



Picker Engineering Program

# Communication Systems, Modulation, and Multiplexing

EGR 320: Signals & Systems  
Lecture 23: April 1, 2011

## ***Quote from A. Bruce Carlson. Communication Systems (1986)***

“Attention, the Universe! By kingdoms, right wheel!” This prophetic phrase is the first telegraph message on record. It was sent over a 16-km line by Samuel F.B. Morse in 1838. Thus was born a new era, the era of electrical communication.

Over the next century and a half, communication engineering had advanced to the point that earthbound TV viewers could watch astronauts working in space. Telephone, radio, and television have become integral parts of modern life. Computers talk to computers via intercontinental networks. Certainly great strides have been made since the days of Morse. Equally certain, coming decades will bring many new achievements of communication engineering.

[http://people.deas.harvard.edu/~ionesc/cscie129/lectures/lecture8/graphic%20telegraphs/graphic\\_tel.html](http://people.deas.harvard.edu/~ionesc/cscie129/lectures/lecture8/graphic%20telegraphs/graphic_tel.html)

From "From Semaphore to Satellite" a volume published on the occasion of the centenary of the International Telecommunication Union in 1965.

"... two great pioneers are Samuel Finley Breeze Morse (1791-1872) and Alfred Vail, his partner. Morse was an American painter of historic scenes of some distinction and in 1835 he was appointed Professor of the Literature of Arts and Design at New York University in New York City). It was during a return voyage from Europe in 1832, where he had gone to study art, that he became interested in electromagnets; their properties were demonstrated to him by a fellow-passenger during his voyage. To Morse, this was a new and ingenious device and his mind became engrossed with the idea of using an electromagnet as the operative element in an electric telegraph."

"The essence of Morse's idea was to use the passage of an electric current through an electromagnet to deflect a pen or pencil in such a way that they could mark a strip of paper passing underneath them. The permanent recording of telegraphic messages onto paper was certainly a distinct new contribution and in 1835 his appointment to the University allowed him sufficient time to construct during that year his first, though still crude, telegraph. Much remained to be done before it could become of real practical use and only when in 1837 the mechanical abilities of Alfred Vail were joined with persistent advocacy of Samuel Morse was the way opened to success."

A. Bruce Carlson, *Communication Systems* (1986)

Table 1.3-1 A chronology of electrical communication

Year	Event
1800-1837	<i>Preliminary developments</i> Volta discovers the primary battery; the mathematical treatises by Fourier, Cauchy, and Laplace; experiments on electricity and magnetism by Oersted, Ampere, Faraday, and Henry; Ohm's law (1826); early telegraph systems by Gauss, Weber, and Wheatstone.
1838-1866	<i>Telegraphy</i> Morse perfects his system; Steinheil finds that the earth can be used for a current path; commercial service initiated (1844); multiplexing techniques devised; William Thomson (Lord Kelvin) calculates the pulse response of a telegraph line (1855); transatlantic cables installed by Cyrus Field and associates.
1845	Kirchhoff's circuit laws enunciated.
1864	Maxwell's equations predict electromagnetic radiation.
1876-1899	<i>Telephony</i> Acoustic transducer perfected by Alexander Graham Bell, after earlier attempts by Reis; first telephone exchange, in New Haven, with eight lines (1878); Edison's carbon-button transducer; cable circuits introduced; Strowger devises automatic step-by-step switching (1887); the theory of cable loading by Heaviside, Pupin, and Campbell.
1887-1907	<i>Wireless telegraphy</i> Heinrich Hertz verifies Maxwell's theory; demonstrations by Marconi and Popov; Marconi patents a complete wireless telegraph system (1897); the theory of tuning circuits developed by Sir Oliver Lodge; commercial service begins, including ship-to-shore and transatlantic systems.
1892-1899	Oliver Heaviside's publications on operational calculus, circuits, and electromagnetics.
1904-1920	<i>Communication electronics</i> Lee De Forest invents the Audion (triode) based on Fleming's diode; basic filter types devised by G. A. Campbell and others; experiments with AM radio broadcasting; transcontinental telephone line with electronic repeaters completed by the Bell System (1915); multiplexed carrier telephony introduced; E. H. Armstrong perfects the superheterodyne radio receiver (1918); first commercial broadcasting station, KDKA, Pittsburgh.
1920-1928	<i>Transmission theory</i> Landmark papers on the theory of signal transmission and noise by J. R. Carson, H. Nyquist, J. B. Johnson, and R. V. L. Hartley.
1923-1938	<i>Television</i> Mechanical image-formation system demonstrated by Baird and Jenkins; theoretical analysis of bandwidth requirements; Farnsworth and Zworykin propose electronic systems; vacuum cathode-ray tubes perfected by DuMont and others; field tests and experimental broadcasting begin.

1927	Federal Communications Commission established.
1931	Teletypewriter service initiated.
1934	H. S. Black develops the negative-feedback amplifier.
1936	Armstrong's paper states the case for FM radio.
1937	Alec Reeves conceives pulse code modulation.
1938–1945	<i>World War II</i> Radar and microwave systems developed; FM used extensively for military communications; improved electronics, hardware, and theory in all areas.
1944–1947	<i>Statistical communication theory</i> Rice develops a mathematical representation of noise; Weiner, Kolmogoroff, and Kotel'nikov apply statistical methods to signal detection.
1948–1950	<i>Information theory and coding</i> C. E. Shannon publishes the founding papers of information theory; Hamming and Golay devise error-correcting codes.
1948–1951	Transistor devices invented by Bardeen, Brattain, and Shockley.
1950	Time-division multiplexing applied to telephony.
1953	Color TV standards established in the United States.
1955	J. R. Pierce proposes satellite communication systems.
1956	First transoceanic telephone cable (36 voice channels).
1958	Long-distance data transmission system developed for military purposes.
1960	Maiman demonstrates the first laser.
1961	Integrated circuits go into commercial production.
1962	Satellite communication begins with Telstar I.
1962–1966	<i>High-speed digital communication</i> Data transmission service offered commercially; wideband channels designed for digital signaling; pulse code modulation proves feasible for voice and TV transmission; major breakthroughs in the theory and implementation of digital transmission, including error-control coding methods by Viterbi and others, and the development of adaptive equalization by Lucky and coworkers.
1963	Solid-state microwave oscillators perfected by Gunn.
1964	Fully electronic telephone switching system (No. 1 ESS) goes into service.
1965	Mariner IV transmits pictures from Mars to earth.
1966–1975	<i>Wideband communication systems</i> Cable TV systems; commercial satellite relay service becomes available; optical links using lasers and fiber optics; ARPANET created (1969) followed by other intercontinental computer networks.
1975–1985	<i>State of the art</i> Integrated-circuit communication modules; high-frequency power MOS devices; digital signal processing with microprocessors; filter circuits using switched capacitors and surface acoustic waves; rate distortion theory and predictive coding applied to data compression.

## A Generic Communication System

A. Bruce Carlson, *Communication Systems* (1986)

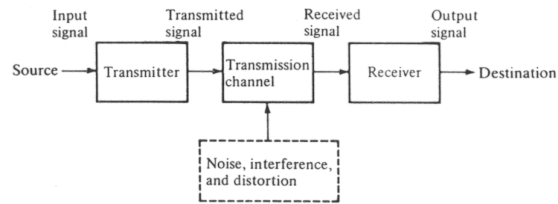


Figure 1.1-2 Elements of a communication system.

- **Transmitter:** Processes the input signal to produce a transmitted signal suited to the characteristics of the transmission channel. Signal processing for transmission almost always involves modulation and may also include coding.
- **Transmission Channel:** Electrical medium that bridges the distance from source to destination. It may be a pair of wires, a coaxial cable, or a radio wave or laser beam.
- **Receiver:** Operates on the output signal from the channel. Receiver operations include demodulation and decoding to reverse the signal-processing performed at the transmitter.

## What are the relevant quantities for AM radio?

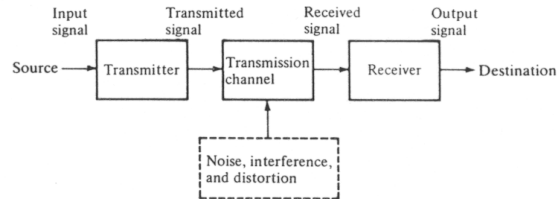


Figure 1.1-2 Elements of a communication system.

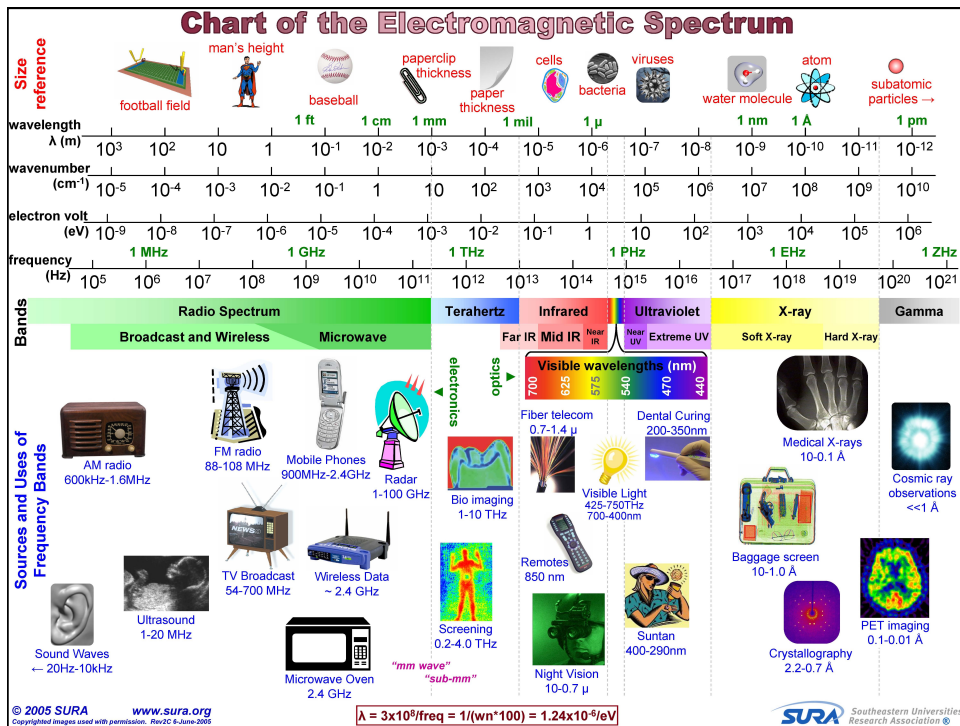
## Some Important Terms

- Modulation
- Modulating signal
- Carrier signal
- Demodulation

•**Purpose:** generate a modulated signal suited to the characteristics of the transmission channel

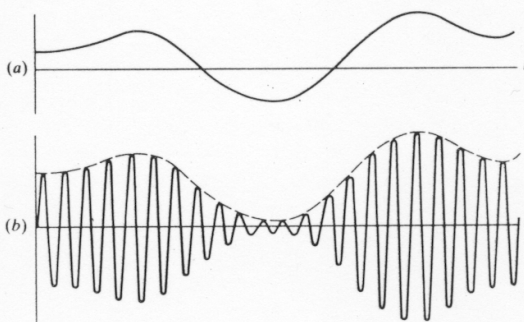
•**Relevant Definitions:** “Modulation involves two waveforms: a modulating signal that represents the message, and a carrier wave that suits the particular application. A modulator systematically alters the carrier wave in correspondence with the variations of the modulating signal. The resulting modulated wave thereby “carries” the message information. We generally require that modulation be a reversible operation, so the message can be retrieved by the complementary process of demodulation.”

*A. Bruce Carlson. Communication Systems (1986)*



## Amplitude Modulation (AM)

Figure from Carlson, *Communication Systems* (1986)



Message signal:

$$m(t)$$

Carrier Wave:

$$c(t) = A_c \cos(\omega_c t)$$

## 2 Cases of Amplitude Modulation and Demodulation:

- Double Sideband - Suppressed Carrier Modulation (Amplitude modulation with a sinusoidal carrier)

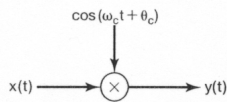
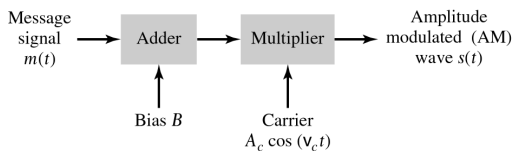


Figure 8.3 Amplitude modulation with a sinusoidal carrier.

- Full Amplitude Modulation

$$s(t) = A_c [1 + k_a m(t)] \cos(\omega_c t)$$

$$s(t) = k_a [m(t) + B] A_c \cos(\omega_c t)$$



## Generation of an AM Wave (DSB - suppressed Carrier): A Simplified Frequency Domain View

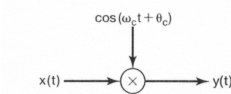
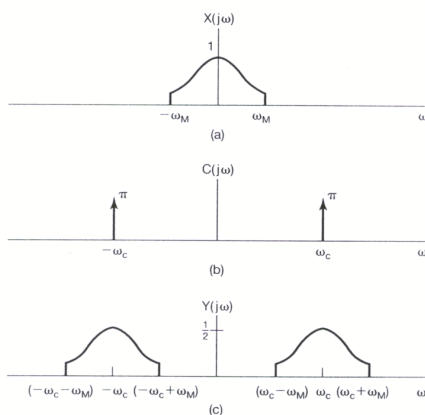


Figure 8.3 Amplitude modulation with a sinusoidal carrier.

Figure 8.4 Effect in the frequency domain of amplitude modulation with a sinusoidal carrier: (a) spectrum of modulating signal  $x(t)$ ; (b) spectrum of carrier  $c(t) = \cos \omega_c t$ ; (c) spectrum of amplitude-modulated signal.

Note:  $x(t)$  is recoverable from  $y(t)$  only when  $\omega_c > \omega_M$ .

# Demodulation:

Figures from Oppenheim and Willsky. Signals & Systems (1997)

From the modulation steps:

$$y(t) = x(t) \cos(\omega_c t).$$

Modulate  $y(t)$  with the same sinusoidal carrier:

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

Using the trigometric identity

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

we solve for  $w(t)$ :

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

How can we recover  $x(t)$  from  $w(t)$ ?

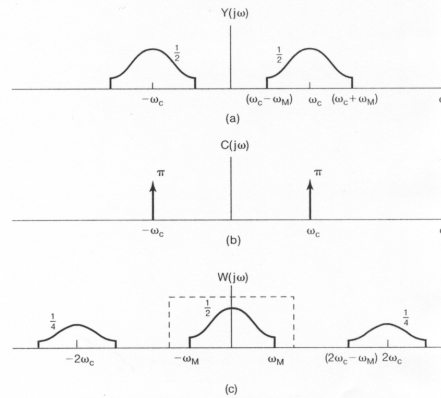


Figure 8.6 Demodulation of an amplitude-modulated signal with a sinusoidal carrier: (a) spectrum of modulated signal; (b) spectrum of carrier signal; (c) spectrum of modulated signal multiplied by the carrier. The dashed line indicates the frequency response of a lowpass filter used to extract the demodulated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

# Amplitude Modulation and Demodulation:

Figures from Oppenheim and Willsky. Signals & Systems (1997)

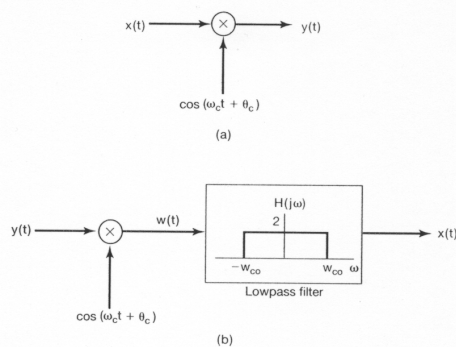


Figure 8.8 Amplitude modulation and demodulation with a sinusoidal carrier: (a) modulation system; (b) demodulation system. The lowpass filter cut-off frequency  $\omega_{co}$  is greater than  $\omega_M$  and less than  $2\omega_c - \omega_M$ .

This process has assumed that the demodulating and modulating signals are synchronized in phase.

- Why? What does this mean?
- What are some of the advantages/disadvantages of synchronous demodulation?

## 2 Cases of Amplitude Modulation and Demodulation:

- Double Sideband - Suppressed Carrier Modulation

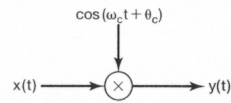


Figure 8.3 Amplitude modulation with a sinusoidal carrier.

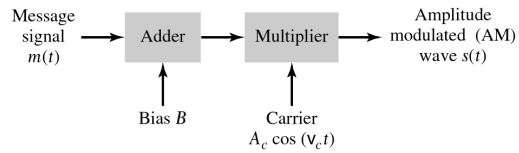
Requires synchronous demodulation

$$s(t) = y(t) = x(t) \cos(\omega_c t + \theta_c)$$

- Full Amplitude Modulation

$$s(t) = A_c [1 + k_a m(t)] \cos(\omega_c t)$$

$$s(t) = k_a [m(t) + B] A_c \cos(\omega_c t)$$



## Asynchronous Demodulation (AM):

Figures from Oppenheim and Willsky. Signals & Systems (1997)

Asynchronous demodulation avoids the need for synchronization between the modulator and demodulator. With asynchronous demodulation:

- $x(t)$  must always be positive  
(e.g,  $x(t) = A[1 + k_m(t)] \cos \omega_c t$  with  $A > k$ )
- $x(t)$  must vary slowly compared to  $\omega_c$   
(e.g,  $\omega_M \ll \omega_c$ ).

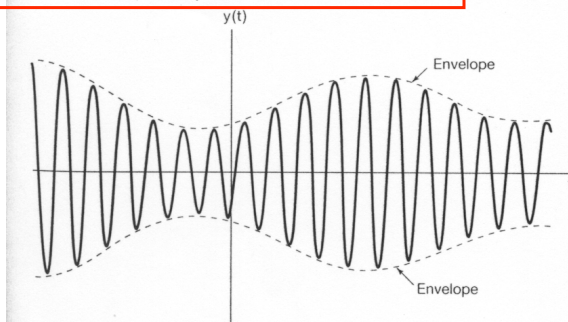
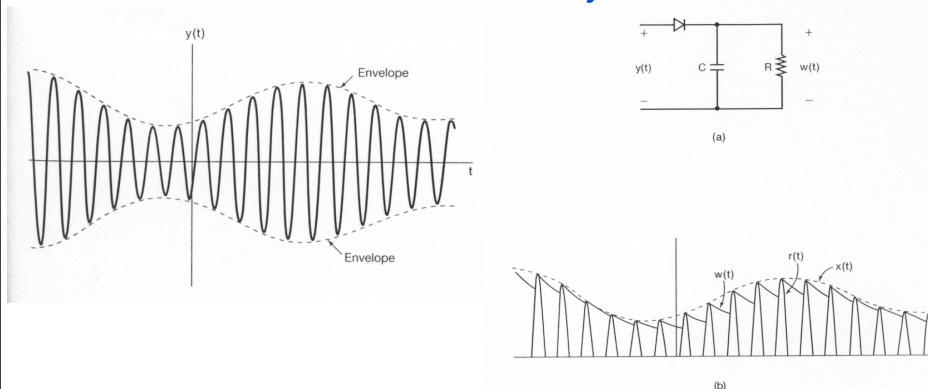


Figure 8.10 Amplitude-modulated signal for which the modulating signal is positive. The dashed curve represents the envelope of the modulated signal.

# Asynchronous Demodulation (AM):

Figures from Oppenheim and Willsky. Signals & Systems (1997)

## A circuit for asynchronous demodulation



**Figure 8.11** Demodulation by envelope detection: (a) circuit for envelope detection using half-wave rectification; (b) waveforms associated with the envelope 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 relationship between  $x(t)$  and  $w(t)$  has been exaggerated in (b) for purposes of illustration. In a practical asynchronous demodulation system,  $w(t)$  would typically be a much closer approximation to  $x(t)$  than depicted here.

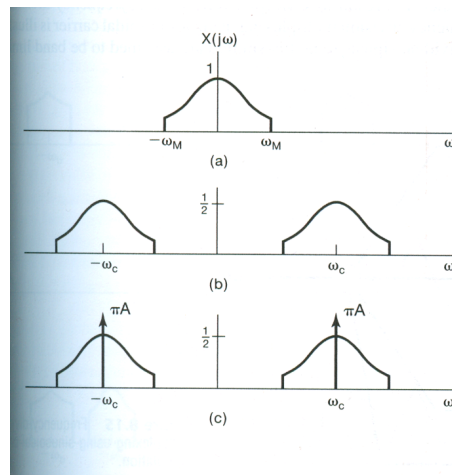
## Generation of Full AM Wave: A Frequency Domain View

$$\begin{aligned}
 s(t) &\xleftrightarrow{FT} S(j\omega) \\
 m(t) &\xleftrightarrow{FT} M(j\omega) \\
 s(t) &= A_c[1 + k_a m(t)] \cos(\omega_c t)
 \end{aligned}$$

$$\begin{aligned}
 S(j\omega) &\xleftrightarrow{FT} \pi A_c[\delta(\omega - \omega_c) + \delta(\omega + \omega_c)] + \\
 &\quad \frac{1}{2} k_a A_c [M(j\omega - j\omega_c) + M(j\omega + j\omega_c)]
 \end{aligned}$$

## Generation of an AM Wave: A Frequency Domain View

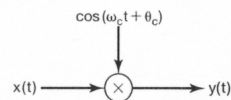
$$S(j\omega) \xleftrightarrow{FT} \pi A_c [\delta(\omega - \omega_c) + \delta(\omega + \omega_c)] + \frac{1}{2} k_a A_c [M(j\omega - j\omega_c) + M(j\omega + j\omega_c)]$$



**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.

## 2 Cases of Amplitude Modulation and Demodulation: Which do you think is used for public radio?

- Double Sideband - Suppressed Carrier Modulation



**Figure 8.3** Amplitude modulation with a sinusoidal carrier.

$$s(t) = y(t) = x(t) \cos(\omega_c t + \theta_c)$$

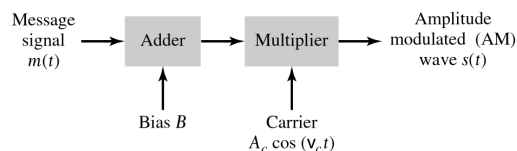
Requires synchronous demodulation

- Full Amplitude Modulation

Carrier wave transmission wastes power

$$s(t) = A_c [1 + k_a m(t)] \cos(\omega_c t)$$

$$s(t) = k_a [m(t) + B] A_c \cos(\omega_c t)$$



# Multiplexing: Sending signals simultaneously over the same channel

## Frequency-division Multiplexing (FDM)

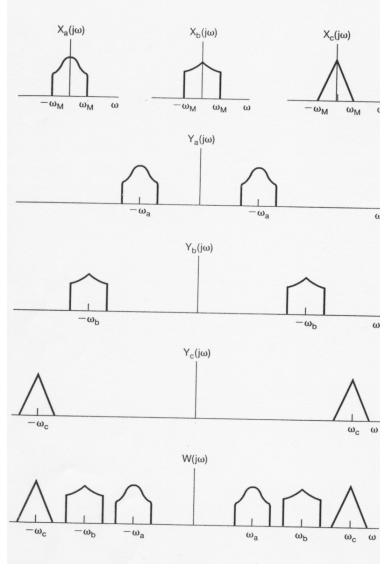


Figure 8.16 Spectra associated with the frequency-division multiplexing system of Figure 8.15.

# How does the circuit for asynchronous demodulation work?

Figure from Oppenheim and Willsky. Signals & Systems (1997)

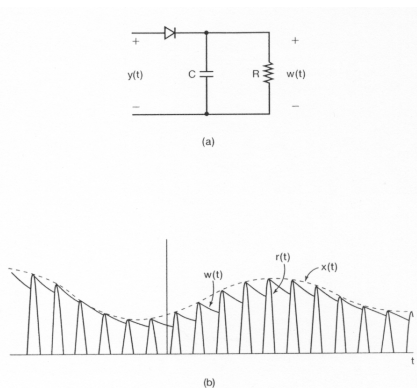


Figure 8.11 Demodulation by envelope detection: (a) circuit for envelope detection using half-wave rectification; (b) waveforms associated with the envelope detector in (a):  $r(t)$  is the half-wave rectified signal,  $x(t)$  is the true envelope, and  $w(t)$  is the envelope obtained from the circuit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

