Lecture 17:Modulation, Broadcast Radio*

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Abstract

Modulation is widely used to encode a signal so as to more effectively utilize it. Modulation is fundamental to electronic communication systems—radio, TV, satellite communications, cell phones, etc.

Lecture #17:
MODULATION, BROADCAST RADIO
Motivation:

- Modulation is widely used to encode a signal so as to more effectively utilize it.
- Modulation is fundamental to electronic communication systems—radio, TV, satellite communications, cell phones, etc.

Outline:

- General description of modulation
- Amplitude modulation
- Broadcast AM radio
- Conclusions

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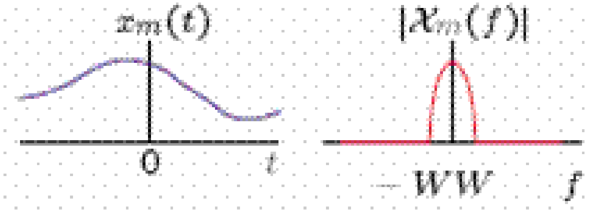
I. GENERAL DESCRIPTION OF MODULATION

1/ Overview

The word modulation in an electronic context means to recode a signal for the purpose of more effectively manipulating that signal. For example, suppose we have some signal xm(t) that we wish to process in some way.



For example, we wish to

- transmit it through a channel,
- filter it,
- amplify it,
- display it,
- record it.

However, it is not efficient, convenient, economical, or possible to do so directly. Then we encode the signal and process the encoded signal to improve some aspect of the processing.

2/ Wave-parameter modulation

Modulation can involve varying some feature of a CT signal to encode the signal. Varying the amplitude of a sinusoid (amplitude modulation or AM) or its frequency (frequency modulation or FM) in proportion to a signal is called wave-parameter modulation.

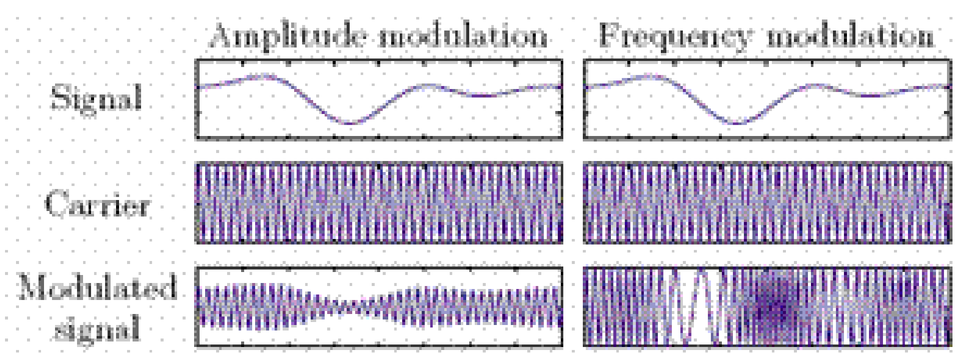


Figure 1

3/ Pulse-parameter modulation

Modulation can also encode the CT signal with the parameters of pulses called pulse-parameter modulation. A number of different pulse-parameter modulation schemes are shown below.

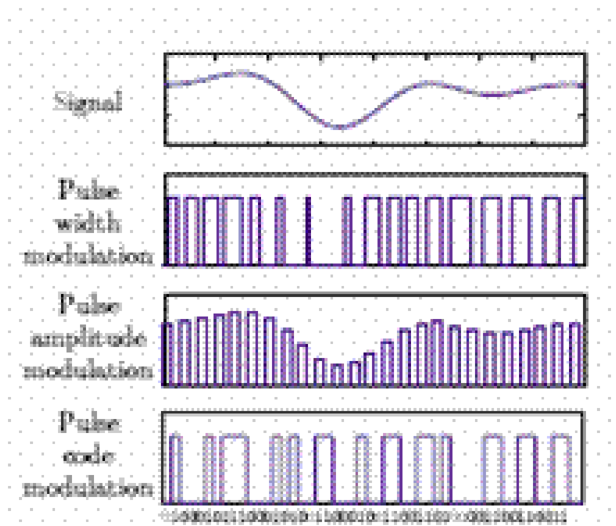


Figure 2

In PWM, the width of pulses encodes the amplitude of the CT signal. In PAM the amplitude of pulses encodes the CT signal. In PCM the amplitude of the quantized CT signal is encoded as a binary number that is represented by a pulse code.

4/ Example of the use of modulation — pigeon telemetry

An ornithologist wishes to record the sounds made by a Lahore pigeon (shown below) while in flight.

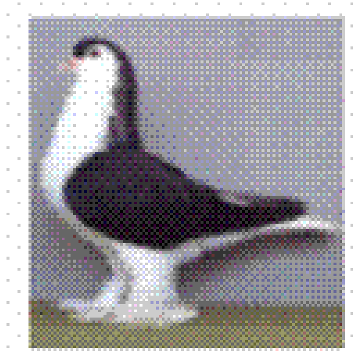


Figure 3

Typical pigeon sounds have a spectrum in the frequency range 0.1-3 kHz. Since the pigeon is in flight, we need to make a small (light weight) system consisting of a microphone and a telemetering system that will transmit the sound information.

One might simply transduce the audio signal from the microphone and transmit the electrical signal to the ground. A question arises — what size antenna is needed to transmit the signal in an energetically efficiently manner?

For energetic efficiency, the dimensions of the antenna cannot be orders of magnitude smaller than the wavelength of the transmitted signal. The wavelength λ of the transmitted signal is

$\lambda = \frac{c}{f} \approx \frac{3 \times 10^8 m/s}{3 \times 10^3 \text{Hz}} \approx 100\text{km}$

If we make the antenna $\lambda/10$, then the antenna dimensions are at least 10 km. Thus, the antenna dimensions exceed that of the pigeon by a factor of more than 104!

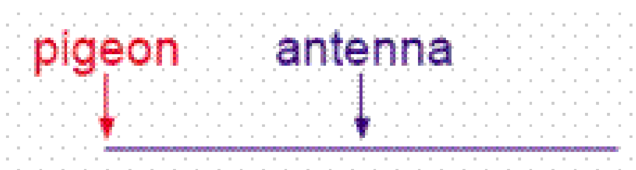


Figure 4

On the left is a scale drawing of the pigeon (in red) and the antenna (in dark blue).

The pigeon will not get off the ground!

One solution is to move the spectrum of the transduced pigeon sounds to a high frequency, to transmit this modulated signal to the ground, and then to demodulate to audio frequencies.

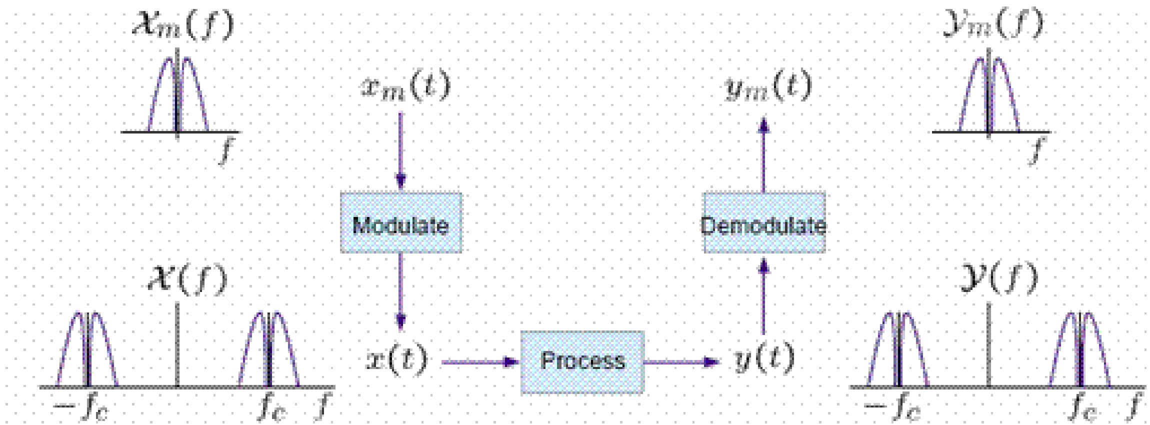


Figure 5

If the signal is transmitted at a carrier frequency $f_c = 600$Mhz, then the $\lambda \approx \frac{3\times10^8\,\mathrm{m/s}}{6\times10^8\mathrm{Hz}} \approx 0.5m$ so that an antenna whose length is $\lambda/10 \approx 5$ cm which is much more manageable for the pigeon.

5/ Narrow-band signals

The modulated transduced pigeon sound has a spectrum that is centered about the carrier frequency f_c and has a bandwidth of $2f_m$ where f_m is the maximum frequency of the pigeon sound.

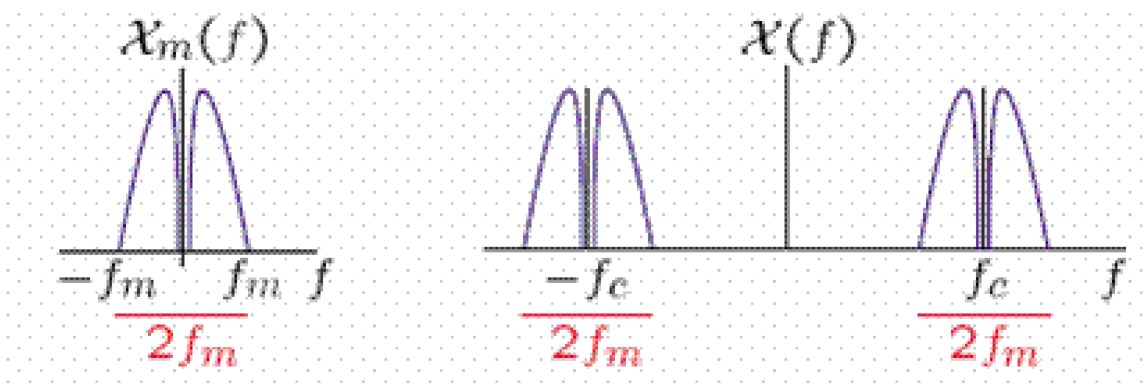


Figure 6

For the pigeon sound we have $f_m = 3$ kHz and $f_c = 600$ MHz. Thus, the bandwidth is only $10^{-5}$of the carrier frequency — an example of a narrowband signal.

An arbitrary narrowband signal can be expressed as

$x(t) = x_c(t)\cos(2\pi f_c t) + x_s(t)\sin(2\pi f_c t)$

where $x_c(t)$and $x_s(t)$ are lowpass time functions. We can expand x(t) as follows

$x(t) = \frac{1}{2}\left(x_c(t) + \frac{1}{j}x_s(t)\right)e^{j2\pi f_c t} + \frac{1}{2}\left(x_c(t) - \frac{1}{j}x_s(t)\right)e^{-j2\pi f_c t}$,

$x(t) = R\{\left(x_c(t) + \frac{1}{j}x_s(t)\right)e^{j2\pi f_c t}\}$,

$x(t) = a(t)\cos(2\pi f_c t + \varphi(t))$,

Where

$a(t) = \sqrt{x_c^2(t) + x_s^2(t)}$ and $\varphi(t) = -\tan^{-1}\frac{x_s(t)}{x_c(t)}$.

An arbitrary narrowband signal can be written as

$x(t) = a(t)\,\mathrm{Cos}(2\pi f_c t + \varphi(t))$

Thus, a general narrowband signal contains both amplitude and phase/frequency modulation. In amplitude modulation (AM) $\varphi(t)$ is constant; in phase/frequency modulation (PM or FM) a(t) is constant.

II. AMPLITUDE MODULATION

1/ AM, suppressed carrier

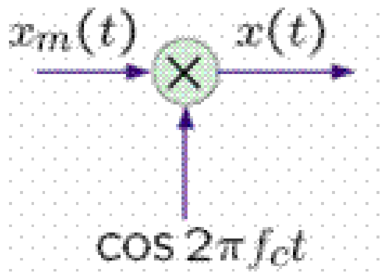


Figure 7

Perhaps the simplest amplitude modulation scheme is the suppressed carrier scheme in which

$x(t) = x_m(t) \times \cos(2\pi f_c t)$

Therefore, the Fourier transform is

$x(f) = x_m(f) * F\{\cos(2\pi f_c t)\}$,

$x(f) = x_m(f) * \frac{1}{2}(\delta(f - f_c) + \delta(f + f_c))$,

$x(f) = \frac{1}{2}(x_m(f - f_c) + x_m(f + f_c))$.

The Fourier transform of the modulated signal x(t) can be obtained graphically.

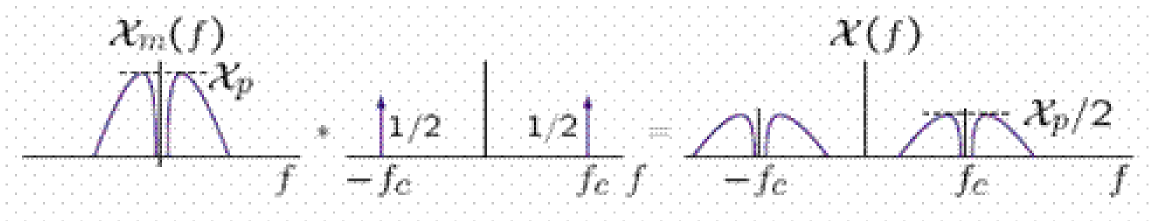


Figure 8

The Fourier transform $X_m(f)$ is repeated at $\pm f_c$.
2/ Demodulation (detection) of AM, suppressed carrier

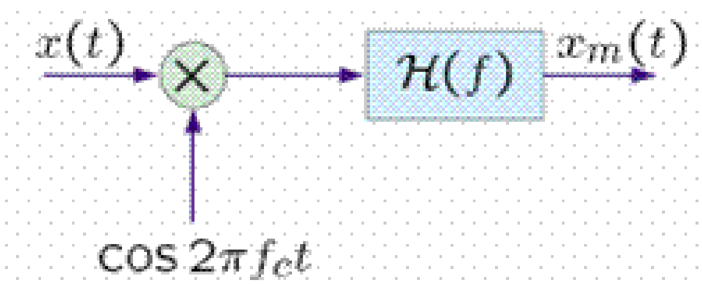


Figure 9

The original signal $x_m(t)$ can be recovered by modulating the modulated signal and passing the result through a lowpass filter, a process called demodulation or detection.

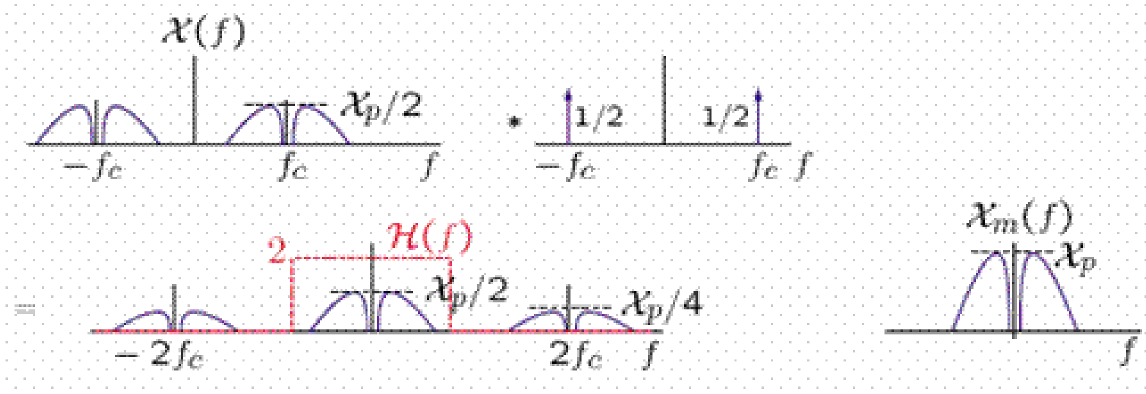
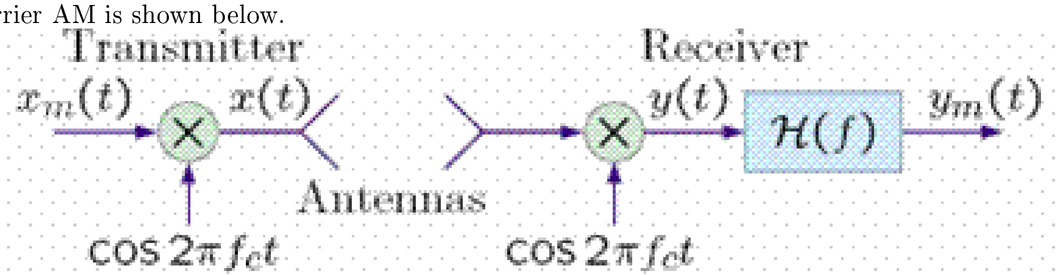


Figure 10

3/ AM, suppressed carrier radio

A radio communication system that consists of a transmitter and receiver and which uses suppressed carrier AM is shown below.



Therefore,

x $(t) = x_m(t)\cos(2\pi f_c t), y(t) = x(t)\cos(2\pi f_c t)$, and

y $(t) = x_m(t)\cos^2(2\pi f_c t) = \frac{x_m(t)}{2}(1+\cos(4\pi f_c t))$.

Hence,

$Y(f) = \frac{1}{2}X_m(f) + \frac{1}{4}X_m(f-2f_c) + \frac{1}{4}X_m(f+2f_c)$.

The spectrum of y(t) involves the spectrum of $\cos^2(2\pi f_c t)$ which can be found by the trigonometric identity or as shown below.

$y(t) = x_m(t)\cos^2(2\pi f_c t) = x_m(t)\times\cos(2\pi f_c t)\times\cos(2\pi f_c t)$

can be written as

$Y(f) = X_m(f) * F\{\cos(2\pi f_c t)\} * F\{\cos(2\pi f_c t)\}$

The Fourier transform of $F\{\cos(2\pi f_c t)\} * F\{\cos(2\pi f_c t)\}$ is shown below.

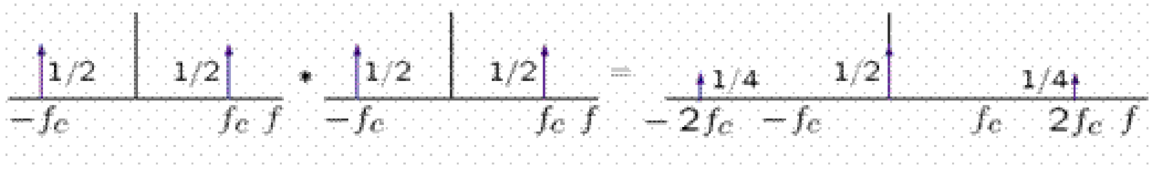


Figure 11

Thus, using Fourier transform properties it is easy to derive trigonometric identities.
Two-minute miniquiz problem
Problem 23-1 — AM, suppressed carrier radio
A slight alternative to the AM suppressed carrier radio system is shown below.

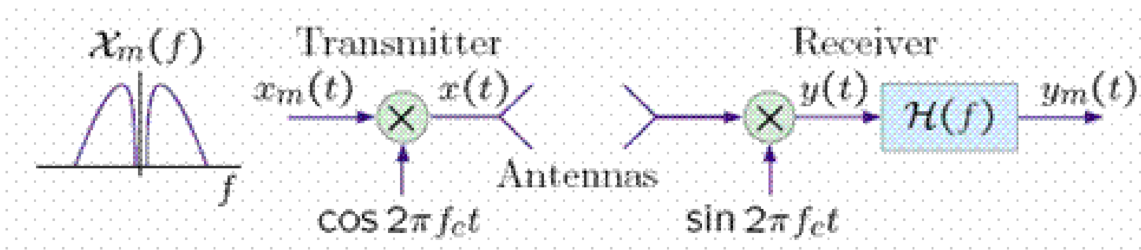


Figure 12

Using an appropriate low pass filter, H(f), to detect $X_m(f)$, determine the spectrum $Y_m(f)$.
Solution
We need to convolve the spectrum of the modulated function X(f) with the Fourier transform of Sin $(2\pi f_c t)$.

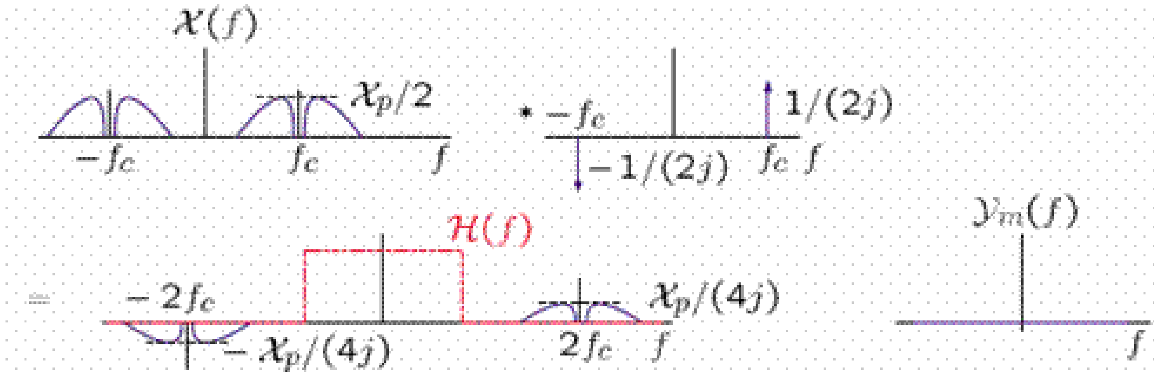


Figure 13

Thus, the output is zero.

The following reviews the results for suppressed carrier radio.

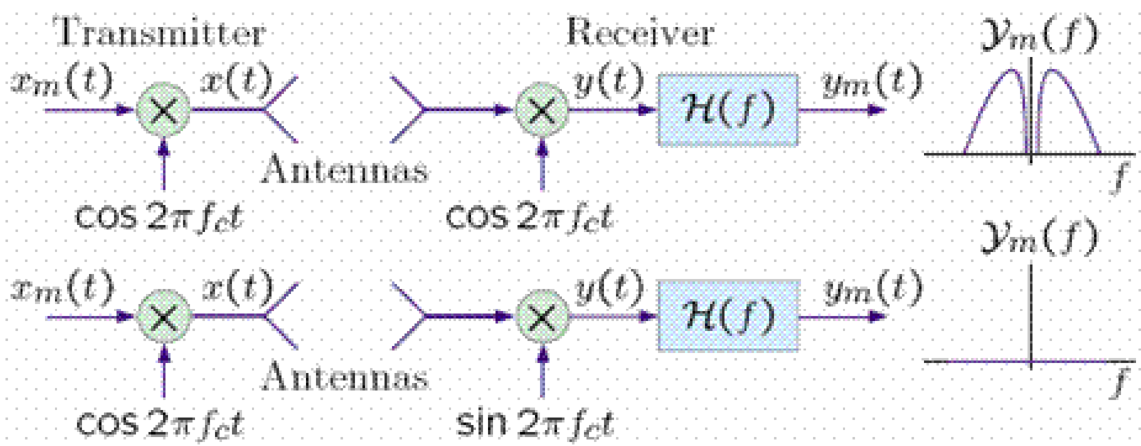


Figure 14

Suppressed carrier AM requires that the transmitter and receiver be perfectly synchronized. A small difference in frequency of transmitter and receiver oscillators results in a drift in the phase difference between the oscillators which causes variations in the amplitude of the detected signal, called signal strength fading.

4/ Synchronous detection

Synchronous detection is effectively used when the oscillators in the modulator and detector are the same. For example in the chopper-stabilized DC amplifier shown below.

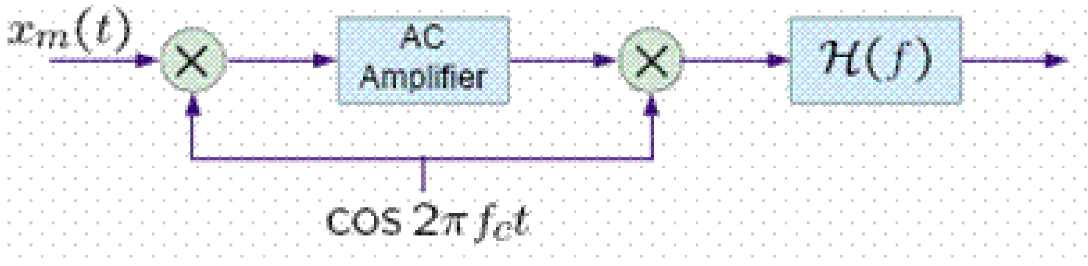


Figure 15

In DC amplifiers, the signal component at DC interacts with the biasing of the transistors in the amplifier complicating the design. In a chopper stabilized amplifier, the DC signal is modulated, amplified by an AC amplifier, and then detected. Thus, amplification at DC is achieved with an AC amplifier.

III. BROADCAST AM RADIO

1/ Brief history

Figure 16

1864 James Clerk Maxwell published his equations of electromagnetism.

Figure 17

1887 Heinrich Hertz proved that waves travel through the "ether" by creating a spark in a gap between two wires and picking up a voltage in a loop of wire — the first transmitter and receiver of electromagnetic waves.

Brief history, cont'd

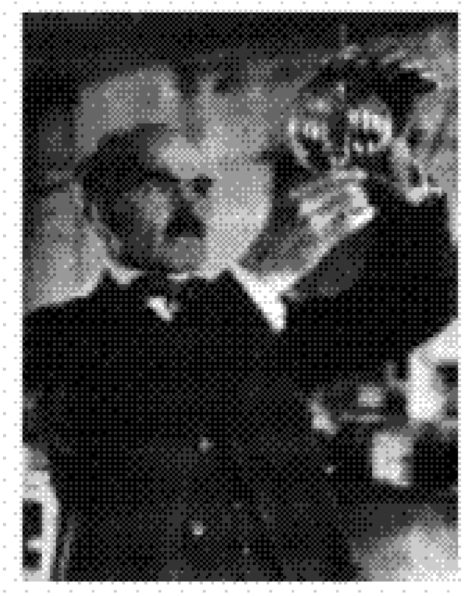


Figure 18

1896 Guglielmo Marconi took out patents on a system of wireless telegraphy.

1906 Lee de Forrest invented the triode vacuum tube for sensitive detection of telegraphy signals. Despite the fact that De Forrest did not understand how the "audion" worked this invention began the modern electronic era.

1906 Reginald Aubrey Fessenden transmitted voice and music over radio waves using a 100,000 Hz alternator designed by Charles Steinmetz at General Electric Company. This was the beginning of broadcasting of audio over the airways.

Figure 19

1912 Edwin Howard Armstrong analyzed the operation of the audion tube and made the first vacuum tube amplifier as part of a sensitive receiver of wireless telegraphy. He used regeneration now called feedback. Noting that the vacuum tube circuit could be made to oscillate, he used this to make the first electronic transmitter. Armstrong's work ushered in the modern era of radio transmission and reception.

Figure 20

1916 David Sarnoff, working for the Marconi Company, envisaged “music boxes” (radios) as consumer products and the system of radio broadcast as we have it today.

1918 Armstrong enlisted in the army during World War I and worked for the Signal Corps in Paris. He developed the superheterodyne receiver which became, and is to this day, the basis of AM radio receivers.

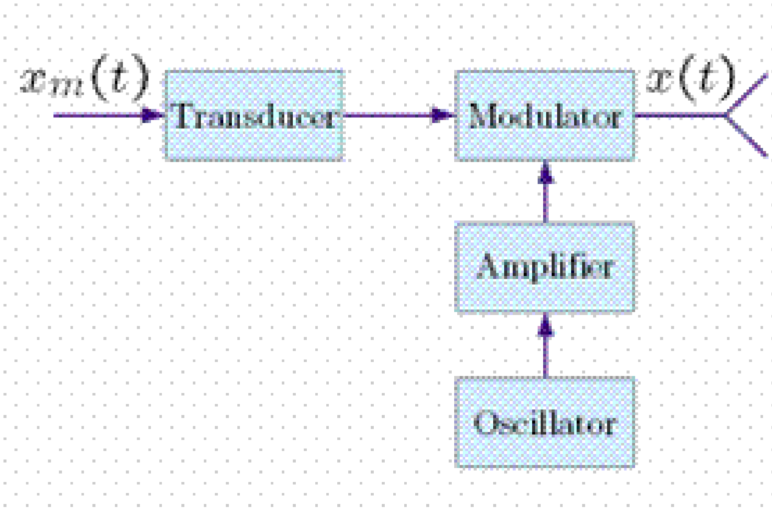
1919 The Radio Corporation of America was formed out of General Electric Company and the American Marconi Company with David Sarnoffas commercial manager. Between 1918 and 1923 radio broadcasting became pervasive as inexpensive radios became widely available. Sarnoffb ecame president and perhaps the most powerful person in the burgeoning communications industry.

2/ The conception of broadcast radio

The important conception was to develop a radio broadcast system that consisted of relatively small number of transmitters each transmitting at different (carrier) frequencies and a large numbers of inexpensive receivers that could be tuned to different transmission frequencies. In order to be sufficiently inexpensive so that everyone could own one, the receivers had to be simple to manufacture. Thus, the system consisted of a small number of expensive transmitters and a large number of inexpensive receivers.

3/ AM radio transmitter

A typical AM radio transmitter has a block diagram shown below.



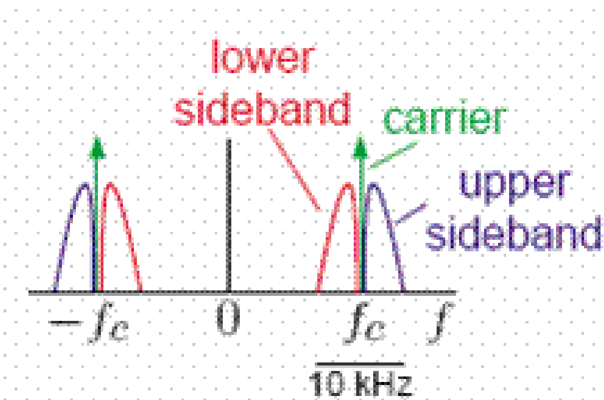
The modulator produces a signal that has the form

$x(t) = A(1 + x_m(t))\cos(2\pi f_c t)$

Thus, the transmitted signal has the same spectrum as the suppressed carrier AM signal except that the carrier frequency is broadcast. Thus, synchronization of transmitter and receiver is achieved.

4/ Spectrum of transmitted signal

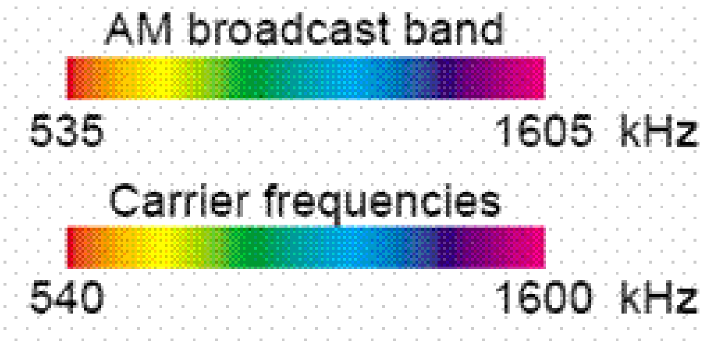
The typical spectrum of an AM station is shown below with the nomenclature defined for its different components.



The Federal Communication Commission (FCC) allots 10 kHz of bandwidth for each station. Stations in any one locale differ in their carrier frequencies, which are the numbers indicated on the radio dial.

5/ AM broadcast band

The FCC allocates frequency bands in the radio spectrum (3kHz- 300GHz) for communications purposes. The frequency band from 535 to 1605 kHz is reserved for AM broadcast radio. This is a bandwidth of 1070 kHz. Since each station is allotted a bandwidth of 10 kHz, 107 non-overlapping stations can operate in each locale.



6/ Signal at input to an AM receiver

An AM receiver input spectrum consists of AM signals of different carrier frequencies and different signal strengths resulting from differences in strengths of transmitters and differences in their distances from the receiver.

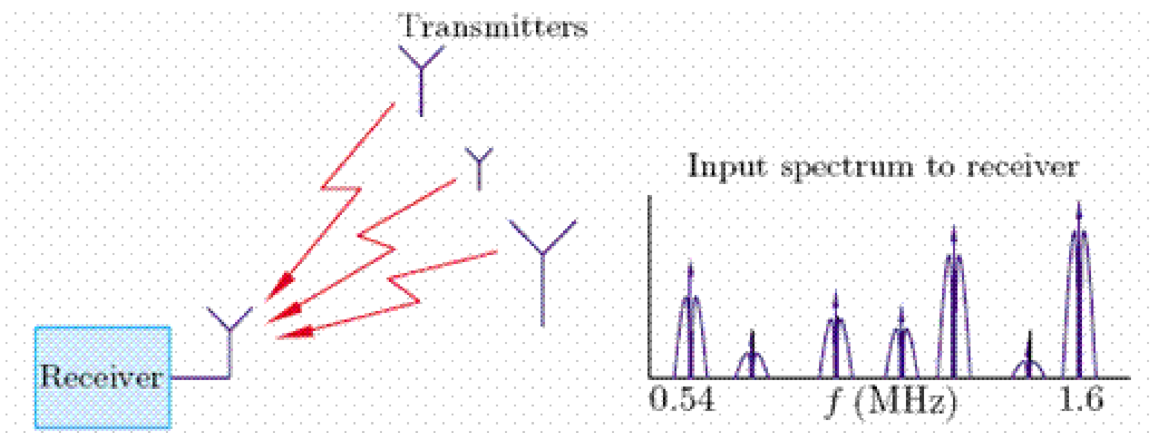


Figure 21

The receiver allows the listener to tune into a station and minimizes the interference of other stations.

7/ Superheterodyne AM receiver

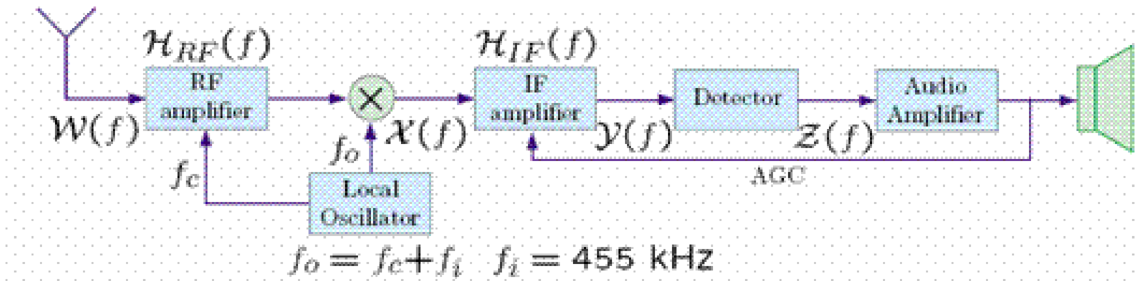


Figure 22

Radio frequency (RF) amplifier. Tunable, broadly frequency selective amplifier that attenuates image station at $f_c + 2f_i$ and has a gain of 5-15 dB.

Local oscillator. Provides frequencies f_c to the RF amplifier and $f_0 = f_c + f_i$ to the modulator.

Intermediate frequency (IF) amplifier. Fixed frequency (at f_i), highly frequency selective amplifier with a gain of 30 dB.

Audio amplifier. Amplifier with a gain 15-30 dB.

This design has two important attributes: (1) it segregates sharp frequency selectivity from tuning in different stages which simplifies the design; (2) it distributes overall gain over three frequency ranges which improves the stability of the receiver.

The RF amplifier provides some frequency selectivity about the selected station carrier frequency f_c. The modulator shifts the spectrum of the output of the RF amplifier so that the frequency f_c is shifted to f_i with another copy of the spectrum centered on $f_c + 2f_i$. The IF amplifier is sharply tuned and centered on fi.

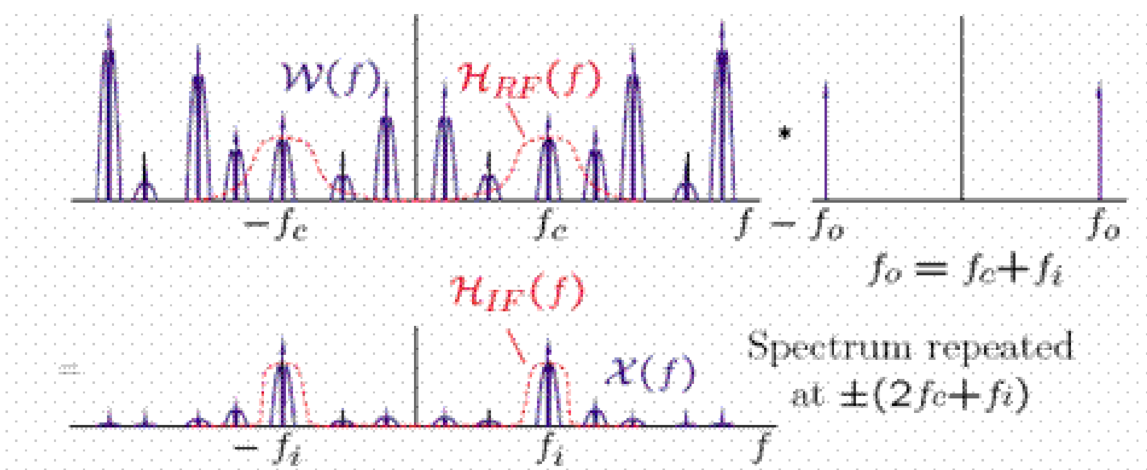


Figure 23

The spectrum of the output of the IF amplifier is the spectrum of the selected station shifted from f_c to f_i . Hence, the output is an AM signal whose carrier frequency is f_i.

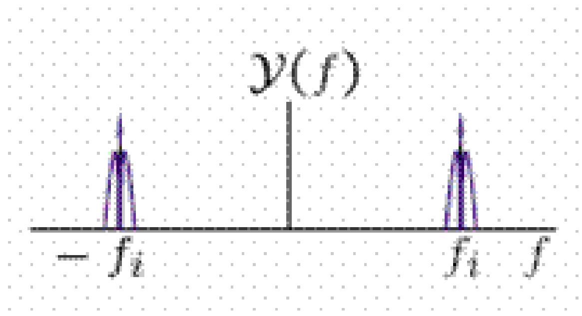


Figure 24

This system modulates the selected station from f_c to f_i . However, note that a station whose carrier frequency is $f_c + 2f_i$ is also modulated down to f_i. A purpose of the RF amplifier is to attenuate this image station.

The peak (or envelope) detector demodulates the AM signal. A simple circuit that detects an AM signal is shown below.

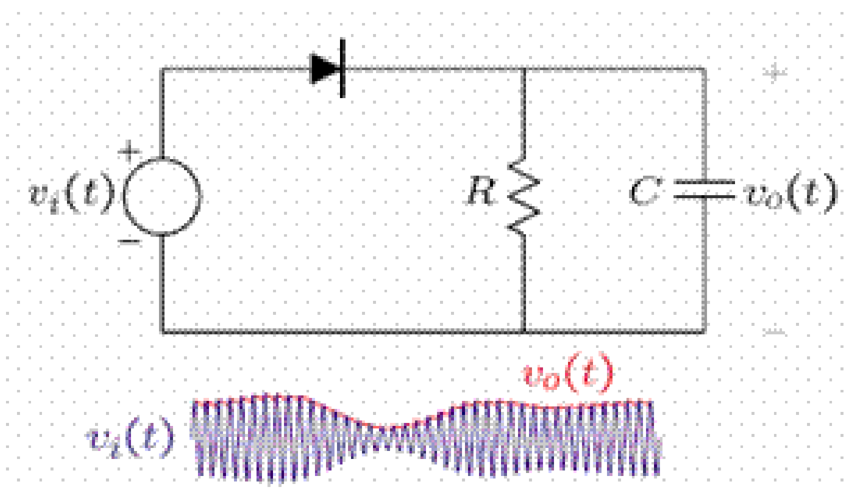


Figure 25

The peak detector works well when

For these conditions, the filter attenuates the carrier frequency

$f_c \gg \frac{1}{2\pi \mathrm{RC}} \gg f_m$
but not the frequency of the signal

SIMULINK can be used to study properties of the peak detector. The following is a block diagram of a peak detector that can be found in the matlab folder as peakdetector.m.

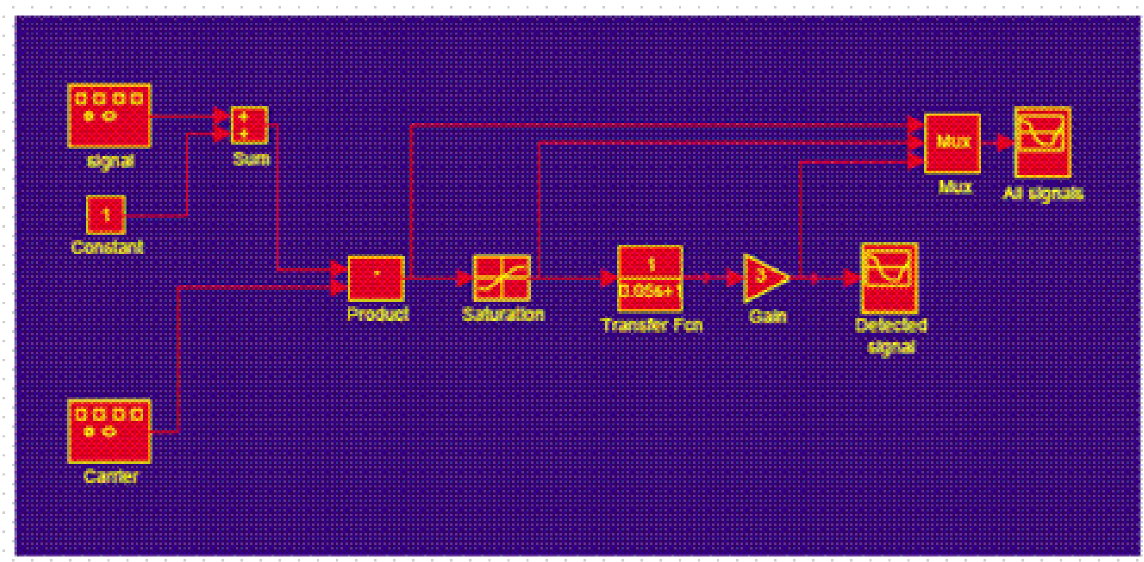


Figure 26

IV. CONCLUSIONS

Technological developments, such as the use of modulation for signal transmission, can have enormous social implications. The development of telegraphy, telephony, radio, TV, and now the internet, cable TV, and cellular phones have revolutionized how people relate to each other world wide.

Exercises .[1]

Solutions of Exercises.[2]

[1] See the file at <http://cnx.org/content/m26691/latest/ps10.pdf>
[2] See the file at <http://cnx.org/content/m26691/latest/ps10sol.pdf>