Introduction

- **Amplitude Modulation System**
- **Angle Modulation System**
  - ➢ **Frequency Modulation**
  - ➢ **Phase Modulation**
- **Digital Communication**
- **Elements of Information Theory**
- **Advanced Communication Techniques**

Tools for communication

- Fourier Series
- Fourier Transform

Fourier Series

- Every composite periodic signal can be represented with a series of sine and cosine functions.

- The functions are integral harmonics of the fundamental frequency "f" of the composite signal.

- Using the series we can decompose any periodic signal into its harmonics.

periodic signal

- Periodic signals repeat with some *period* T, while aperiodic, or non periodic, signals do not. We can define a periodic function through the following mathematical expression, where t can be any number and T is a positive constant:

- f(t) =f(T + t) (1) …………………..(1)

- The *fundamental period* of our function, f(t) , is the smallest value of T that the still allows equation-1 to be true.

A periodic signal with period T_0
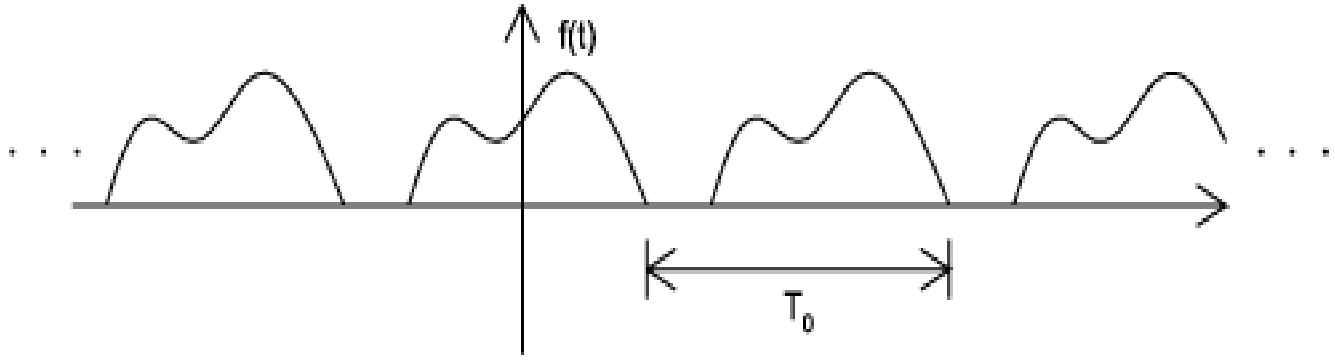

An aperiodic signal
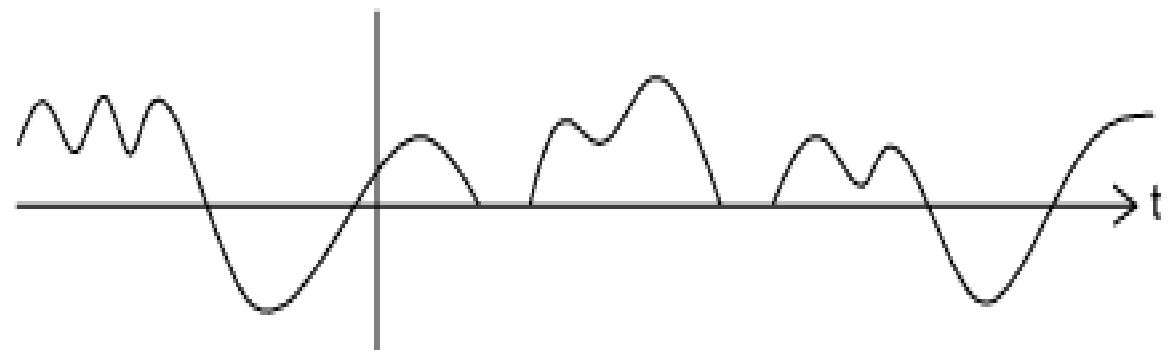
Fourier Transform

- Fourier Transform is a tool that changes a time domain signal to a frequency domain signal and vice versa.

Why frequency domain analysis?

➢ Allows simple algebra rather than time-domain differential equations to be used

➢ Transfer functions can be applied to transmitter, communication channel and receiver

➢ Channel bandwidth, noise and power are easier to evaluate

➢ Easy to pick out frequencies.

Basic analog communications system
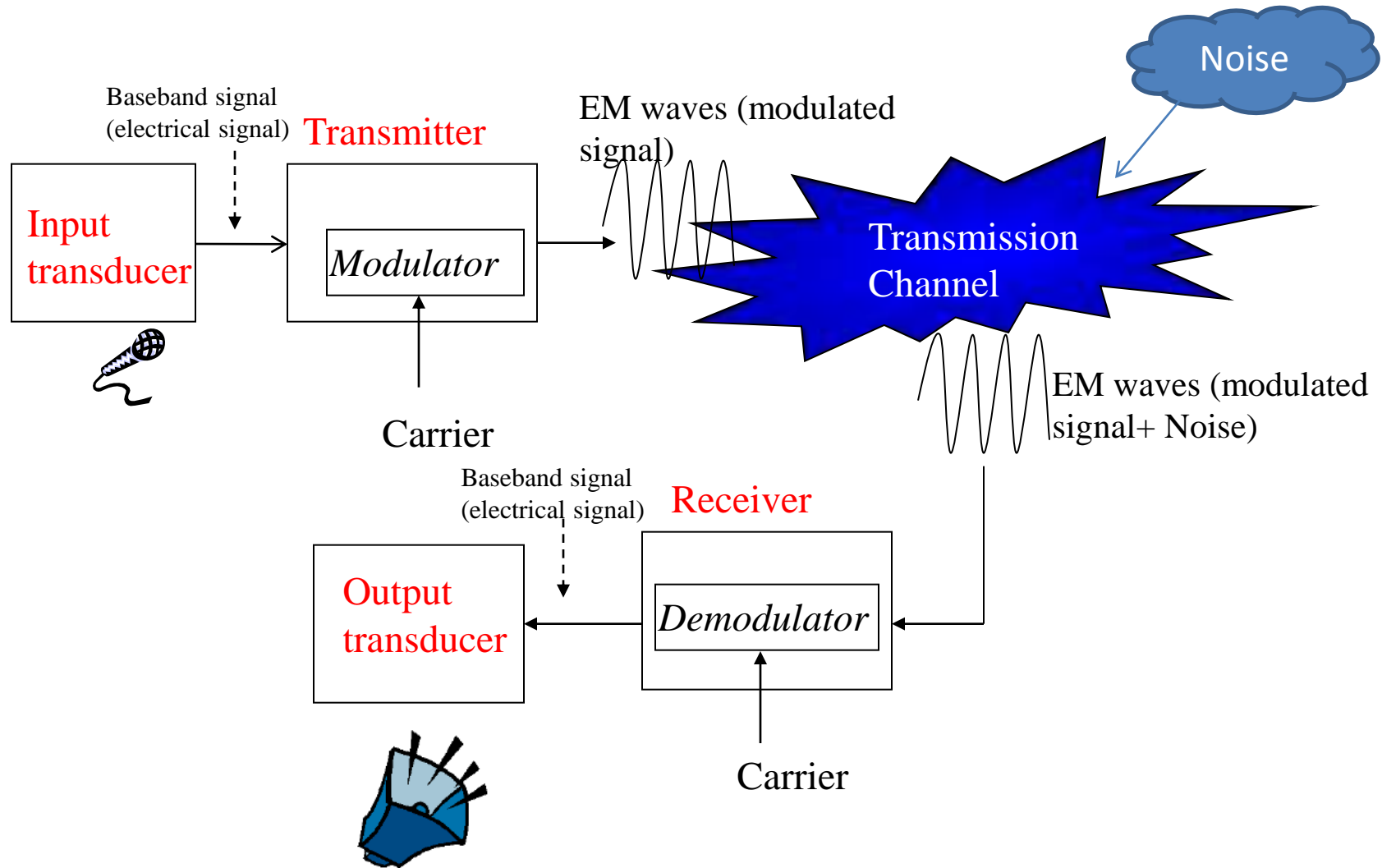
Introduction

- Definition of COMMUNICATION?
- Why do we need to communicate?
- Definition of COMMUNICATION SYSTEM (Electronic Communication System)?
- Why do we need to communicate electronically?
- How to communicate?
- Interference in communications? How to overcome?

Introduction to Communication Systems

❑Communication – Basic process of exchanging information from one location (source) to destination (receiving end).

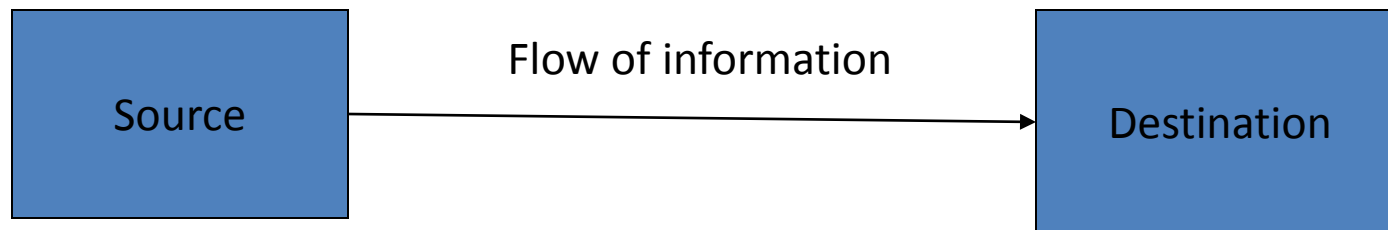❑Refers – process of sending, receiving and processing of information/signal/input from one point to another point.

Figure 1 : A simple communication system

❏Electronic Communication System – defined as the whole mechanism of sending and receiving as well as processing of information electronically from source to destination.

❏Example – Radiotelephony, broadcasting, point-to-point, mobile communications, computer communications, radar and satellite systems.

Objectives

❑Communication System – to produce an accurate replica of the transmitted information that is to transfer information between two or more points (destinations) through a communication channel, with minimum error.

❑Besides – interactive purposes, business and social

NEED FOR COMMUNICATION

❖ Interaction purposes – enables people to interact in a timely fashion on a global level in social, political, economic and scientific areas, through telephones, electronic-mail and video conference.

❖ Transfer Information – Tx in the form of audio, video, texts, computer data and picture through facsimile, telegraph or telex and internet.

❖ Broadcasting – Broadcast information to masses, through radio, television or teletext.

Terms Related To Communications

- Message – physical manifestation produced by the information source and then converted to electrical signal before transmission by the transducer in the transmitter.

- Transducer – Device that converts one form of energy into another form.

- Input Transducer – placed at the transmitter which convert an input message into an electrical signal.

- Example – Microphone which converts sound energy to electrical energy.

| Message | → | Input Transducer | → | Electrical Signal |
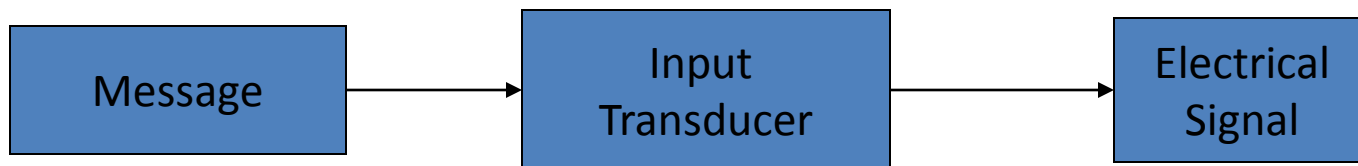
- Output Transducer – placed at the receiver which converts the electrical signal into the original message.

- Example – Loudspeaker which converts electrical energy into sound energy.

| Electrical Signal | → | Output Transducer | → | Message |
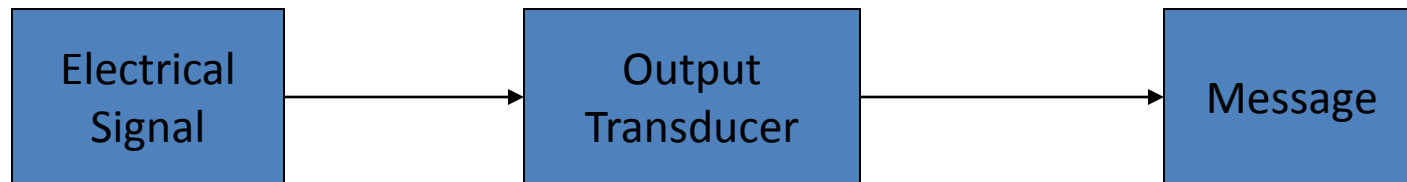
- Signal – electrical voltage or current which varies with time and is used to carry message or information from one point to another.

- Information – defined as what is being conveyed by the telecommunication environment or as knowledge or facts. It can be in analogue form (voice, video, music) or digital form (binary-coded numbers, graphics symbols or database information).

Basic Requirements of Communication Systems.

❑ Rate of Information Transfer – defined as the amount of info that must be communicated from source to destination in a certain period of time. It determines the physical form and the techniques used to transmit and receive information.

❑ The rate of information transfer must be reasonable and acceptable rate for each communication system.

❑Purity of Received Signal – the received signal must be the same as the transmitted signal

❑Simplicity of the system – must be convenience in order to be effective and efficient/easy to use.

❑Reliability – User must be able to depend on a communication system. It must work when needed and transmit/receive information without errors or with an acceptable errors.

Elements of a Communication System

❑The basic elements are : Source, Transmitter, Channel, Receiver and Destination.

```
┌──────────────┐   ┌──────────────┐   ┌──────────────┐   ┌──────────────┐   ┌──────────────┐
│ Information   │──▶│ Transmitter  │──▶│  Channel/    │──▶│  Receiver    │──▶│ Destination  │
│ Source       │   │              │   │ Transmission │   │              │   │              │
│              │   │              │   │ Medium       │   │              │   │              │
└──────────────┘   └──────────────┘   └──────────────┘   └──────────────┘   └──────────────┘
                                              ▲
                                       ┌──────────────┐
                                       │              │
                                       │    Noise     │
                                       │              │
                                       └──────────────┘
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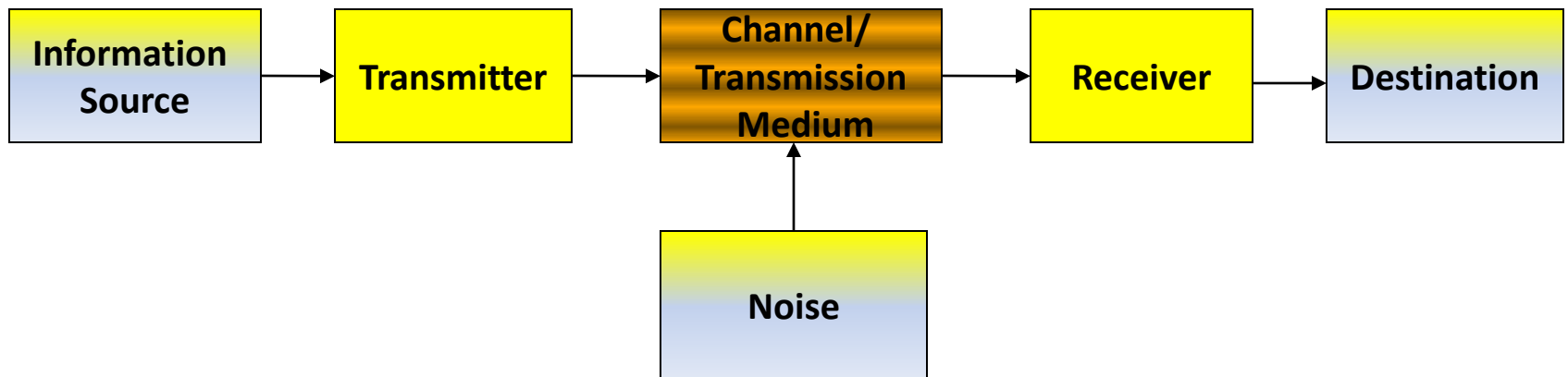
Figure : Basic Block Diagram of a Communication System

Function of each Element.

❑Information Source – the communication system exists to send messages. Messages come from voice, data, video and other types of information.

❑Transmitter – Transmit the input message into electrical signals such as voltage or current into electromagnetic waves such as radio waves, microwaves that is suitable for transmission and compatible with the channel. Besides, the transmitter also do the modulation and encoding (for digital signal).
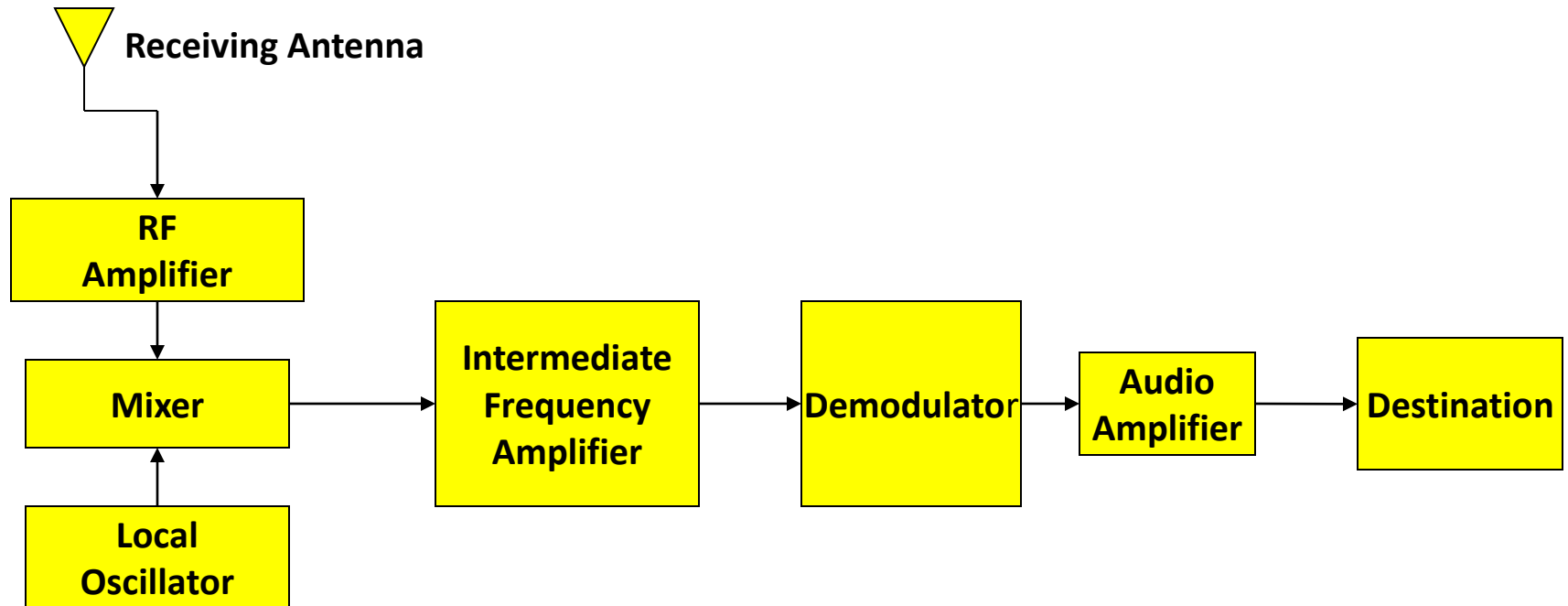
Block Diagram of a Transmitter

Transmitting Antenna

Modulating Signal	→	Audio Amplifier	→	Modulator	→	RF Amplifier

Carrier Signal
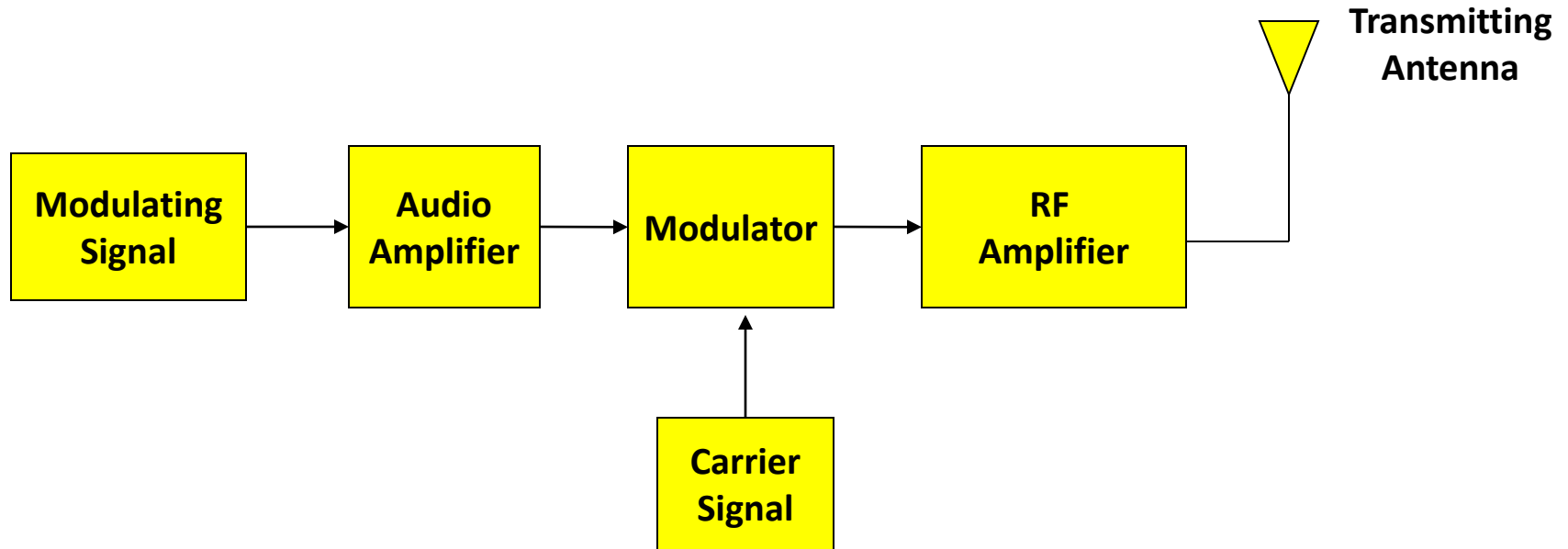
❑Channel/Medium – is the link or path over which information flows from the source to destination. Many links combined will establish a communication networks.

❑There are 5 criteria of a transmission system; Capacity, Performance, Distance, Security and Cost which includes the installation, operation and maintenance.

❑2 main categories of channel that commonly used are; line (guided media) and free space (unguided media)

❑ Receiver – Receives the electrical signals or electromagnetic waves that are sent by the transmitter through the channel. It is also separate the information from the received signal and sent the information to the destination.

❑ Basically, a receiver consists of several stages of amplification, frequency conversion and filtering.

Block Diagram of a Receiver

Receiving Antenna

RF Amplifier

Mixer

Local Oscillator

Intermediate Frequency Amplifier

Demodulator

Audio Amplifier

Destination

Limitations in a Communication System

- There are 2 categories of limitations:-
  - Technological
  - Physical

- Technological Constraint includes equipment availability, economy and cost factor, national and international law (ITU-T) and interaction with existing systems.

- Physical Constraint includes bandwidth and noise.

Cont…….physical constraint

- Bandwidth – defined as the information carrying capacity of a system or the frequency content of a signal.

- BW is the difference between the upper frequency f_H and the lower frequency f_L of the signal.

- Example: The voice frequency ranges from 300 Hz to 3400 Hz. Therefore, the BW is 3.1 kHz.

- The limitation due to BW is applied to both signals and systems as a measure of speed. Means that the shorter transmission time will result in high-speed transmission of the signal, which require large BW and hence increasing the cost of the system

Cont……physical constraint

- Noise – defined as unwanted electrical energy present in the usable passband of a communication circuit. It is unavoidable.

- Noise is measured in terms of Signal-to-Noise ratio (SNR).

- Its limitation, Higher SNR…..higher transmitted power and higher cost.

- Noise Factor, denoted by F and defined as the ratio of SNR at the input to the SNR at the output of a network.
  - F = (SNR)input / (SNR)output
  - Noise Figure = 10 log F dB

- Noise figure or noise factor is used to compare the performance of a communication system. Higher SNR, lower F is better in a communication systems.

Unit-1

Amplitude Modulation System

NEED FOR MODULATION

- PRACTICABILITY OF ANTENNA

"FOR EFFICIENT RADIATION AND RECEPTION THE TRANSMITTING AND RECEIVING ANTENNAS SHOULD HAVE LENGTHS COMPARABLE TO QUARTER WAVE LENGTHS OF FREQUENCY USED"

- NARROWBANDING

BAND EDGE RATIO SHOULD BE APPROXIMATELY UNITY.

- MULTIPLEXING

SIMULTANEOUS TRANSMISSION OF MULTIPLE MESSAGE

- COMMON PROCESSING

- REDUCED NOISE

Amplitude Modulation

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).

- Use in commercial broadcasting of both audio and video signals.

- Also used for two-way mobile radio communications, such as citizens band (CB) radio.

AM Waveforms
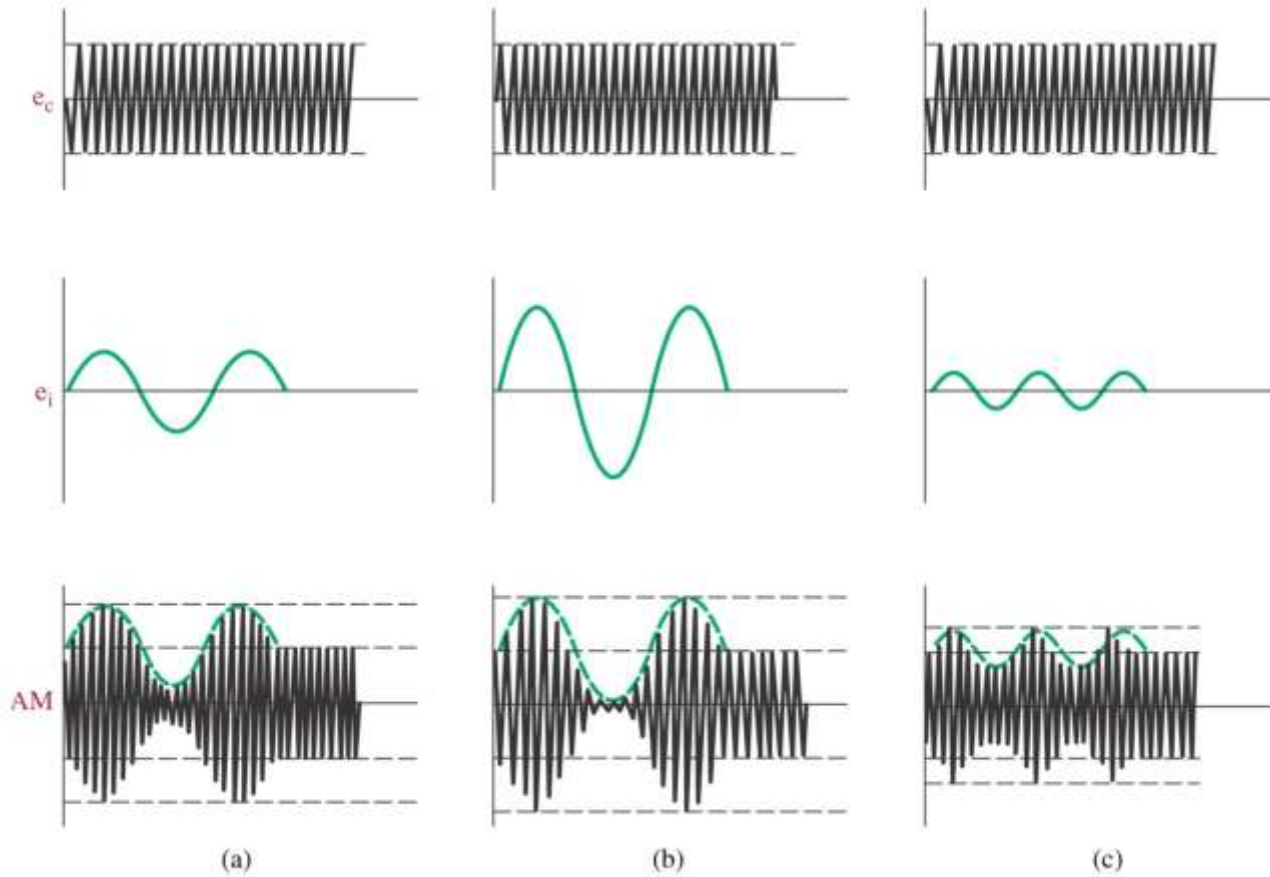
Equation of the AM Wave

$$e = (E_c + E_i \sin\omega_i t)\sin\omega_c t$$

E_c = peak amplitude of carrier

E_i = peak amplitude of intelligence

$\omega_i t$ = radian frequency of intelligence

$\omega_c t$ = radian frequency of carrier

ω = 2π

AM Analysis

- The instantaneous value of the AM waveform can be developed as follows.

- The equation for the amplitude of an AM waveform can be written as the carrier peak amplitude, Ec, plus the intelligence signal.

$$E = E_c + e_i$$

We know, $e_i = E_i \sin \omega_i t$

$$E = E_c + E_i \sin \omega_i t$$

AM Analysis

Ratio of $E_i / E_c = m = $ Modulation index

$$E = E_c + mE_c \sin \omega_i t$$
$$= E_c(1 + m \sin \omega_i t)$$

The instantaneous value for the AM wave is the amplitude, E, times $\sin \omega_c t$

$$e = E \sin \omega_c t$$
$$= E_c(1 + m \sin \omega_i t) \sin \omega_c t$$

AM Analysis

Remember the trigonometric identity :

$$\sin x \sin y = \tfrac{1}{2}[\cos(x - y) - \cos(x + y)]$$

We can write e as follows:

$$e = E_c \sin \omega_c t + [m\, E_c /2]\cos(\omega_c - \omega_i)t - [m\, E_c /2]\cos(\omega_c + \omega_i)t$$
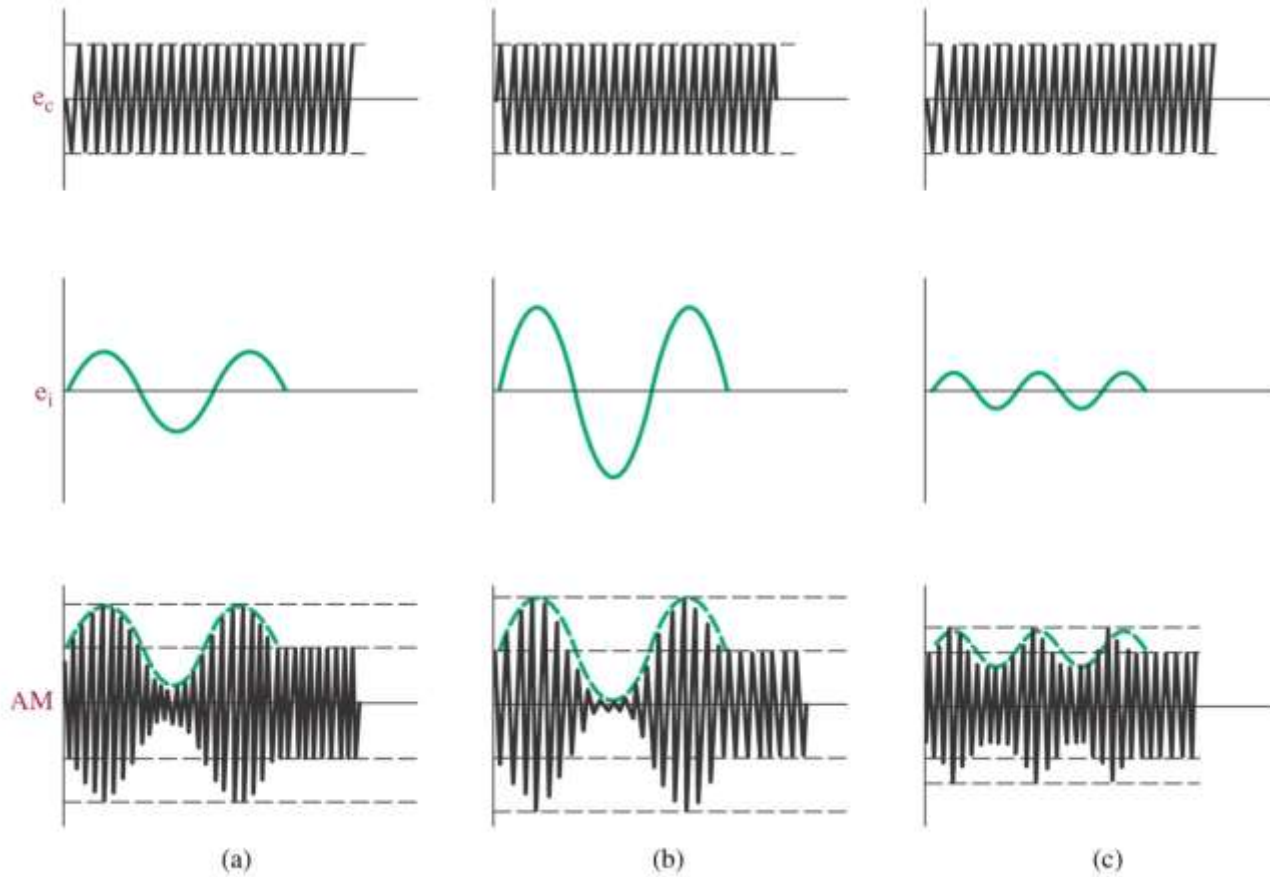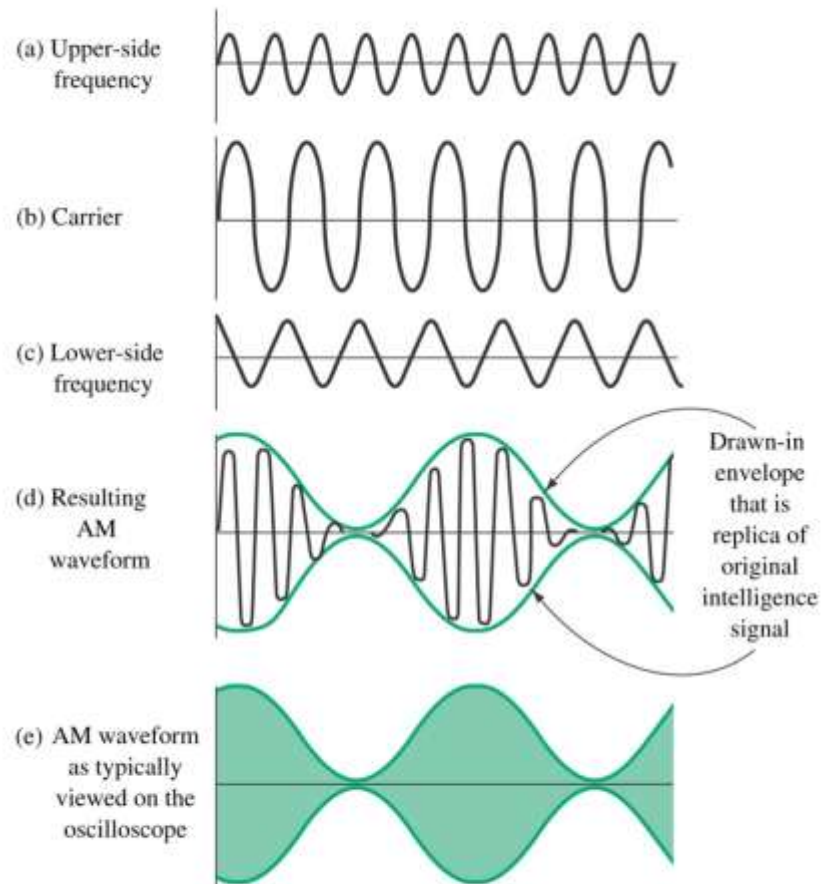
Frequency Spectrum
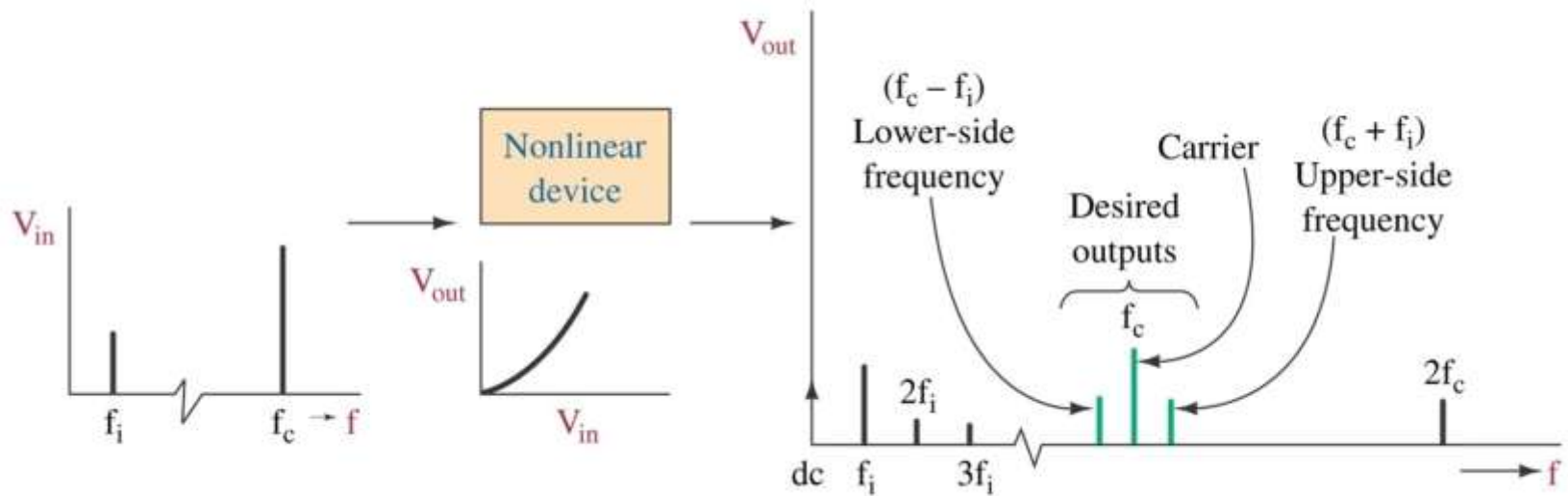
The AM Waveform

The three components that form the AM waveform are listed below:

1. The *lower-side frequency* $(f_c - f_i)$
2. The *carrier frequency* (f_c)
3. The *upper-side frequency* $(f_c + f_i)$

AM Waveforms

Carrier and Side Frequency Components

(a) Upper-side frequency

(b) Carrier

(c) Lower-side frequency

(d) Resulting AM waveform

Drawn-in envelope that is replica of original intelligence signal

(e) AM waveform as typically viewed on the oscilloscope

Upper and Lower Sidebands

- In most systems the intelligence signal is a complex waveform containing components from roughly 200Hz to 3KHz.

- If this is used to modulate the carrier there would be a whole band of side frequencies.

- The band of frequencies above the carrier is term the upper sideband.

- The band of frequencies below the carrier is called the lower sideband.
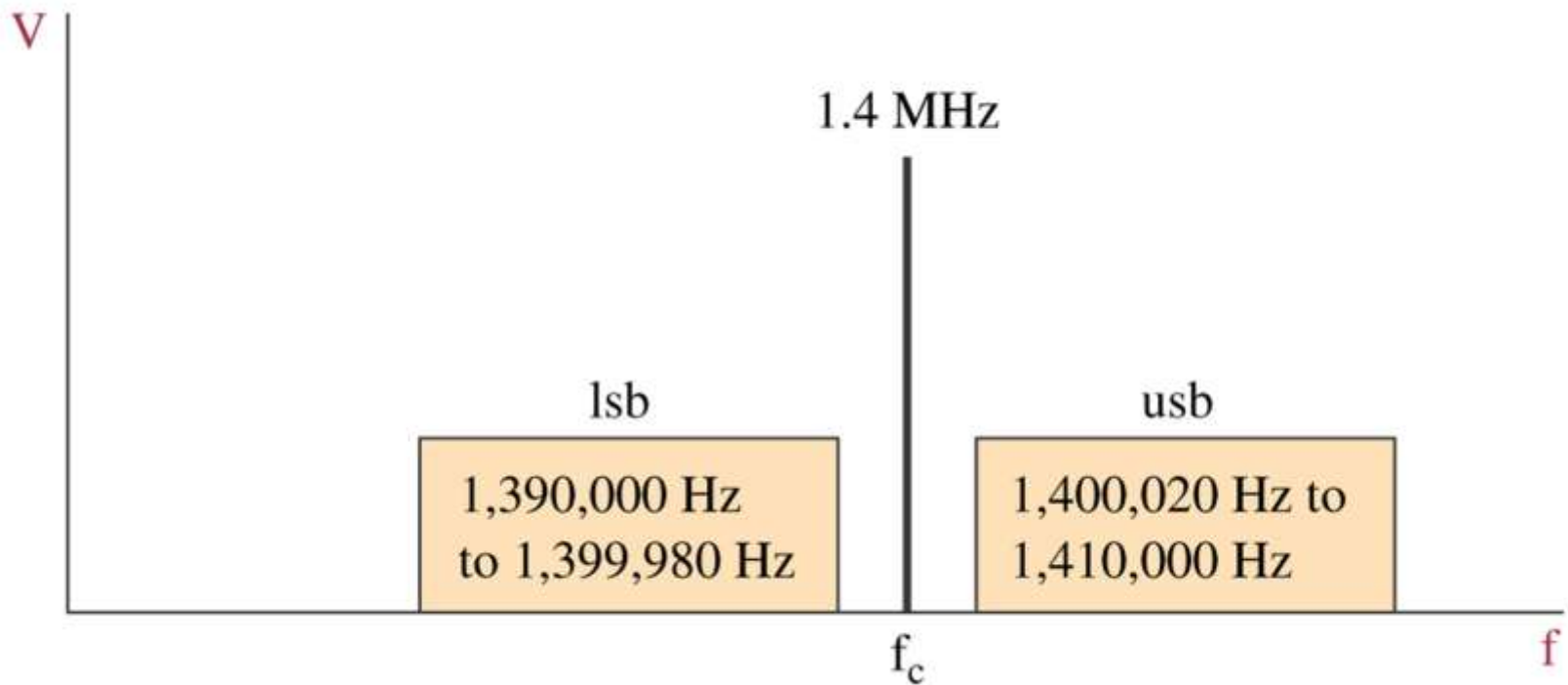
Upper and Lower Sidebands
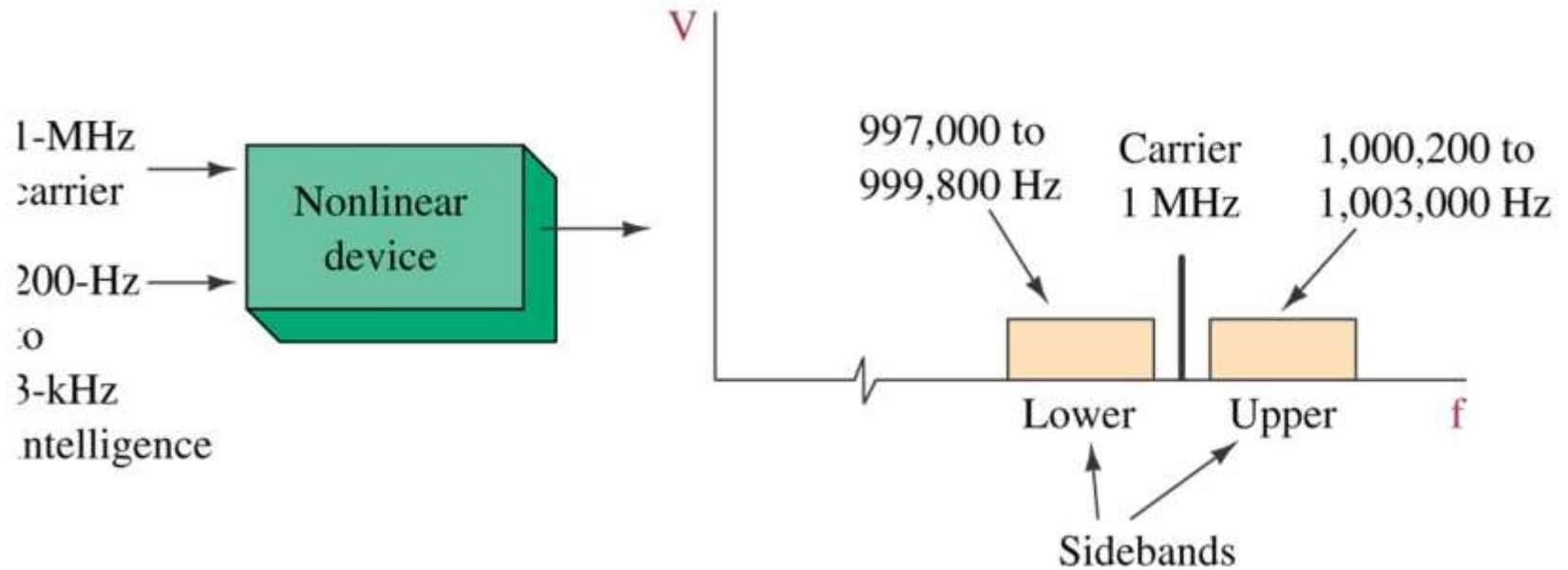
Example

A 1.4MHz carrier is modulated by a music signal that has frequency components from 20Hz to 10kHz. Determine the range of frequencies generated for the upper and lower sidebands.
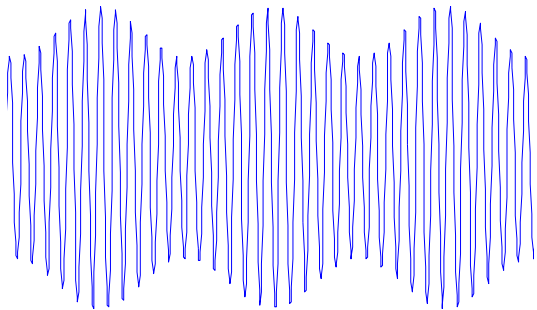
Solution

Modulation index (m)

- The relationship between the modulating signal amplitude V_m and the carrier V_c is a ratio called the modulation index m defined as
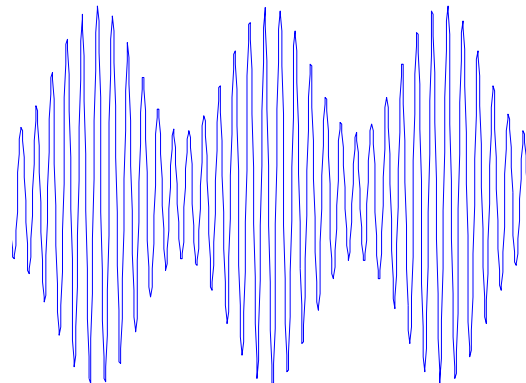
$$m = \frac{V_m}{V_c}$$

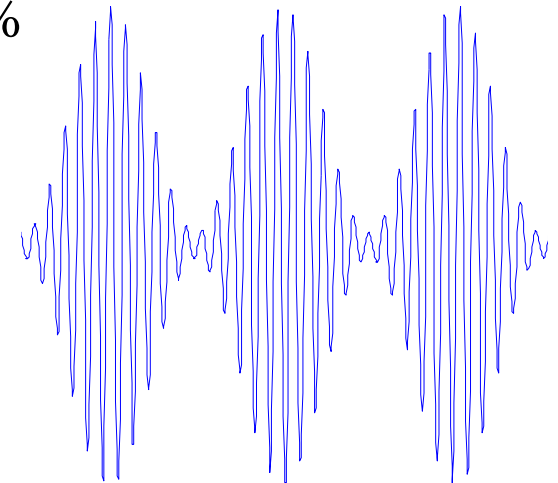- Sometimes m is expressed as a percentage.

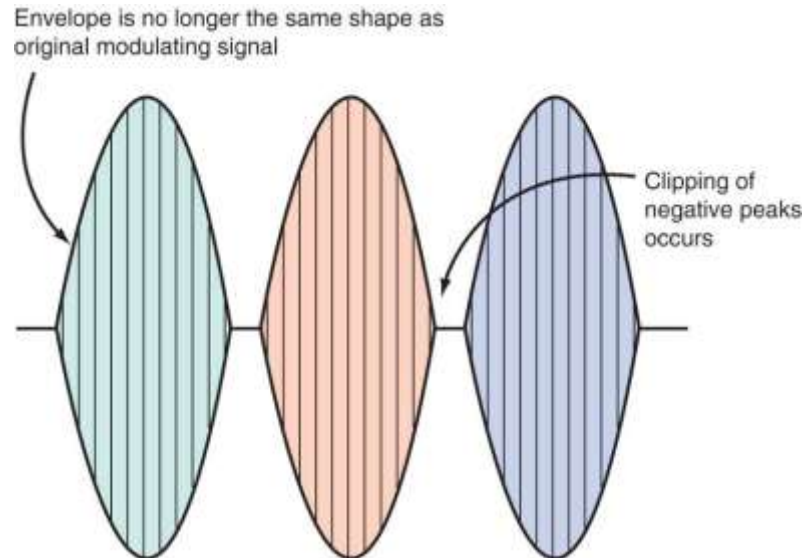$$\text{percent modulation } = m \times 100\%$$

$m = 20\%$ $\qquad\qquad\qquad m = 50\%$ $\qquad\qquad\qquad m = 90\%$
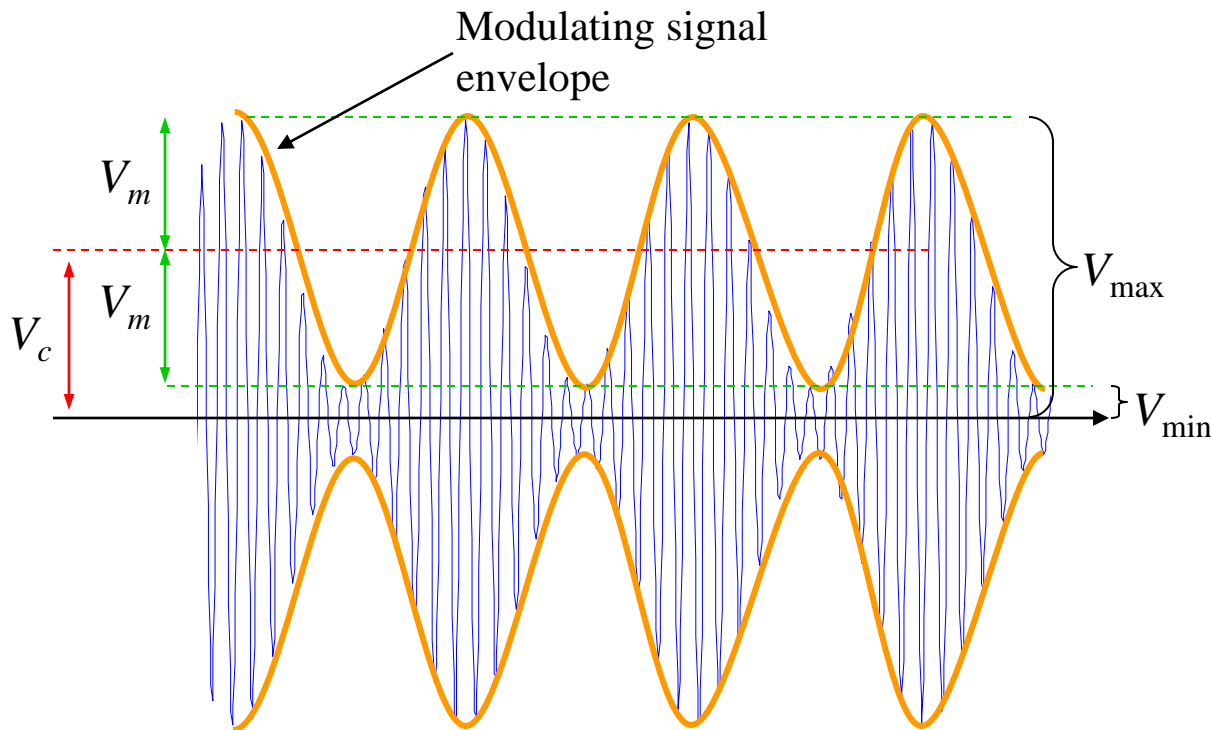
Overmodulation

- m should range between 0 and 1.
- The condition in which $m > 1$ is called overmodulation and will result in distortion.

Envelope is no longer the same shape as original modulating signal

Clipping of negative peaks occurs

Modulation index

- We can also determine the modulation index m from the maximum and minimum values of the envelope of v_{AM}
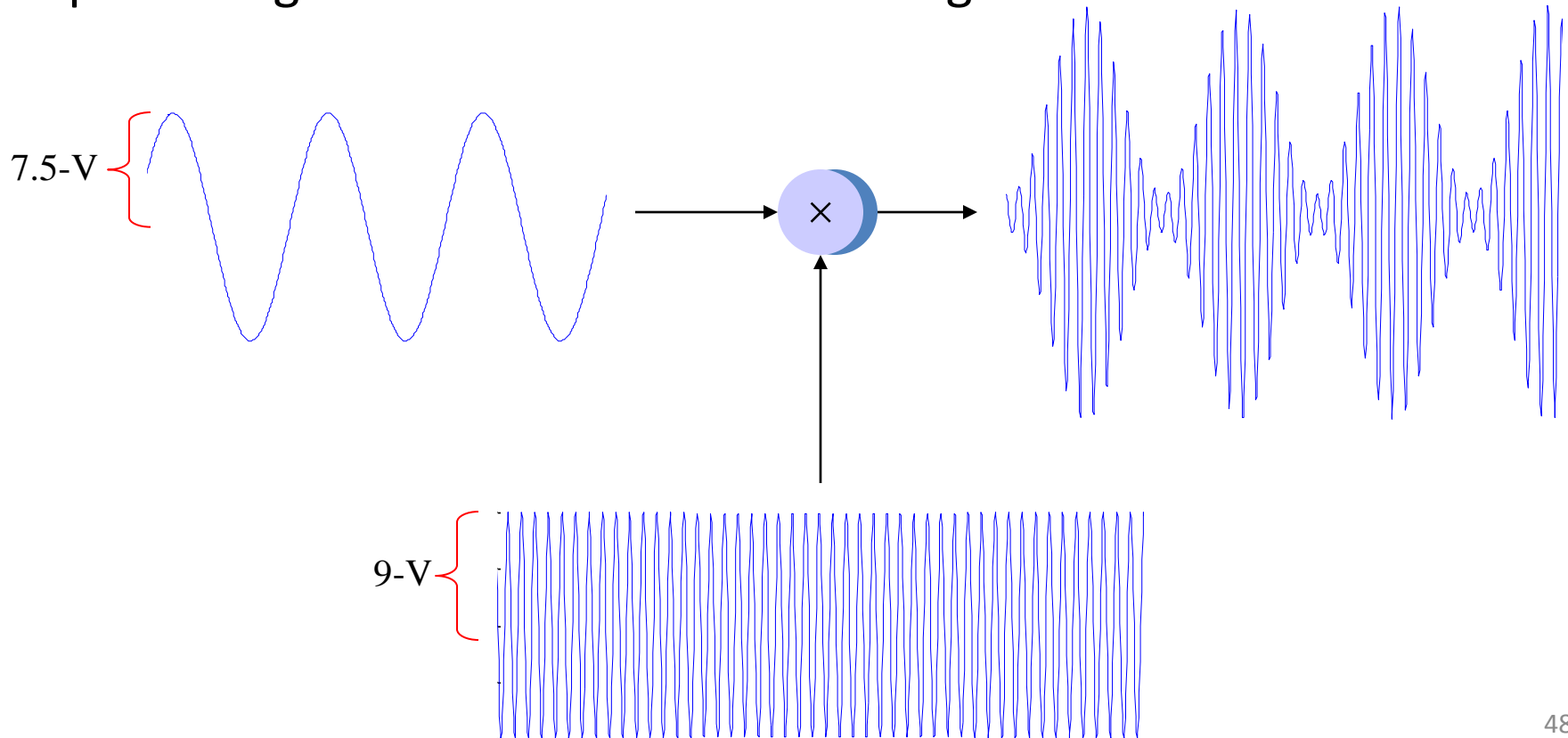
$$V_m = \frac{V_{\max} - V_{\min}}{2}$$

$$V_c = \frac{V_{\max} + V_{\min}}{2}$$

$$m = \frac{V_m}{V_c} = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}}$$

Modulating signal envelope

V_m

V_m

V_c

$V_{\max}$

$V_{\min}$

Example Problem

If a carrier signal with an amplitude of 9 V is mixed with a modulating signal with an amplitude of 7.5 V, what is the percentage modulation of the resulting signal?

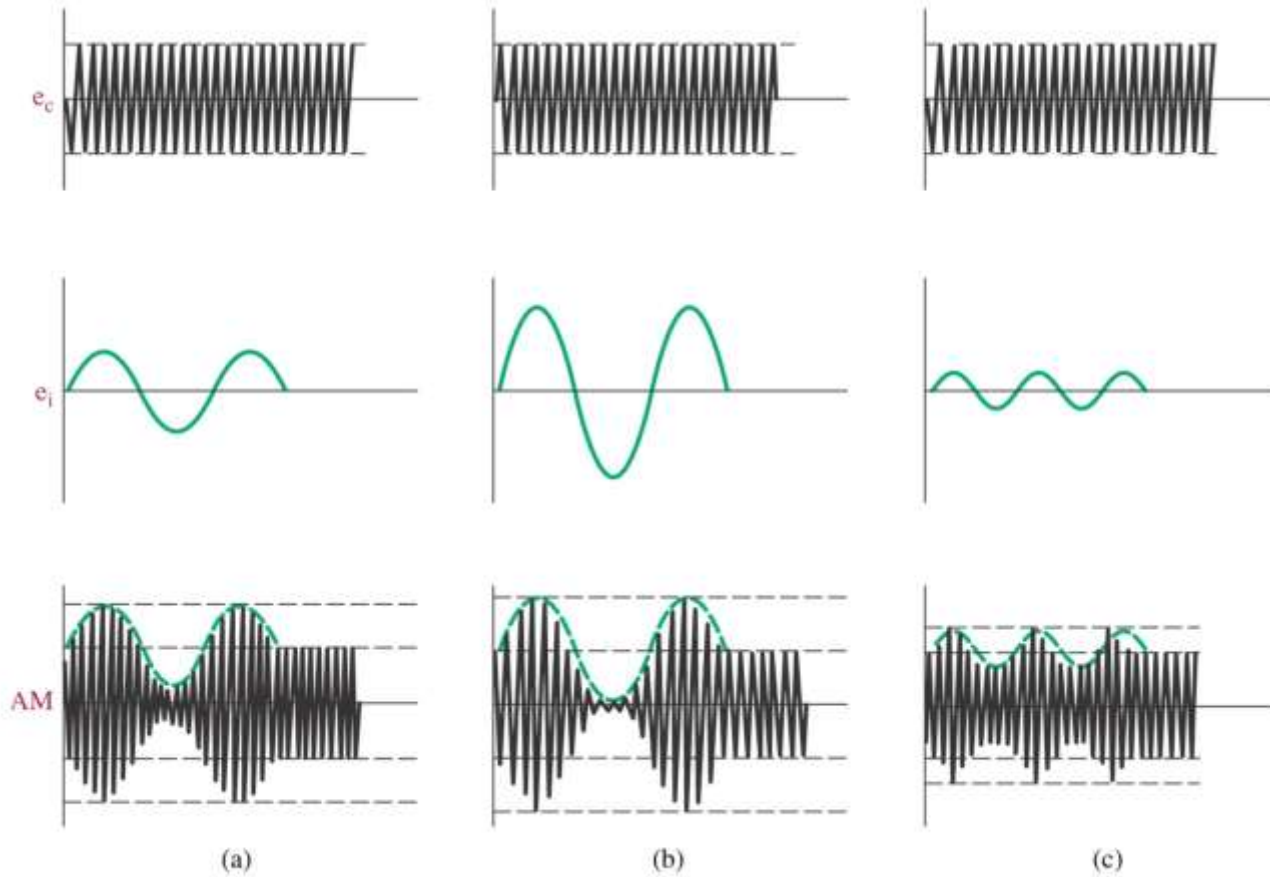7.5-V

×

9-V

Percentage Modulation

- A measure of the extent to which a carrier voltage is varied by the intelligent signal.

- Also known as modulation index or modulation factor and is symbolized by m.

$$0 \leq m \leq 1$$

0 => no modulation
1 => 100% modulation

AM Waveforms

Example

- An unmodulated carrier is 300V p-p. Calculate %m when its maximum p-p value reaches 400, 500, 600.

Overmodulation

- When an excessive intelligent signal overdrives an AM modulator producing percentage modulation exceeding 100 percent.

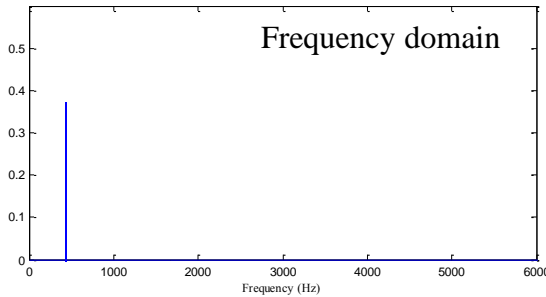- Overmodulation produces sideband splatter. Distortion resulting in an overmodulated AM transmission creating excessive bandwidths.

Overmodulation
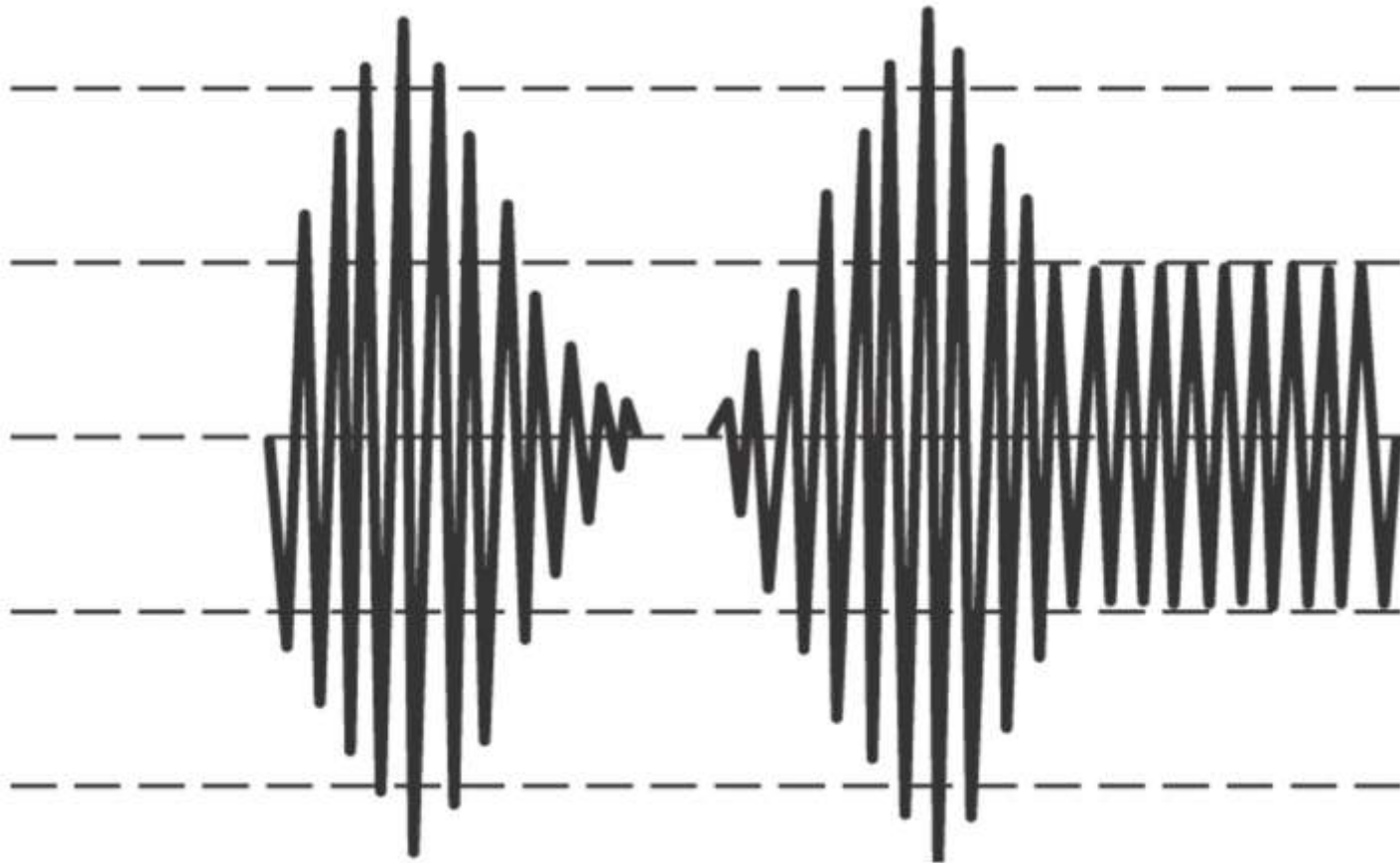
AM in the frequency domain

Information signal v_m
(for tuning fork f_m= 440-Hz)

Amplitude modulated signal v_{AM}
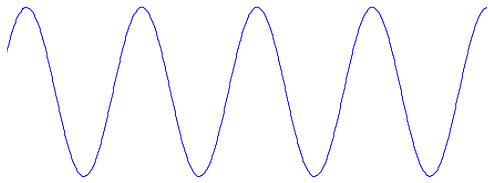
Modulator
or mixer

Frequency domain

Frequency domain

?
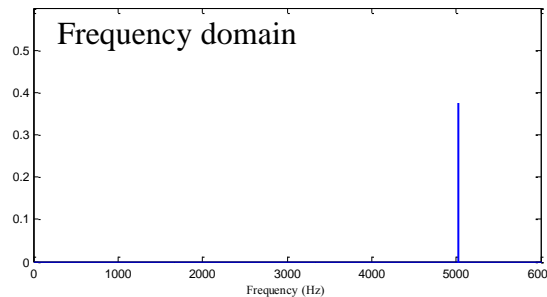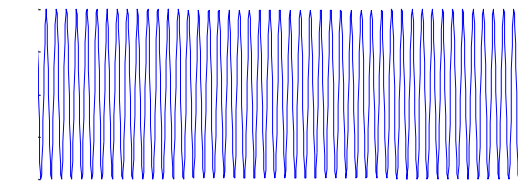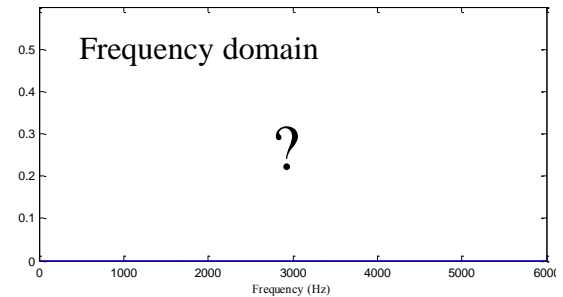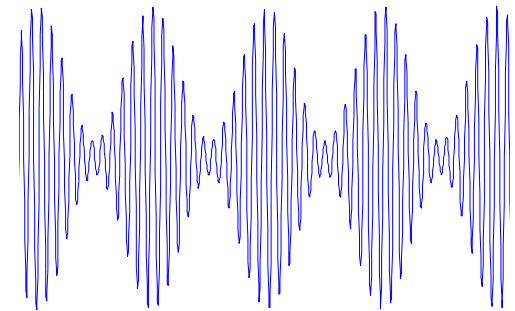
Carrier signal v_c (carrier frequency f_c = 5-kHz)

AM in the frequency domain

- v_{AM} is given

$$v_{\mathrm{AM}} = (V_c + V_m \sin 2\pi f_m t) \sin 2\pi f_c t$$
$$= V_c \sin 2\pi f_c t + (V_m \sin 2\pi f_m t)(\sin 2\pi f_c t)$$

- Applying the trigonometric identity for the product of two sine functions

$$\sin A \, \sin B = \frac{\cos(A-B)}{2} - \frac{\cos(A+B)}{2}$$

we can write

$$v_{\mathrm{AM}} = V_c \sin 2\pi f_c t + \frac{V_m}{2} \sin 2\pi (f_c - f_m)t - \frac{V_m}{2} \sin 2\pi (f_c + f_m)t$$
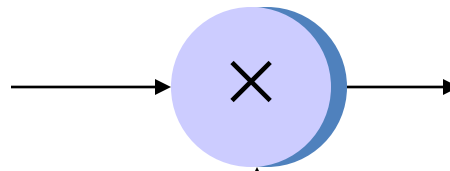
AM in the frequency domain

- This form shows that v_{AM} consists of just three frequency components.

$$v_{\mathrm{AM}} = \frac{V_m}{2}\sin 2\pi(f_c - f_m)t + V_c \sin 2\pi f_c t - \frac{V_m}{2}\sin 2\pi(f_c + f_m)t$$

Lower sideband
$\left(f_{\mathrm{LSB}} = f_c - f_m\right)$

Carrier frequency f_c

Upper sideband
$\left(f_{\mathrm{USB}} = f_c + f_m\right)$

Amplitude modulated signal v_{AM}

Frequency domain

$f_c = 5000$ Hz

$f_{\mathrm{LSB}} = 5000 - 440$
$= 4560$ Hz

$f_{\mathrm{USB}} = 5000 + 440$
$= 5440$ Hz
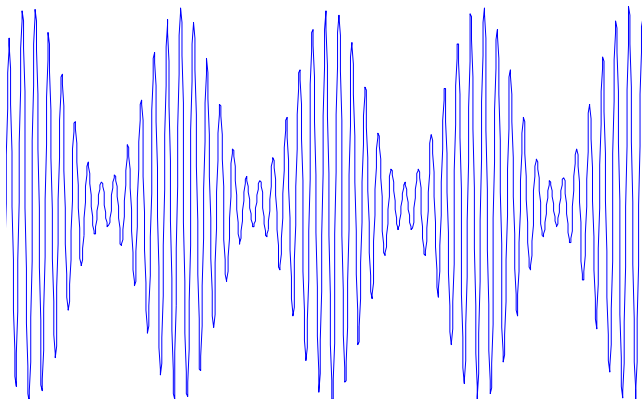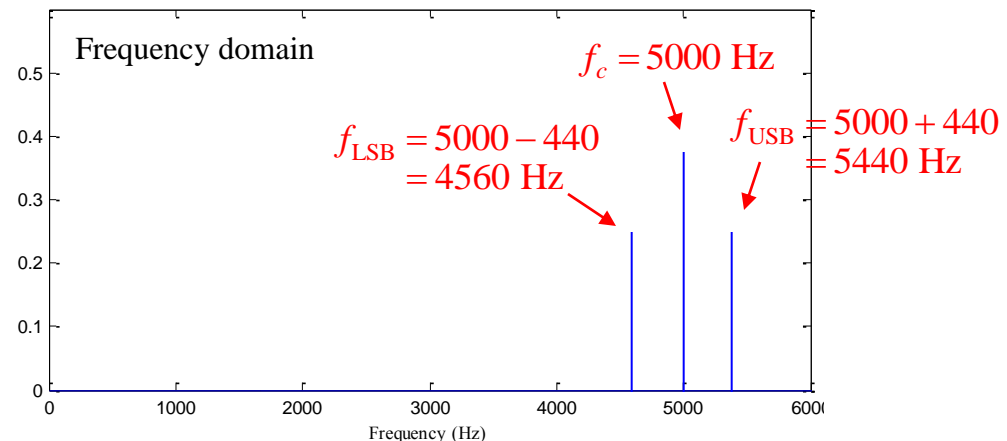
Example

- Determine the maximum sideband power if the carrier output is 1 kW and calculate the total maximum transmitted power.

Solution

Max sideband power occurs when m = 1 or 100%. At this percentage modulation each side frequency is ½ the carrier amplitude.

$$E_{SF} = mE_c/2$$

Since power is proportional to the square of the voltage, each has ¼ of the carrier power.

¼ x 1kW = 250W

Total sideband power = 2 x 250 = 500W

Total transmitted power = 1kW + 500W = 1.5kW

Importance of High Percentage Modulation

- It in important to use a high a percentage of modulation as possible while ensuring that overmodulation does not occur.

- The sidebands contain the information and have maximum power at 100% modulation.

- Useful equation

$$P_t = P_c(1 + m^2/2)$$

P_t = Total transmitted power (sidebands and carrier)
P_c = Carrier power

Importance of High Percentage Modulation

$$I_t = I_c\sqrt{(1 + m^2/2)}$$

I_t = Total transmitted current

I_c = Carrier current

m = Modulating index

Example

1. A 500W carrier is to be modulated to a 90% level. Determine the total transmitted power.

2. An AM broadcast station operates at its maximum allowed total output of 50kW and at 95% modulation. How much of its transmitted power is intelligence (sidebands)?

3. The antenna current of an AM transmitter is 12A when unmodulated but increase to 13A when modulated. Calculate %m.

Effective Modulation Index

If a carrier is modulated by more than a single sine wave, the effective modulation index is given by:

$$m_{eff} = \sqrt{(m_1^2 + m_2^2 + m_3^2 + ...)}$$

Note that the total modulation index must not exceed 1 or distortion will occur.

m_{eff} can be used in all previously developed equations using m.

Example

- A transmitter with a 10kW carrier transmit 11.2kW when modulated with a single sine wave. Calculate the modulation index. If the carrier is simultaneously modulated with another sine wave at 50 percent modulation, calculate the total transmitted power.

Baseband vs Passband Transmission

- Baseband signals:
  - Voice (0-4kHz)
  - TV (0-6 MHz)
- A signal may be sent in its baseband format when a <u>dedicated</u> <u>wired</u> channel is available.
- Otherwise, it must be converted to passband.

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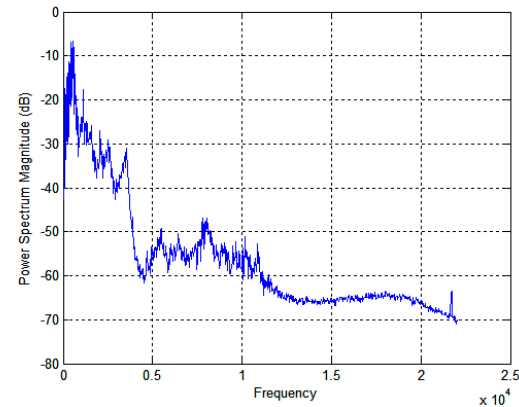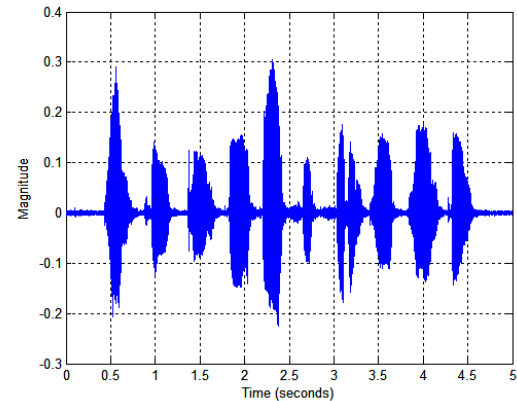
Types of Amplitude Modulation (AM)

- **Double Sideband with carrier (we will call it AM)**: This is the most widely used type of AM modulation. In fact, all radio channels in the AM band use this type of modulation.

- **Double Sideband Suppressed Carrier (DSBSC):** This is the same as the AM modulation above but without the carrier.

- **Single Sideband (SSB):** In this modulation, only half of the signal of the DSBSC is used.

- **Vestigial Sideband (VSB):** This is a modification of the SSB to ease the generation and reception of the signal.

Double Sideband Suppressed Carrier (DSBSC)

- Assume that we have a message signal $m(t)$ with bandwidth $2\pi B$ rad/s (or B Hz). $m(t) \Leftrightarrow M(\omega)$.

- Let $c(t)$ be a carrier signal, $c(t) = \cos(\omega_c t)$, $\omega_c \gg 2\pi B$

- $g_{DSBSC}(t) = m(t) \cdot \cos(\omega_c t)$

  $\Leftrightarrow (1/2) [M(\omega - \omega_c) + M(\omega + \omega_c)].$

$m(t) \longrightarrow$ X $\longrightarrow g_{\text{DSBSC}}(t)$

$c(t)$
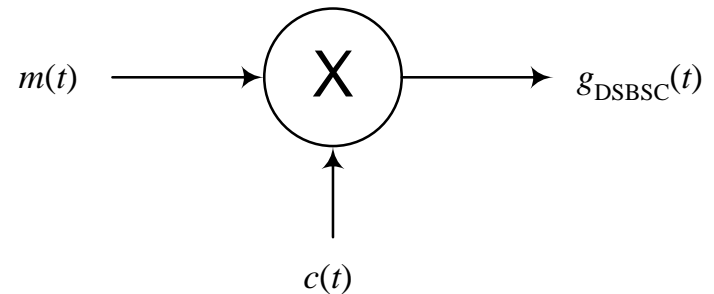
DSBSC Modulator (transmitter)

Time and Frequency Representation of DSBSC Modulation Process

DSBSC Demodulation

$g_{DSBSC}(t)$ ────────→ Ⓧ ──── $e(t)$ ──→ | $H_{LPF}(\omega)$ BW $= 2\pi B$ | ──→ $f(t)$

$c(t)$
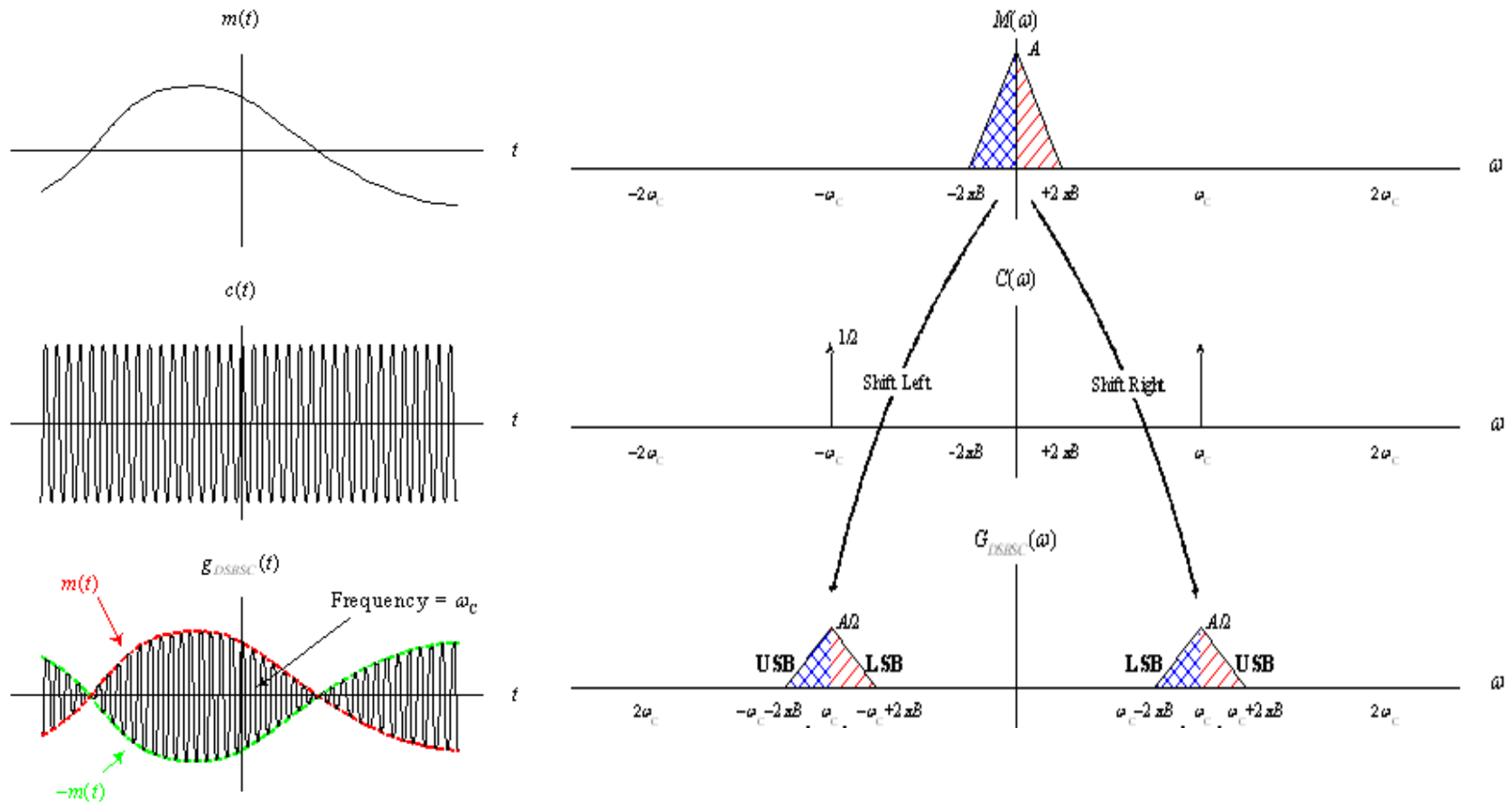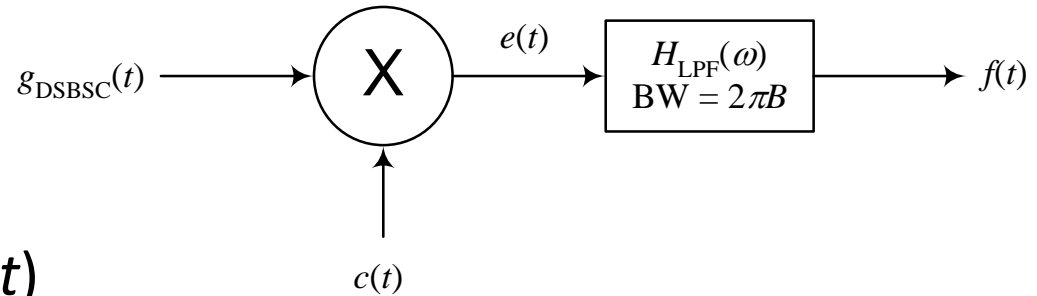
DSBSC Demodulator (receiver)

- $e\,(t) = g_{DSBSC}(t)\cdot\cos(\omega_c t)$
  $= m(t)\cdot\cos^2(\omega_c t)$
  $= (1/2)\,m(t)\,[1 + \cos(2\omega_c t)]$
  $= (1/2)\,m(t) + (1/2)\,m(t)\cos(2\,\omega_c t)$

- $E(\omega) \Leftrightarrow (1/2)\,M(\omega) + (1/4)\,[M(\omega - 2\,\omega_c) + M(\omega + 2\,\omega_c)]$.

- The output signal $f(t)$ of the LPF will be
  $f\,(t) = (1/2)\,m(t) \Leftrightarrow (1/2)\,M(\omega)$.

Time and Frequency Representation of DSBSC Demodulation Process
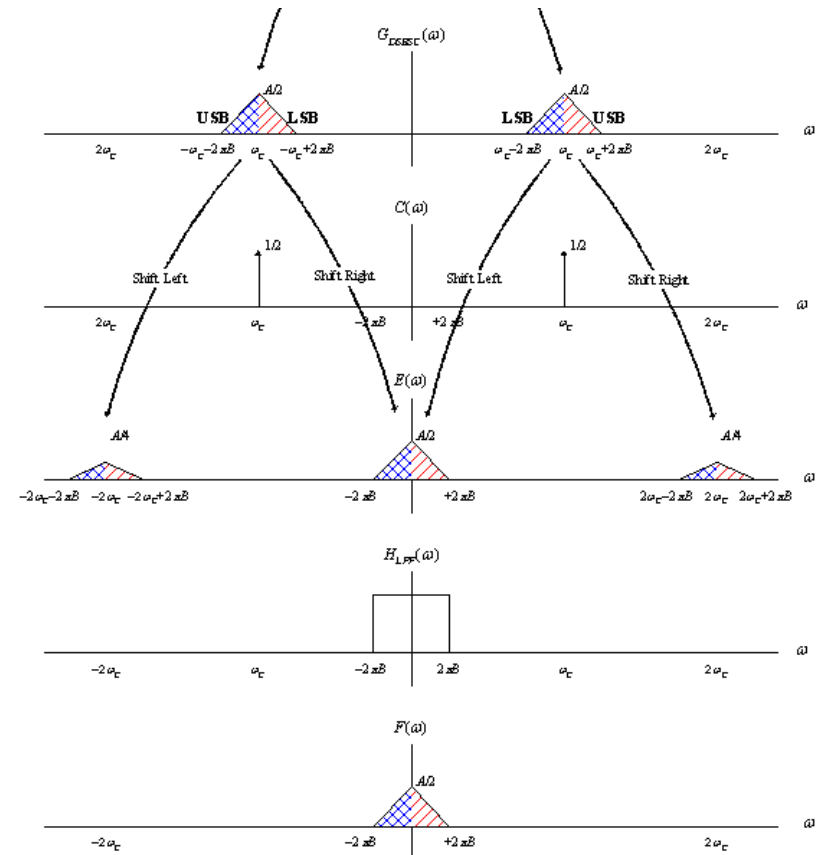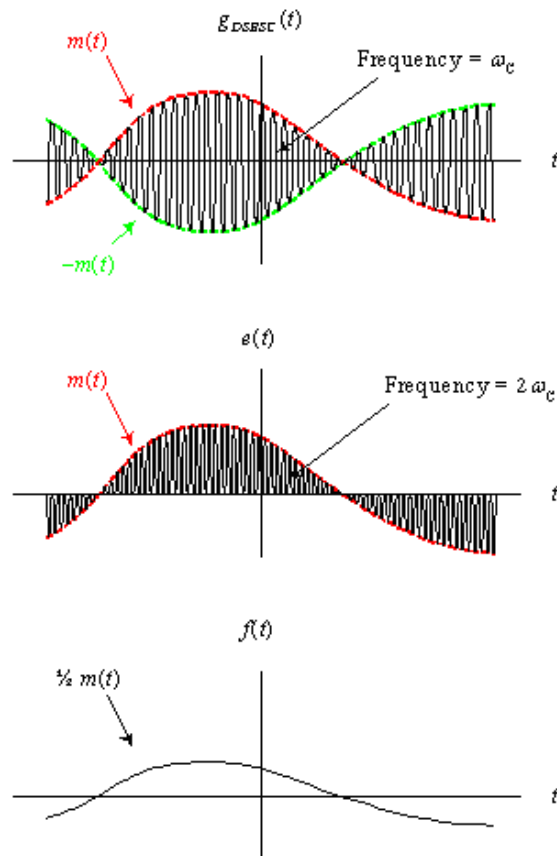
Modulator Circuits

- Basically we are after multiplying a signal with a carrier.
- There are three realizations of this operation:
  - Multiplier Circuits
  - Non-Linear Circuits
  - Switching Circuits

Non-Linear Devices (NLD)

- A NLD is a device whose input-output relation is non-linear. One such example is the diode ($i_D = e^{v_D/v_T}$).

- The output of a NLD can be expressed as a power series of the input, that is
$$y(t) = ax(t) + bx^2(t) + cx^3(t) + \ldots$$

- When $x(t) \ll 1$, the higher powers can be neglected, and the output can be approximated by the first two terms.

- When the input $x(t)$ is the sum of two signal, $m(t)+c(t)$, $x^2(t)$ will have the product term $m(t)c(t)$

Non-Linear Modulators
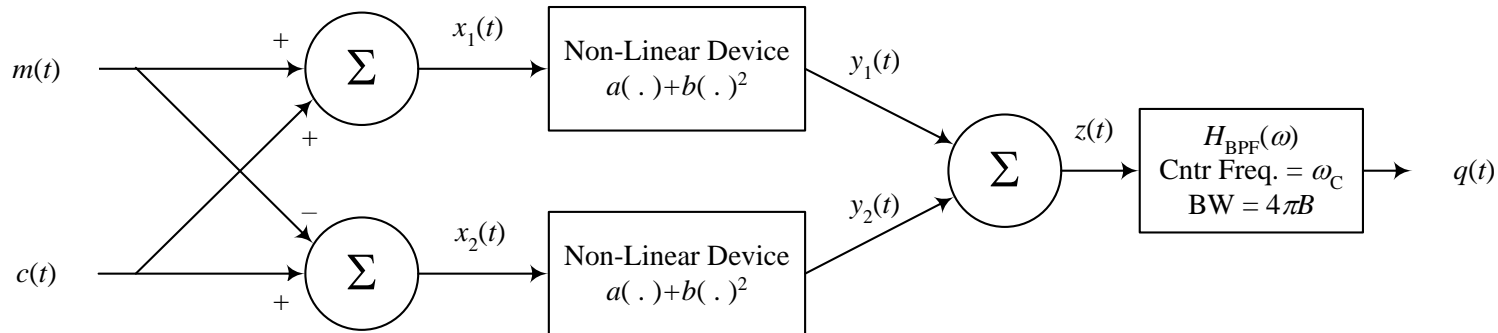
DSBSC modulation using non-linear device

$$x_1(t) = c(t) + m(t) = \cos(\omega_C t) + m(t)$$
$$x_1(t) = c(t) - m(t) = \cos(\omega_C t) - m(t)$$

$$y_1(t) = a\big[\cos(\omega_C t) + m(t)\big] + b\big[\cos(\omega_C t) + m(t)\big]^2$$
$$= a\cos(\omega_C t) + am(t) + bm^2(t) + 2bm(t)\cdot\cos(\omega_C t) + b\cos^2(\omega_C t)$$
$$= \underbrace{am(t)}_{Undesired} + \underbrace{bm^2(t)}_{Undesired} + \underbrace{2bm(t)\cdot\cos(\omega_C t)}_{Desired} + \underbrace{a\cos(\omega_C t)}_{Undesired} + \underbrace{\frac{b}{2}}_{Undesired} + \underbrace{\frac{b}{2}\cos(2\omega_C t)}_{Undesired}$$

$$z(t) = y_1(t) - y_2(t)$$
$$= \underbrace{2am(t)}_{Undesired} + \underbrace{4bm(t)\cdot\cos(\omega_C t)}_{Desired}$$

$$y_2(t) = a\big[\cos(\omega_C t) - m(t)\big] + b\big[\cos(\omega_C t) - m(t)\big]^2$$
$$= a\cos(\omega_C t) - am(t) + bm^2(t) - 2bm(t)\cdot\cos(\omega_C t) + b\cos^2(\omega_C t)$$
$$= \underbrace{-am(t)}_{Undesired} + \underbrace{bm^2(t)}_{Undesired} - \underbrace{2bm(t)\cdot\cos(\omega_C t)}_{Desired} + \underbrace{a\cos(\omega_C t)}_{Undesired} + \underbrace{\frac{b}{2}}_{Undesired} + \underbrace{\frac{b}{2}\cos(2\omega_C t)}_{Undesired}$$

Switching Modulators

- Any periodic function can be expressed as a series of cosines (Fourier Series).

- The information signal, $m(t)$, can therefore be, equivalently, multiplied by any periodic function, and followed by BPF.

- Let this periodic function be a train of pulses.

- Multiplication by a train of pulses can be realized by simple *switching*.

Switching Modulator Illustration
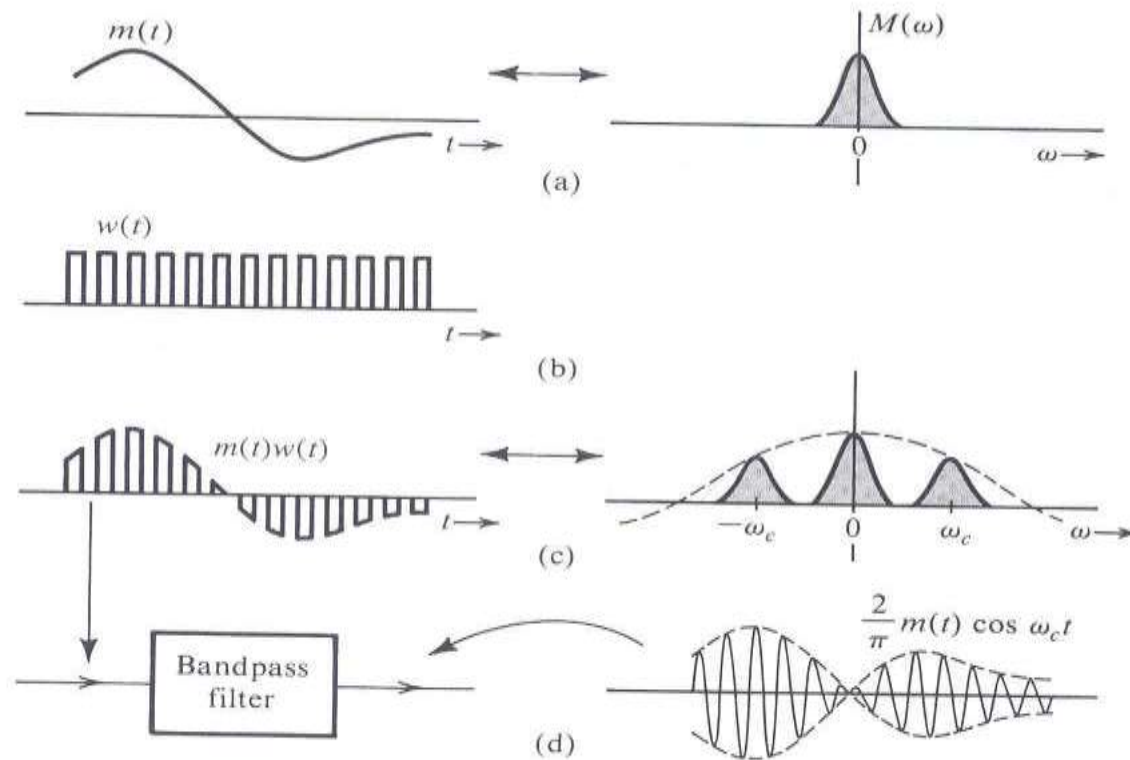
Figure 4.4 Switching modulator for DSB-SC.

Switching Modulator: Diode Bridge
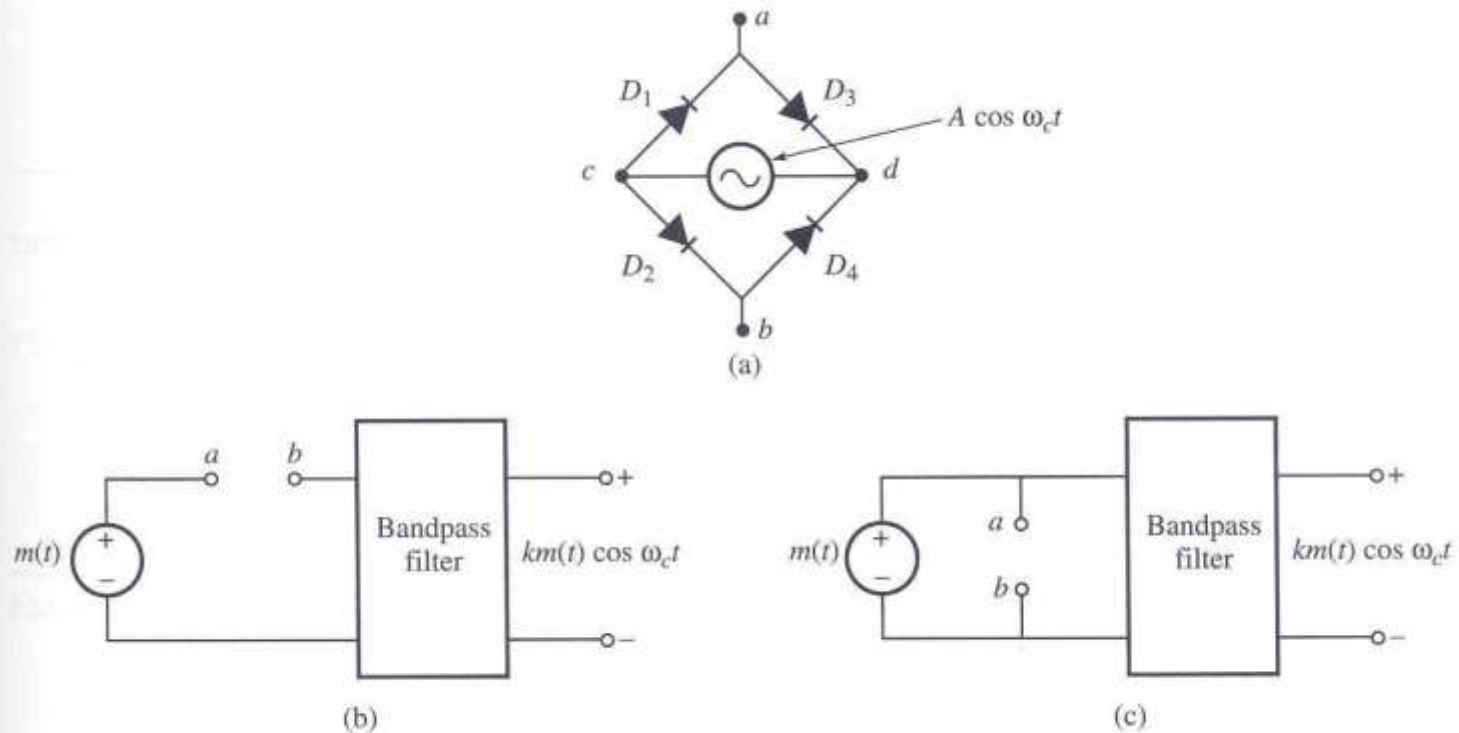
Figure 4.5 (a) Diode-bridge electronic switch. (b) Series-bridge diode modulator. (c) Shunt-bridge diode modulator.

Switching Modulator: Ring
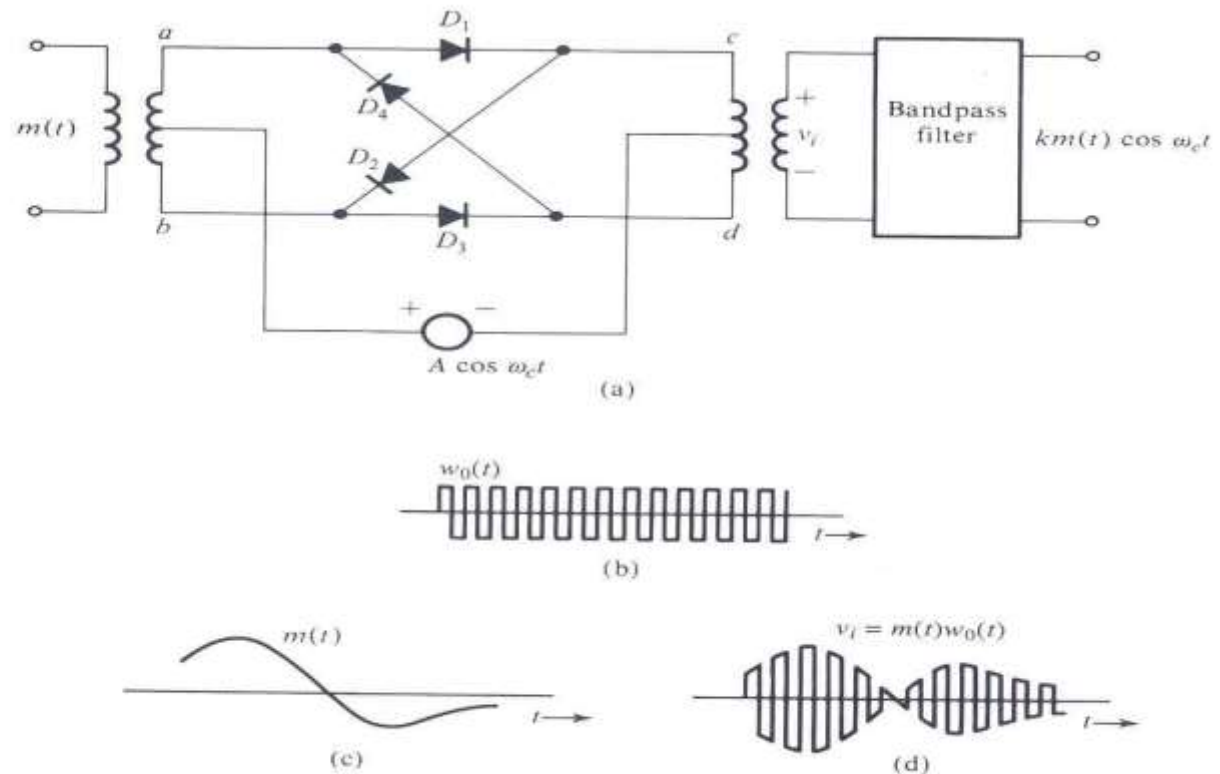
Figure 4.6   Ring modulator.

Demodulation of DSBSC

- The modulator circuits can be used for demodulation, but replacing the BPF by a LPF of bandwidth B Hz.

- The receiver must generate a carrier frequency in phase and frequency synchronization with the incoming carrier.

- This type of demodulation is therefore called *coherent* demodulation (or detection).

$g_{\text{DSBSC}}(t) \longrightarrow \bigotimes \xrightarrow{e(t)} \boxed{\begin{array}{c} H_{\text{LPF}}(\omega) \\ \text{BW} = 2\pi B \end{array}} \longrightarrow f(t)$

$c(t)$
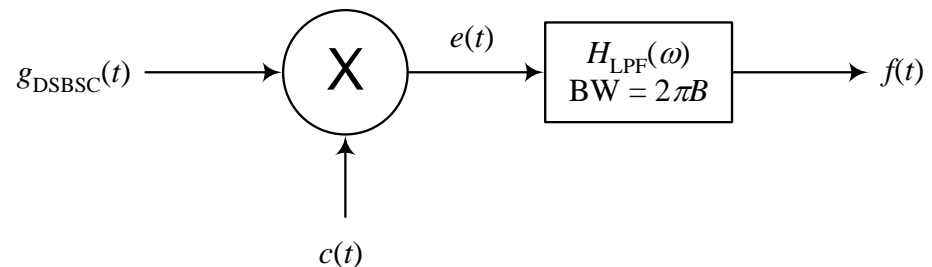
DSBSC Demodulator (receiver)

From DSBSC to DSBWC (AM)

- Carrier recovery circuits, which are required for the operation of coherent demodulation, are sophisticated and could be quite costly.

- If we can let $m(t)$ be the envelope of the modulated signal, then a much simpler circuit, the *envelope detector*, can be used for demodulation (non-coherent demodulation).

- How can we make $m(t)$ be the envelope of the modulated signal?

Definition of AM

- Shift $m(t)$ by some DC value "A" such that $A+m(t) \geq 0$. Or $A \geq m_{peak}$

$$g_{AM}(t) = [A + m(t)]\cos(\omega_C t)$$
$$= A\cos(\omega_C t) + m(t)\cos(\omega_C t)$$

- Called DSBWC. Here will refer to it as Full AM, or simply AM
- Modulation index $\mu = m_p/A$.
- $0 \leq \mu \leq 1$
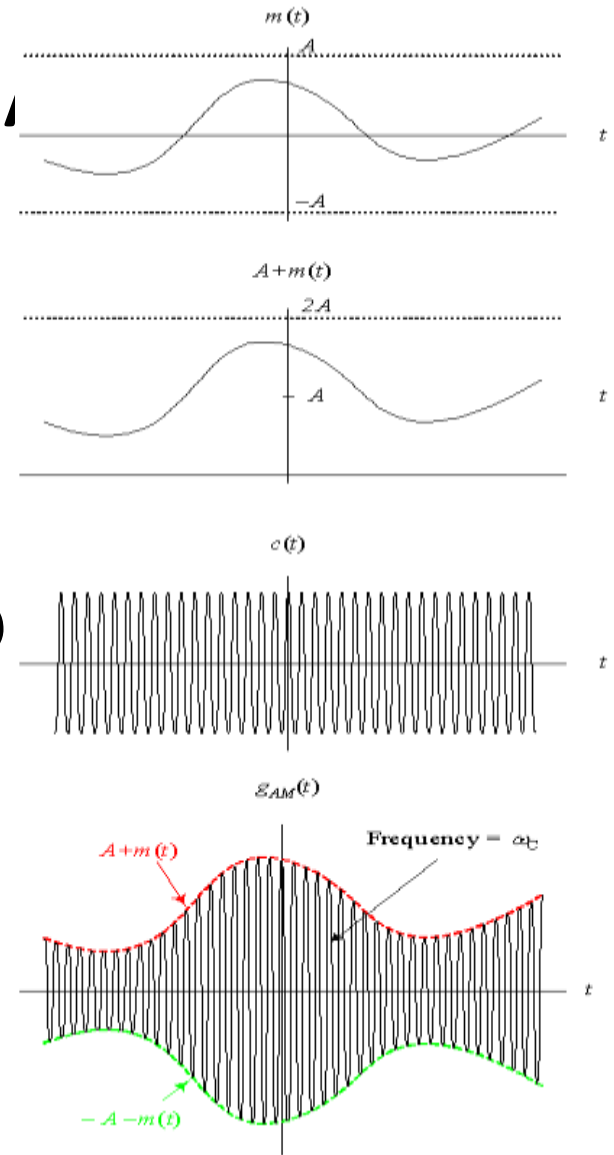
Spectrum of AM

$$g_{AM}(t) \Leftrightarrow \pi A[\delta(\omega - \omega_C) + \delta(\omega + \omega_C)] + \frac{1}{2}[M(\omega - \omega_C) + M(\omega + \omega_C)]$$
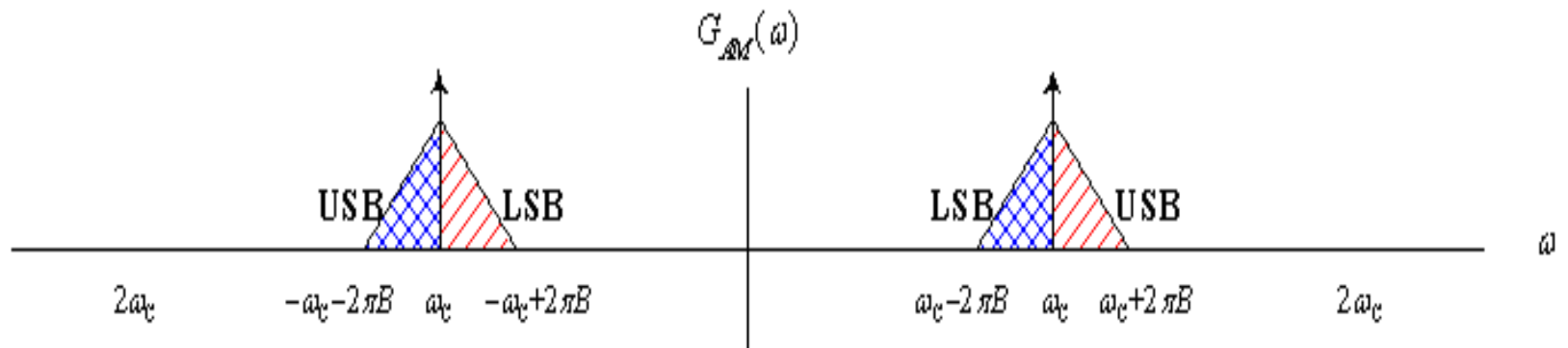
The "Buy" and "Price" of AM

- Buy: Simplicity in demodulation.
- Price: Waste in Power

$g_{AM}(t) = A\cos\omega_c t + m(t)\cos\omega_c t$

Carrier Power $P_c = A^2/2$ (carries no information)

Sideband Power $P_s = P_m/2$ (useful)

Power efficiency $= \eta = P_s/(P_c + P_s) = P_m/(A^2 + P_m)$
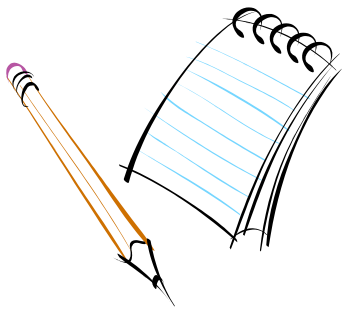
Tone Modulation

- $m(t) = B\cos(\omega_m t)$

- $g(t) = [A + B\cos(\omega_m t)]\cos\omega_c t = A[1 + \mu\cos(\omega_m t)]\cos\omega_c t$

- $\eta = (B^2/2)/(B^2/2 + A^2) = \mu^2/(2+\mu^2)$

- Under best conditions, μ=1 ➜ η_{max} =1/3 =33%

- For μ = 0.5, η = 11.11%

- For practical signals, η < 25%

? Would you use AM or DSBSC?

Generation of AM

- AM signals can be generated by any DSBSC modulator, by using $A+m(t)$ as input instead of $m(t)$.

- In fact, the presence of the carrier term can make it even simpler. We can use it for switching instead of generating a local carrier.

- The switching action can be made by a single diode instead of a diode bridge.

AM Generator

- *A >> m*(*t*)
  (to ensure switching
  at every period).
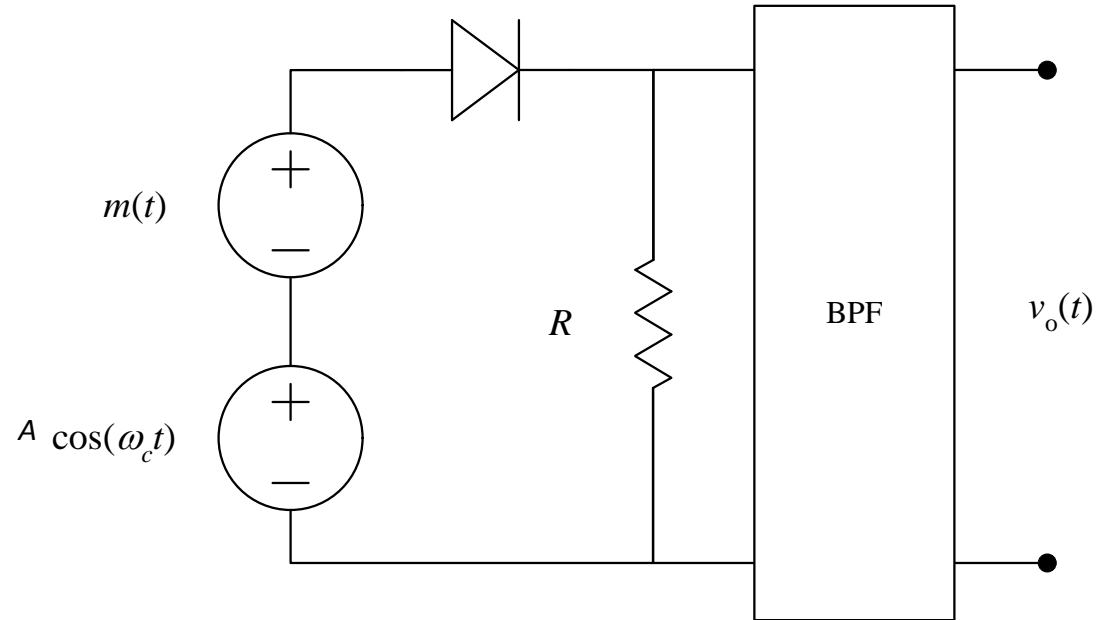
- $v_R = [\cos\omega_c t + m(t)][1/2 + 2/\pi(\cos\omega_c t - 1/3\cos 3\omega_c t + \ldots)]$
  $= (1/2)\cos\omega_c t + (2/\pi)m(t)\cos\omega_c t$ + other terms (suppressed by BPF)

- $v_o(t) = (1/2)\cos\omega_c t + (2/\pi)m(t)\cos\omega_c t$

AM Modulation Process (Frequency)

$M(\omega) + \frac{1}{2}[\delta(\omega - \omega_c) + \delta(\omega + \omega_c)]$ — *Message*

Carrier

$-2\omega_c$ $-\omega_c$ $-2\pi B$ $+2\pi B$ ω_c $2\omega_c$ ω

Signal to the right of MODULATOR Diode   *Baseband Component*

$-2\omega_c$ $-\omega_c$ $-2\pi B$ $+2\pi B$ ω_c $2\omega_c$ ω

Desired AM Components at ω_c

Undesired AM Components at $2\omega_c$, $3\omega_c$, ...

$H_{BPF}(\omega)$

$-2\omega_c$ ω_c $-2\pi B$ $2\pi B$ ω_c $2\omega_c$ ω

$G_{AM}(\omega)$

USB   LSB   LSB   USB

$2\omega_c$ $-\omega_c - 2\pi B$ ω_c $-\omega_c + 2\pi B$ $\omega_c - 2\pi B$ ω_c $\omega_c + 2\pi B$ $2\omega_c$ ω

85
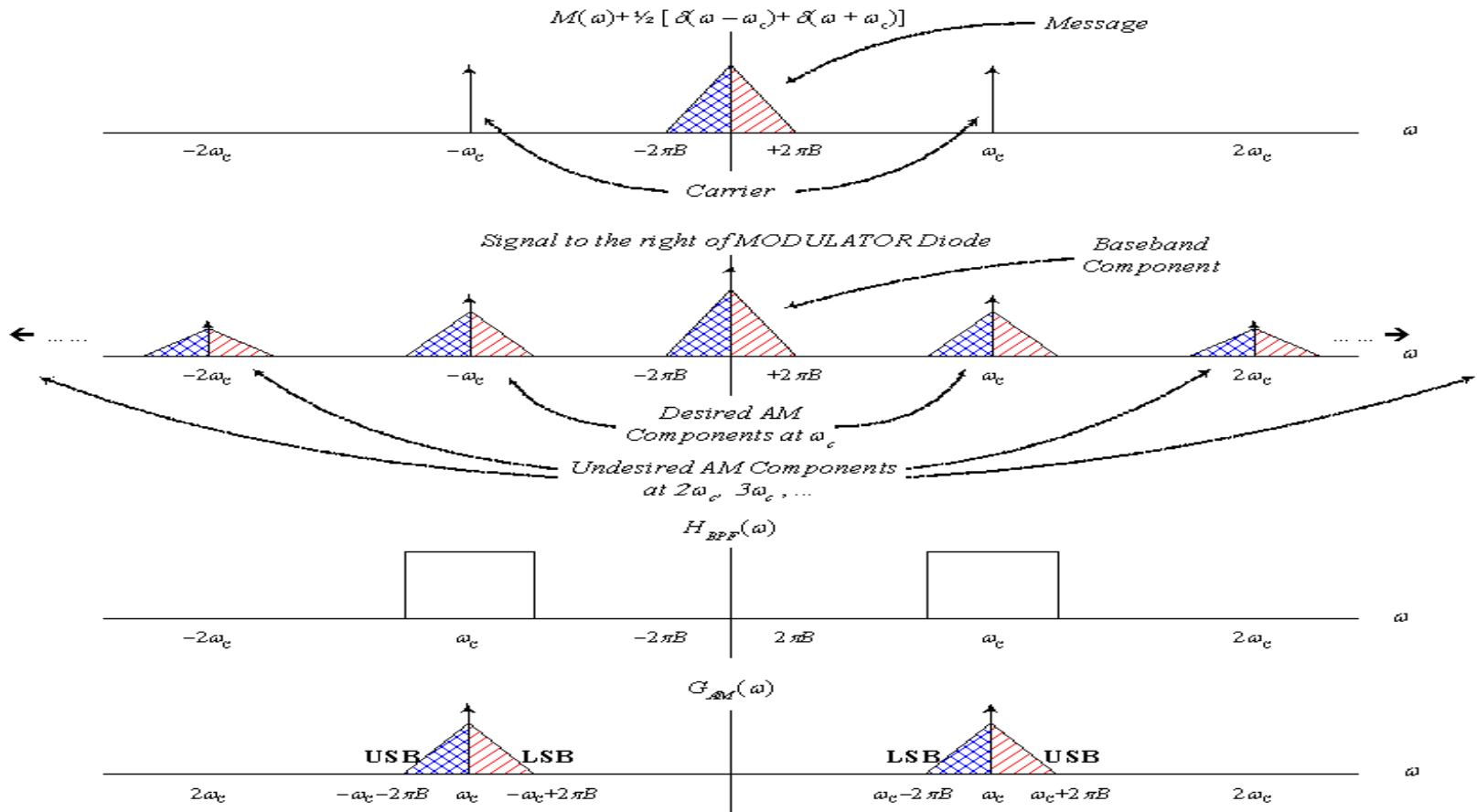
AM Demodulation: Rectifier Detector

- Because of the presence of a carrier term in the received signal, switching can be performed in the same way we did in the modulator.

The circuit shows a source $[A+m(t)]\cos(\omega_c t)$ connected through a diode to a resistor, then to an LPF block, followed by a capacitor C and resistor R, with output $m(t)$.
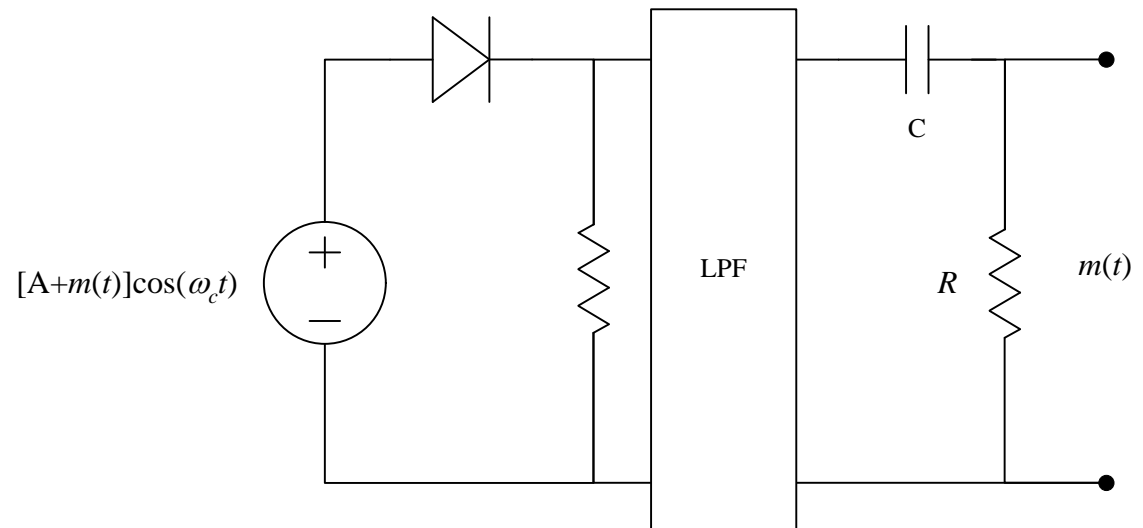
Rectifier Detector: Time Domain
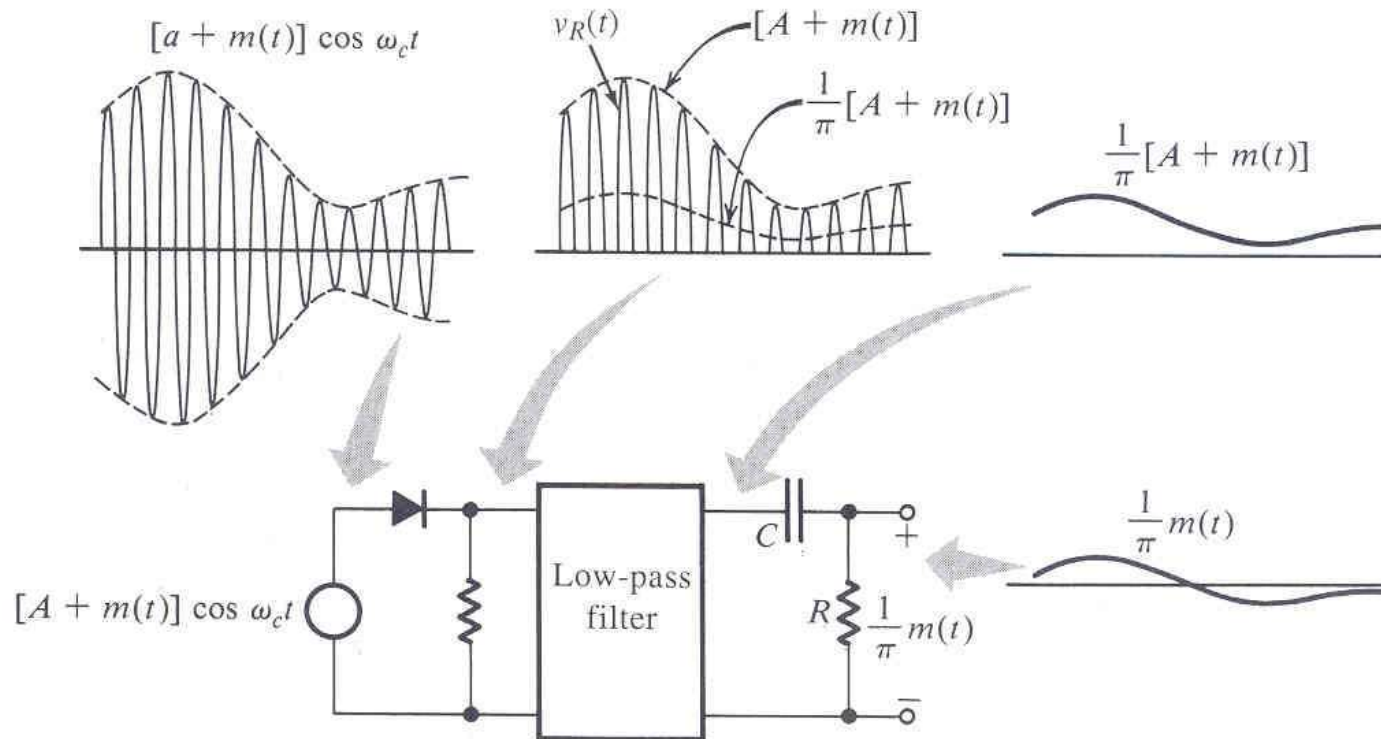
Figure 4.11   Rectifier detector for AM.

Rectifier Detector (Frequency Domain)

Envelope Detector

The circuit diagram shows an envelope detector with source $[A+m(t)]\cos(\omega_c t)$, a diode D, capacitor C, resistor R, and output $v_o(t)$.
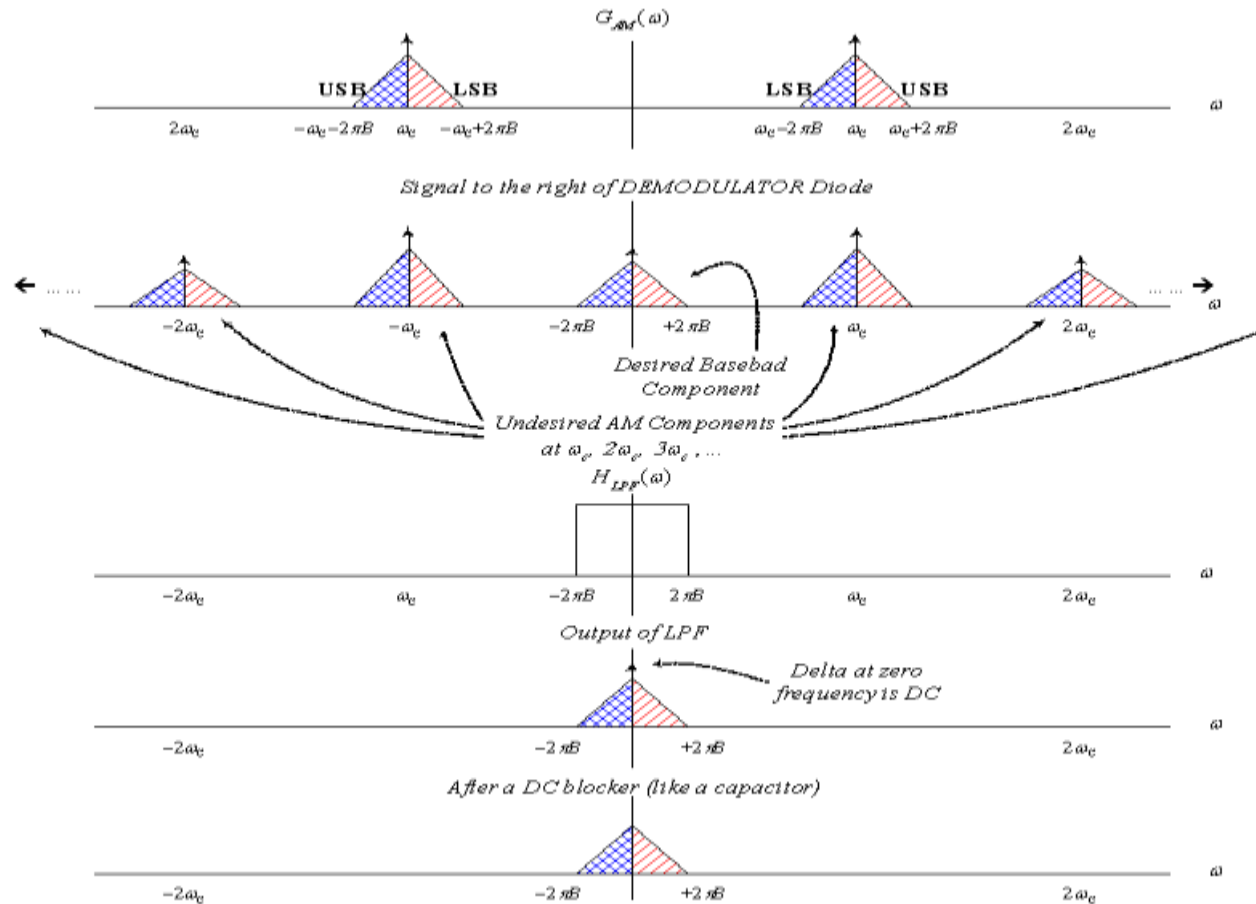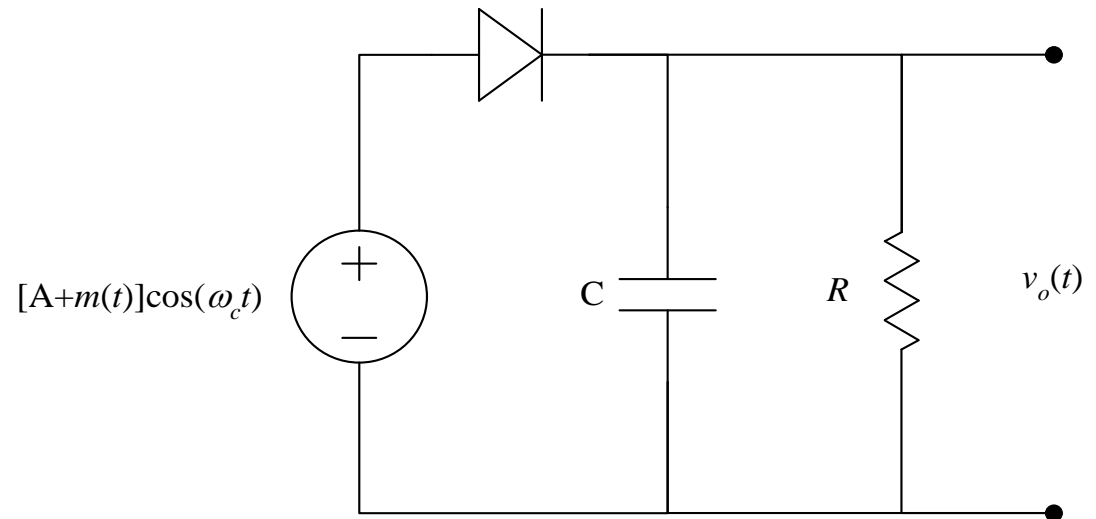
- When D is forward-biased, the capacitor charges and follows input.
- When D is reverse-biased, the capacitor discharges through R.

Envelope Detection

- The operations of the circuit requires careful selection of $\tau = RC$

- If *RC* is too large, discharging will be slow and the circuit cannot follow a decreasing envelope.

- When *RC* is too small the ripples will be high.

- $1/(2\pi B) \ll \tau \ll 1/\omega_c$

- The ripples are finally removed by LPF.

- The DC value is blocked by a capacitor.
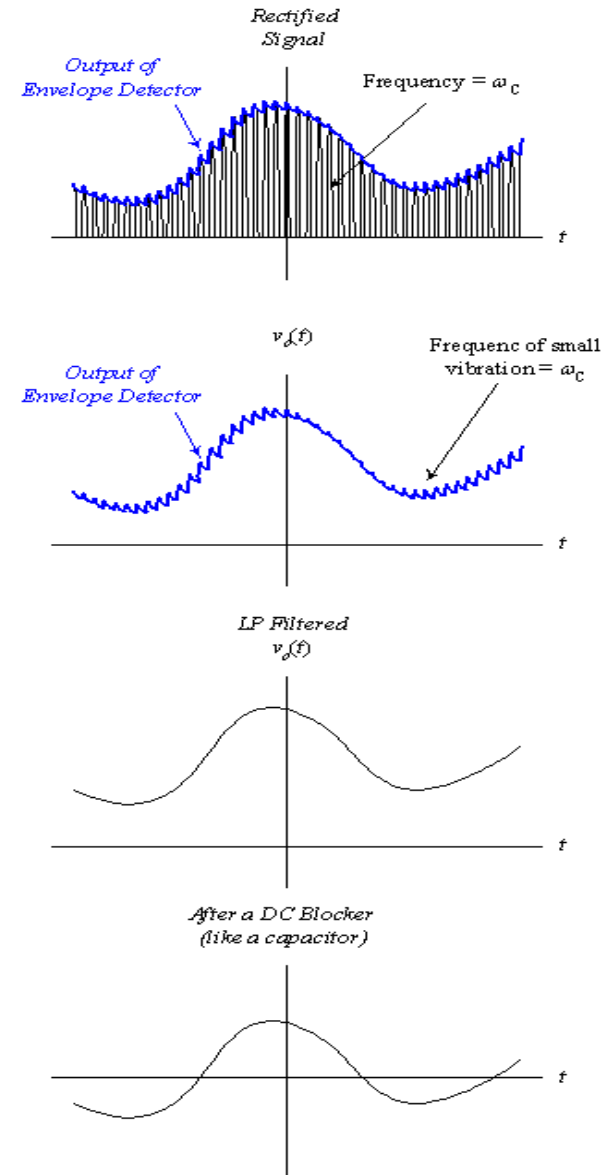
Quadrature Amplitude Modulation (QAM)

- In DSBSC or AM the modulated signal occupies double the bandwidth of the baseband signal.

- It is possible to send two signals over the same band, one modulated with a cosine and one with sine.

- Interesting enough, the two signals can be received separately after demodulation.

$$m_1(t)\cos^2(\omega_c t) + m_2(t)\sin(\omega_c t)\cos(\omega_c t)$$
$$= m_1(t)/2 + m_1(t)\cos(2\omega_c t)/2 + m_2(t)\sin(2\omega_c t)/2$$

Baseband   Around $2\omega_c$ Around $2\omega_c$

IN-PHASE
modulator branch

$m_1(t)$ ⟶ X ⟶ $m_1(t)\cos(\omega_c t)$

$\cos(\omega_c t)$

X

$H_{LPF}(\omega)$
BW $= 2\pi B$ ⟶ $m_1(t)/2$

$\cos(\omega_c t)$

IN-PHASE
demodulator branch

Phase Shifter
$-\pi/2$

$\sin(\omega_c t)$

Σ

Phase Shifter
$-\pi/2$

$\sin(\omega_c t)$

QUADRATURE
demodulator branch

$m_2(t)$ ⟶ X ⟶ $m_2(t)\sin(\omega_c t)$

QUADRATURE
modulator branch

$m_1(t)\cos(\omega_c t) + m_2(t)\sin(\omega_c t)$

X

$H_{LPF}(\omega)$
BW $= 2\pi B$ ⟶ $m_2(t)/2$

$$m_1(t)\sin(\omega_c t)\cos(\omega_c t) + m_2(t)\sin^2(\omega_c t)$$
$$= m_1(t)\sin(2\omega_c t)/2 + m_2(t)/2 - m_2(t)\cos(2\omega_c t)/2$$

Around $2\omega_c$ Baseband   Around $2\omega_c$

QAM Modulator/Demodulator

92

$m_1(t)\cos(\omega_c t)\cos[(\omega_c+\Delta\omega)t+\theta] + m_2(t)\sin(\omega_c t)\cos[(\omega_c+\Delta\omega)t+\theta]$
$=(1/2)[m_1(t)\cos(\Delta\omega t+\theta) + m_1(t)\cos(2\omega_c t+\Delta\omega t+\theta) - m_2(t)\sin(\Delta\omega t+\theta) + m_2(t)\sin(2\omega_c t+\Delta\omega t+\theta)]$

Baseband   Around $2\omega_c$ Baseband   Around $2\omega_c$

$m_1(t)\cos(\omega_c t)$

$m_1(t)$ → X

$\cos(\omega_c t)$

X $\boxed{\begin{array}{c} H_{LPF}(\omega) \\ BW = 2\pi B \end{array}}$ → $(1/2)[m_1(t)\cos(\Delta\omega t+\theta) - m_2(t)\sin(\Delta\omega t+\theta)]$

$\cos[(\omega_c+\Delta\omega)t+\theta]$

$\boxed{\begin{array}{c} \text{Phase Shifter} \\ -\pi/2 \end{array}}$

Σ

$\boxed{\begin{array}{c} \text{Phase Shifter} \\ -\pi/2 \end{array}}$

$\sin(\omega_c t)$

$\sin[(\omega_c+\Delta\omega)t+\theta]$

$m_2(t)$ → X

$m_2(t)\sin(\omega_c t)$

X $\boxed{\begin{array}{c} H_{LPF}(\omega) \\ BW = 2\pi B \end{array}}$ → $(1/2)[m_1(t)\sin(\Delta\omega t+\theta) + m_2(t)\cos(\Delta\omega t+\theta)]$

$m_1(t)\cos(\omega_c t) + m_2(t)\sin(\omega_c t)$

$m_1(t)\cos(\omega_c t)\sin[(\omega_c+\Delta\omega)t+\theta] + m_2(t)\sin(\omega_c t)\sin[(\omega_c+\Delta\omega)t+\theta]$
$=(1/2)[m_1(t)\sin(\Delta\omega t+\theta) + m_1(t)\sin(2\omega_c t+\Delta\omega t+\theta) + m_2(t)\cos(\Delta\omega t+\theta) - m_2(t)\cos(2\omega_c t+\Delta\omega t+\theta)]$

Baseband   Around $2\omega_c$ Baseband   Around $2\omega_c$

QAM Modulator/Demodulator with Demodulator Carrier Phase and/or Frequency Error

Single-Side Band (SSB) Modulation

- DSBSC (as well as AM) occupies double the bandwidth of the baseband signal, although the two sides carry the same information.

- Why not send only one side, the upper or the lower?

- **Modulation:** similar to DSBSC. Only change the settings of the BPF (center frequency, bandwidth).

- **Demodulation:** similar to DSBSC (coherent)

SSB Representation
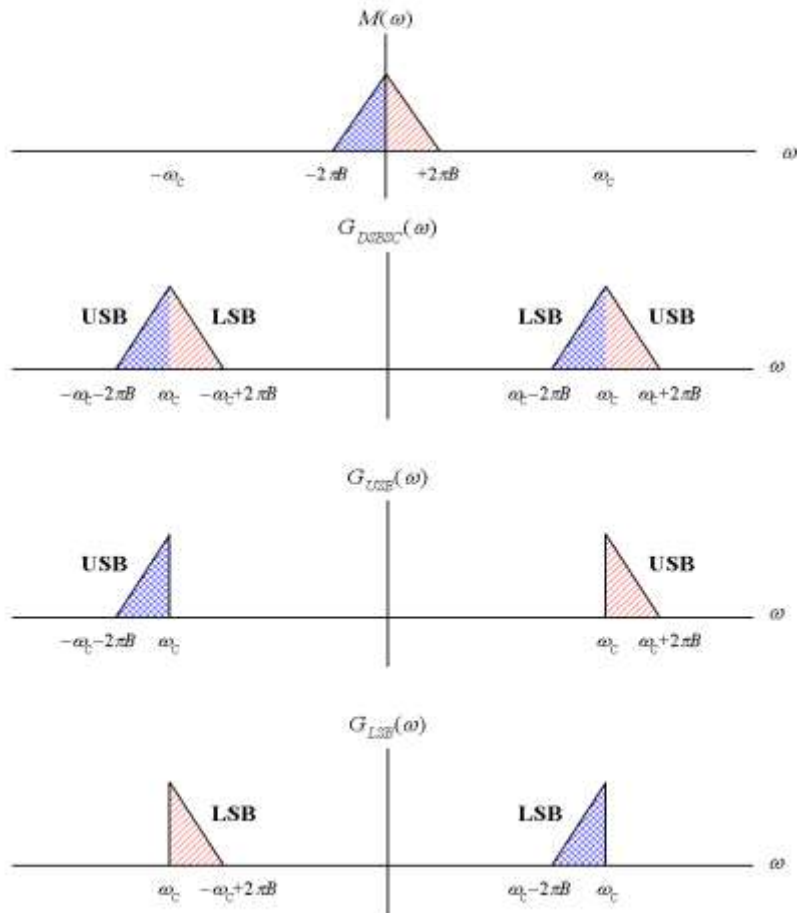
How would we represent the SSB signal in the time domain?

$g_{USB}(t) = ?$

$g_{LSB}(t) = ?$

Time-Domain Representation of SSB (1/2)

$M(\omega) = M_+(\omega) + M_-(\omega)$

Let $m_+(t) \leftrightarrow M_+(\omega)$ and $m_-(t) \leftrightarrow M_-(\omega)$

Then: $m(t) = m_+(t) + m_-(t)$ [linearity]

Because $M_+(\omega)$, $M_-(\omega)$ are not even

➜ $m_+(t)$, $m_-(t)$ are complex.
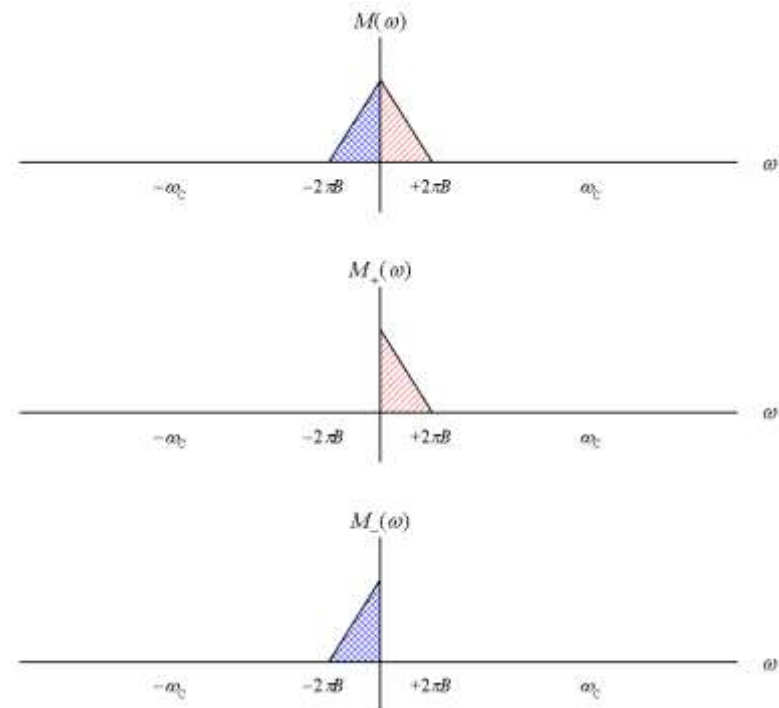
Since their sum is real they must be conjugates.

$m_+(t) = \frac{1}{2}[m(t) + j\, m_h(t)]$

$m_-(t) = \frac{1}{2}[m(t) - j\, m_h(t)]$

What is $m_h(t)$?

$M(\omega)$

$-\omega_c$ $-2\pi B$ $+2\pi B$ ω_c ω

$M_+(\omega)$

$-\omega_c$ $-2\pi B$ $+2\pi B$ ω_c ω

$M_-(\omega)$

$-\omega_c$ $-2\pi B$ $+2\pi B$ ω_c ω

Time-Domain Representation of SSB (2/2)

$M(\omega) = M_+(\omega) + M_-(\omega)$

$M_+(\omega) = M(\omega)u(\omega);\ M_-(\omega) = M(\omega)u(-\omega)$

$\text{sgn}(\omega)=2u(\omega) -1$ ➔ $u(\omega)= \frac{1}{2} + \frac{1}{2}\,\text{sgn}(\omega);\ u(-\omega) = \frac{1}{2} -\frac{1}{2}\,\text{sgn}(\omega)$

$M_+(\omega) = \frac{1}{2}[\, M(\omega) + M(\omega)\text{sgn}(\omega)]$

$M_-(\omega) = \frac{1}{2}\,[M(\omega)\ -\ M(\omega)\text{sgn}(\omega)]$

Comparing to:

$m_+(t) = \frac{1}{2}\,[m(t) + j\, m_h(t)] \longleftrightarrow \frac{1}{2}\,[M(\omega) + j\, M_h(\omega)]$

$m_-(t)\ = \frac{1}{2}\,[m(t) - j\, m_h(t)]\ \longleftrightarrow \frac{1}{2}\,[M(\omega) -\ j\, M_h(\omega)]$

We find

$M_h(\omega) = -\ j\, M(\omega)\cdot\text{sgn}(\omega)$ where $m_h(t) \longleftrightarrow M_h(\omega)$

Hilbert Transform

- $m_h(t)$ is known as the Hilbert Transform (HT) of $m(t)$.
- The transfer function of this transform is given by:
  $H(\omega) = -j\,\text{sgn}(\omega)$

$$|H(\omega)| = 1$$

$$1$$

$$\omega$$

$$H(\omega) = -j\,\text{sgn}(\omega)$$

$$j$$

$$\omega$$

$$-j$$

$$\theta_H(\omega) = -(\pi/2)\,\text{sgn}(\omega)$$

$$\pi/2$$

$$\omega$$

$$-\pi/2$$
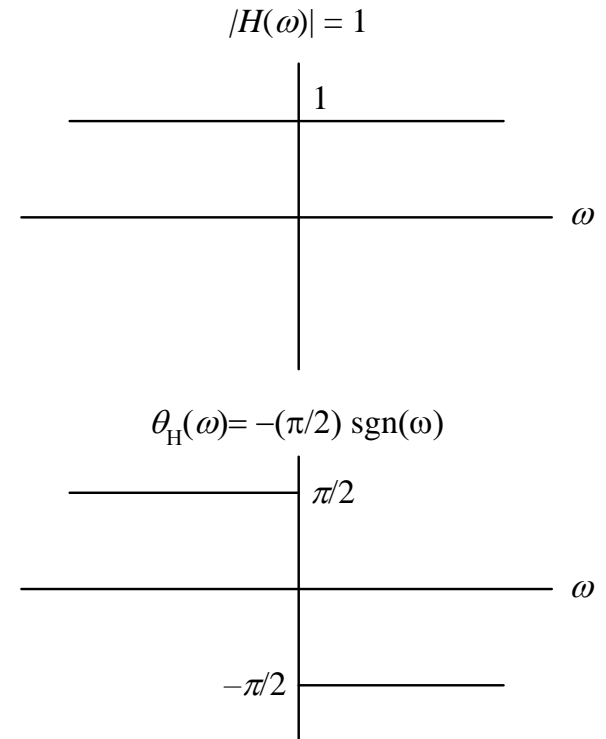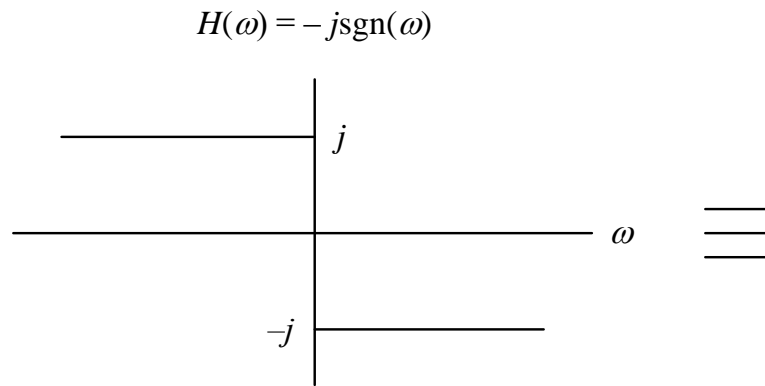
- It is basically a $\pi/2$ phase shifter

Hilbert Transform of cos($\omega_c t$)

$\cos(\omega_c t) \leftrightarrow \pi [\delta(\omega - \omega c) + \delta(\omega + \omega c)]$

$\text{HT}[\cos(\omega_c t)] \leftrightarrow -j \, \text{sgn}(\omega) \, \pi [\delta(\omega - \omega c) + \delta(\omega + \omega c)]$

$= j \, \text{sgn}(\omega) \, \pi [-\delta(\omega - \omega c) - \delta(\omega + \omega c)]$

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

$= j \, \pi [\delta(\omega + \omega c) - \delta(\omega - \omega c)] \leftrightarrow \sin(\omega_c t)$

Which is expected since:

$\cos(\omega_c t - \pi/2) = \sin(\omega_c t)$

Time-Domain Operation for Hilbert Transformation

For Hilbert Transformation $H(\omega) = -j\,\text{sgn}(\omega)$.

What is $h(t)$?

$\text{sgn}(t) \leftrightarrow 2/(j\omega)$ [From FT table]

$2/(jt) \leftrightarrow 2\pi\,\text{sgn}(-\omega)$ [symmetry]

$1/(\pi t) \leftrightarrow -j\,\text{sgn}(\omega)$

Since $M_h(\omega) = -\,j\,M(\omega)\cdot\text{sgn}(\omega) = H(\omega)\cdot M(\omega)$

Then
$$m_h(t) = \frac{1}{\pi t} * m(t)$$

$$= \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{m(\alpha)}{t-\alpha}d\alpha$$

Finally …

$$g_{USB}(t) = m_+(t)e^{j\omega_C t} + m_-(t)e^{-j\omega_C t}$$

$$g_{LSB}(t) = m_+(t)e^{-j\omega_C t} + m_-(t)e^{j\omega_C t}$$

$$g_{USB}(t) = \frac{1}{2}m(t)e^{j\omega_C t} + \frac{1}{2}jm_h(t)e^{j\omega_C t}$$

$$+ \frac{1}{2}m(t)e^{-j\omega_C t} - \frac{1}{2}jm_h(t)e^{-j\omega_C t}$$

$$= m(t)\cos(\omega_C t) - m_h(t)\sin(\omega_C t)$$

$$g_{LSB}(t) = \frac{1}{2}m(t)e^{j\omega_C t} - \frac{1}{2}jm_h(t)e^{j\omega_C t}$$

$$+ \frac{1}{2}m(t)e^{-j\omega_C t} + \frac{1}{2}jm_h(t)e^{-j\omega_C t}$$

$$= m(t)\cos(\omega_C t) + m_h(t)\sin(\omega_C t)$$
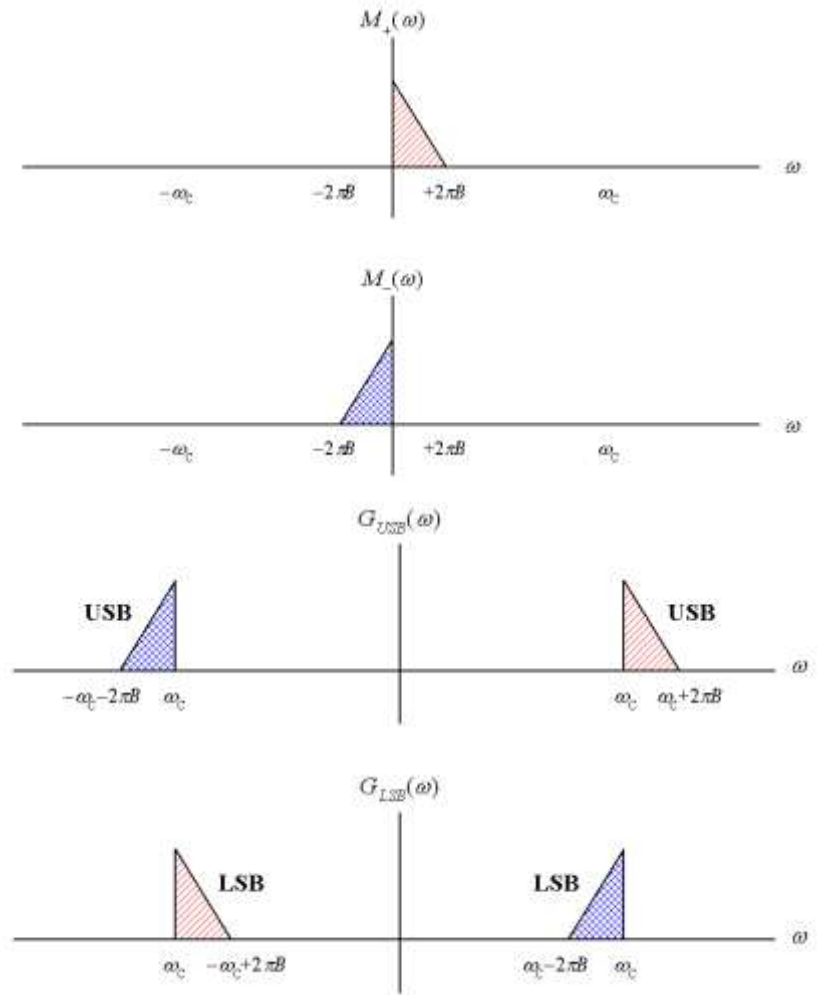
$$G_{USB}(\omega) = M_+(\omega - \omega_C) + M_-(\omega + \omega_C)$$

$$G_{LSB}(\omega) = M_+(\omega + \omega_C) + M_-(\omega - \omega_C)$$

101

Generation of SSB

- Selective Filtering Method
  Realization based on spectrum analysis

- Phase-Shift Method
  Realization based on time-domain expression of the modulated signal

Selective Filtering
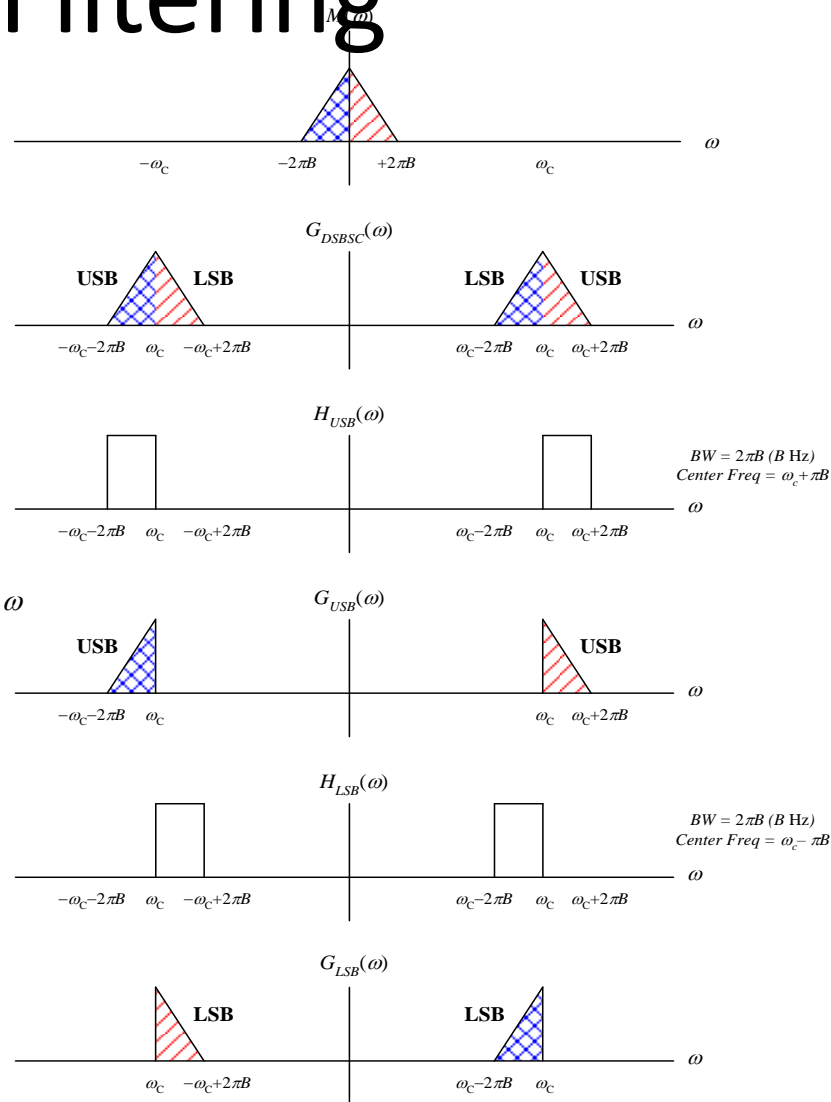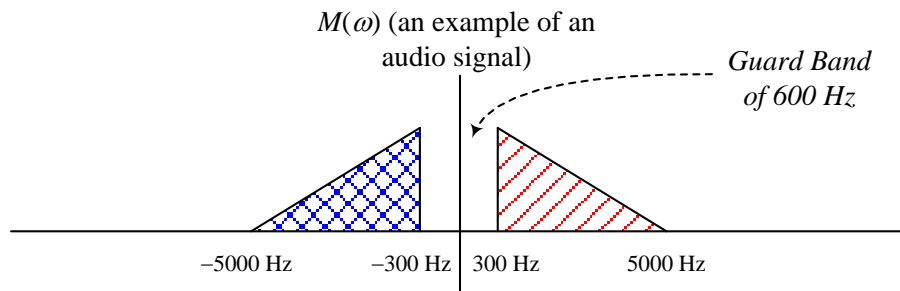
Phase Shifting

$$g_{USB}(t) = m(t)\cos(\omega_C t) - m_h(t)\sin(\omega_C t)$$
$$g_{LSB}(t) = m(t)\cos(\omega_C t) + m_h(t)\sin(\omega_C t)$$
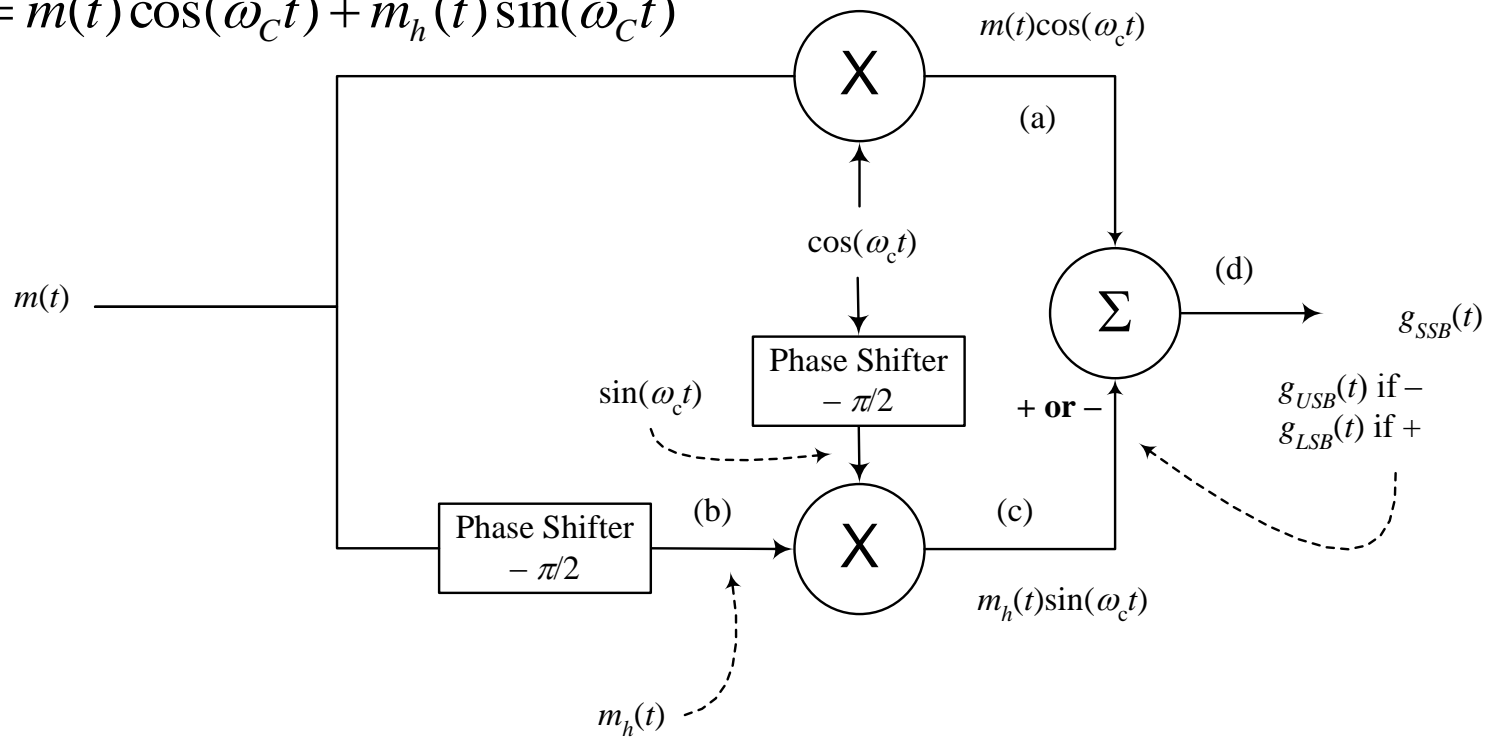
SSB Modulator

Phase-shifting Method: Frequency-Domain Illustration
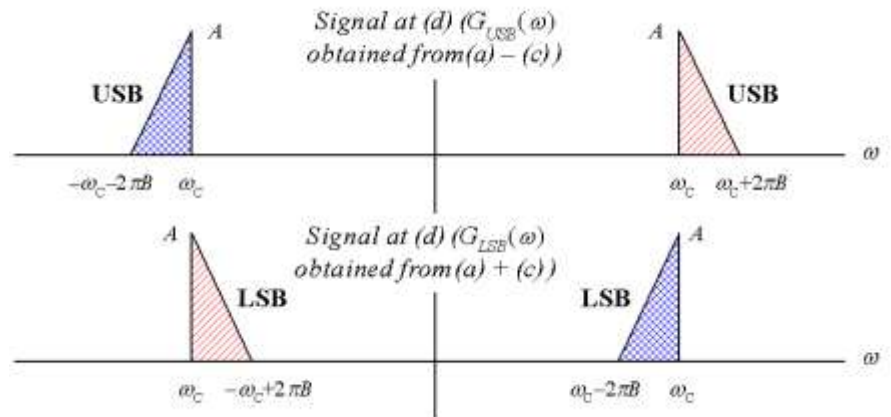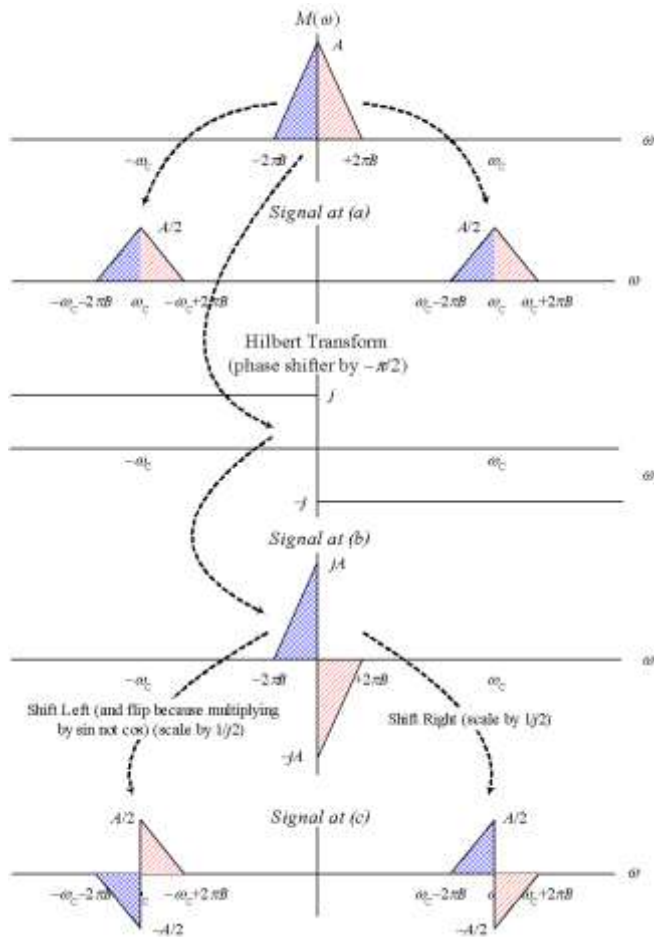
SSB Demodulation (Coherent)

$$g_{SSB}(t) = m(t)\cos(\omega_C t) \pm m_h(t)\sin(\omega_C t)$$

$$g_{SSB}(t)\cos(\omega_C t) = \frac{1}{2}m(t)[1 + \cos(2\omega_C t)] \pm \frac{1}{2}m_h(t)\sin(2\omega_C t)$$

$$\text{LPF Output} = \frac{1}{2}m(t)$$

$g_{SSB}(t)$
(Upper or Lower
Side bands)
→ X → $H_{LPF}(\omega)$ BW $= 2\pi B$ → $m(t)$

$\cos(\omega_c t)$
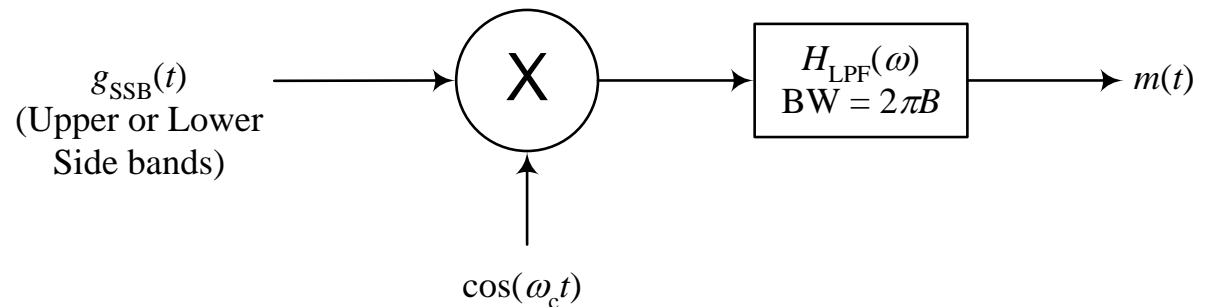
SSB Demodulator (receiver)

FDM in Telephony

- FDM is done in stages
  - Reduce number of carrier frequencies
  - More practical realization of filters
- Group: 12 voice channels $\times$ 4 kHz = 48 kHz occupy the band 60-108 kHz
- Supergroup: 5 groups $\times$ 48 kHz = 240 kHz occupy the band 312-552
- Mastergroup: 10 S-G $\times$ 240 kHz = 2400 kHz occupy the band 564-3084 kHz

FDM Hierarchy
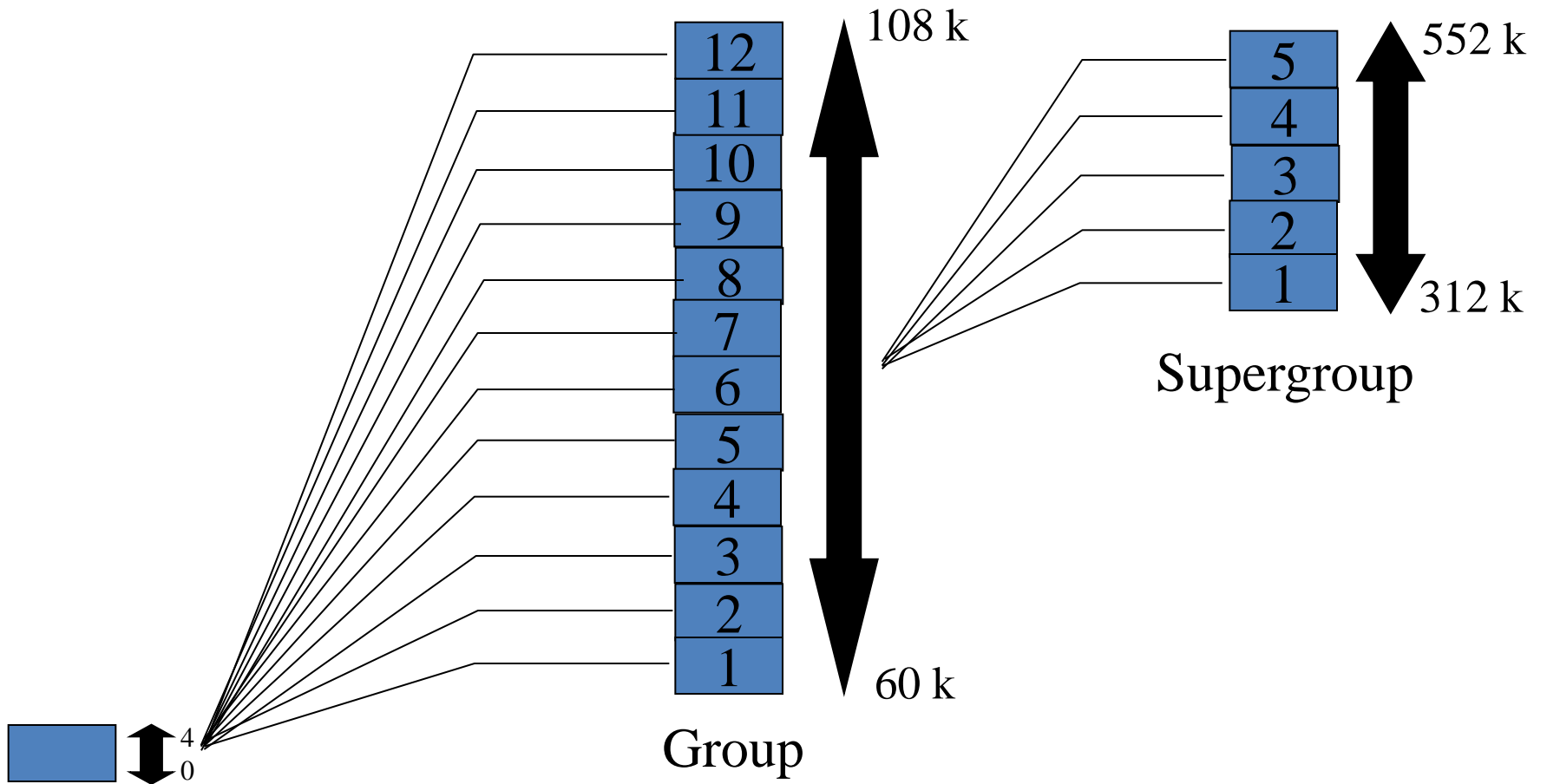
Vestigial Side Band Modulation (VSB)

- What if we want to generate SSB using selective filtering but there is no guard band between the two sides?
  ➜ We will filter-in a *vestige* of the other band.

- Can we still recover our message, without distortion, after demodulation?
  Yes. If we use a proper LPF.

Filtering Condition of VSB

$$g_{DSBSC}(t) = 2m(t)\cos(\omega_C t)$$

$$G_{DSBSC}(\omega) = M(\omega - \omega_C) + M(\omega + \omega_C)$$

$$G_{VSB}(\omega) = H_{VSB}(\omega)[M(\omega - \omega_C) + M(\omega + \omega_C)]$$

$$X(\omega) = H_{VSB}(\omega - \omega_C)\left[\underbrace{M(\omega - 2\omega_C)}_{at + 2\omega_C} + \underbrace{M(\omega)}_{Baseband}\right]$$

$$+ H_{VSB}(\omega + \omega_C)\left[\underbrace{M(\omega)}_{baseband} + \underbrace{M(\omega + 2\omega_C)}_{at - 2\omega_C}\right]$$

$$Z(\omega) = H_{LPF}(\omega)[H_{VSB}(\omega - \omega_C) + H_{VSB}(\omega + \omega_C)]M(\omega)$$

$$H_{LPF}(\omega) = \frac{1}{H_{VSB}(\omega - \omega_C) + H_{VSB}(\omega + \omega_C)} \quad ; |\omega| \leq 2\pi B$$

$m(t) \longrightarrow$ X $\xrightarrow{g_{DSBSC}(t)}$ $H_{VSB}(\omega)$ (BPF) $\longrightarrow g_{VSB}(t)$

$2\cos(\omega_c t)$

VSB Modulator (transmitter)

$g_{VSB}(t) \longrightarrow$ X $\xrightarrow{x(t)}$ $H_{LPF}(\omega)$ BW $= 2\pi B$ $\longrightarrow m(t)$

$2\cos(\omega_c t)$

VSB Demodulator (receiver)

110

$H_{VSB}(\omega)$

$-\omega_C$

ω_C

ω

Shifted filter components

ω

What happens outside the band of the demodulated signal is not important . So, the LPF does not have to inverse this part.

$H_{VSB}(\omega-\omega_c)+H_{VSB}(\omega+\omega_c)$

ω

Band of Signal

$H_{VSB}(\omega-\omega_c) = 1/[H_{VSB}(\omega-\omega_c)+H_{VSB}(\omega+\omega_c)]$
over the band of the signal only

ω

Band of Signal
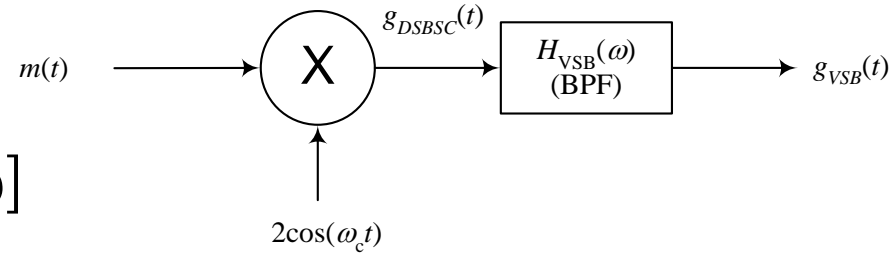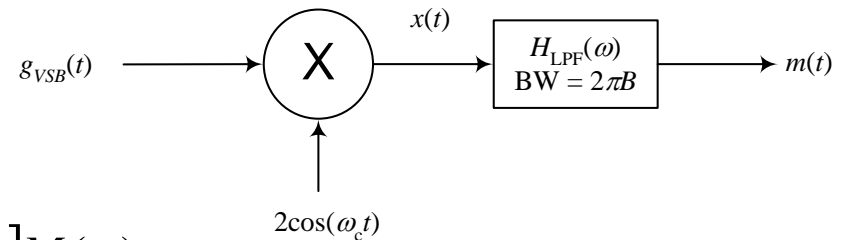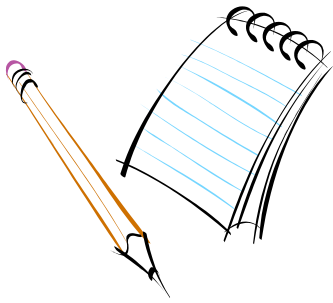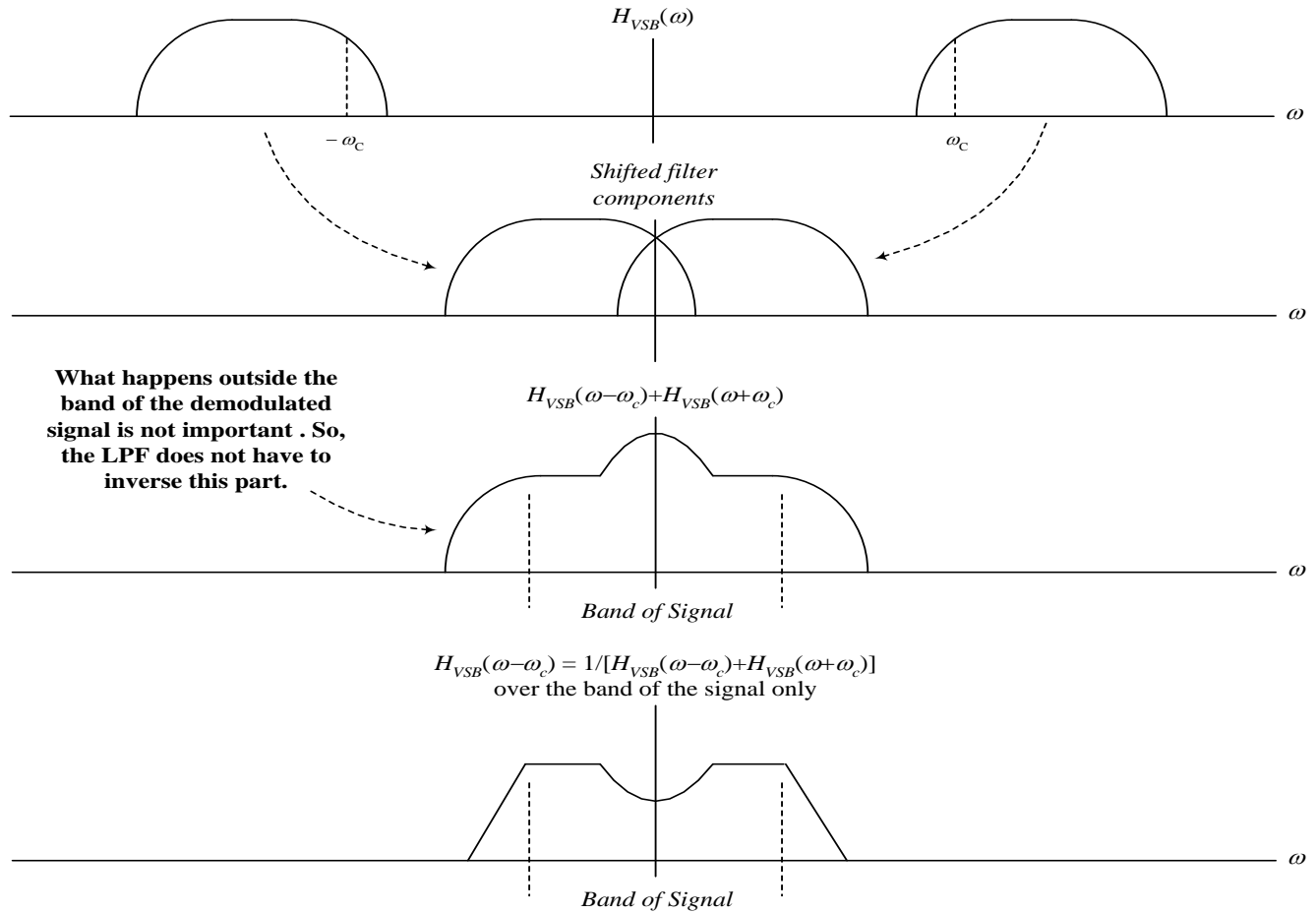
VSB Filter: Special Case

- Condition For distortionless demodulation:

$$H_{LPF}(\omega) = \frac{1}{H_{VSB}(\omega - \omega_C) + H_{VSB}(\omega + \omega_C)} \ ; \ |\omega| \le 2\,\pi\,B$$

- If we impose the condition on the filter at the modulator:

$$H_{VSB}(\omega - \omega_c) + H_{VSB}(\omega + \omega_c) = 1 \ ; \ |\omega| \le 2\,\pi\,B$$

Then $\quad H_{LPF} = 1$ for $|\omega| \le 2\,\pi\,B$ (Ideal LPF)

- $H_{VSB}(\omega)$ will then have odd symmetry around ω_c over the transition period.

$M(\omega)$

$-\omega_c$ $-2\pi B$ $+2\pi B$ ω_c

$G_{DSBSC}(\omega)$

$-\omega_c$ ω_c

$H_{VSB}(\omega)$

$2\pi B\ (B\ \text{Hz}) < BW < 4\pi B\ (2B\ \text{Hz})$

$-\omega_c$ ω_c

$G_{VSB}(\omega)$

$-\omega_c$ ω_c

$X(\omega)$

$-2\omega_c$ $-\omega_c$ ω_c $2\omega_c$

$H_{LPF}(\omega)$

$-\omega_c$ ω_c

$M(\omega)$

$-\omega_c$ ω_c

113
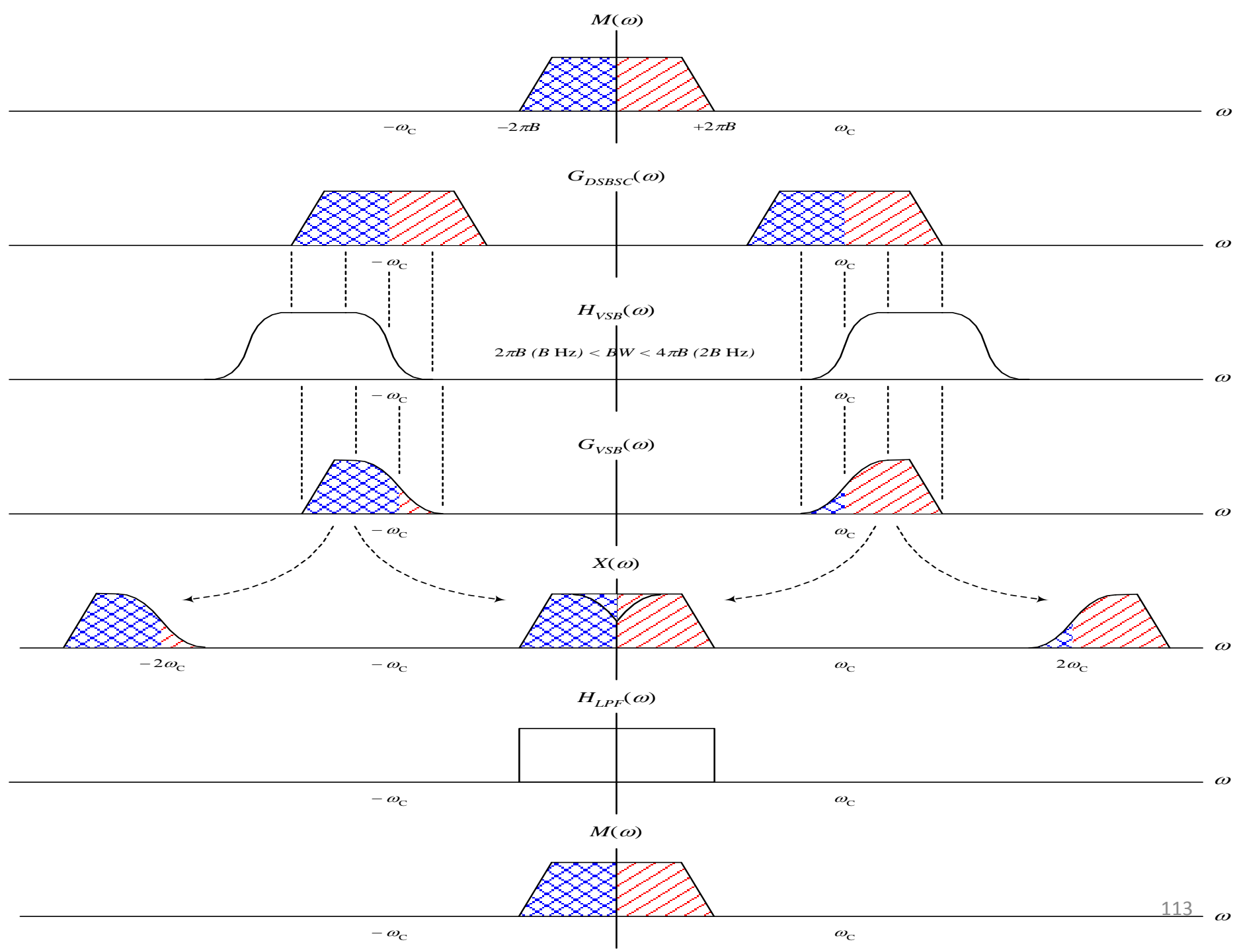
AM Broadcasting

- Allocated the band 530 kHz – 1600 kHz (with minor variations)

- 10 kHz per channel. (9 kHz in some countries)

- More that 100 stations can be licensed in the same geographical area.

- Uses AM modulation (DSB + C)

AM station Reception

- In theory, any station can be extracted from the stream of spectra by tuning the receiver BPF to its center frequency. Then demodulated.
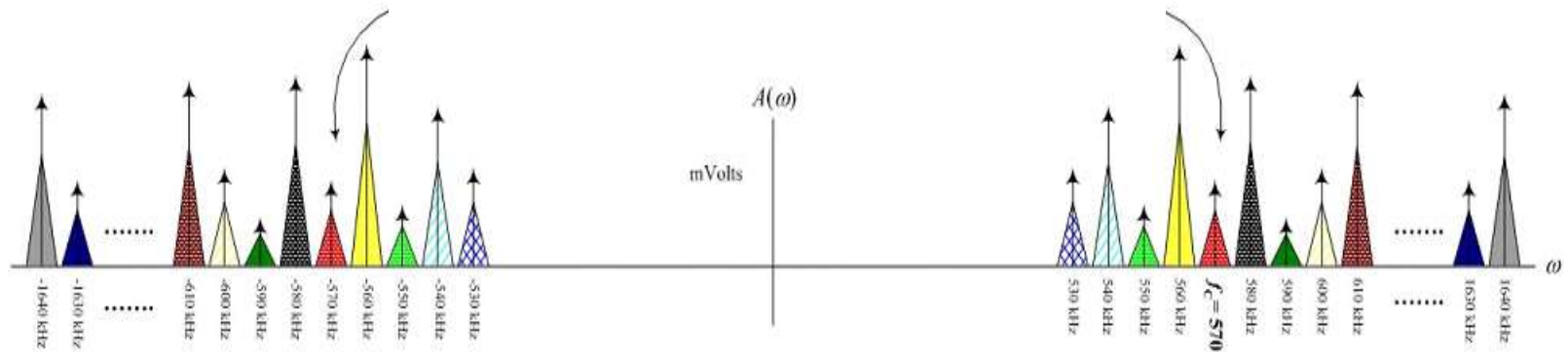
- Impracticalities:
  - Requires a BPF with very high Q-factor ($Q = f_c / B$).
  - Particularly difficult if the filter is to be tunable.

Solution: Superheterodyne receiver

- Step 1: **Frequency Translation from RF to IF**
  Shift the desired station to another fixed pass band
  (called Intermediate Frequency IF = 455 kHz)

- Step 2: **Bandpass Filtering at IF**
  Build a good BPF around IF to extract the desired station.
  It is more practical now, because IF is relatively low
  (reasonable Q) and the filter is not tunable.

- Step 3: **Demodulation**
  Use Envelope Detector

$B(\omega)$

10s of mVolts

530 kHz, 540 kHz, 550 kHz, 560 kHz, $f_c = 570\ kHz$, 580 kHz, 590 kHz, 600 kHz, 610 kHz, 1630 kHz, 1640 kHz

-1640 kHz, -1630 kHz, -610 kHz, -600 kHz, -590 kHz, -580 kHz, -570 kHz, -560 kHz, -550 kHz, -540 kHz, -530 kHz

A copy goes to some frequency here

A copy goes to some frequency here

$D(\omega)$

10s of mVolts

-1640 kHz, -1630 kHz, -610 kHz, -600 kHz, -590 kHz, -580 kHz, -570 kHz, -560 kHz, -550 kHz, -540 kHz, -530 kHz, -455 kHz, $f_{IF} = 455\ kHz$, 530 kHz, 540 kHz, 550 kHz, 560 kHz, $f_c = 570\ kHz$, 580 kHz, 590 kHz, 600 kHz, 610 kHz, 1630 kHz, 1640 kHz

A copy goes to some other frequency here

A copy goes to some frequency here

IF BPF & Amplifier

Relatively high amplifier gain (50 to 100)

IF Filter location is fixed at f_{IF}=455 kHz and has a bandwidth of 10 kHz. The amplifier gain is relatively high. The channel of interest is always shifted here.

-455 kHz, $f_{IF} = 455\ kHz$

$E(\omega)$

Volts

-455 kHz, $f_{IF} = 455\ kHz$

117

The Local Oscillator

- What should be the frequency of the local oscillator used for translation from RF to IF?

$$f_{LO} = f_c + f_{IF} \qquad \text{(up-conversion)}$$
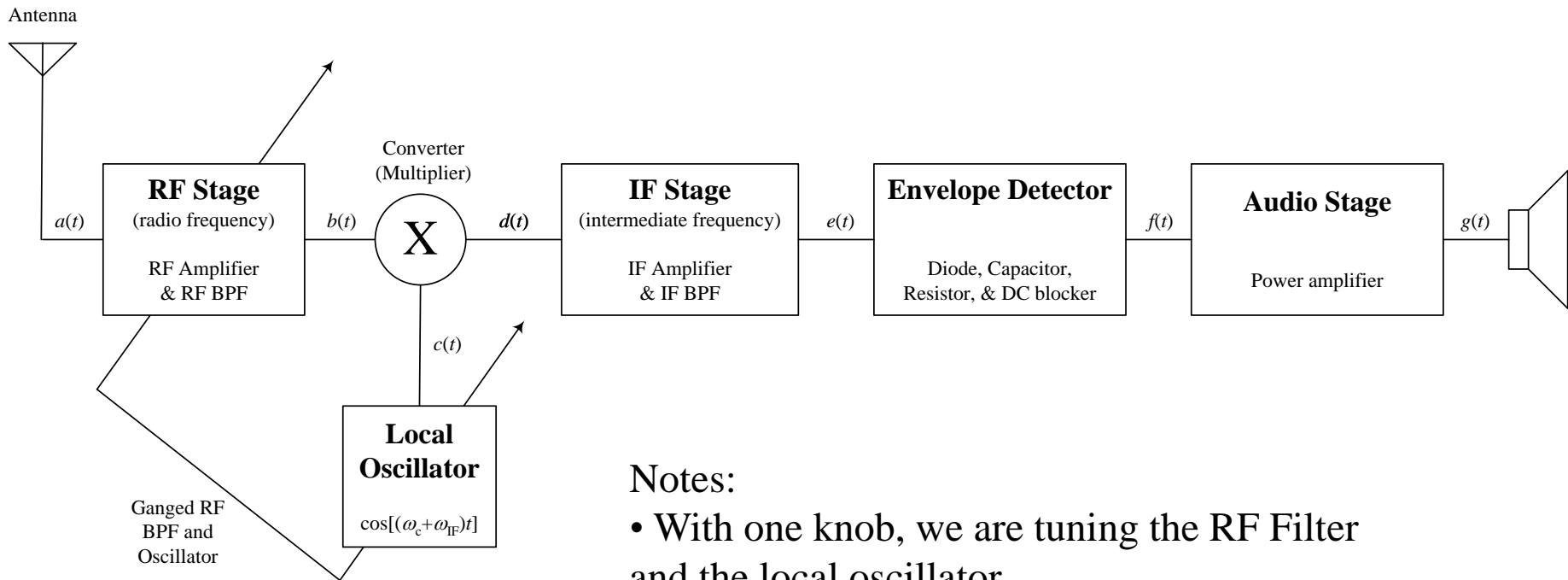
or

$$f_{LO} = f_c - f_{IF} \qquad \text{(down-conversion)}$$

- Tuning ratio = $f_{LO,\,max} / f_{LO,\,min}$

- Up-Conversion: $(1600 + 455) / (530 + 455) \approx 2$

- Down-Conversion: $(1600 - 455) / (530 - 455) \approx 12$

- Easier to design oscillator with small tuning ratio.

Image Station Problem

- While up-converting the desired station to IF, we are, at the same time, down-converting another station to IF as well.

- These two stations are called *image stations*, and they are spaced by 2x455=910kHz.

- Solution:
  Before conversion, use a BPF (at RF) centered at f_c of the desired station.
  The purpose of the filter is NOT to extract the desired station, but to suppress its image. Hence, it does not have to be very sharp.
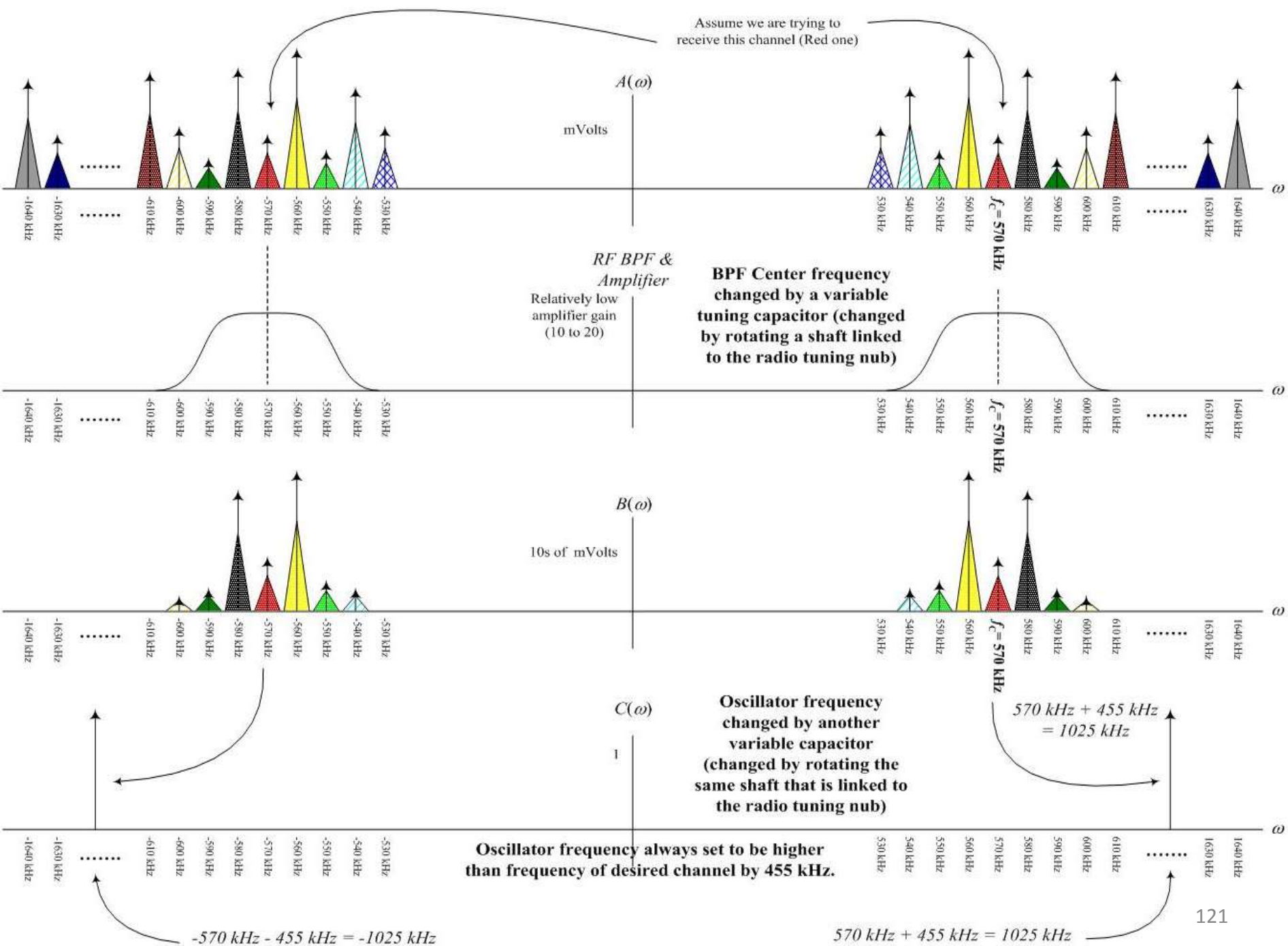
Superheterodyne Receiver Block Diagram

Antenna

RF Stage
(radio frequency)

RF Amplifier
& RF BPF

$a(t)$

$b(t)$

Converter
(Multiplier)

X

$d(t)$

IF Stage
(intermediate frequency)

IF Amplifier
& IF BPF

$e(t)$

Envelope Detector

Diode, Capacitor,
Resistor, & DC blocker

$f(t)$

Audio Stage

Power amplifier

$g(t)$

$c(t)$

Local
Oscillator

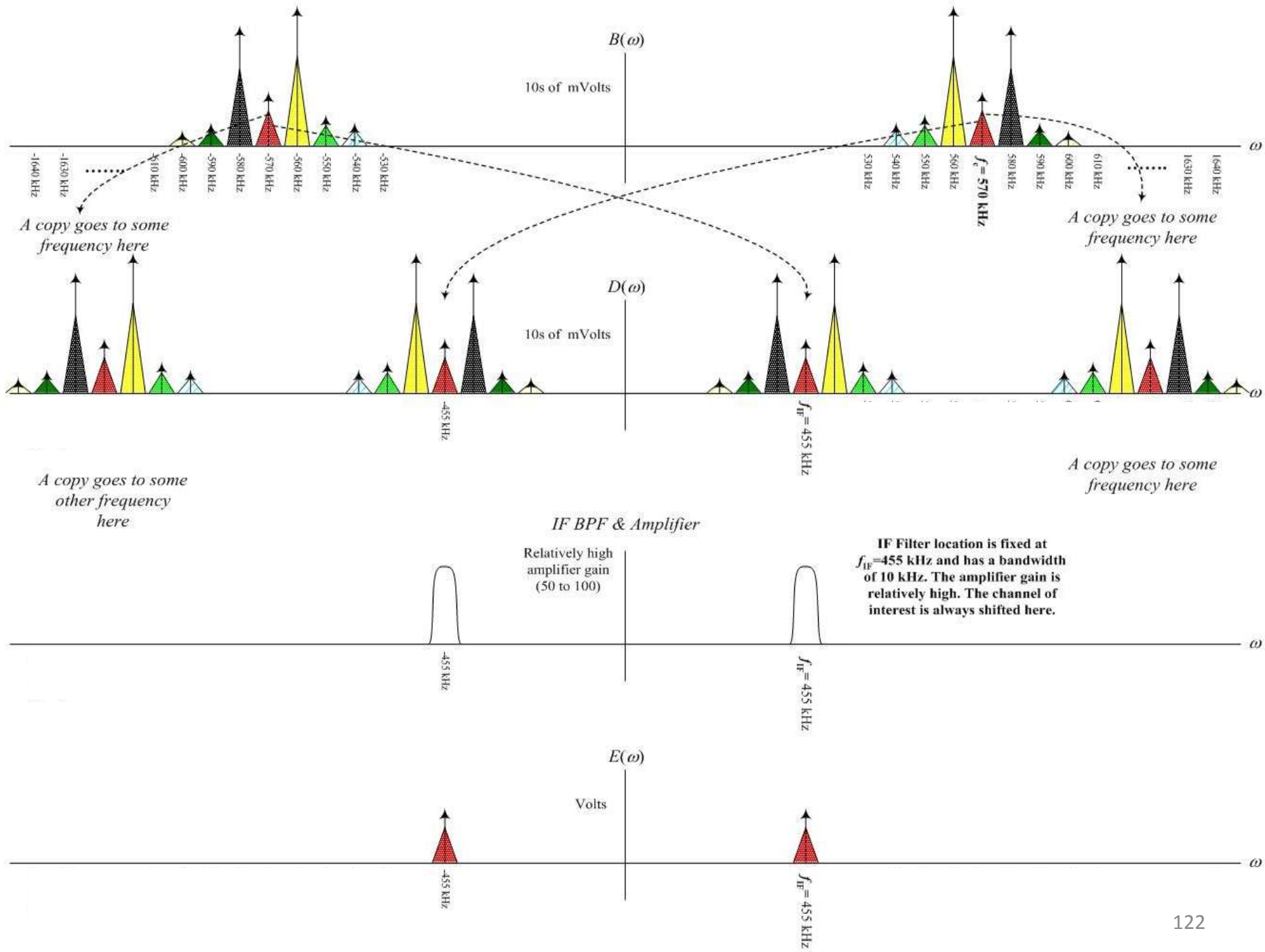$\cos[(\omega_c + \omega_{IF})t]$

Ganged RF
BPF and
Oscillator

Notes:
- With one knob, we are tuning the RF Filter and the local oscillator.
- The filter are designed with high gain to provide amplification as well.

Assume we are trying to receive this channel (Red one)

$A(\omega)$

mVolts

-1640 kHz, -1630 kHz, ..., -610 kHz, -600 kHz, -590 kHz, -580 kHz, -570 kHz, -560 kHz, -550 kHz, -540 kHz, -530 kHz

530 kHz, 540 kHz, 550 kHz, 560 kHz, $f_C = 570$ kHz, 580 kHz, 590 kHz, 600 kHz, 610 kHz, ..., 1630 kHz, 1640 kHz

RF BPF & Amplifier

Relatively low amplifier gain (10 to 20)

BPF Center frequency changed by a variable tuning capacitor (changed by rotating a shaft linked to the radio tuning nub)

$f_C = 570$ kHz

$B(\omega)$

10s of mVolts

$C(\omega)$

1

Oscillator frequency changed by another variable capacitor (changed by rotating the same shaft that is linked to the radio tuning nub)

570 kHz + 455 kHz = 1025 kHz

Oscillator frequency always set to be higher than frequency of desired channel by 455 kHz.

-570 kHz - 455 kHz = -1025 kHz

570 kHz + 455 kHz = 1025 kHz

121

$B(\omega)$

10s of mVolts

-1640 kHz -1630 kHz -610 kHz -600 kHz -590 kHz -580 kHz -570 kHz -560 kHz -550 kHz -540 kHz -530 kHz

530 kHz 540 kHz 550 kHz 560 kHz f_c = 570 kHz 580 kHz 590 kHz 600 kHz 610 kHz 1630 kHz 1640 kHz

A copy goes to some frequency here

A copy goes to some frequency here

$D(\omega)$

10s of mVolts

-455 kHz

f_{IF} = 455 kHz

A copy goes to some other frequency here

A copy goes to some frequency here

IF BPF & Amplifier

Relatively high amplifier gain (50 to 100)

IF Filter location is fixed at f_{IF}=455 kHz and has a bandwidth of 10 kHz. The amplifier gain is relatively high. The channel of interest is always shifted here.

-455 kHz

f_{IF} = 455 kHz

$E(\omega)$

Volts

-455 kHz

f_{IF} = 455 kHz

122

-Multiplexing: Simultaneous transmission of multiple signals across a single data link.

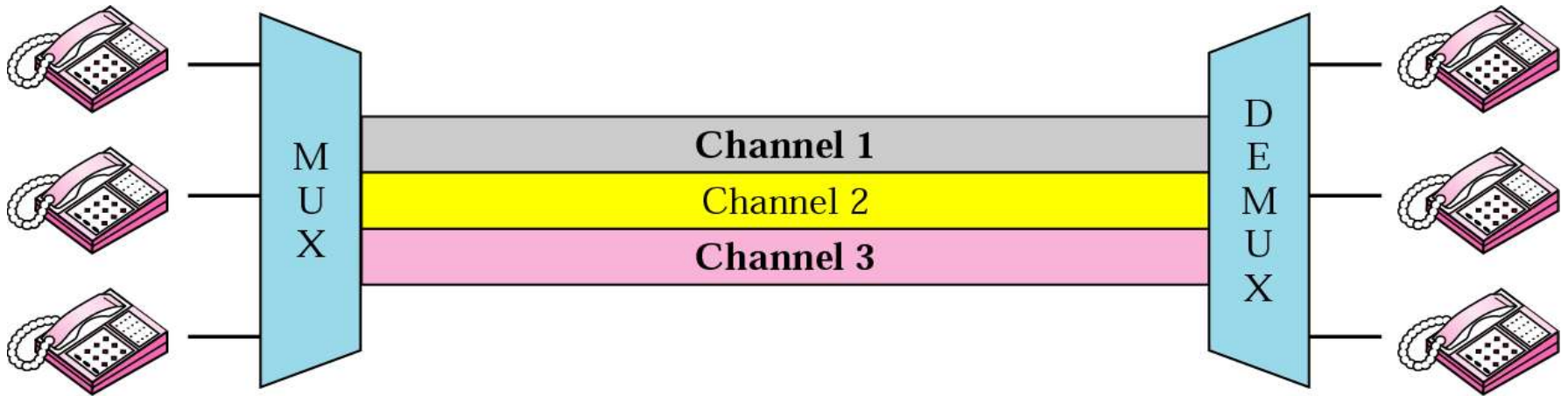-In a multiplexed system, *n* lines share the bandwidth of one link.

1 link, 4 channels

M U X

D E M U X

Dividing a link into channels
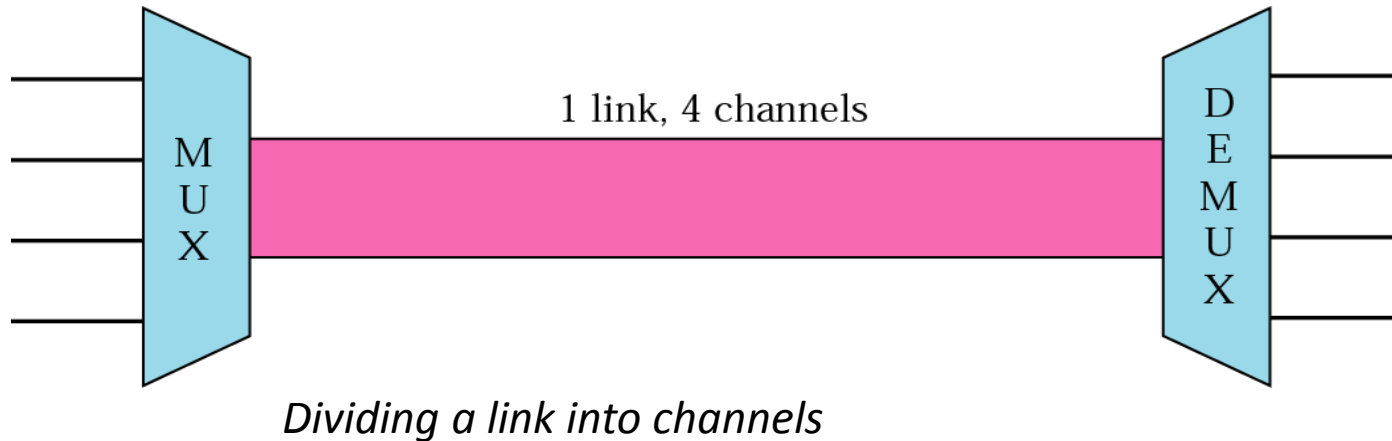
- Link: The physical path.

- Channel: Portion of link that carries a transmission between a pair of lines.

- One link can have many (*n*) channels.

FDM (Frequency-division multiplexing)
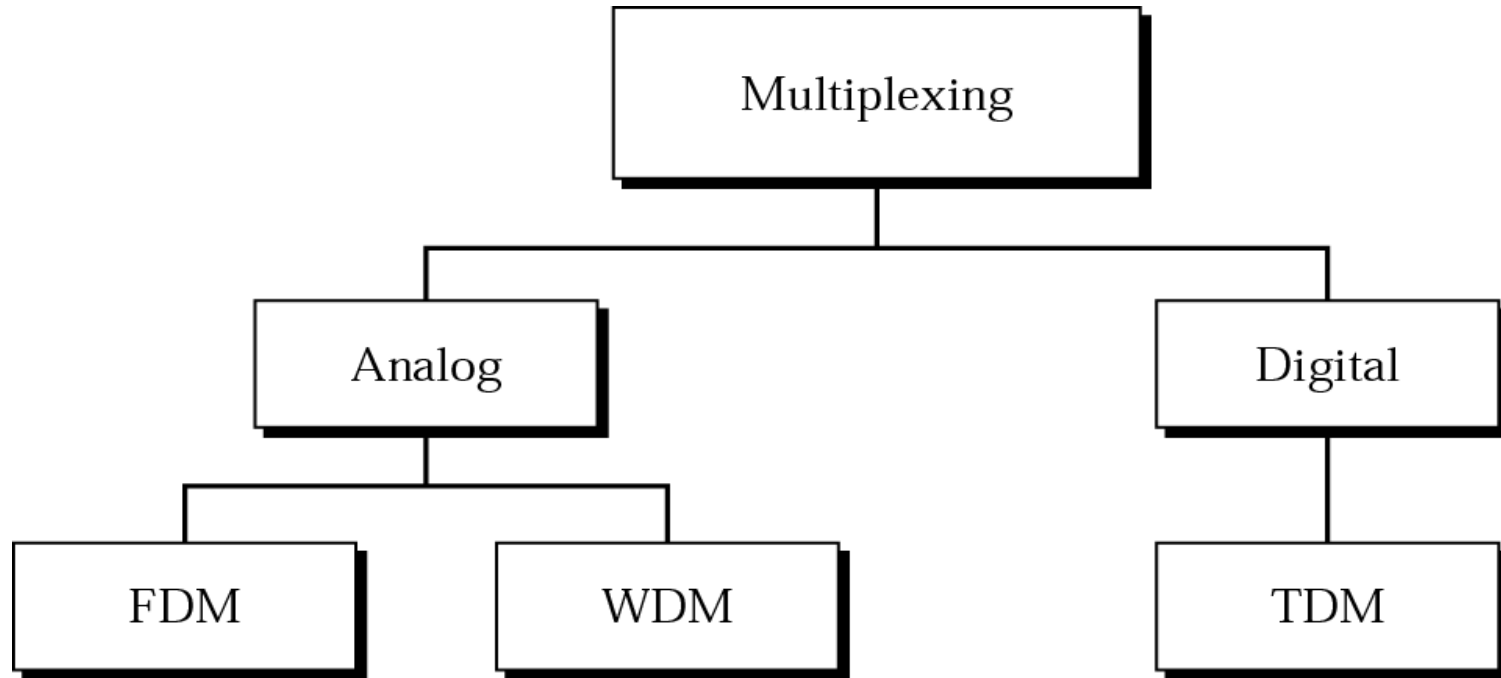
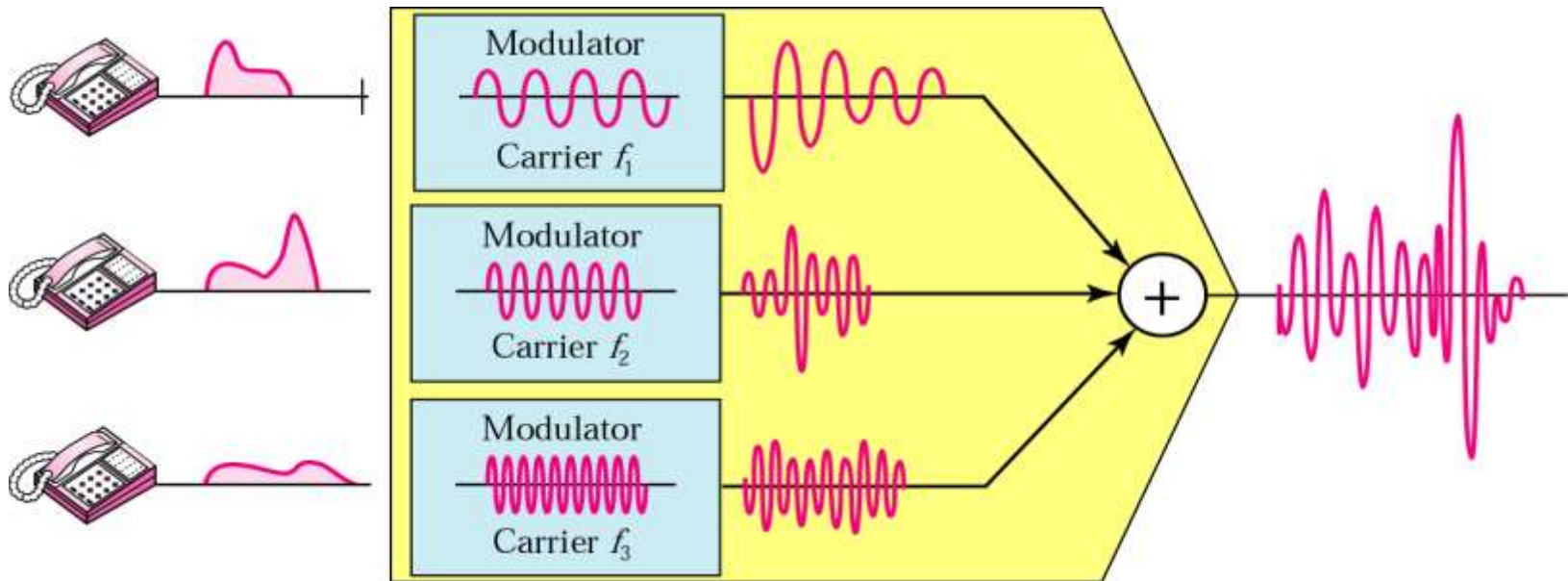
Categories of multiplexing

FDM (Frequency-division multiplexing)

FDM

- Channels must be separated by guard band to prevent signals from overlapping.

- Carrier frequencies must not interfere with the original data frequencies.

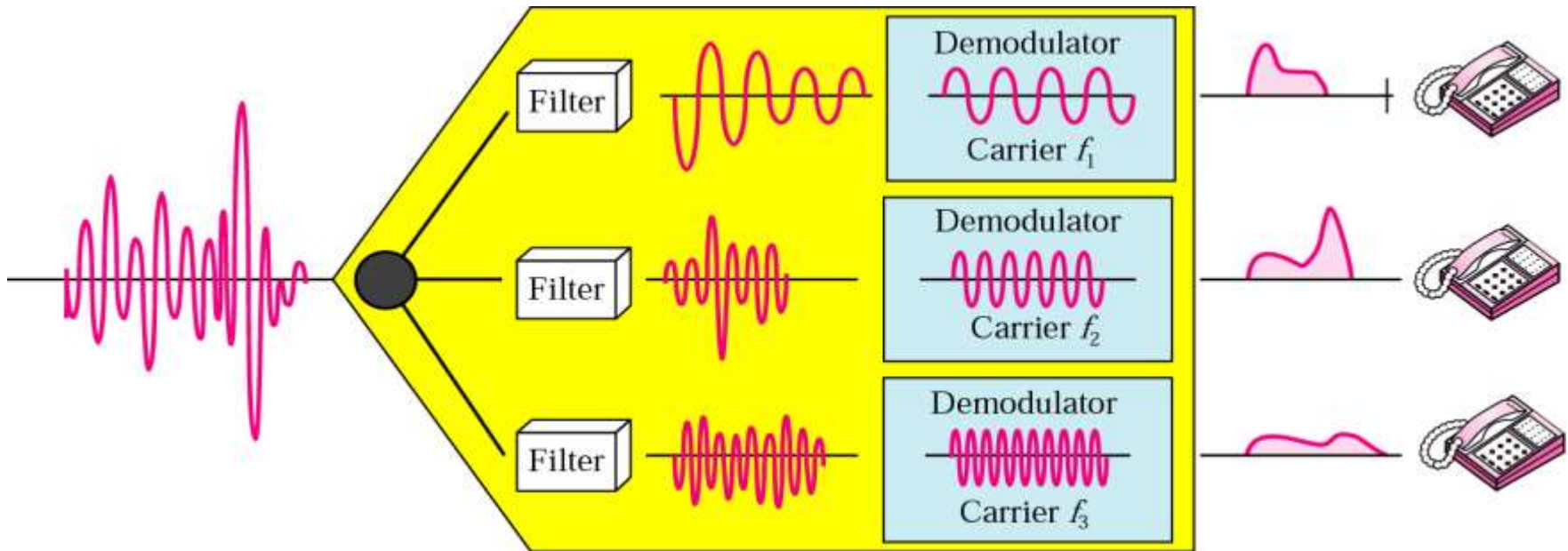# FDM (Frequency-division multiplexing)c

(1) Multiplexing Process

FDM process

- Each telephone generates a signal of similar frequency range.
- Signals are modulated onto different carrier frequencies(f_1, f_2 and f_3).

FDM (Frequency-division multiplexing)

(2) Demultiplexing Process

- Demultiplexer uses a series of filters to decompose the multiplexed signal.


FDM demultiplexing example

Example 1

Assume that a voice channel occupies a bandwidth of 4 KHz. We need to combine three voice channels into a link with a bandwidth of 12 KHz, from 20 to 32 KHz. Show the configuration using the frequency domain without the use of guard bands.

Solution

Shift (modulate) each of the three voice channels to a different bandwidth, as shown in Figure 6.6

FDM (Frequency-division multiplexing)

Shift and combine

Higher bandwidth link

Filter and shift
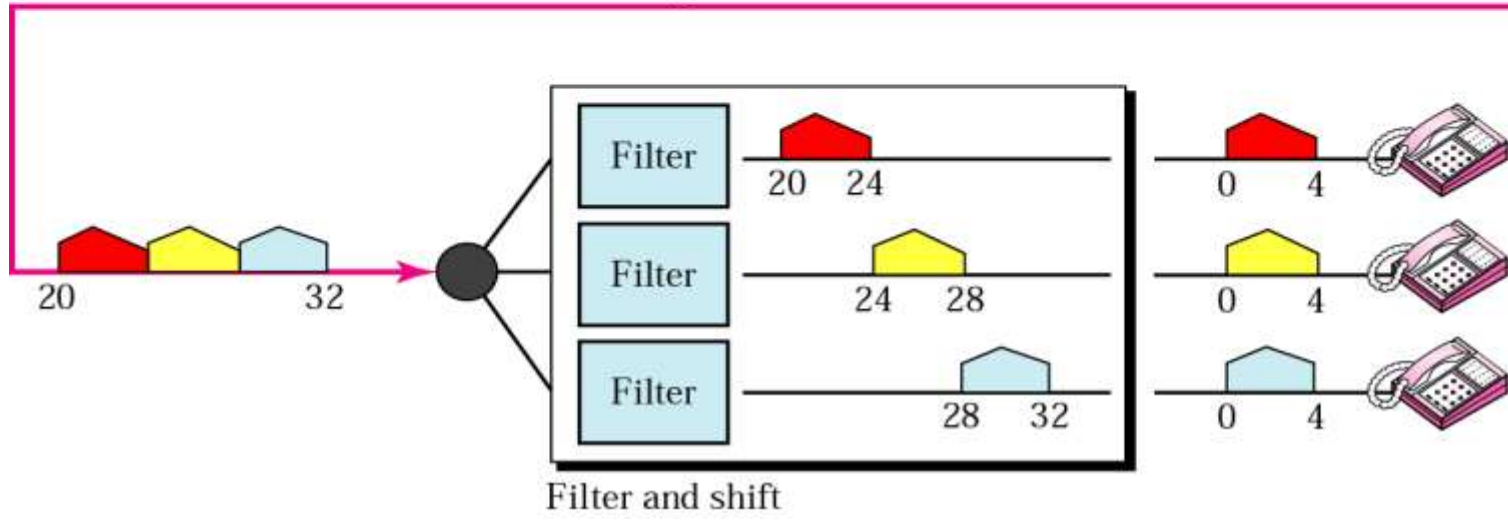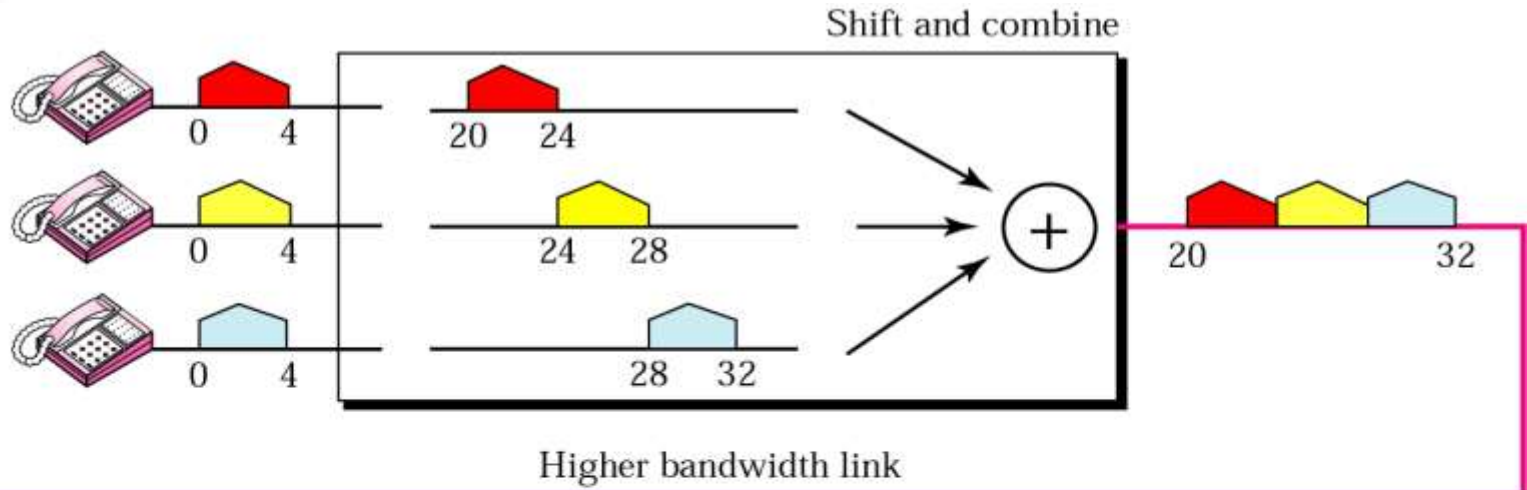
Example 2

Five channels, each with a 100-KHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 KHz between the channels to prevent interference?
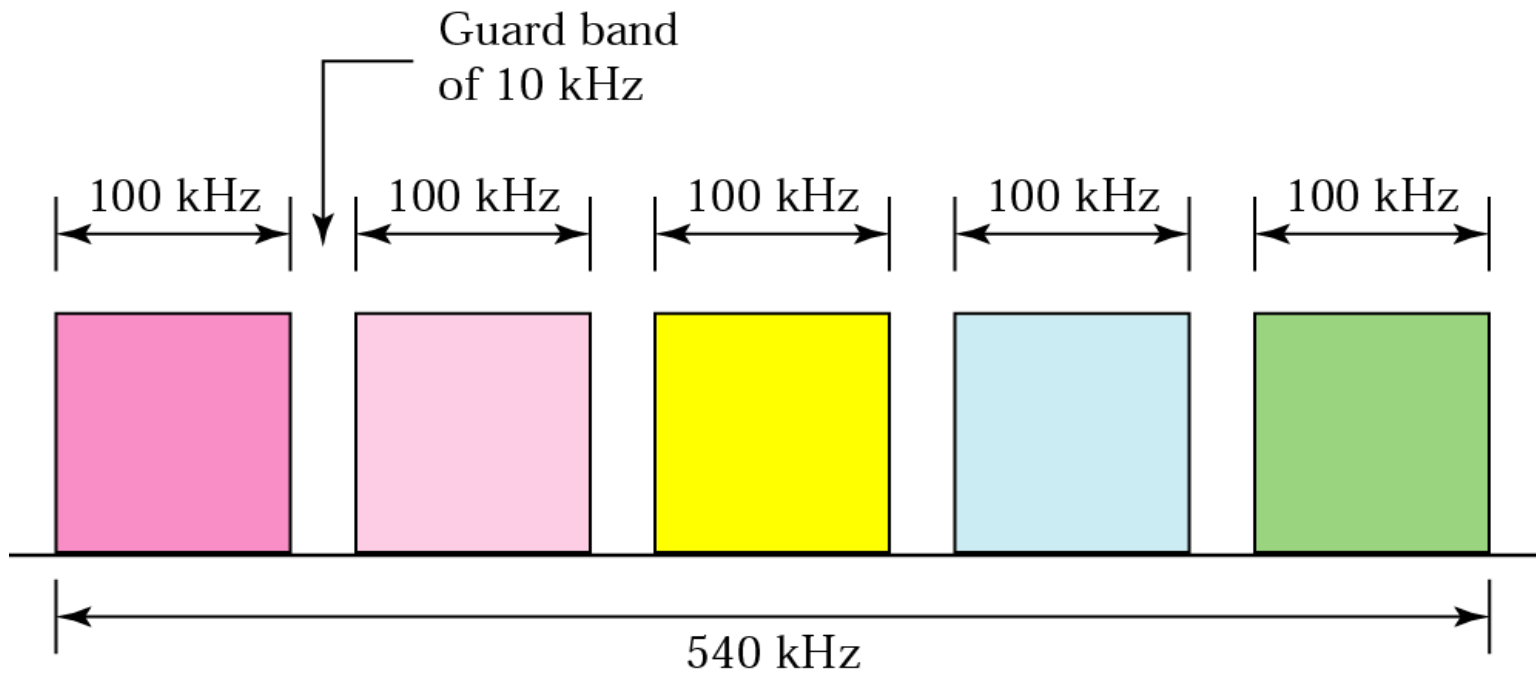
Solution

For five channels, we need at least four guard bands. This means that the required bandwidth is at least

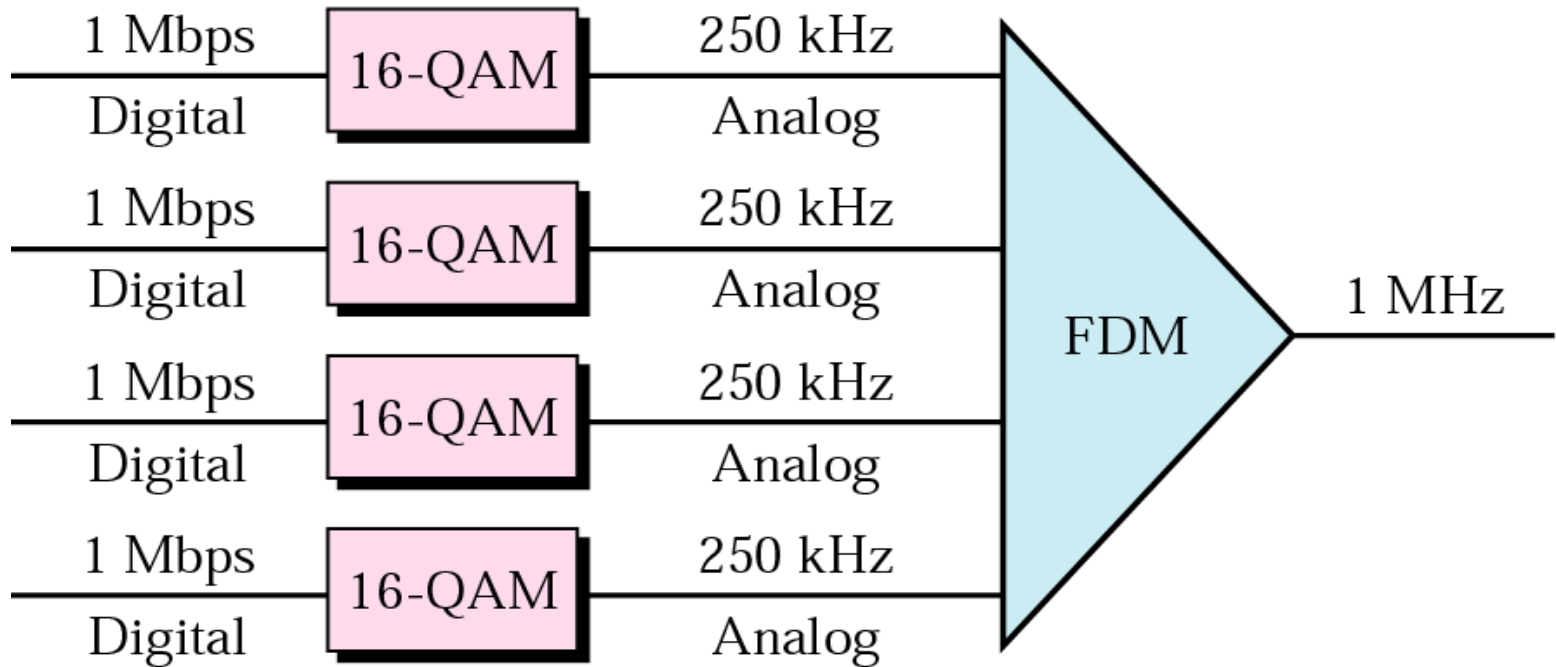$$5 \times 100 + 4 \times 10 = 540 \text{ KHz,}$$

as shown in Figure 6.7

Example 2

Example 3

Four data channels (digital), each transmitting at 1 Mbps, use a satellite channel of 1 MHz. Design an appropriate configuration using FDM

Solution

The satellite channel is analog. We divide it into four channels, each channel having a 250-KHz bandwidth. Each digital channel of 1 Mbps is modulated such that each 4 bits are modulated to 1 Hz. One solution is 16-QAM modulation. Figure 6.8 shows one possible configuration.

Example 3