 for $c(t)$ given by eq. (8.1). In Section 8.4 we give an example of one of the applications in which there are particular advantages to using a system, such as in Figure 8.2, employing two sinusoidal carriers with a phase difference of $\pi/2$.

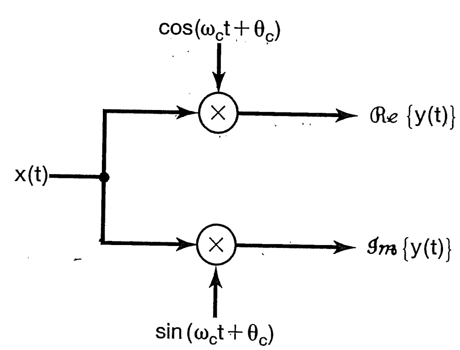


Figure 8.2 Implementation of amplitude modulation with a complex exponential carrier $c(t) = e^{j(\omega_c t+\theta_c)}$.

8.1.2 Amplitude Modulation with a Sinusoidal Carrier

In many situations, using a sinusoidal carrier of the form of eq. (8.2) is often simpler than and equally as effective as using a complex exponential carrier. In effect, using a sinusoidal carrier corresponds to retaining only the real or imaginary part of the output of Figure 8.2. A system that uses a sinusoidal carrier is depicted in Figure 8.3.

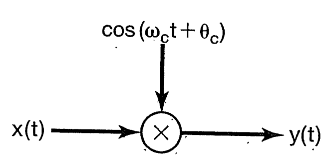


Figure 8.3 Amplitude modulation with a sinusoidal carrier.

The effect of amplitude modulation with a sinusoidal carrier in the form of eq. (8.2) can be analyzed in a manner identical to that in the preceding subsection. Again, for

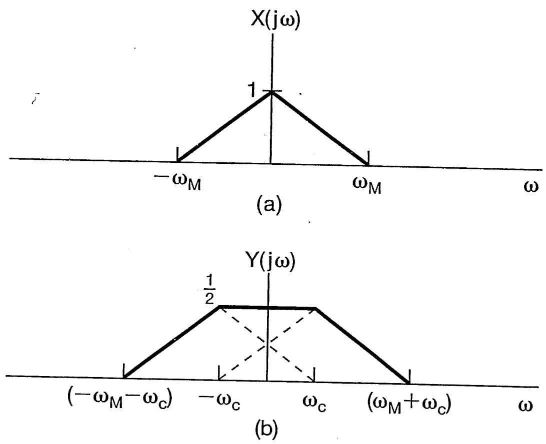


Figure 8.5 Sinusoidal amplitude modulation with carrier $\cos \omega_c t$ for which $\omega_c = \omega_M/2$: (a) spectrum of modulating signal; (b) spectrum of modulated signal.

8.2 DEMODULATION FOR SINUSOIDAL AM

At the receiver in a communication system, the information-bearing signal $x(t)$ is recovered through demodulation. In this section, we examine the process of demodulation for sinusoidal amplitude modulation, as introduced in the previous section. There are two commonly used methods for demodulation, each with its own advantages and disadvantages. In Section 8.2.1 we discuss the first of these, a process referred to as *synchronous demodulation,* in which the transmitter and receiver are synchronized in phase. In Section 8.2.2, we describe an alternative method referred to as *asynchronous demodulation.*

8.2.1 Synchronous Demodulation

Assuming that $\omega_c > \omega_M$, demodulation of a signal that was modulated with a sinusoidal carrier is relatively straightforward. Specifically, consider the signal

$$y(t) = x(t)\cos \omega_c t. \tag{8.11}$$

As was suggested in Example 4.21, the original signal can be recovered by modulating $y(t)$ with the same sinusoidal carrier and applying a lowpass filter to the result. To see this, consider

$$w(t) = y(t)\cos \omega_c t. \tag{8.12}$$

Figure 8.6 shows the spectra of $y(t)$ and $w(t)$, and we observe that $x(t)$ can be recovered from $w(t)$ by applying an ideal lowpass filter with a gain of 2 and a cutoff frequency that is greater than ω_M and less than $2\omega_c - \omega_M$. The frequency response of the lowpass filter is indicated by the dashed line in Figure 8.6(c).

The basis for using eq. (8.12) and a lowpass filter to demodulate $y(t)$ can also be seen algebraically. From eqs. (8.11) and (8.12), it follows that

$$w(t) = x(t)\cos^2 \omega_c t,$$

convenience we choose $\theta_c = 0$. In this case, the spectrum of the carrier s

$$C(j\omega) = \pi[\delta(\omega - \omega_c) + \delta(\omega + \omega_c)],$$

and thus, from eq. (8.4),

$$Y(j\omega) = \frac{1}{2}[X(j\omega - j\omega_c) + X(j\omega + j\omega_c)].$$

With $X(j\omega)$ as depicted in Figure 8.4(a), the spectrum of $y(t)$ is that shown i Note that there is now a replication of the spectrum of the original signal, both $+\omega_c$ and $-\omega_c$. As a consequence, $x(t)$ is recoverable from $y(t)$ only i otherwise the two replications will overlap in frequency. This is in contrast complex exponential carrier, for which a replication of the spectrum of the or centered only around ω_c. Specifically, as we saw in Section 8.1.1, in the cas modulation with a complex exponential carrier, $x(t)$ can always be recove for any choice of ω_c by shifting the spectrum back to its original location b by $e^{-j\omega_c t}$, as in eq. (8.7). With a sinusoidal carrier, on the other hand, as Figure 8.4, if $\omega_c < \omega_M$, then there will be an overlap between the two r $X(j\omega)$. For example, Figure 8.5 depicts $Y(j\omega)$ for $\omega_c = \omega_M/2$. Clearly, th $x(t)$ is no longer replicated in $Y(j\omega)$, and thus, it may no longer be possible t from $y(t)$.

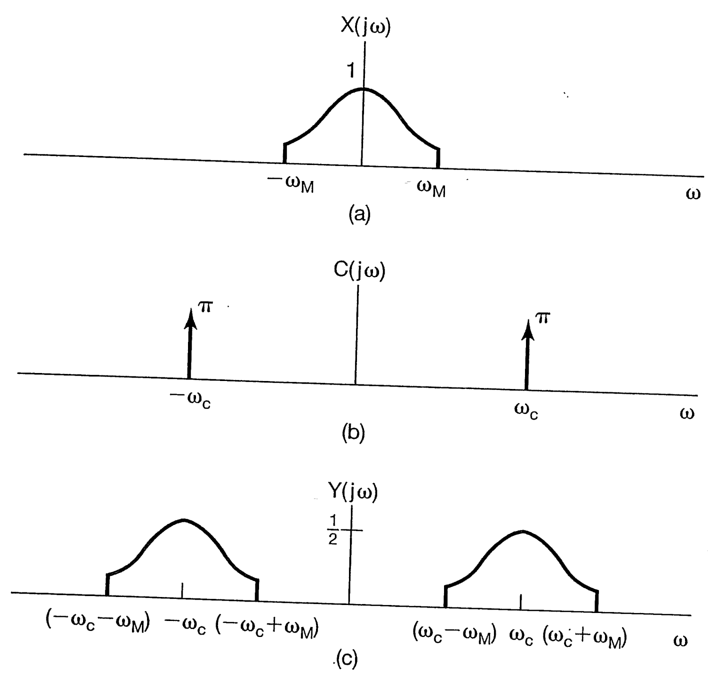


Figure 8.4 Effect in the domain of amplitude modu sinusoidal carrier: (a) spec modulating signal $x(t)$; (b) of carrier $c(t) = \cos \omega_c t$; (of amplitude-modulated sig

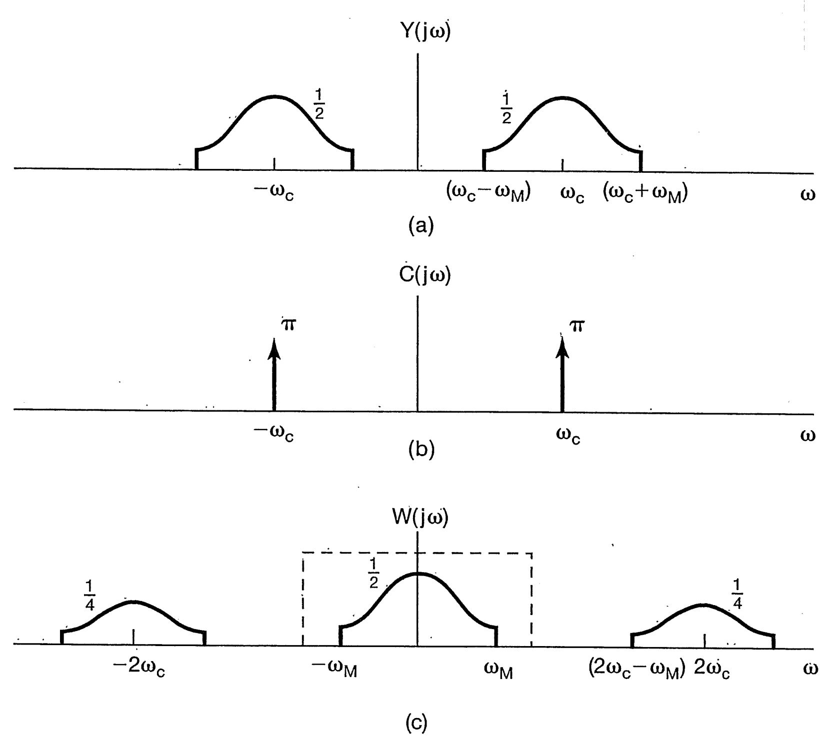


Figure 8.6 Demodulation of an amplitude-modulated signal with a sinusoidal carrier: (a) spectrum of modulated signal; (b) spectrum of carrier signal; (c) spectrum of modulated signal multiplied by the carrier. The dashed line indicates the frequency response of a lowpass filter used to extract the demodulated signal.

or, using the trigonometric identity

$$\cos^2 \omega_c t = \frac{1}{2} + \frac{1}{2}\cos 2\omega_c t,$$

we can rewrite $w(t)$ as

$$w(t) = \frac{1}{2}x(t) + \frac{1}{2}x(t)\cos 2\omega_c t. \qquad (8$$

Thus, $w(t)$ consists of the sum of two terms, namely one-half the original signal and half the original signal modulated with a sinusoidal carrier at twice the original ca frequency ω_c. Both of these terms are apparent in the spectrum shown in Figure 8. Applying the lowpass filter to $w(t)$ corresponds to retaining the first term on the right-h side of eq. (8.13) and eliminating the second term.

The overall system for amplitude modulation and demodulation using a com exponential carrier is depicted in Figure 8.7, and the overall system for modulation demodulation using a sinusoidal carrier is depicted in Figure 8.8. In these figures, have indicated the more general case in which, for both the complex exponential and sinusoidal carrier, a carrier phase θ_c is included. The modification of the preceding anal so as to include θ_c is straightforward and is considered in Problem 8.21.

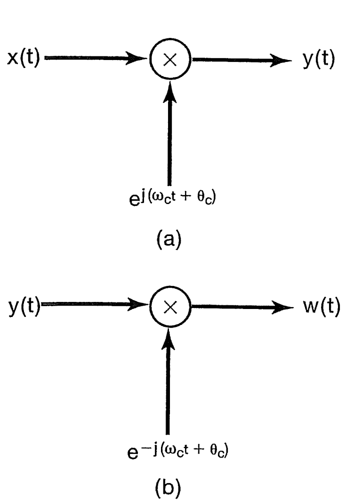


Figure 8.7 System for amplitude modulation and demodulation using a complex exponential carrier: (a) modulation; (b) demodulation.

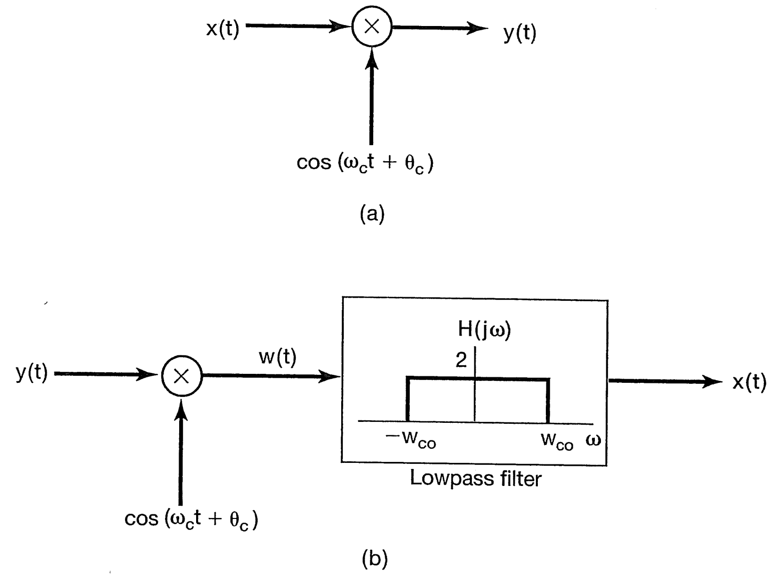


Figure 8.8 Amplitude modulation and demodulation with a sinusoidal carrier: (a) modulation system; (b) demodulation system. The lowpass filter cutoff frequency W_{co} is greater than ω_M and less than $2\omega_c - \omega_M$.

In the systems of Figures 8.7 and 8.8, the demodulating signal is assumed to be synchronized in phase with the modulating signal, and consequently the process is referred to as *synchronous demodulation.* Suppose, however, that the modulator and demodulator are not synchronized in phase. For the case of the complex exponential carrier, with θ_c denoting the phase of the modulating carrier and ϕ_c the phase of the demodulating carrier,

$$y(t) = e^{j(\omega_c t + \theta_c)} x(t), \tag{8.14}$$

$$w(t) = e^{-j(\omega_c t + \phi_c)} y(t), \tag{8.15}$$

and consequently,

$$w(t) = e^{j(\theta_c - \phi_c)} x(t). \tag{8.16}$$

Thus, if $\theta_c \neq \phi_c$, $w(t)$ will have a complex amplitude factor. For the particular case in which $x(t)$ is positive, $x(t) = |w(t)|$, and thus $x(t)$ can be recovered by taking the magnitude of the demodulated signal.

For the sinusoidal carrier, again let θ_c and ϕ_c denote the phases of the modulating and demodulating carriers, respectively, as indicated in Figure 8.9. The input to the lowpass filter is now

$$w(t) = x(t)\cos(\omega_c t + \theta_c)\cos(\omega_c t + \phi_c), \tag{8.17}$$

or, using the trigonometric identity

$$\cos(\omega_c t + \theta_c)\cos(\omega_c t + \phi_c) = \frac{1}{2}\cos(\theta_c - \phi_c) + \frac{1}{2}\cos(2\omega_c t + \theta_c + \phi_c), \tag{8.18}$$

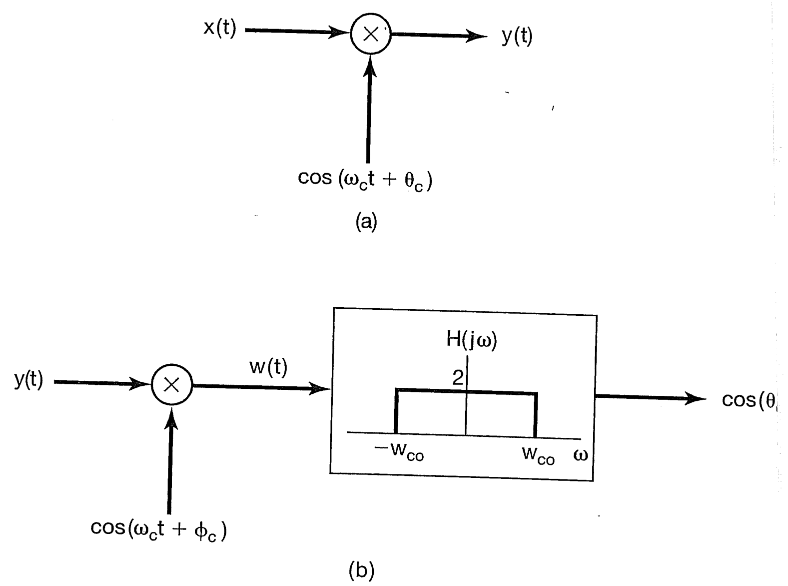


Figure 8.9 Sinusoidal amplitude modulation and demodulation system f which the carrier signals and the modulator and demodulator are not synch nized: (a) modulator; (b) demodulator.

we have

$$w(t) = \frac{1}{2}\cos(\theta_c - \phi_c)x(t) + \frac{1}{2}x(t)\cos(2\omega_c t + \theta_c + \phi_c),$$

and the output of the lowpass filter is then $x(t)$ multiplied by the amplitude fa ϕ_c). If the oscillators in the modulator and demodulator are in phase, $\theta_c =$ output of the lowpass filter is $x(t)$. On the other hand, if these oscillators h difference of $\pi/2$, the output will be zero. In general, for a maximum output si cillators should be in phase. Of even more importance, the phase relation betw oscillators must be maintained over time, so that the amplitude factor $\cos(\theta_c$ not vary. This requires careful synchronization between the modulator and t lator, which is often difficult, particularly when they are geographically sep typical in a communication system. The corresponding effects of, and the ne chronization not only between the phase of the modulator and demodulator, l the frequencies of the carrier signals used in both, are explored in detail in Pr

8.2.2 Asynchronous Demodulation

In many systems that employ sinusoidal amplitude modulation, an alternat ulation procedure referred to as *asynchronous demodulation* is commonly u chronous demodulation avoids the need for synchronization between the mo demodulator. In particular, suppose that $x(t)$ is always positive and that the quency ω_c is much higher than ω_M, the highest frequency in the modula The modulated signal $y(t)$ will then have the general form illustrated in F

In particular, the *envelope* of $y(t)$—that is, a smooth curve connecting the peaks in $y(t)$—would appear to be a reasonable approximation to $x(t)$. Thus, $x(t)$ could be approximately recovered through the use of a system that tracks these peaks to extract the envelope. Such a system is referred to as an *envelope detector.* One example of a simple circuit that acts as an envelope detector is shown in Figure 8.11(a). This circuit is generally followed by a lowpass filter to reduce the variations at the carrier frequency, which are evident in Figure 8.11(b) and which will generally be present in the output of an envelope detector of the type indicated in Figure 8.11(a).

The two basic assumptions required for asynchronous demodulation are that $x(t)$ be positive and that $x(t)$ vary slowly compared to ω_c, so that the envelope is easily tracked. The second condition is satisfied, for example, in audio transmission over a radio-frequency (RF) channel, where the highest frequency present in $x(t)$ is typically 15 to 20 kHz and $\omega_c/2\pi$ is in the range 500 kHz to 2 MHz. The first condition, that $x(t)$ be positive, can be satisfied by simply adding an appropriate constant value to $x(t)$ or, equivalently, by a simple change in the modulator, as shown in Figure 8.12. The output of the envelope detector then approximates $x(t) + A$, from which $x(t)$ is easily obtained.

To use the envelope detector for demodulation, we require that A be sufficiently large so that $x(t) + A$ is positive. Let K denote the maximum amplitude of $x(t)$; that is, $|x(t)| \leq K$. For $x(t)+A$ to be positive, we require that $A > K$. The ratio K/A is commonly referred to as the *modulation index m*. Expressed in percent, it is referred to as the *percent modulation.* An illustration of the output of the modulator of Figure 8.12 for $x(t)$ sinusoidal and for $m = 0.5$ (50% modulation) and $m = 1.0$ (100% modulation), is shown in Figure 8.13.

In Figure 8.14, we show a comparison of the spectra associated with the modulated signal when synchronous demodulation and when asynchronous demodulation are used. We note in particular that the output of the modulator for the asynchronous system in Figure 8.12 has an additional component $A \cos \omega_c t$ that is neither present nor necessary in the synchronous system. This is represented in the spectrum of Figure 8.14(c) by the presence of impulses at $+\omega_c$ and $-\omega_c$. For a fixed maximum amplitude K of the modulating signal, as A is decreased the relative amount of carrier present in the modulated output decreases. Since the carrier component in the output contains no information, its presence

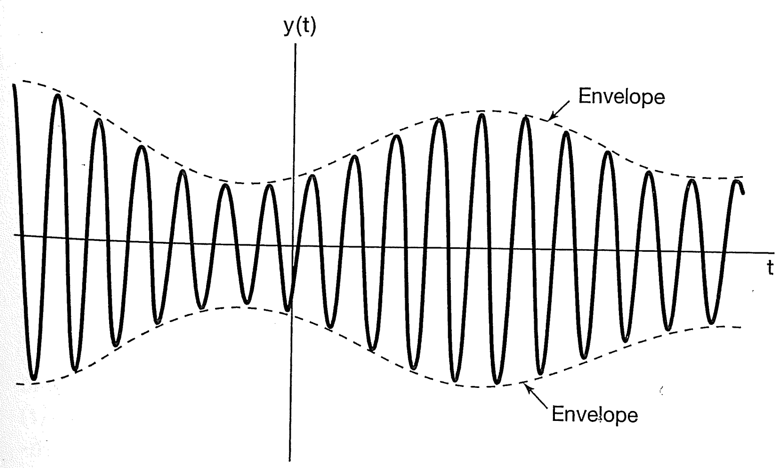


Figure 8.10 Amplitude-modulated signal for which the modulating signal is positive. The dashed curve represents the envelope of the modulated signal.

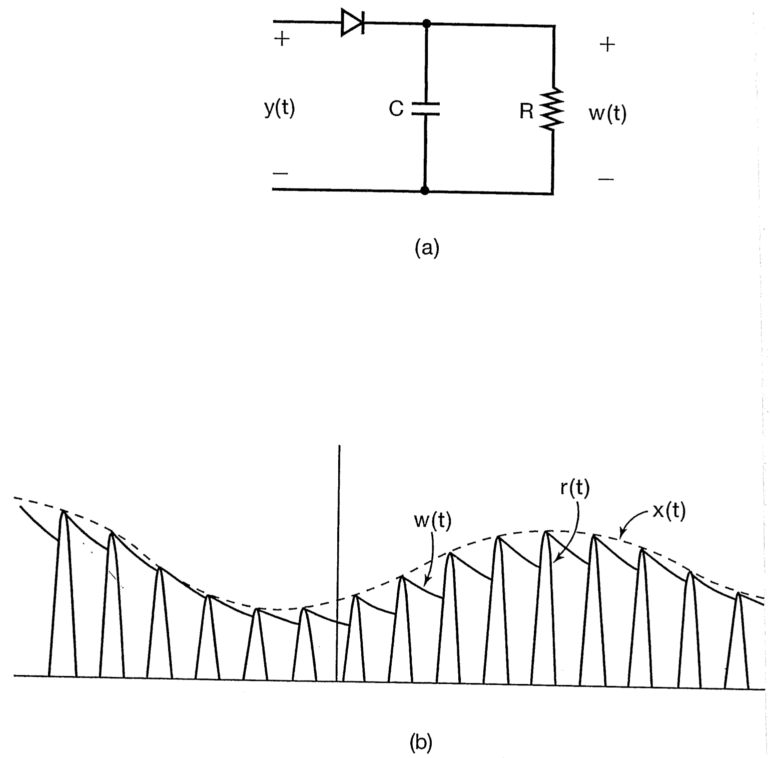


Figure 8.11 Demodulation by envelope detection: (a) circuit for envelop detection using half-wave rectification; (b) waveforms associated with the e velope detector in (a): $r(t)$ is the half-wave rectified signal, $x(t)$ is the true envelope, and $w(t)$ is the envelope obtained from the circuit in (a). The rela tionship between $x(t)$ and $w(t)$ has been exaggerated in (b) for purposes o illustration. In a practical asynchronous demodulation system, $w(t)$ would t cally be a much closer approximation to $x(t)$ than depicted here.

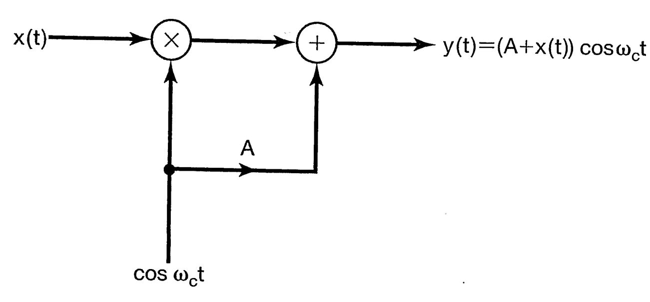


Figure 8.12 Modulat asynchronous modulatior system.

represents an inefficiency—for example, in the amount of power requirec the modulated signal—and thus, in one sense it is desirable to make the rati the modulation index m—as large as possible. On the other hand, the ability envelope detector such as that in Figure 8.11 to follow the envelope and thus improves as the modulation index decreases. Hence, there is a trade-off betw

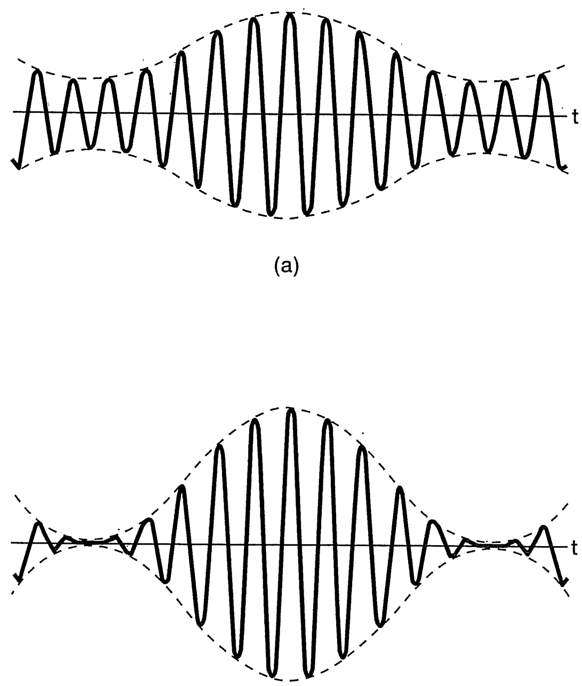


Figure 8.13 Output of the amplitude modulation system of Figure 8.12: (a) modulation index $m = 0.5$; (b) modulation index $m = 1.0$.

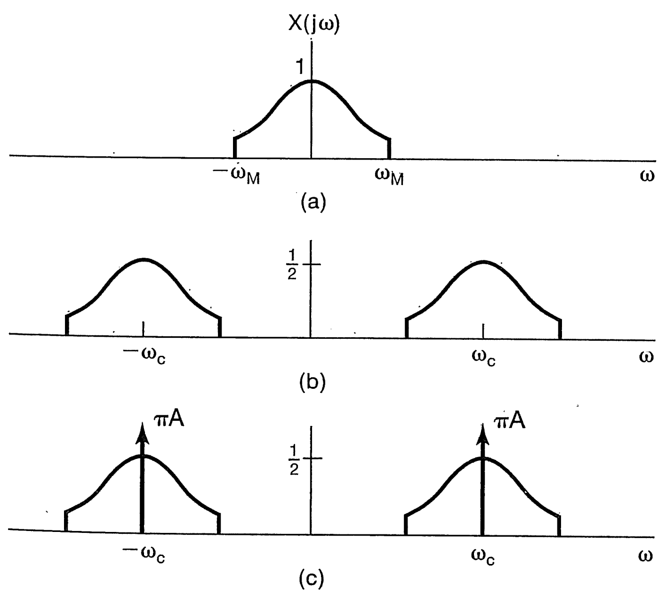


Figure 8.14 Comparison of spectra for synchronous and asynchronous sinusoidal amplitude modulation systems: (a) spectrum of modulating signal; (b) spectrum of $x(t) \cos \omega_c t$ representing modulated signal in a synchronous system; (c) spectrum of $[x(t) + A] \cos \omega_c t$ representing modulated signal in an asynchronous system.

ciency of the system in terms of the power in the output of the modulato of the demodulated signal.

There are a number of advantages and disadvantages to the asynchron demodulation system of Figures 8.11 and 8.12, compared with the synchro Figure 8.8. The synchronous system requires a more sophisticated democ the oscillator in the demodulator must be synchronized with the oscillato lator, both in phase and in frequency. On the other hand, the asynchronou general requires transmitting more power than the synchronous modulator envelope detector to operate properly, the envelope must be positive, or equi must be a carrier component present in the transmitted signal. This is ofte cases such as that associated with public radio broadcasting, in which it mass-produce large numbers of receivers (demodulators) at moderate cost. cost in transmitted power is then offset by the savings in cost for the rec other hand, in situations in which transmitter power requirements are at a in satellite communication, the cost of implementing a more sophisticated receiver is warranted.

8.3 FREQUENCY-DIVISION MULTIPLEXING

Many systems used for transmitting signals provide more bandwidth than i any one signal. For example, a typical microwave link has a total bandwic gigahertz, which is considerably greater than the bandwidth required for on nel. If the individual voice signals, which are overlapping in frequency, h quency content shifted by means of sinusoidal amplitude modulation so tha of the modulated signals no longer overlap, they can be transmitted *simultan* single wideband channel. The resulting concept is referred to as *frequency-di plexing* (FDM). Frequency-division multiplexing using a sinusoidal carrier is Figure 8.15. The individual signals to be transmitted are assumed to be banc

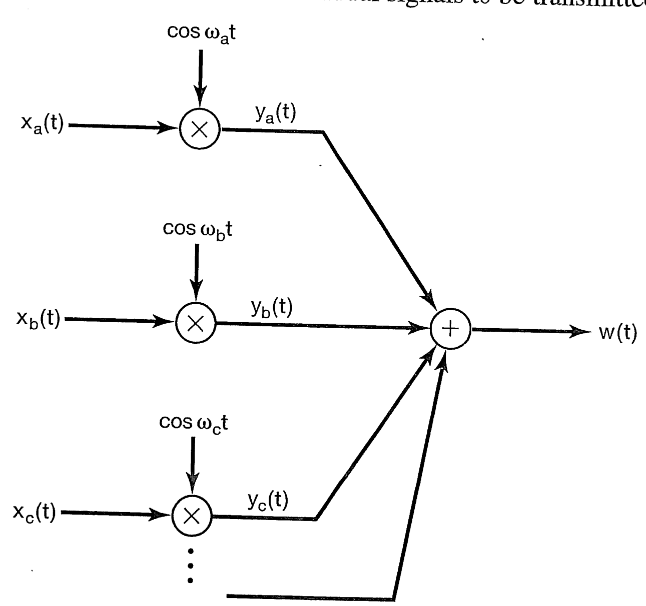


Figure 8.15 Frequency multiplexing using sinusoi modulation.

are modulated with different carrier frequencies. The modulated signals are then summed and transmitted simultaneously over the same communication channel. The spectra of the individual subchannels and the composite multiplexed signal are illustrated in Figure 8.16. Through this multiplexing process, the individual input signals are allocated distinct segments of the frequency band. To recover the individual channels in the demultiplexing process requires two basic steps: bandpass filtering to extract the modulated signal corresponding to a specific channel, followed by demodulation to recover the original signal. This is illustrated in Figure 8.17 to recover channel a, where, for purposes of illustration, synchronous demodulation is assumed.

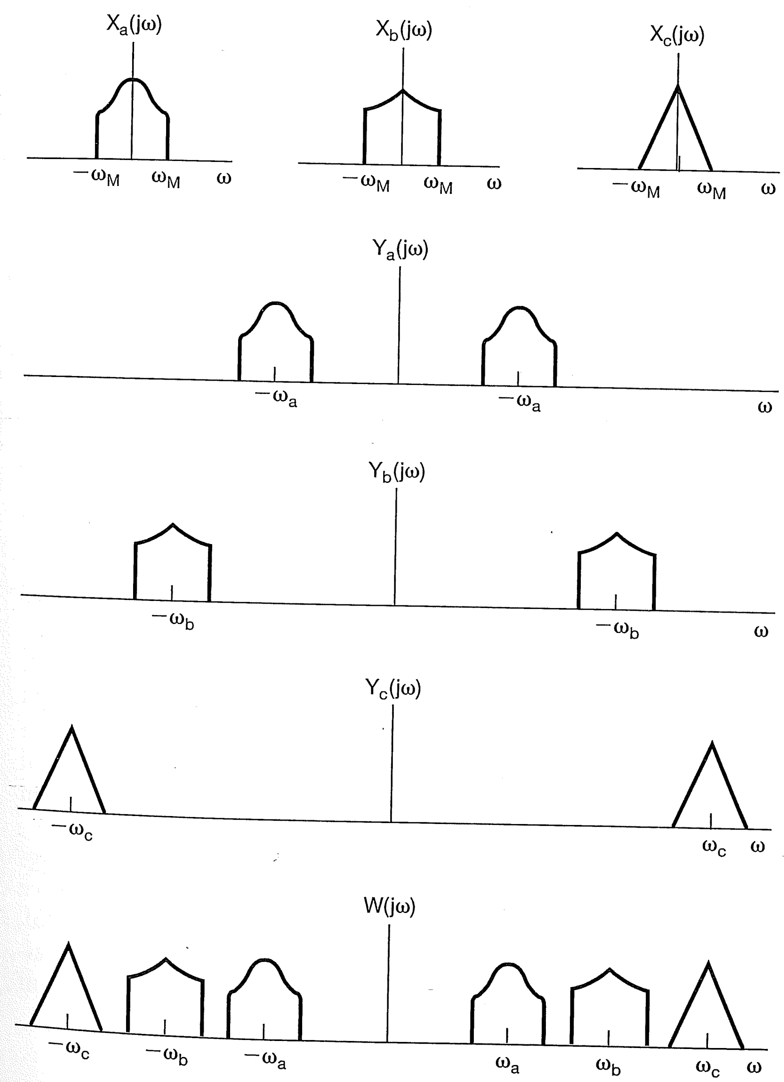


Figure 8.16 Spectra associated with the frequency-division multiplexing system of Figure 8.15.

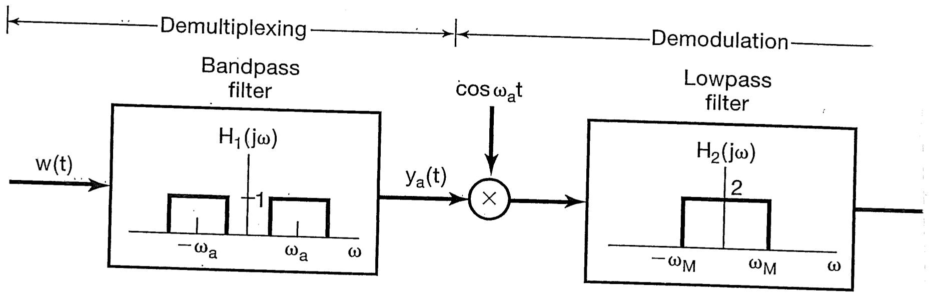


Figure 8.17 Demultiplexing and demodulation for a frequency-division multiplexed signal.

Telephone communication is one important application of frequency-(plexing. Another is the transmission of signals through the atmosphere in In the United States, the use of radio frequencies for transmitting signals (10 kHz to 275 GHz is controlled by the Federal Communications Con different portions of the range are allocated for different purposes. The cation of frequencies is shown in Figure 8.18. As indicated, the freque the neighborhood of 1 MHz is assigned to the AM broadcast band, whe specifically to the use of sinusoidal amplitude modulation. Individual A tions are assigned specific frequencies within the AM band, and thus, r can broadcast simultaneously through this use of frequency-division mu principle, at the receiver, an individual radio station can be selected by ing and demodulating, as illustrated in Figure 8.17. The tuning dial on would then control both the center frequency of the bandpass filter and the the demodulating oscillator. In fact, for public broadcasting, asynchronous and demodulation are used to simplify the receiver and reduce its cost. the demultiplexing in Figure 8.17 requires a sharp cutoff bandpass filter v center frequency. Variable frequency-selective filters are difficult to imp consequently, a fixed filter is implemented instead, and an intermediate st ulation and filtering [referred to in a radio receiver as the *intermediate-fre* stage] is used. The use of modulation to slide the spectrum of the signal bandpass filter replaces the use of a variable bandpass filter in a manner si procedure discussed in Section 4.5.1. This basic procedure is incorporated home AM radio receivers. Some of the more detailed issues involved are c Problem 8.36.

As illustrated in Figure 8.16, in the frequency-division multiplexing sys ure 8.15 the spectrum of each individual signal is replicated at both positive a frequencies, and thus the modulated signal occupies twice the bandwidth of t This represents an inefficient use of bandwidth. In the next section we con ternative form of sinusoidal amplitude modulation, which leads to more effi bandwidth at the cost of a more complicated modulation system.

Frequency range	Designation	Typical uses	Propagation method	Channel features
30–300 Hz	ELF (extremely low frequency)	Macrowave, submarine communication	Megametric waves	Penetration of conducting earth and seawater
0.3–3 kHz	VF (voice frequency)	Data terminals, telephony	Copper wire	
3–30 kHz	VLF (very low frequency)	Navigation, telephone, telegraph, frequency and timing standards	Surface ducting (ground wave)	Low attenuation, little fading, extremely stable phase and frequency, large antennas
30–300 kHz	LF (low frequency)	Industrial (power line) communication, aeronautical and maritime long-range navigation, radio beacons	Mostly surface ducting	Slight fading, high atmospheric pulse
0.3–3 MHz	MF (medium frequency)	Mobile, AM broadcasting, amateur, public safety	Ducting and ionospheric reflection (sky wave)	Increased fading, but reliable
3–30 MHz	HF (high frequency)	Military communication, aeronautical mobile, international fixed, amateur and citizen's band, industrial	Ionospheric reflecting sky wave, 50–400 km layer altitudes	Intermittent and frequency-selective fading, multipath
30–300 MHz	VHF (very high frequency)	FM and TV broadcast, land transportation (taxis, buses, railroad)	Sky wave (ionospheric and tropospheric scatter)	Fading, scattering, and multipath
0.3–3 GHz	UHF (ultra high frequency)	UHF TV, space telemetry, radar, military	Transhorizon tropospheric scatter and line-of-sight relaying	
3–30 GHz	SHF (super high frequency)	Satellite and space communication, common carrier (CC), microwave	Line-of-sight ionosphere penetration	Ionospheric penetration, extraterrestrial noise, high directly
30–300 GHz	EHF (extremely high frequency)	Experimental, government, radio astronomy	Line of sight	Water vapor and oxygen absorption
10^3–10^7 GHz	Infrared, visible light, ultraviolet	Optical communications	Line of sight	

Figure 8.18 Allocation of frequencies in the RF spectrum.

8.4 SINGLE-SIDEBAND SINUSOIDAL AMPLITUDE MODULATION

For the sinusoidal amplitude modulation systems discussed in Section 8.1, the total bandwidth of the original signal $x(t)$ is $2\omega_M$, including both positive and negative frequencies, where ω_M is the highest frequency present in $x(t)$. With the use of a complex exponential carrier, the spectrum is translated to ω_c, and the total width of the frequency band over which there is energy from the signal is still $2\omega_M$, although the modulated signal is now complex. With a sinusoidal carrier, on the other hand, the spectrum of the signal is shifted to $+\omega_c$ *and* $-\omega_c$, and thus, twice the bandwidth is required. This suggests that there is a basic redundancy in the modulated signal with a sinusoidal carrier. Using a technique referred to as *single-sideband modulation,* we can remove the redundancy.

The spectrum of $x(t)$ is illustrated in Figure 8.19(a), in which we have shaded the positive and negative frequency components differently to distinguish them. The spectrum in Figure 8.19(b) results from modulation with a sinusoidal carrier, where v upper and lower sideband for the portion of the spectrum centered at $+\omega_c$ an at $-\omega_c$. Comparing Figures 8.19(a) and (b), we see that $X(j\omega)$ can be rec the upper sidebands at positive and negative frequencies are retained, or a only the lower sidebands at positive and negative frequencies are retained. spectrum if only the upper sidebands are retained is shown in Figure 8. resulting spectrum if only the lower sidebands are retained is shown in F The conversion of $x(t)$ to the form corresponding to Figure 8.19(c) or (d) is *single-sideband modulation* (SSB), in contrast to the *double-sideband mod* of Figure 8.19(b), in which both sidebands are retained.

There are several methods by which the single-sideband signal car One is to apply a sharp cutoff bandpass or highpass filter to the double-side Figure 8.19(b), as illustrated in Figure 8.20, to remove the unwanted sidel is to use a procedure that utilizes phase shifting. Figure 8.21 depicts a sy

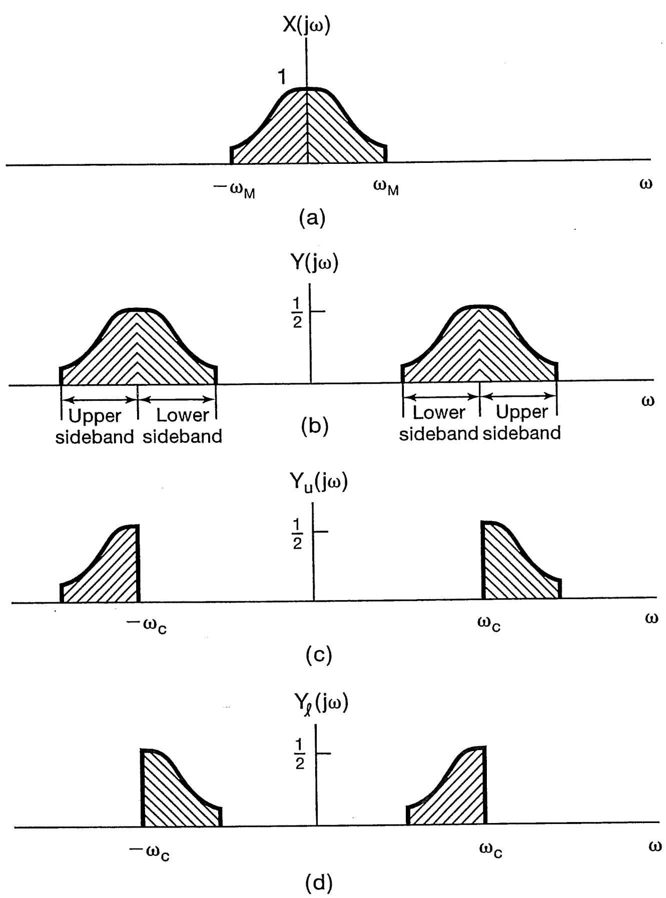


Figure 8.19 Doubl sideband modulation: (modulating signal; (b) ter modulation with a s rier; (c) spectrum with sidebands; (d) spectru lower sidebands.

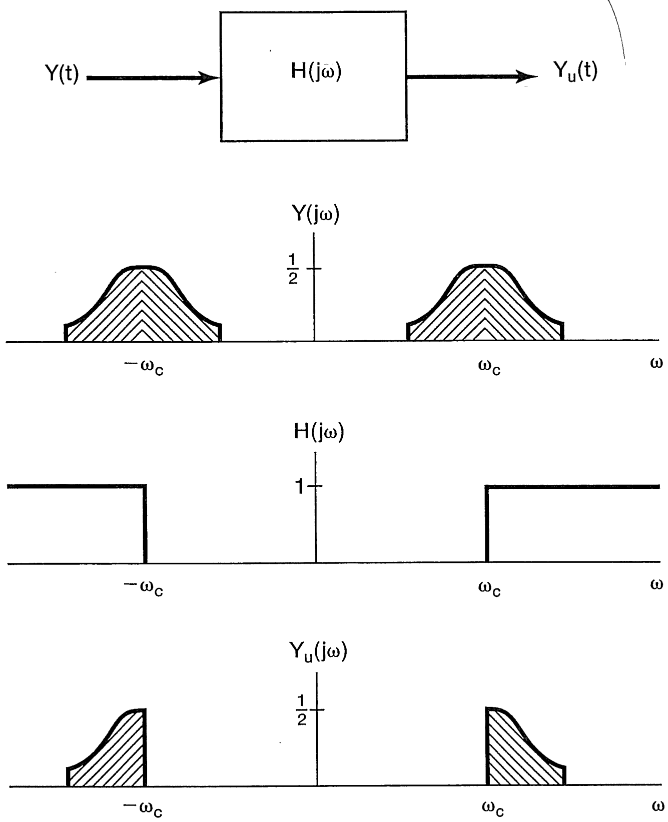


Figure 8.20 System for retaining the upper sidebands using ideal highpass filtering.

to retain the lower sidebands. The system $H(j\omega)$ in the figure is referred to as a "90° phase-shift network," for which the frequency response is of the form

$$H(j\omega) = \begin{cases} -j, & \omega > 0 \\ j, & \omega < 0 \end{cases}. \tag{8.20}$$

The spectra of $x(t)$, $y_1(t) = x(t)\cos\omega_c t$, $y_2(t) = x_p(t)\sin\omega_c t$, and $y(t)$ are illustrated in Figure 8.22. As is examined in Problem 8.28, to retain the upper sidebands instead of the lower sidebands, the phase characteristic of $H(j\omega)$ is reversed so that

$$H(j\omega) = \begin{cases} j, & \omega > 0 \\ -j, & \omega < 0 \end{cases}. \tag{8.21}$$

As is explored in Problem 8.29, synchronous demodulation of single-sideband systems can be accomplished in a manner identical to synchronous demodulation of double-sideband systems. The price paid for the increased efficiency of single-sideband systems is added complexity in the modulator.

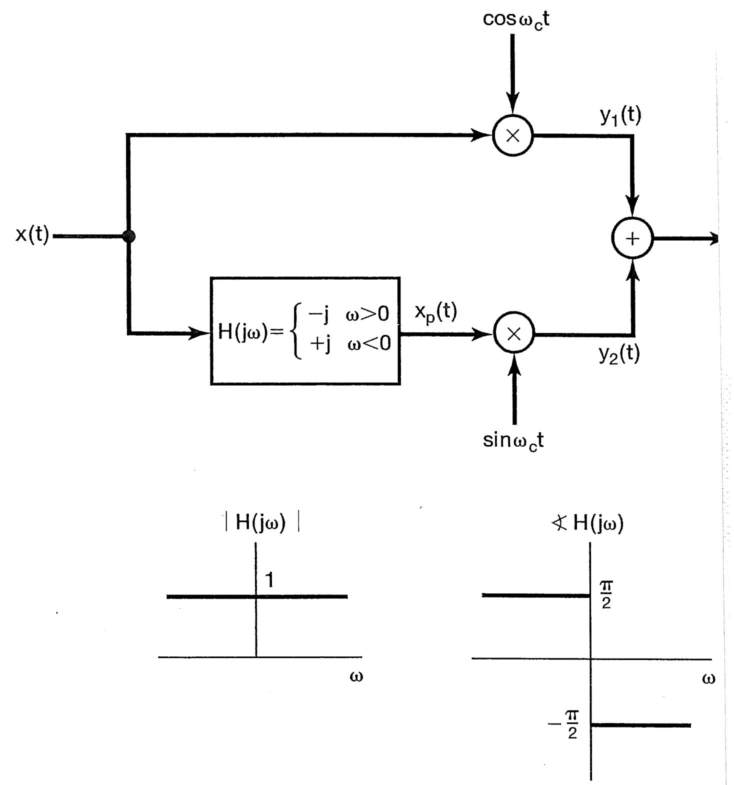


Figure 8.21 System for single-sideband amplitude modulation, using
phase-shift network, in which only the lower sidebands are retained.

In summary, in Sections 8.1 through 8.4 we have seen a number c
complex exponential and sinusoidal amplitude modulation. With asynchr
ulation, discussed in Section 8.2.2, a constant must be added to the moc
so that it is positive. This results in the presence of the carrier signal as a
the modulated output, requiring more power for transmission, but resultir
demodulator than is required in a synchronous system. Alternatively, onl
lower sidebands in the modulated output may be retained, which makes mo
of bandwidth and transmitter power, but requires a more sophisticated mo
soidal amplitude modulation with both sidebands and the presence of a carr
abbreviated as AM-DSB/WC (amplitude modulation, double sideband/wit
when the carrier is suppressed or absent, as AM-DSB/SC (amplitude modu
sideband/suppressed carrier). The corresponding single-sideband systems a
AM-SSB/WC and AM-SSB/SC.

Sections 8.1 through 8.4 are intended to provide an introduction to ma
concepts associated with sinusoidal amplitude modulation. There are man
details and implementation, and the reader is referred to the bibliography fo
of the numerous excellent books that explore this topic further.

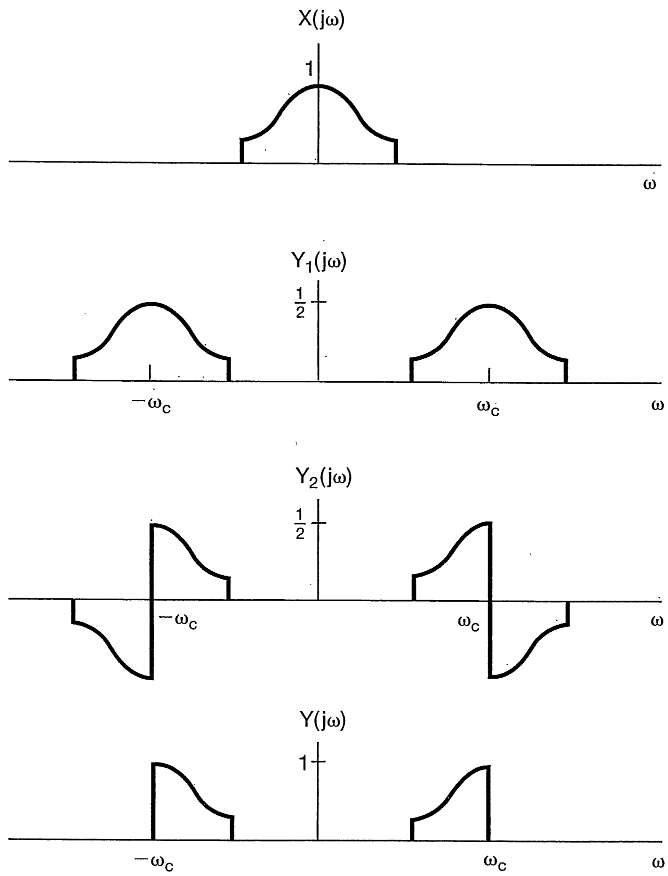


Figure 8.22 Spectra associated with the single-sideband system of Figure 8.21.

8.5 AMPLITUDE MODULATION WITH A PULSE-TRAIN CARRIER

8.5.1 Modulation of a Pulse-Train Carrier

In previous sections, we examined amplitude modulation with a sinusoidal carrier. Another important class of amplitude modulation techniques corresponds to the use of a carrier signal that is a pulse train, as illustrated in Figure 8.23; amplitude modulation of this type effectively corresponds to transmitting equally spaced time slices of $x(t)$. In general, we would not expect that an arbitrary signal could be recovered from such a set of time slices. However, our examination of the concept of sampling in Chapter 7 suggests that this should be possible if $x(t)$ is band limited and the pulse repetition frequency is high enough.

From Figure 8.23,

$$y(t) = x(t)c(t); \tag{8.22}$$

i.e., the modulated signal $y(t)$ is the product of $x(t)$ and the carrier $c(t)$. With $Y(j\omega)$, $X(j\omega)$, and $C(j\omega)$ representing the Fourier transforms of each of these signals, it follows from