Introduction to Electrical and Computer Engineering

Electromagnetic Signals

Building on Module 2

- Signals
- Signal Processing
- Communication Systems

Examples of Communication Systems

- Landline phones
- Cell phones
- Radio
- Broadcast TV
- Cable TV
- Internet
- Wi-Fi
- Computer Networks
- Air Traffic Systems
- Emergency Alert Systems
- Intelligent Transportation Systems

Milestones in Wireless Communications

1890's: Successful demonstrations of wireless telegraphy

1902: First transatlantic radio transmission (Marconi)

1906: First AM radio transmission

1918: Superheterodyne AM receiver invented

1920: First commercial AM radio station in the US (KDKA in Pittsburgh, PA)

1929: BBC begins experimental TV broadcasting

1939: First commercial FM radio station in the US (WHUR in Washington, D.C.)

1941: First field test of color TV broadcasting

1961: Standard for stereo FM broadcasting adopted by FCC

1969: ARPANET (forerunner of internet) established

1976: Ethernet protocol for local area networks published

1979: First developmental cellular system in US

1985: 900 MHz, 2.4 GHz, and 5.8 GHz frequency bands (used for Wi-Fi) opened for public use in the US

1991: First digital cellular standard (GSM)

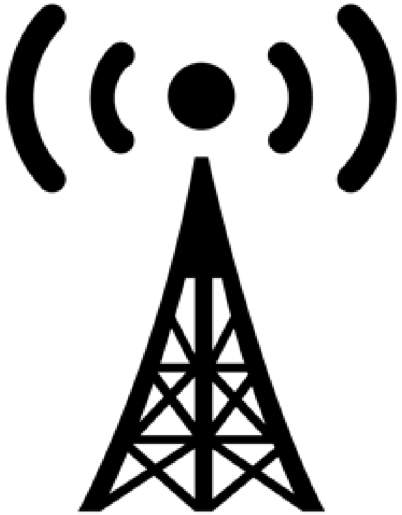
1997: 802.11 Wi-Fi standards published

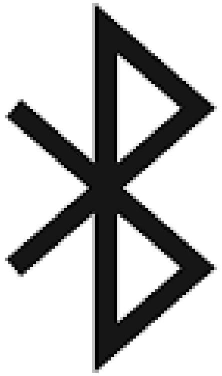
1999: Apple offered first laptop with Wi-Fi capability

2009: Conversion to digital TV standard completed in US

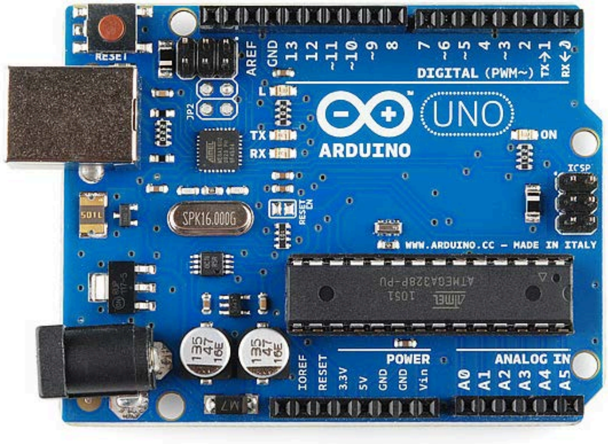
2010 – present: 3G, 4G-LTE, 5G, 6G(?)

Everyday Wireless

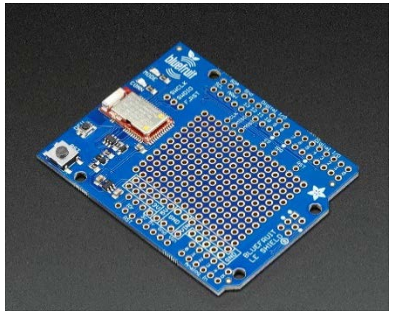


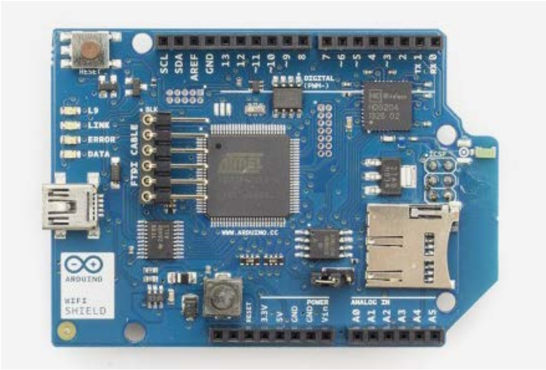


Arduino IDE and Wireless



ATmega328





RF
20 kHz – 300GHz

Bluetooth
2.45 GHz

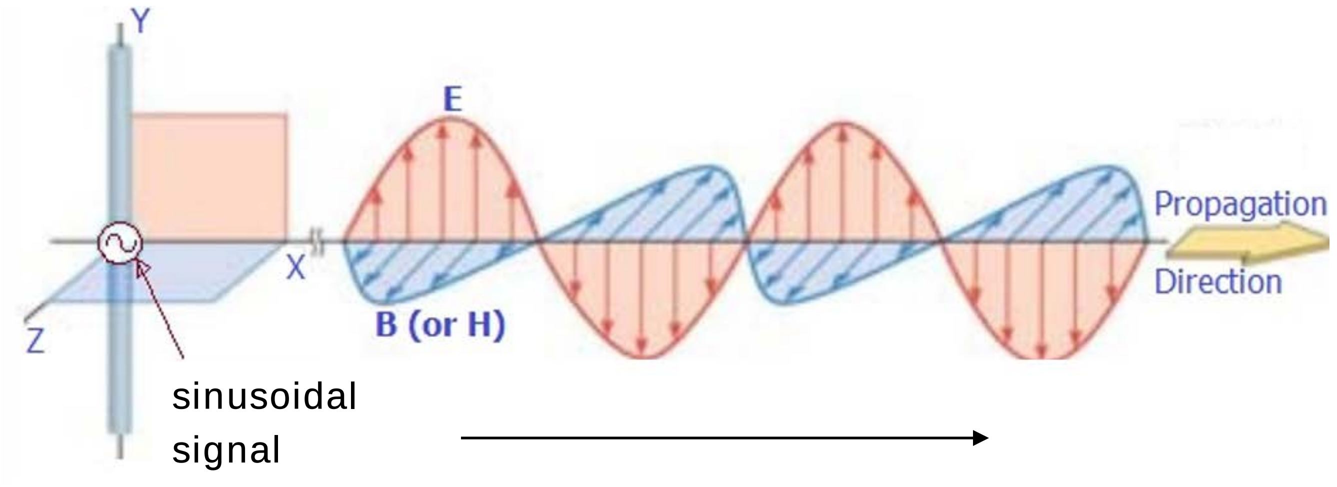
WiFi
2.4 GHz

GSM
1900 MHz

Main Concepts

- EM Waves & Antennas
- Amplitude Modulation
- Frequency Division Multiplexing
- Frequency Selective Filtering
- Superheterodyne Receiver
- Digital Communication Systems

EM Waves and Antennas

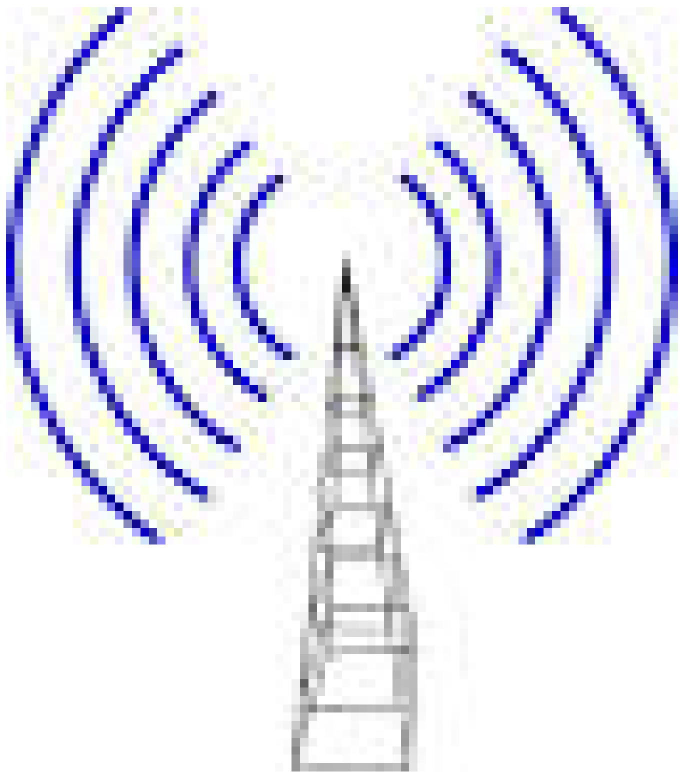


c = 3 x 10^8 m/sec

http://www.rfwireless-world.com/Terminology/Electromagnetic-wave-vs-Surface-Acoustic-wave.html

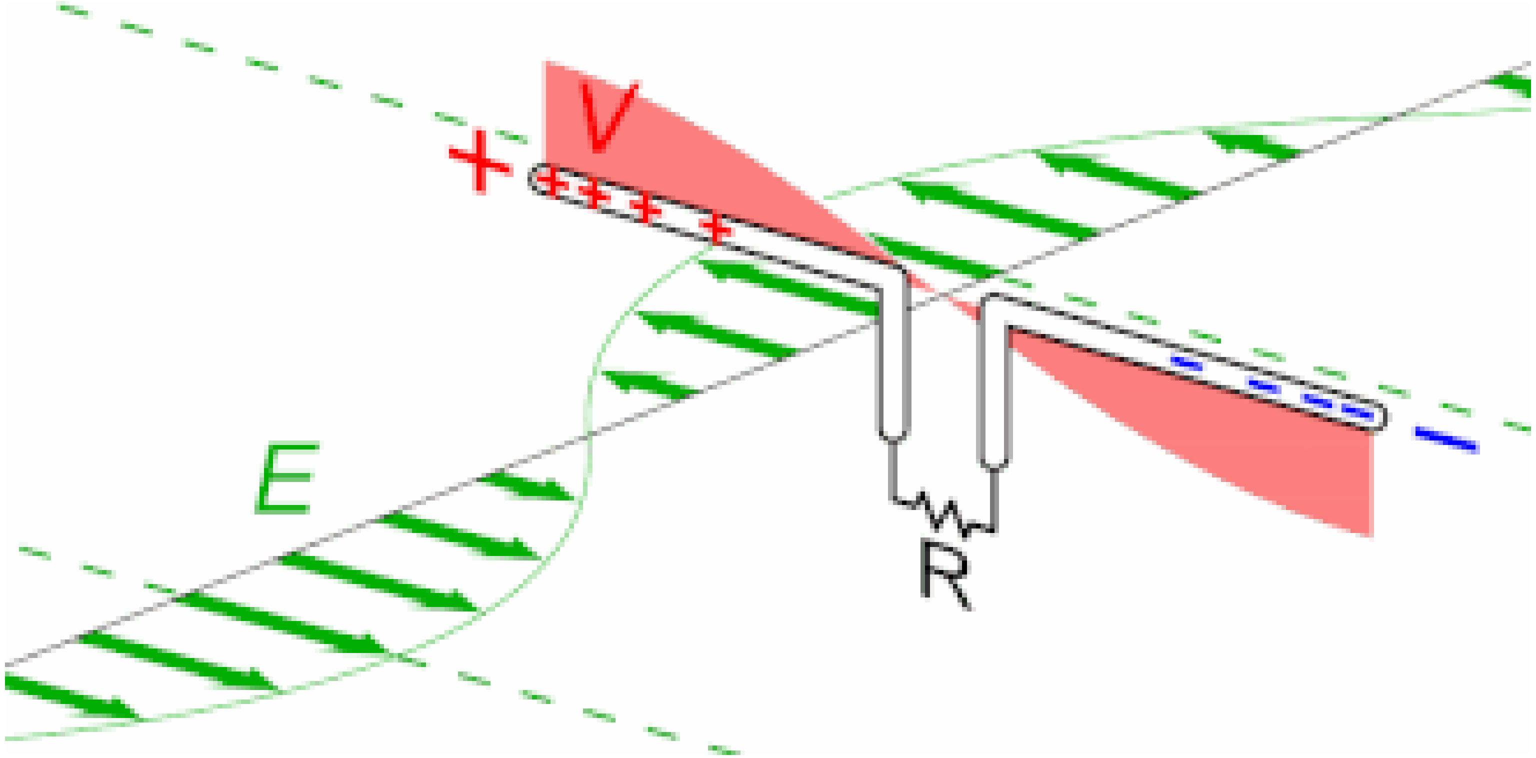
Recall: information carried by oscillating (sinusoidal) components in electrical signal.

Transmit/Receive Antennas



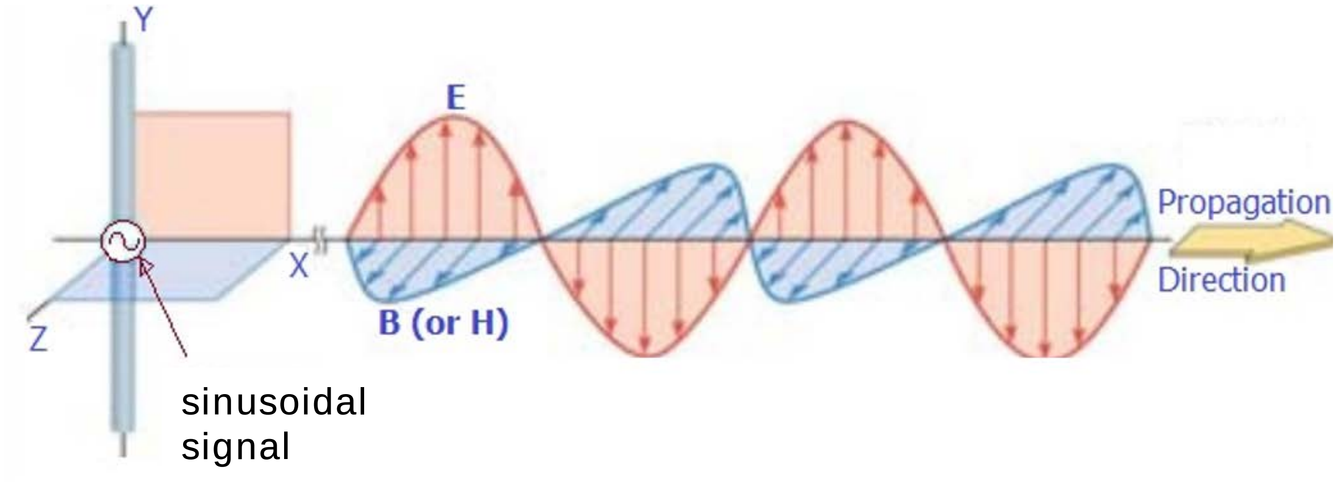
Transmitting antenna

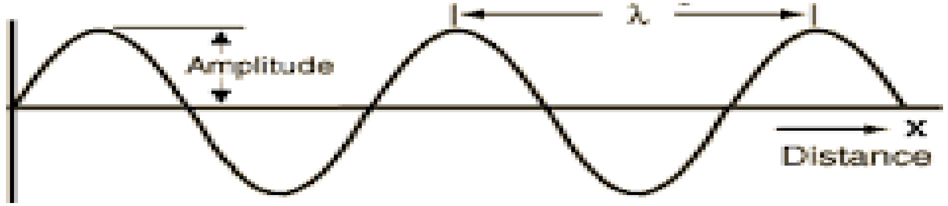
Receiving antenna


V
E
R

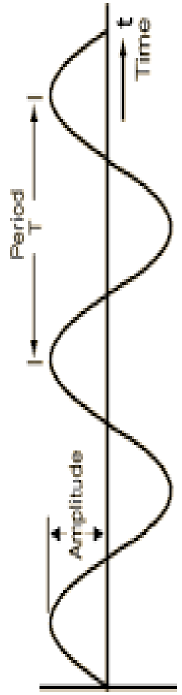
Antennas - 1

$c = 3 \times 10^8$ m/sec





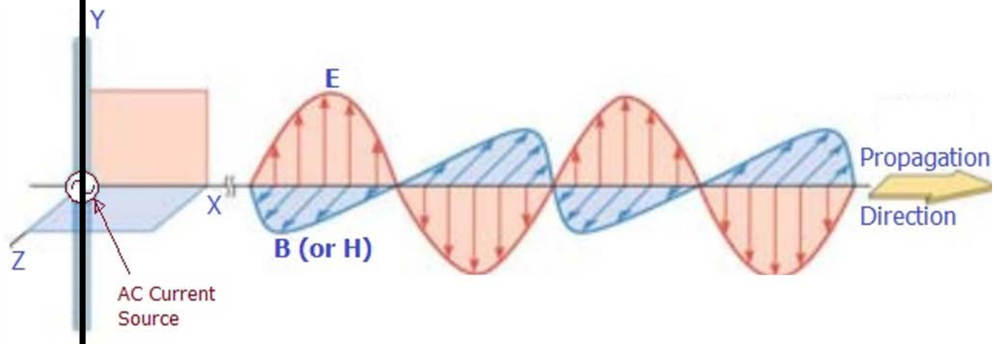
$$\lambda = cT$$



$$f = 1 / T$$

Antennas - 2

$f = 1 / T$



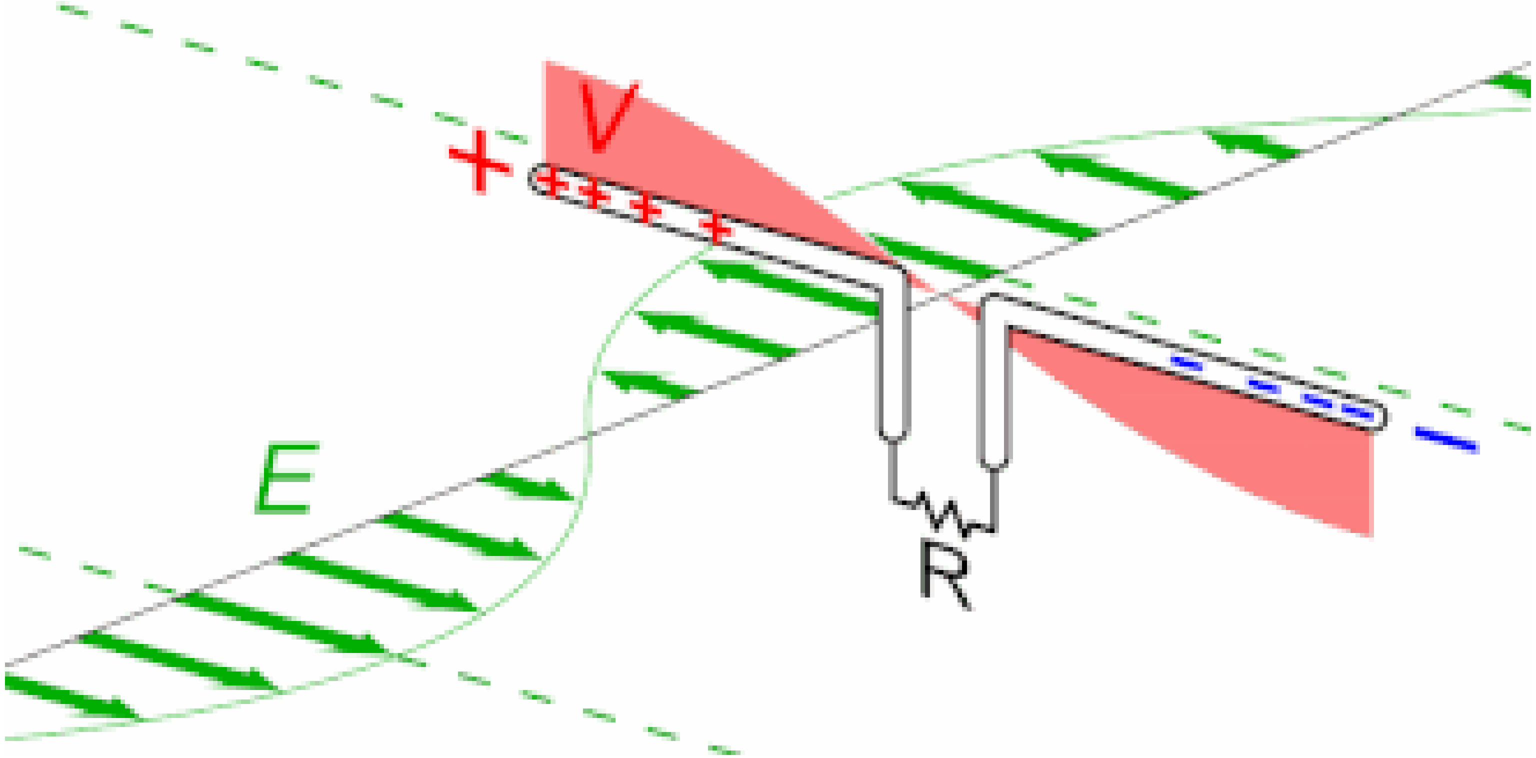
$\lambda = cT$

L_a

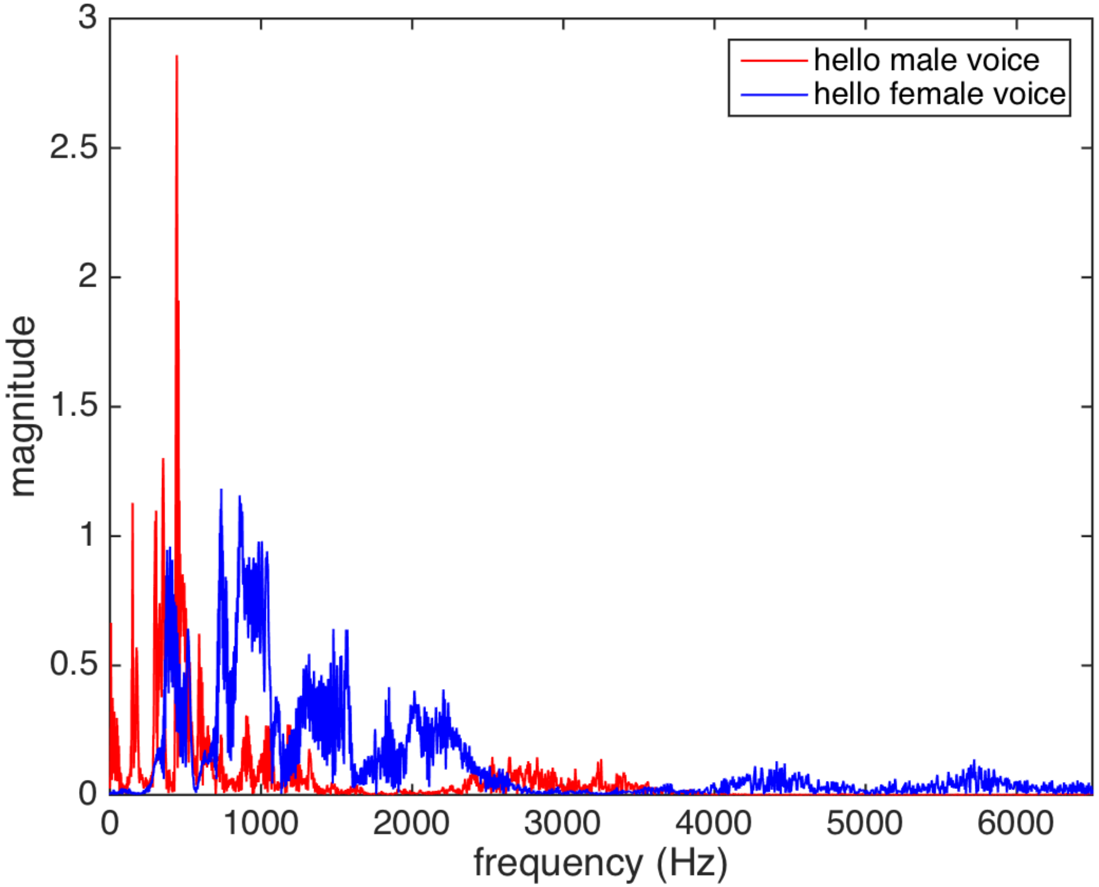
"antenna efficiently converts an electrical signal to propagating EM wave when L_a is a significant fraction of the wavelength λ."

$$\boxed{L_a \geq \lambda/4}$$

$$\boxed{L_a \geq \lambda/4}$$



Antennas - 3



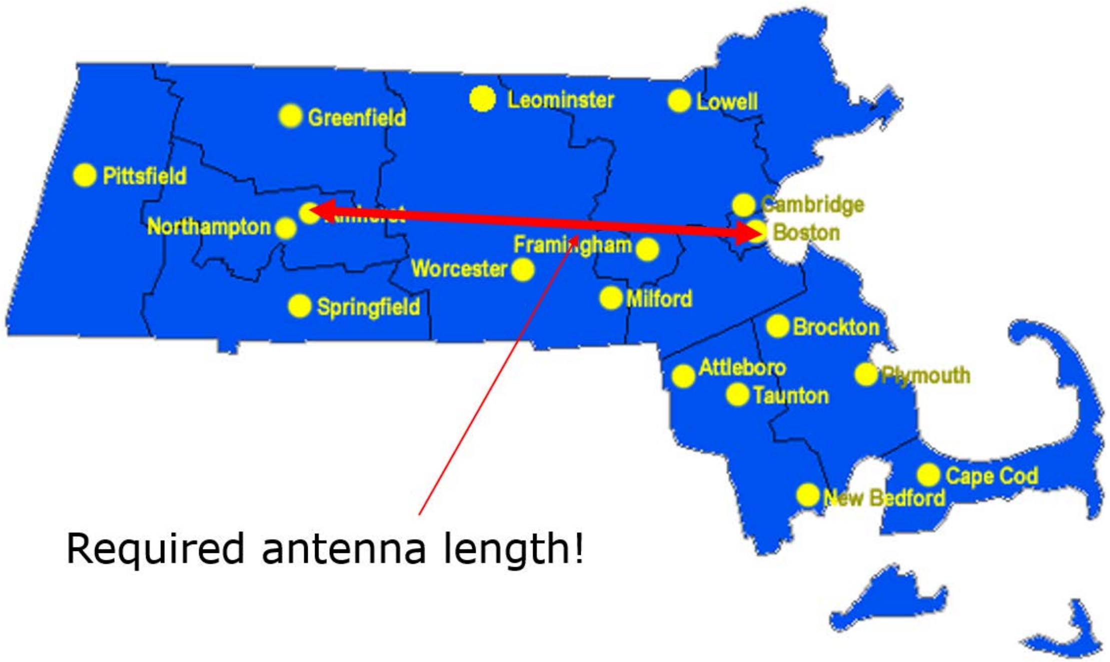
Peak frequency less than 1 kHz.

We say that the “center” frequency is around 600 Hz.

Antennas - 4

$$\lambda = cT = \frac{3 \times 10^8}{600} = 5 \times 10^5 \text{ m}$$

$$L_a = \frac{\lambda}{4} = \frac{5 \times 10^5}{4} = 1.25 \times 10^5 \text{ m} \approx 78 \text{ miles !!!}$$



Antennas - 5

- Greatest efficiency the antenna length needs to be about

$$\frac{\lambda}{4} = \frac{cT}{4} = \frac{c}{4f} \text{ meters}$$

where f is the center frequency of the transmission.

- Suppose f = 1 MHz :

$$\lambda = cT = \frac{3 \times 10^8}{1 \times 10^6} = 300 \text{ meters}$$

- L_a = 300/4 = 75 m << 125 km!

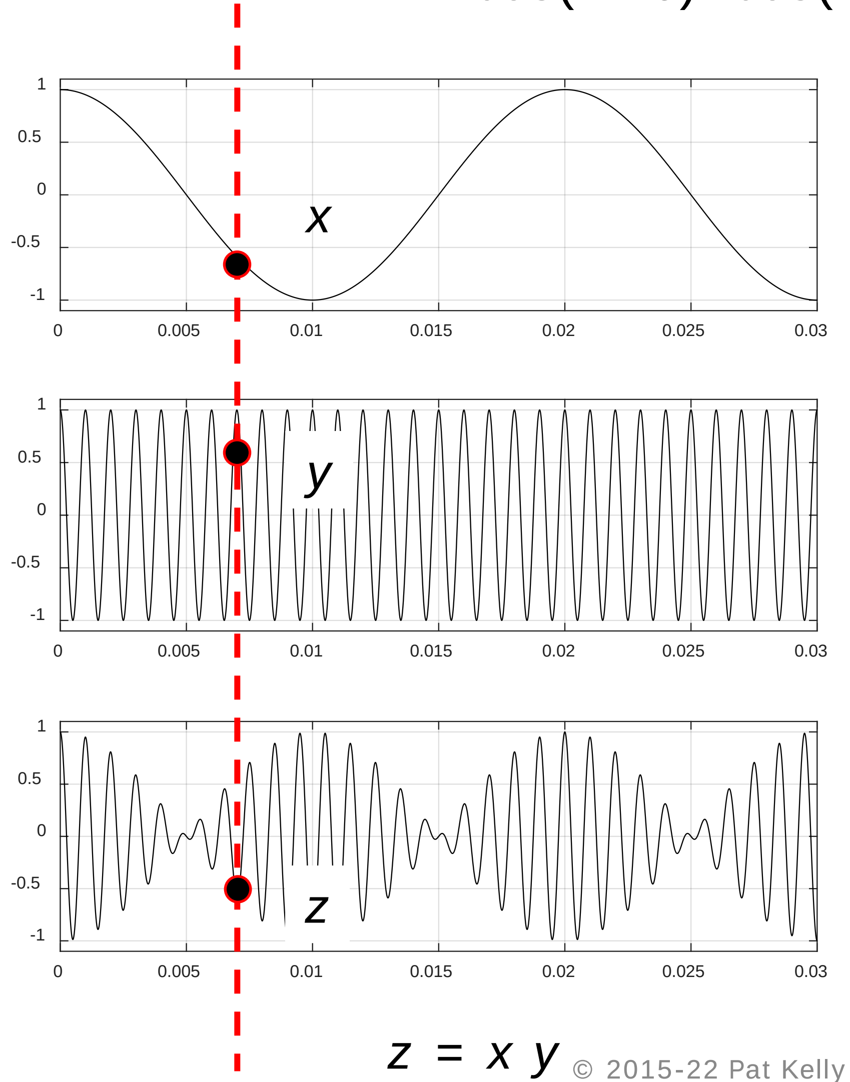
Amplitude Modulation (AM)

- How to increase the center frequency of the transmitted signal so that it can be recovered from the transmission?
- Amplitude Modulation (AM)
- ~ 80 AM radio stations are within listening range of Springfield, MA

Modulation - 1

Multiply the information signal by a high-frequency sinusoid called a carrier f_c

$$\cos(2\pi ft) \cdot \cos(2\pi f_c t)$$



$$\cos(2\pi f t),\ f = 50Hz$$

$$\cos(2\pi f_c t),\quad f_c = 1000Hz$$

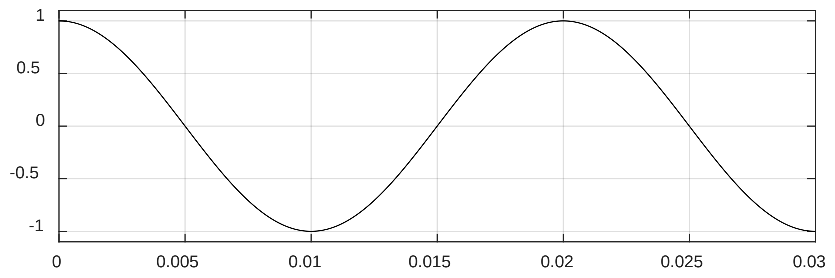
$$\cos(2\pi(50)t) \cdot \cos(2\pi(1000)t)$$

information signal

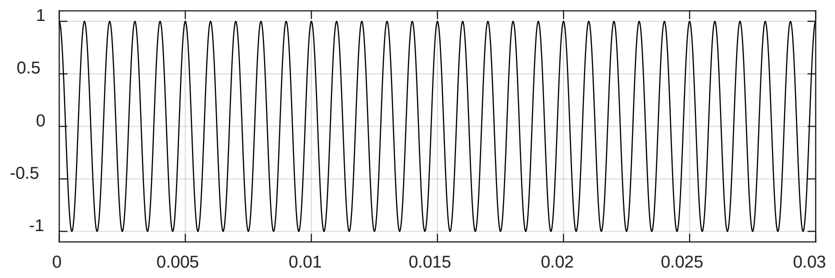
carrier

$z = x\ y$

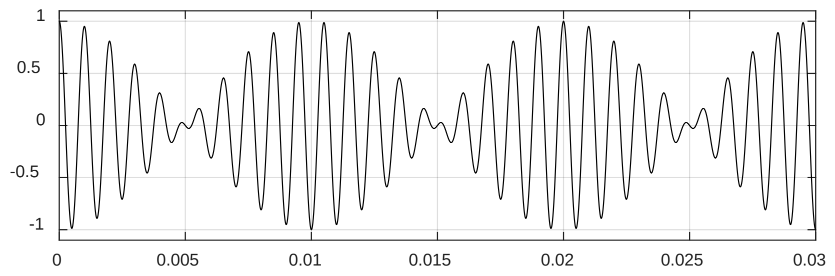
Modulation - 2



Information signal

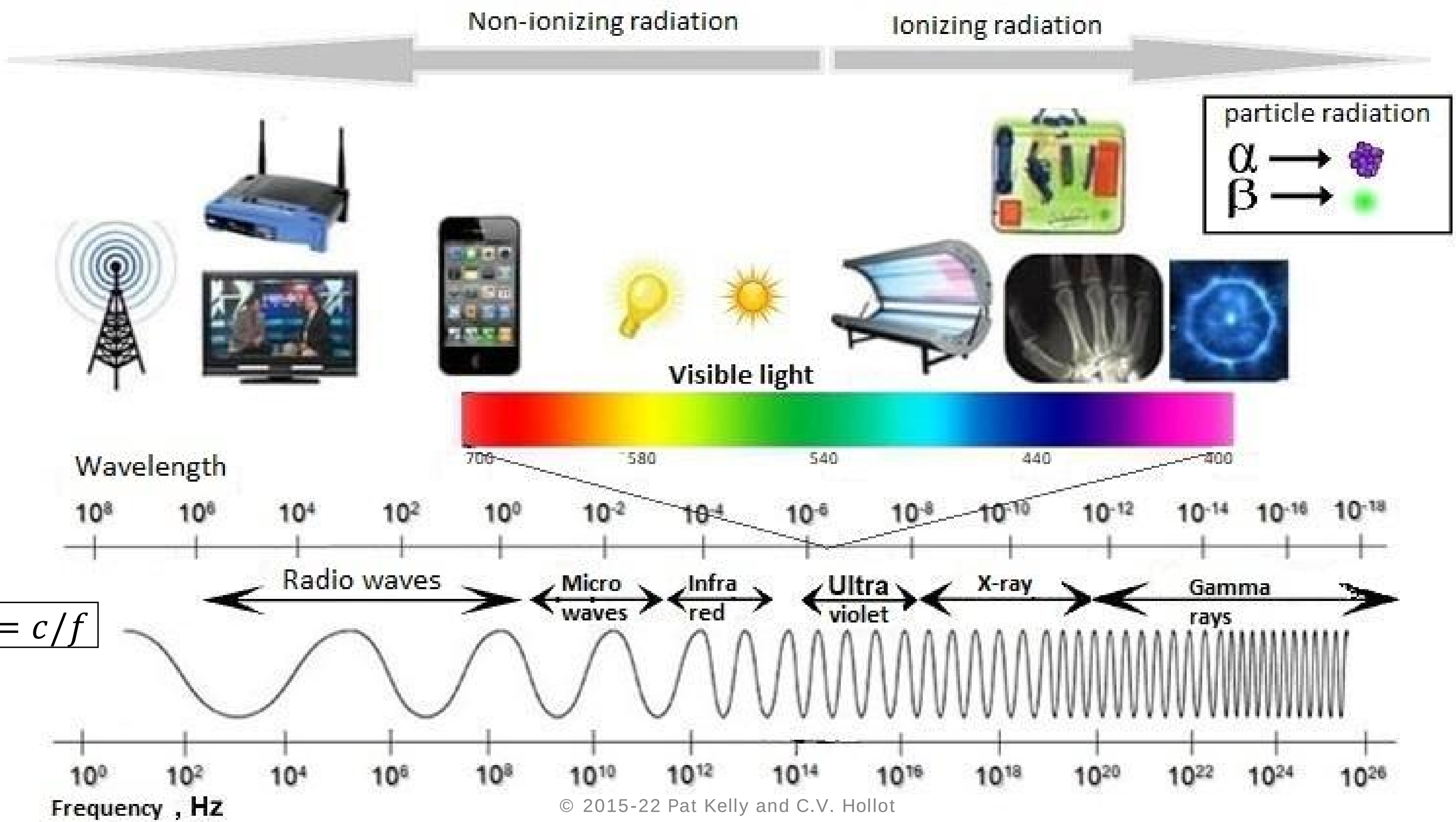


Carrier signal



Amplitude modulated (AM) signal

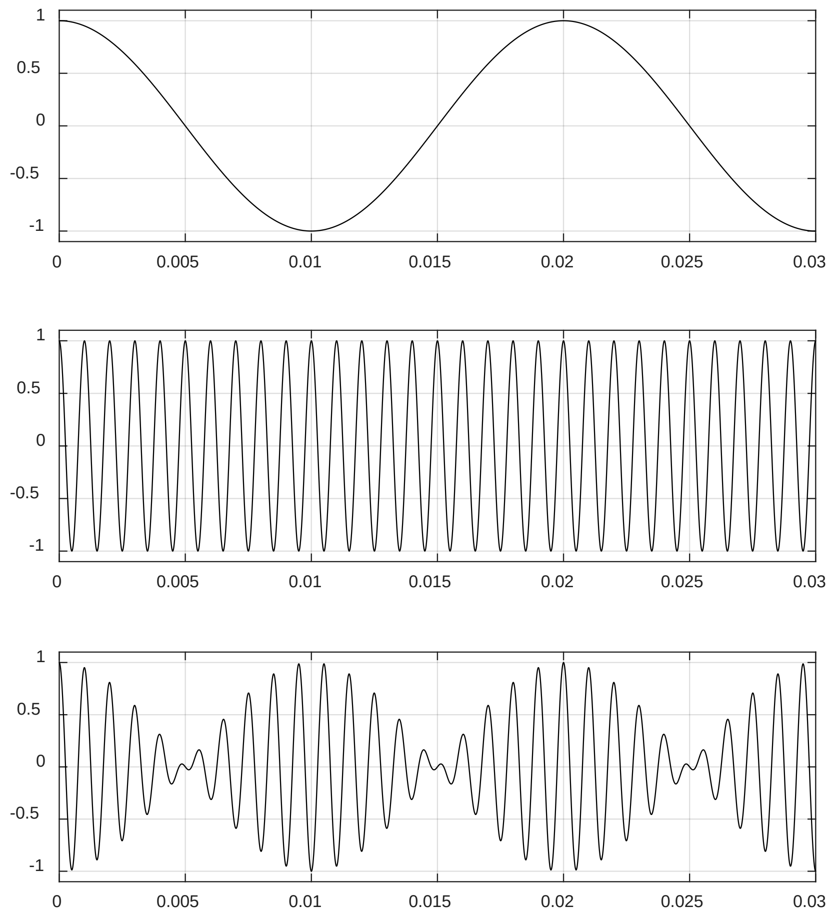
The electromagnetic spectrum

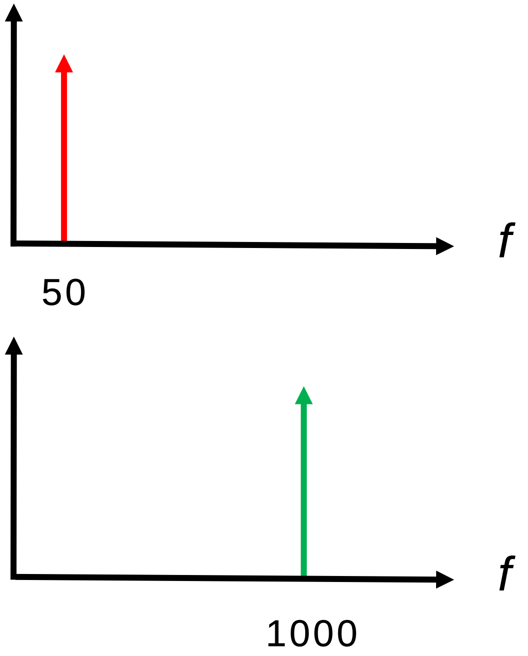


$\boxed{\lambda = cT = c/f}$

Modulation - 3

Note: represent single sinusoidal components with **arrows** in spectrum





Spectrum ???

A little trig

$$a = 2\pi f t$$
$$b = 2\pi f_c t$$

$$\cos(a)\cos(b) = \frac{1}{2}\left[\cos(b+a) + \cos(b-a)\right]$$

$$\cos(2\pi f t)\cos(2\pi f_c t) = \frac{1}{2}\left\{\cos(2\pi[f_c + f]t) + \cos(2\pi[f_c - f]t)\right\}$$

One of the most important principles for communication system design:

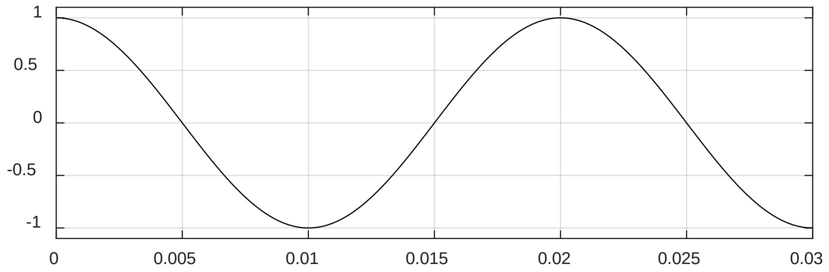
sinusoid of frequency f multiplied by another sinusoid having frequency f_c produces 2 new frequencies

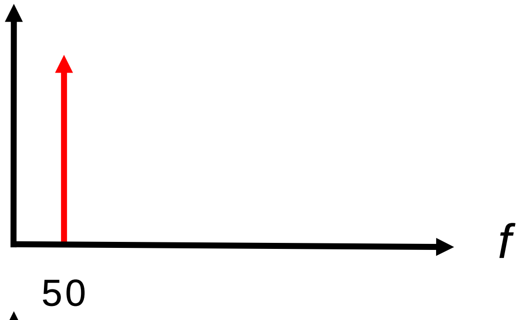
$$f_c + f \quad \text{and} \quad f_c - f$$

Modulation - 4

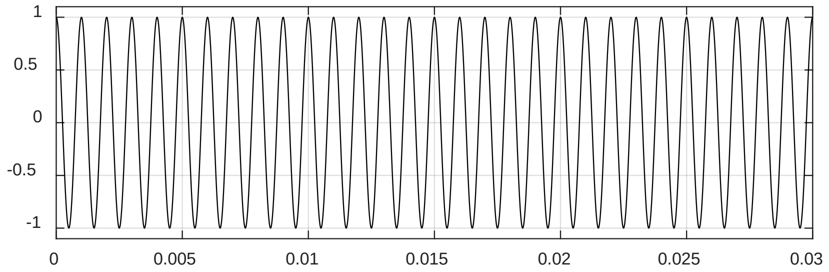
Note: represent single sinusoidal components with **arrows** in spectrum

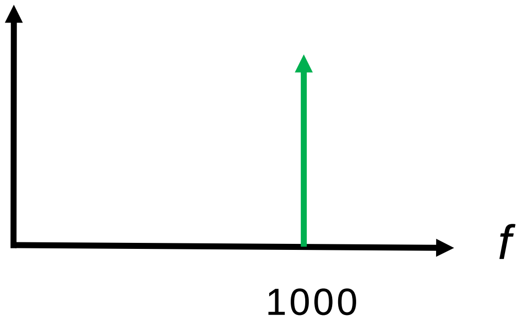
Information signal



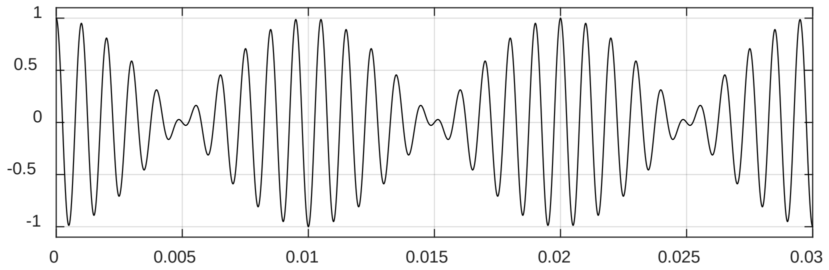


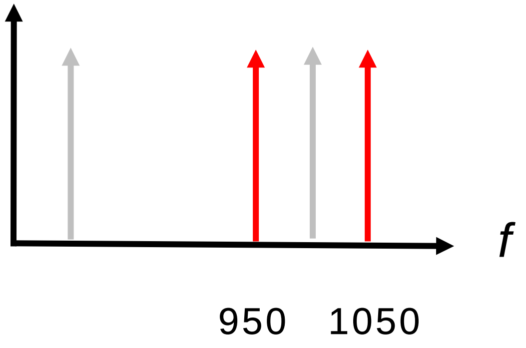
Carrier signal





Amplitude modulated (AM) signal





The AM Signal - 1

$$x_{AM}(t) = [A_x + m(t)]c(t)$$

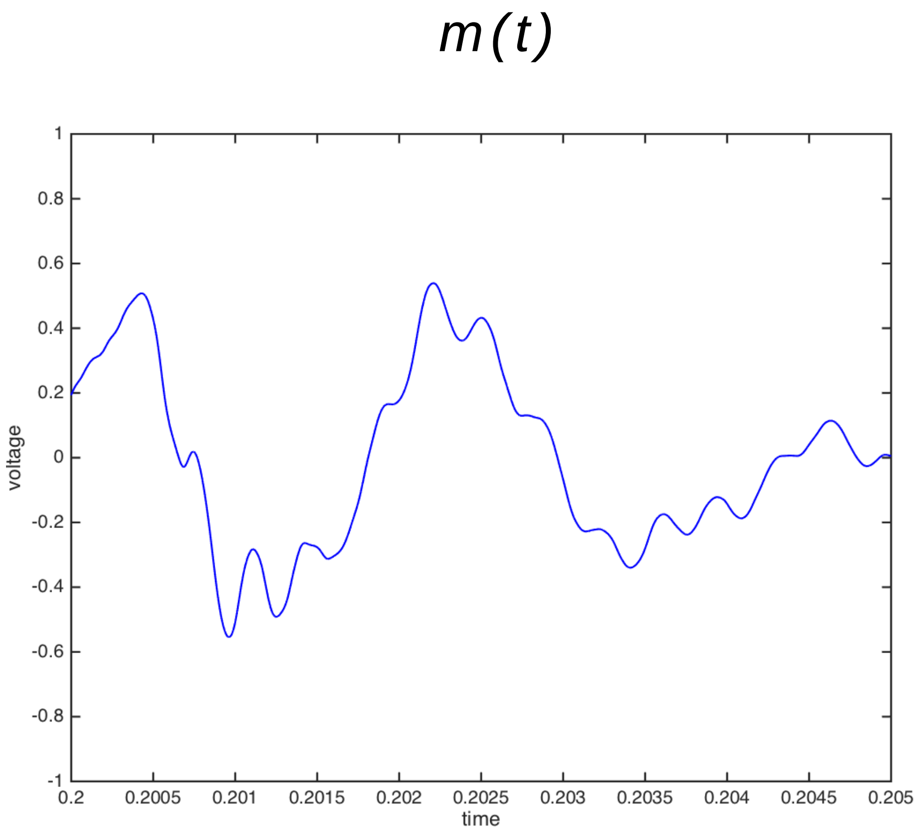
$$m(t) = \text{ message}$$

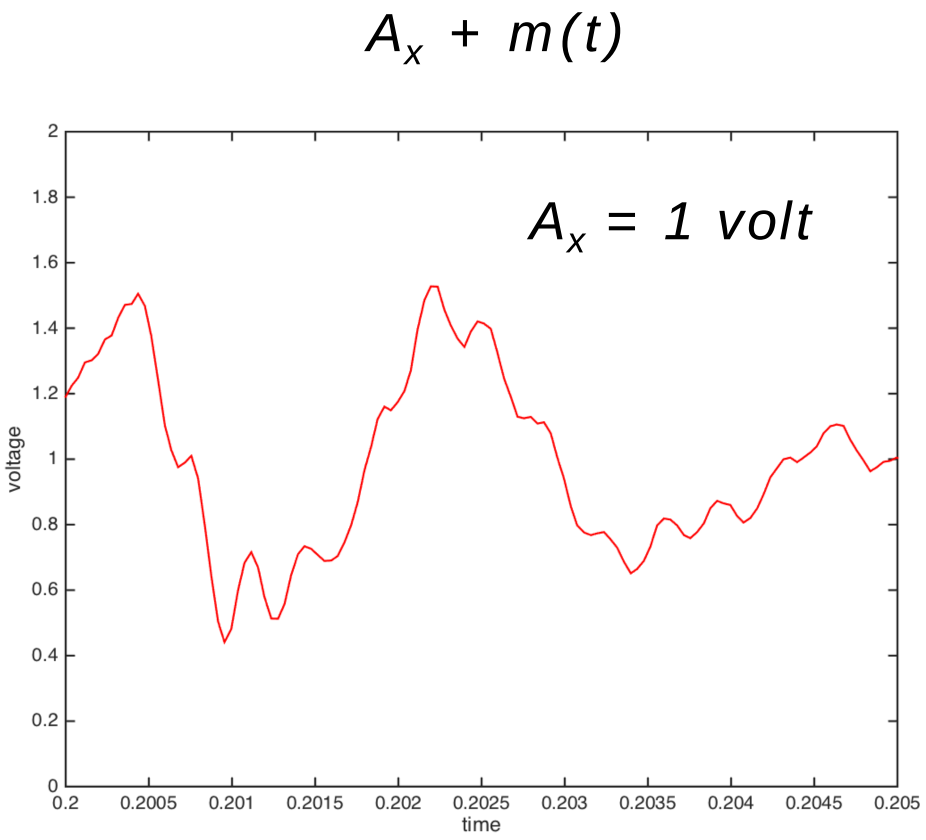
$$A_x = \text{ constant: } A_x + m(t) > 0$$

$$c(t) = \cos(2\pi f_c t) = \text{ carrier}$$

The AM Signal -2

[-0.6, 0.6] volts

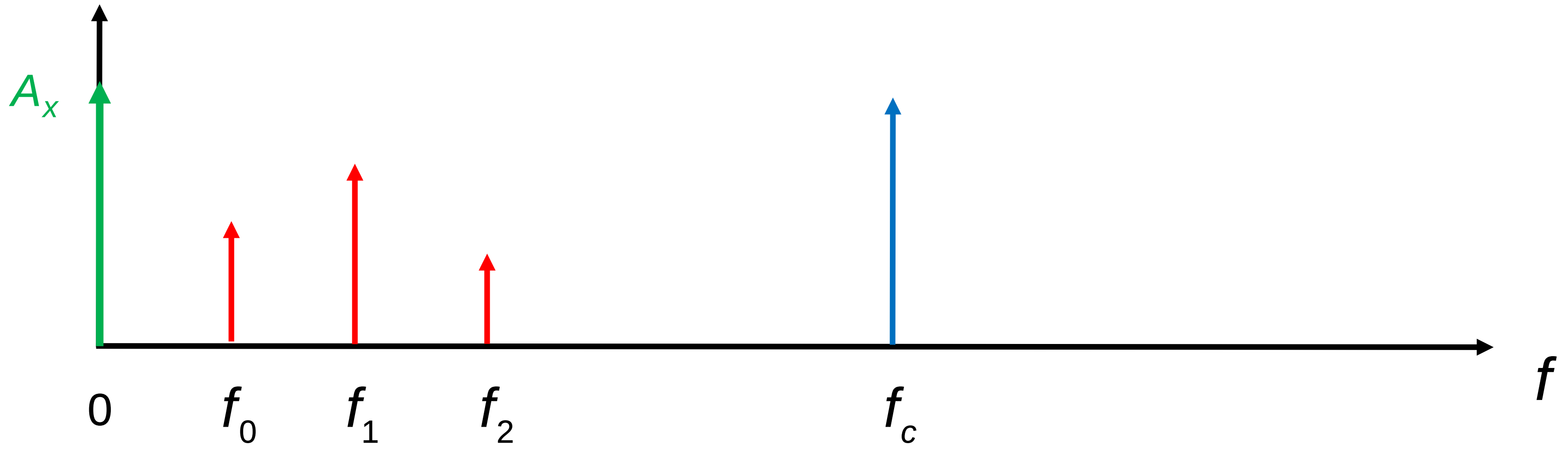




[0.4, 1.6] volts

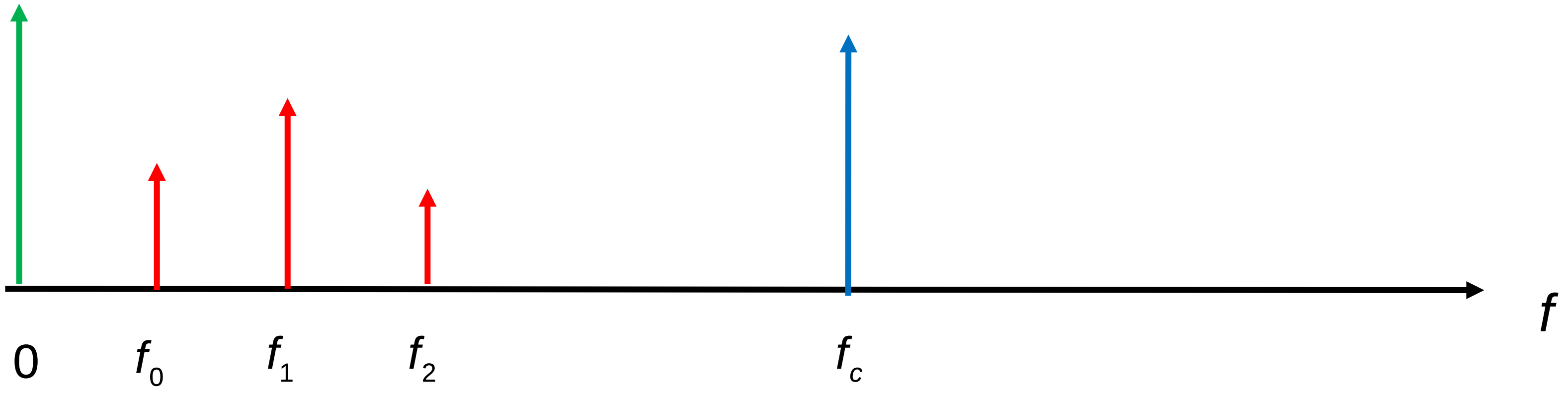
The AM Signal - 3

$$x_{AM}(t) = [A_x + m(t)]c(t)$$

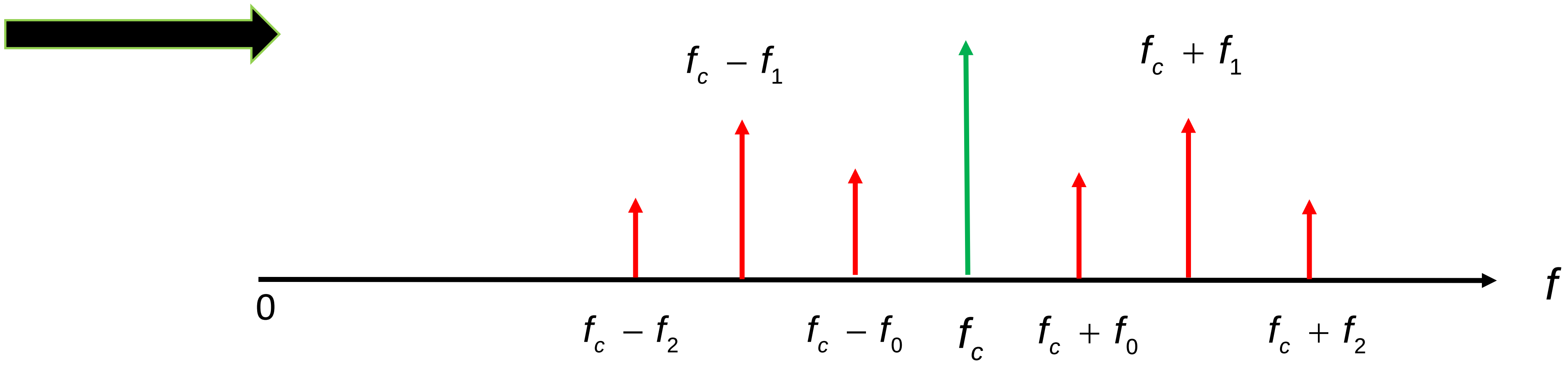


Form A_x + $m(t)$: Since A_x is a constant, it has frequency = 0 we add a frequency component at f = 0.

We have a carrier c(t) with a frequency f_c that is much larger than the highest frequency in $m(t)$.



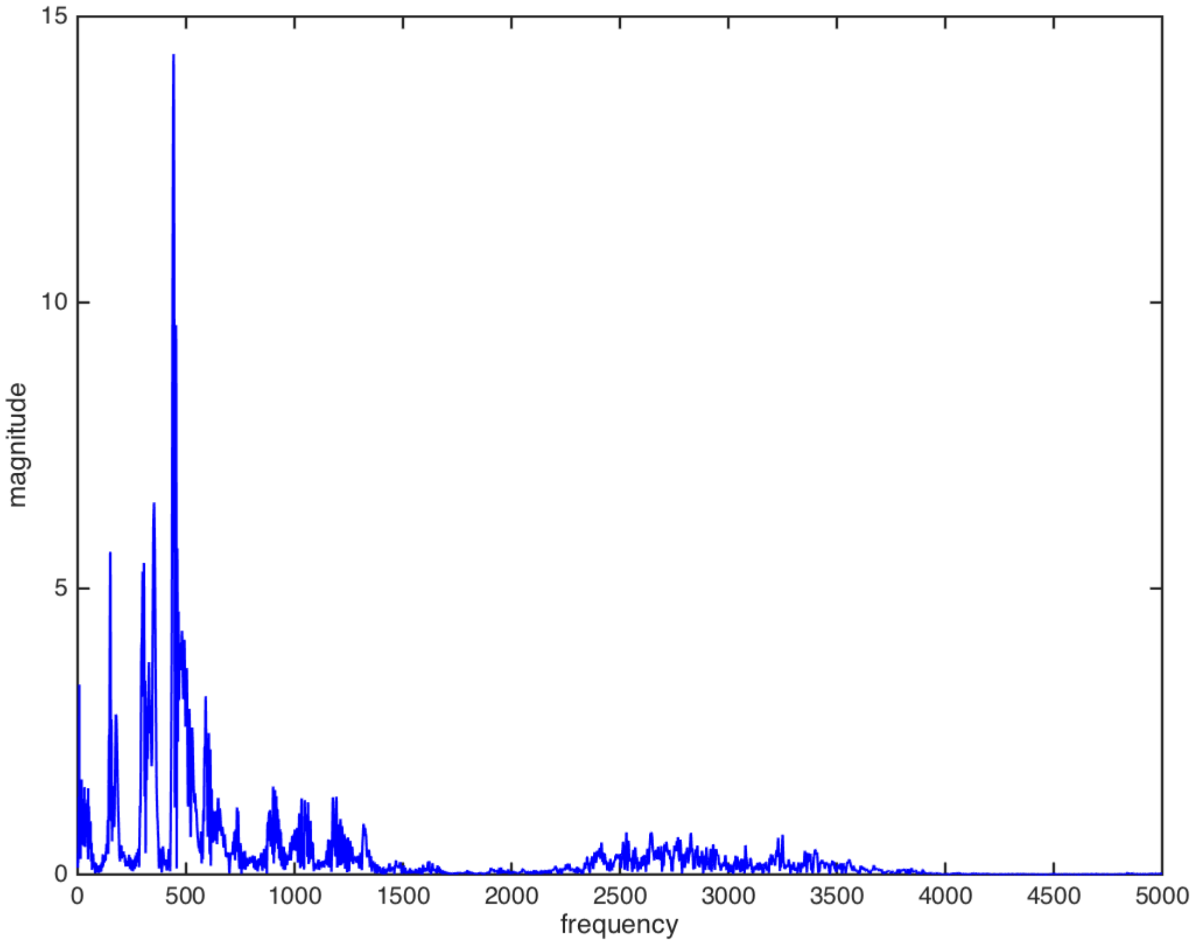
sinusoids at these frequencies • carrier at this frequency



frequency components after amplitude modulation

Example - 1

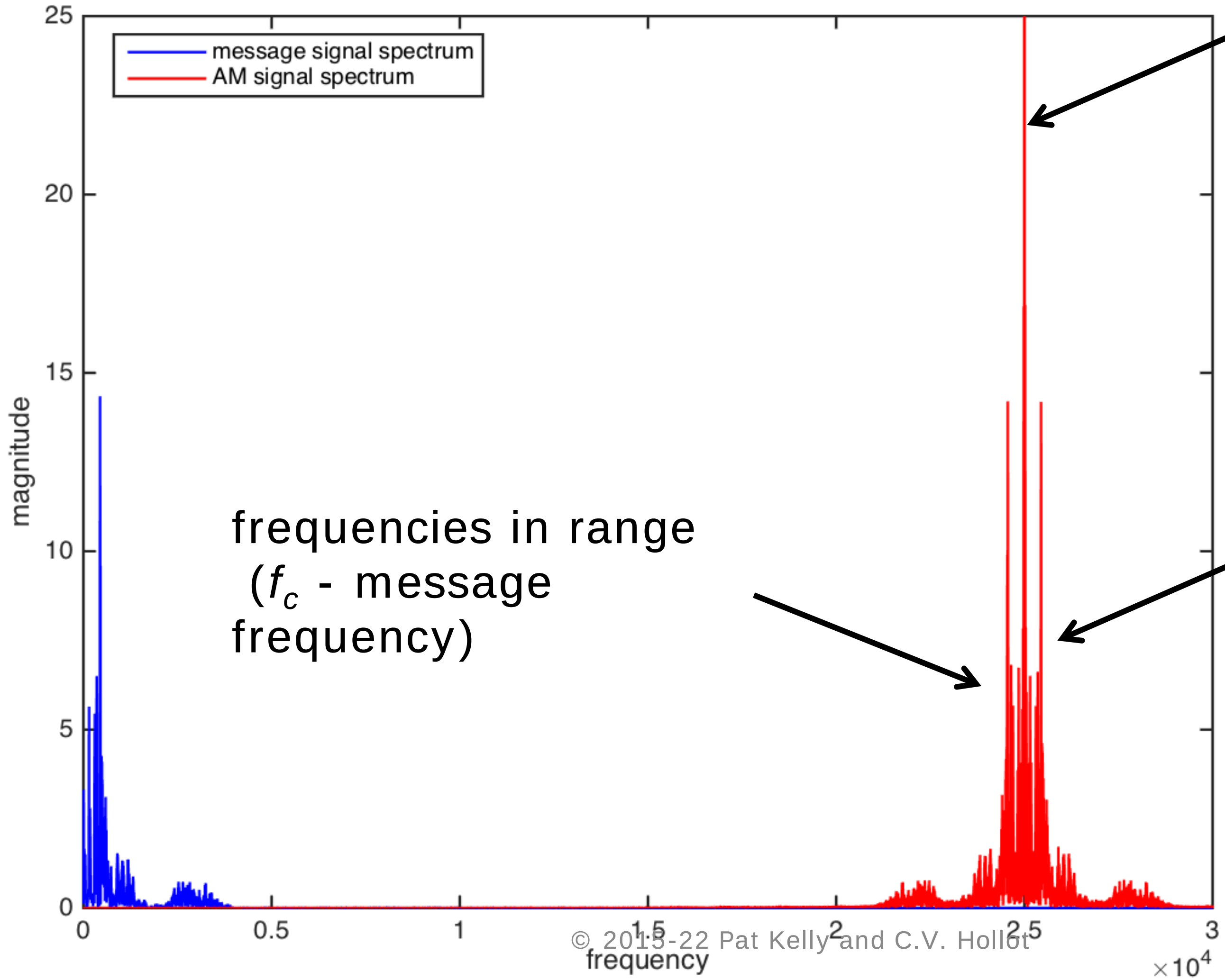
Suppose we have an audio (speech) signal with the spectrum:



highest signal frequency is < 5 kHz.

Example - 2

Form the AM signal $x_{AM}(t) = [A_x + m(t)] \cdot c(t)$, carrier frequency of $f_c = 25$ kHz:



component at carrier frequency

frequencies in range (f_c - message frequency)

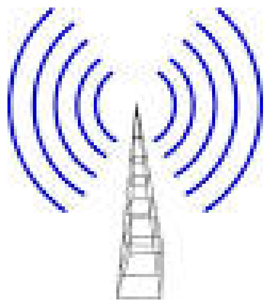
Frequencies in range (f_c + message frequency)

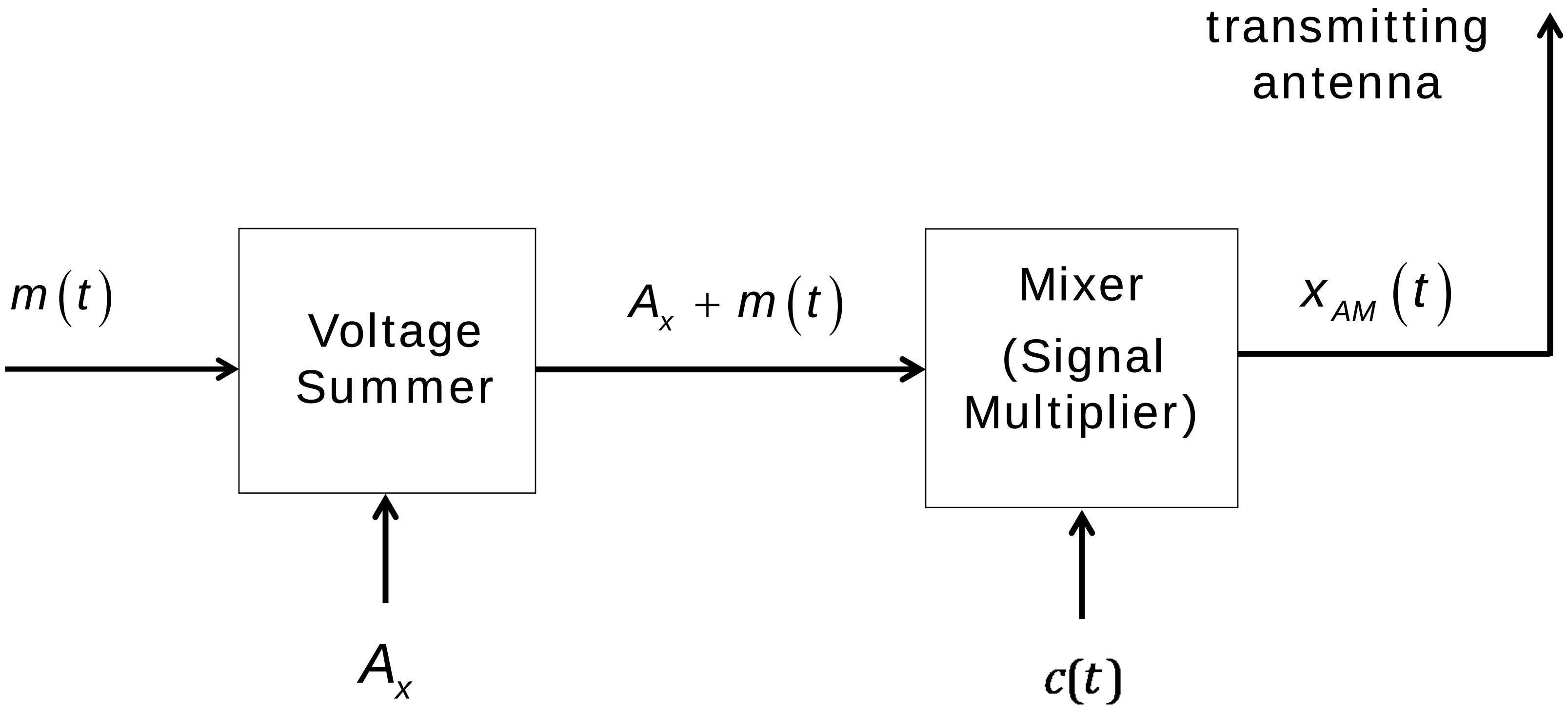
Main Concepts

- EM Waves & Antennas ✓
- Amplitude Modulation ✓
- Frequency Division Multiplexing
- Frequency Selective Filtering
- Superheterodyne Receiver
- Digital Communication Systems

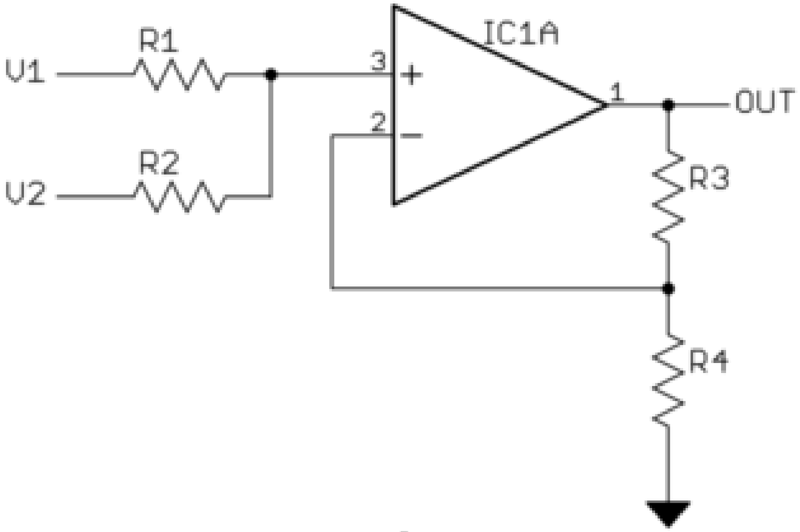
AM Transmitter - 1

$$x_{AM}(t) = [A_x + m(t)]c(t)$$

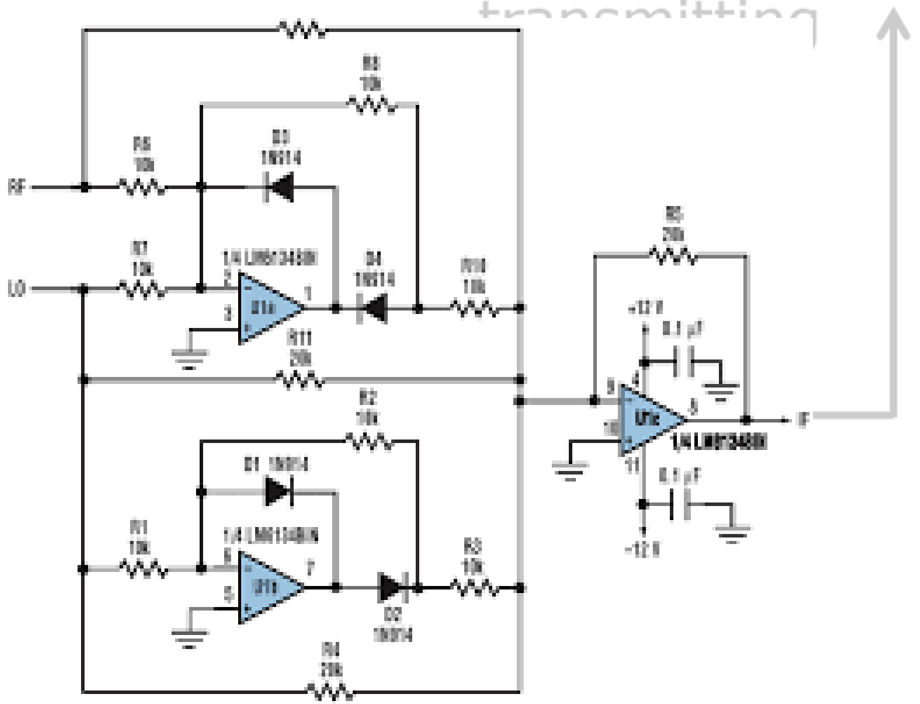




AM Transmitter - 2



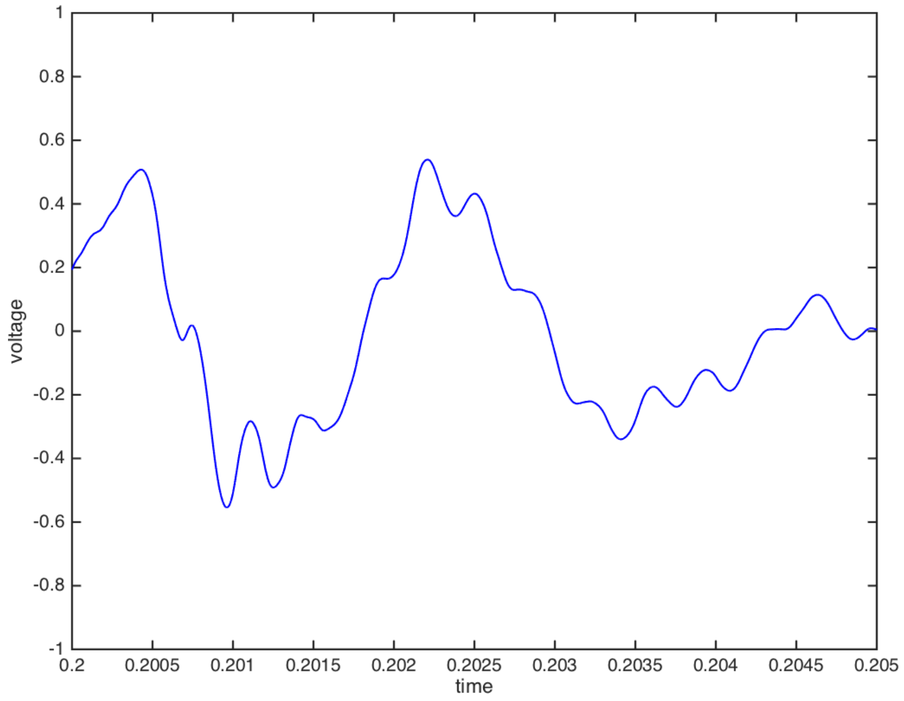
voltage summer



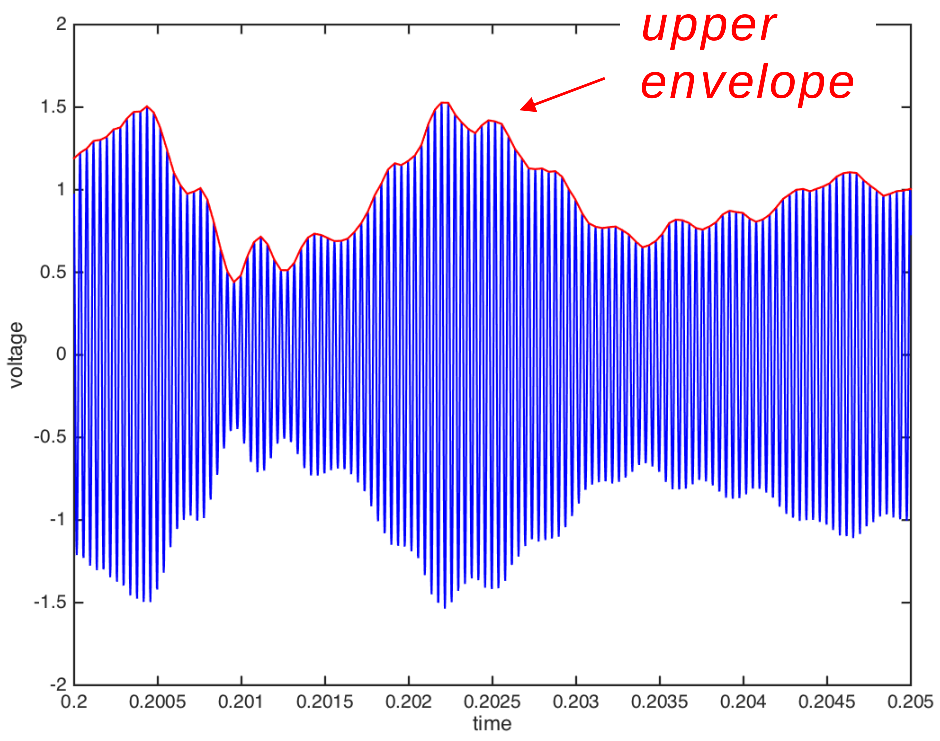
mixer circuit

Onto the AM Receiver!

Transmitted AM Signal

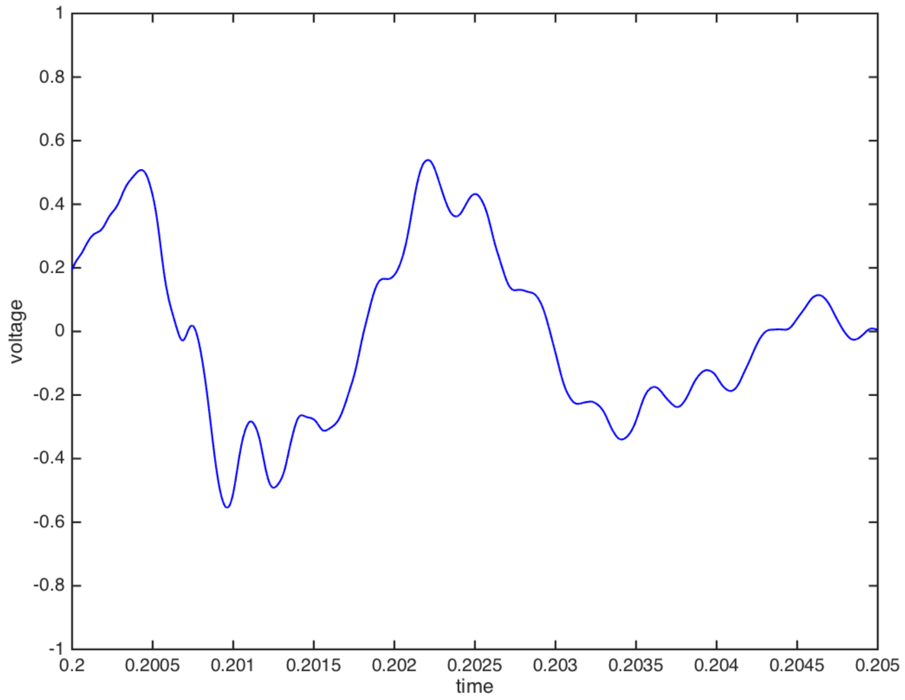


$m(t)$

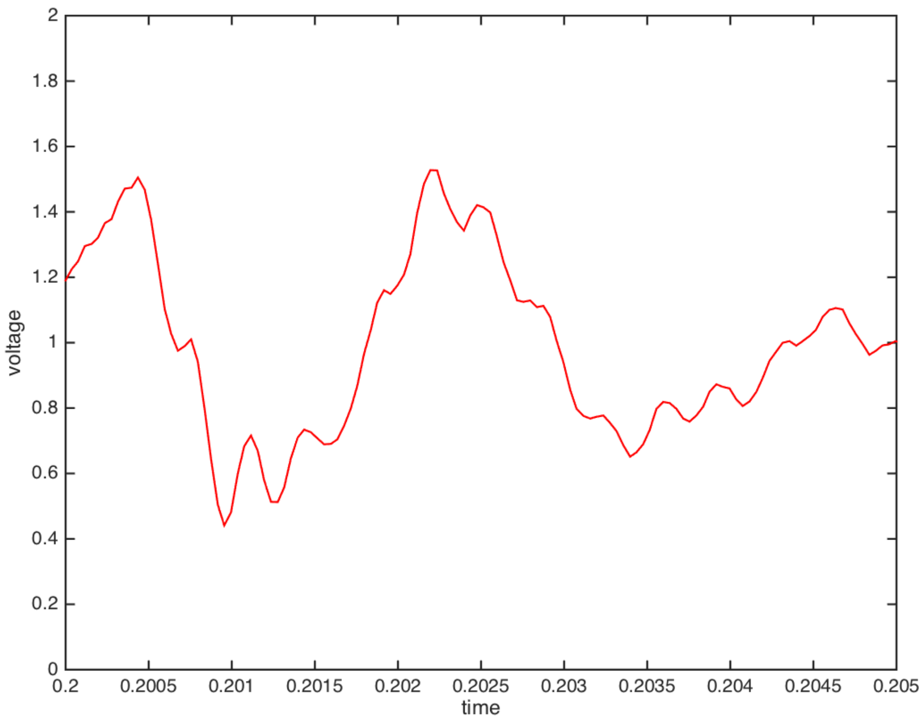


$x_{AM}(t); \quad A_x = 1; \quad f_c = 50kHz$

Upper Envelope

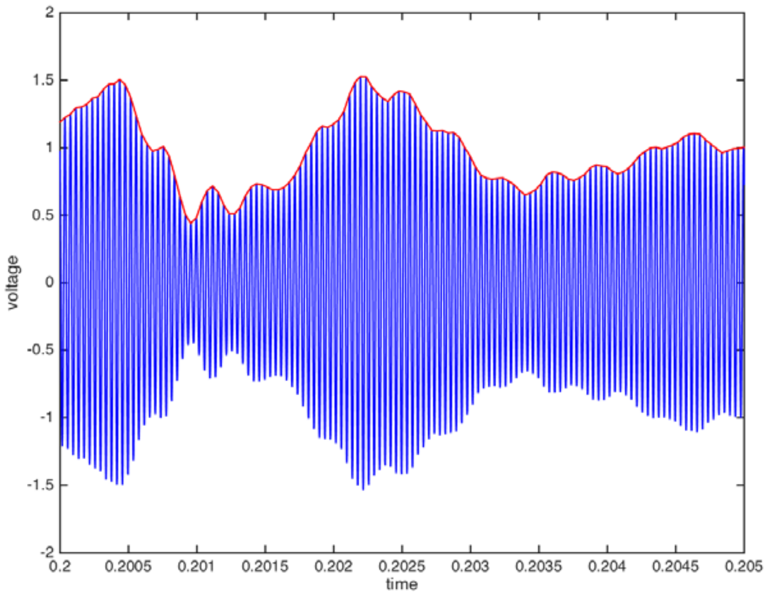


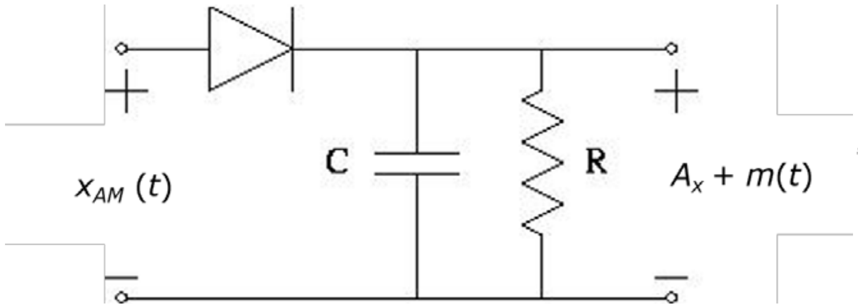
$m(t)$

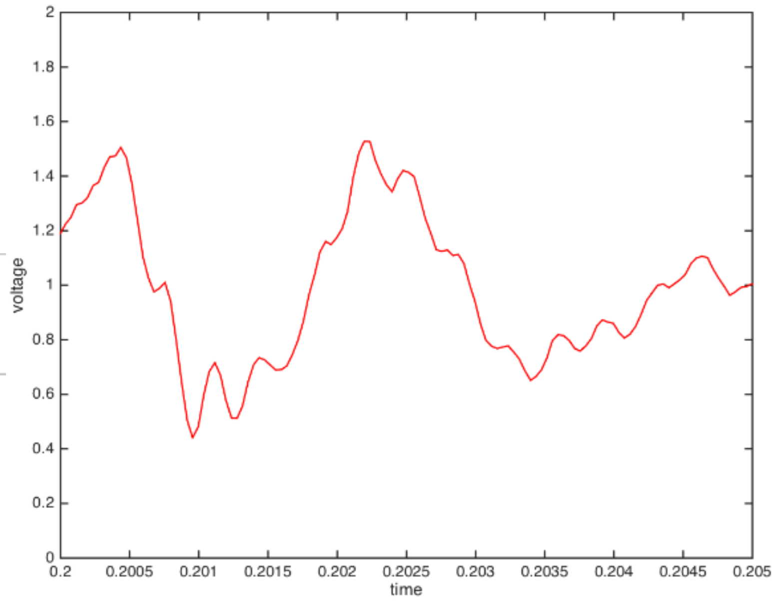


upper envelope of $x_{AM}(t)$

Upper Envelope Detector

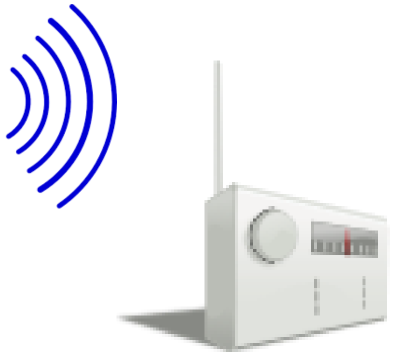


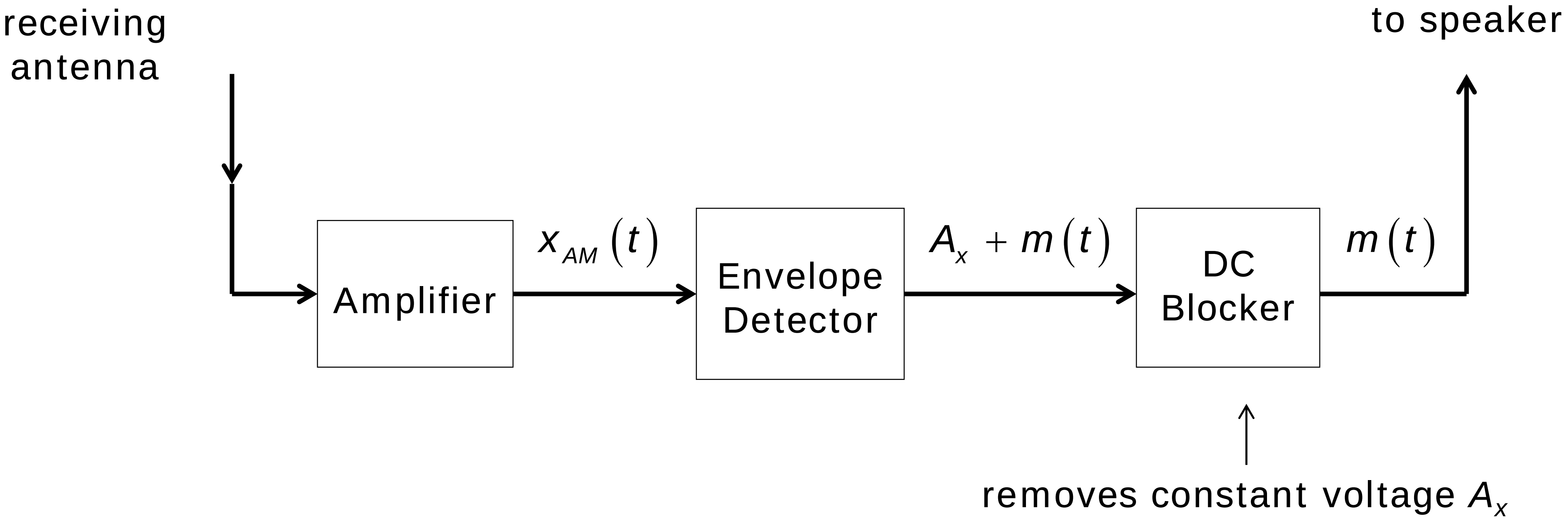




envelope detector

Basic AM Receiver



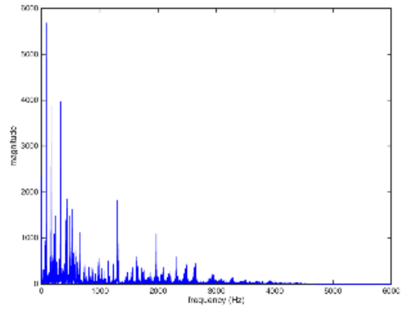


Sidebar:

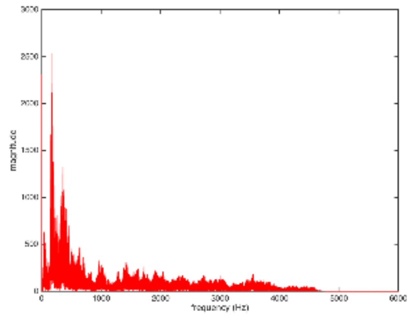
- **DC** = direct current = constant signal
- **AC** = alternating current = sinusoidal signal

Multiple AM Transmitters

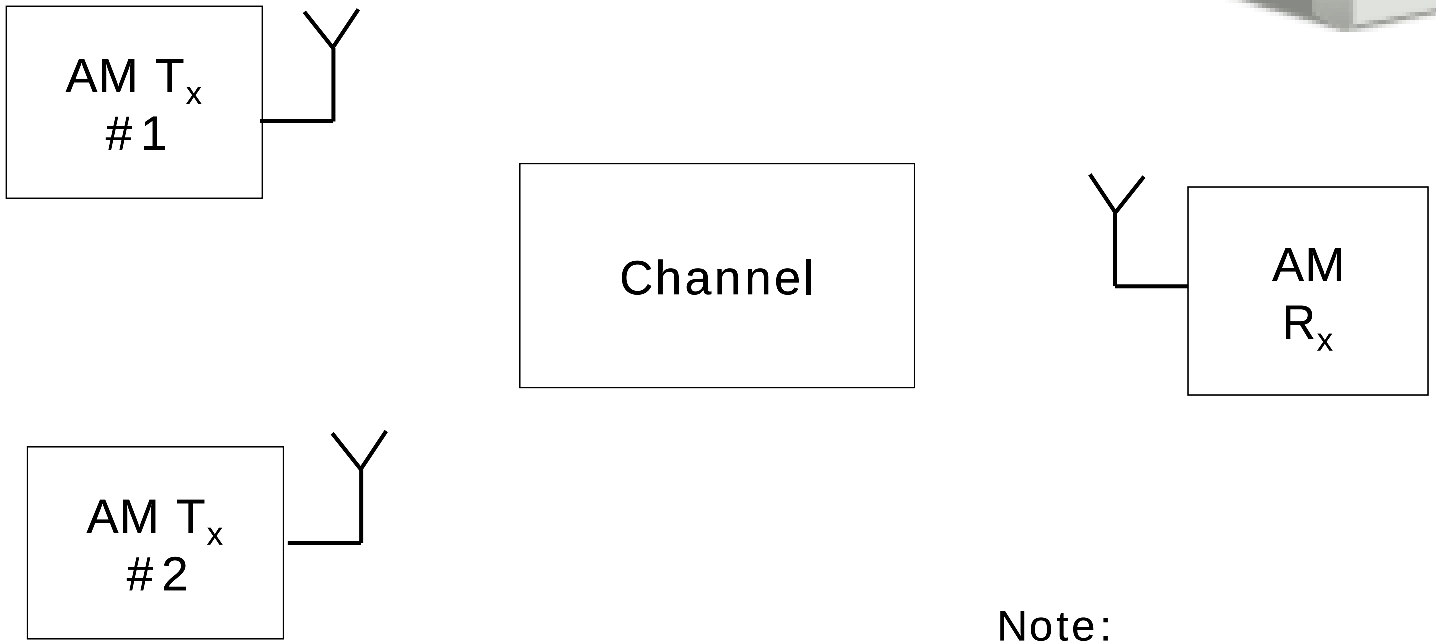
(multiple messages)



music



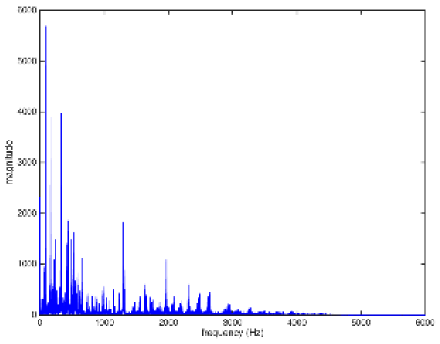
voice



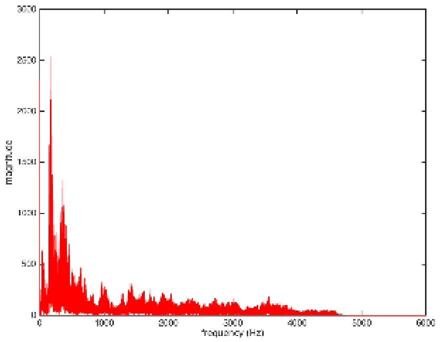
Note:

- T_x = transmitter
- R_x = receiver

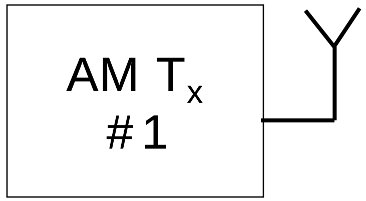
Frequency Division Multiplexing -1
(multiple signals over same channel)



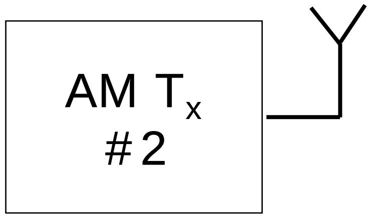
music



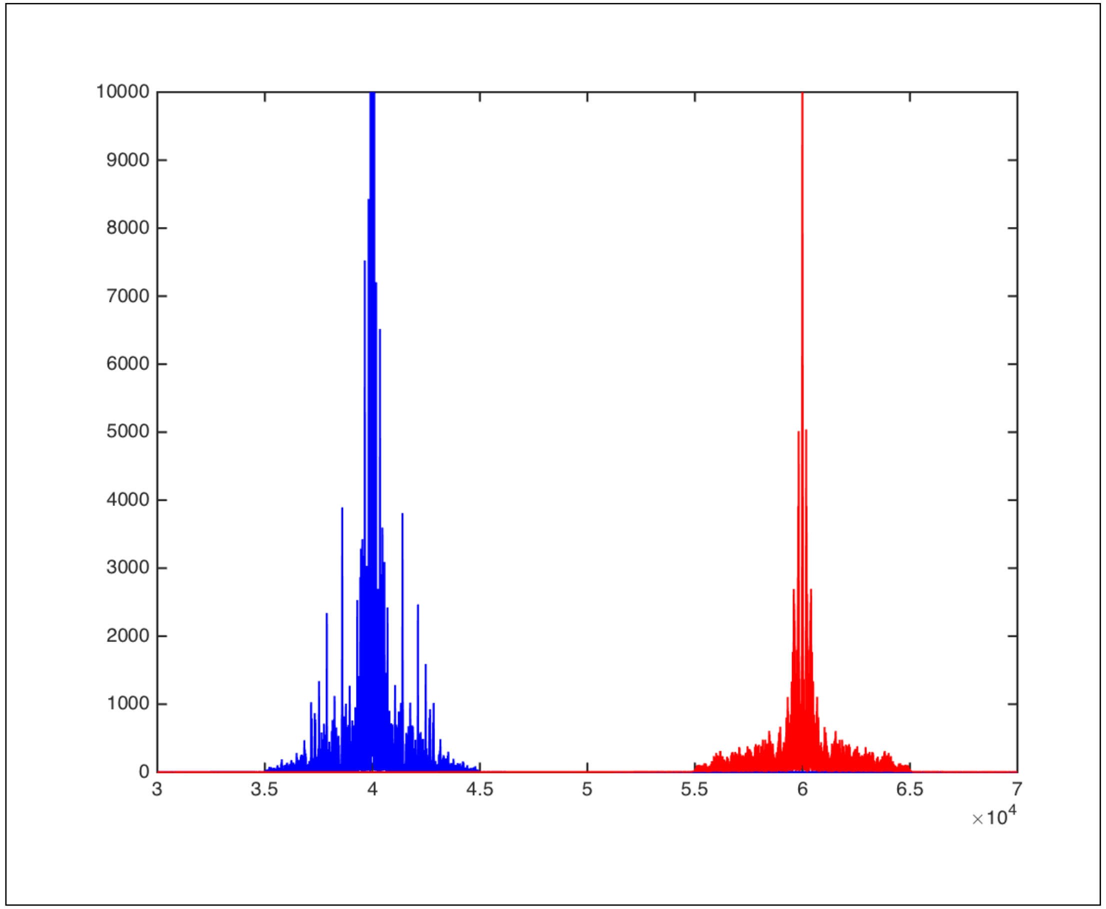
voice



$f_{c1} = 40kHz$



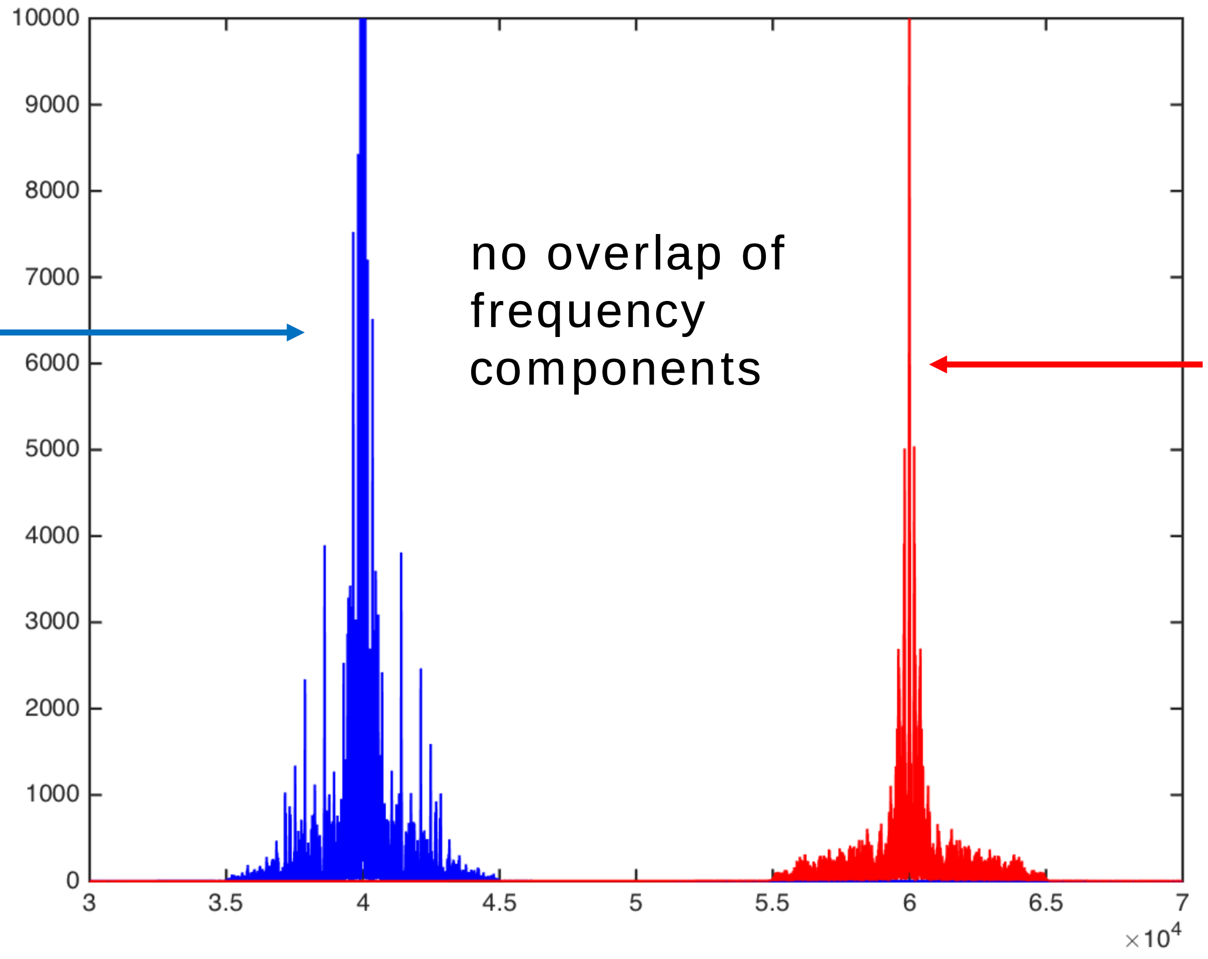
$f_{c2} = 60kHz$



Channel

Frequency Division Multiplexing -2

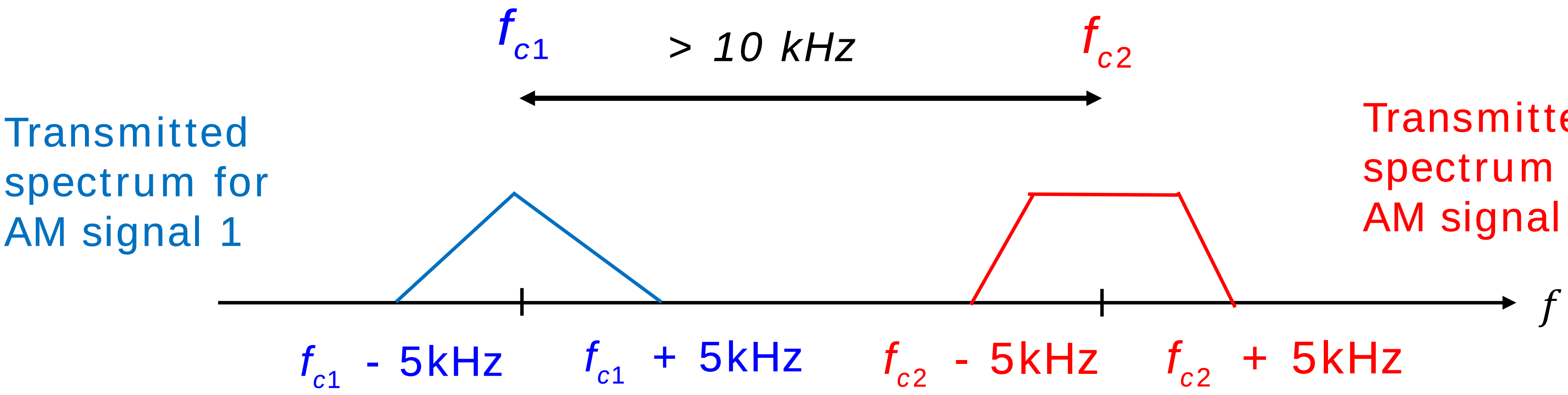
AM spectrum for music signal



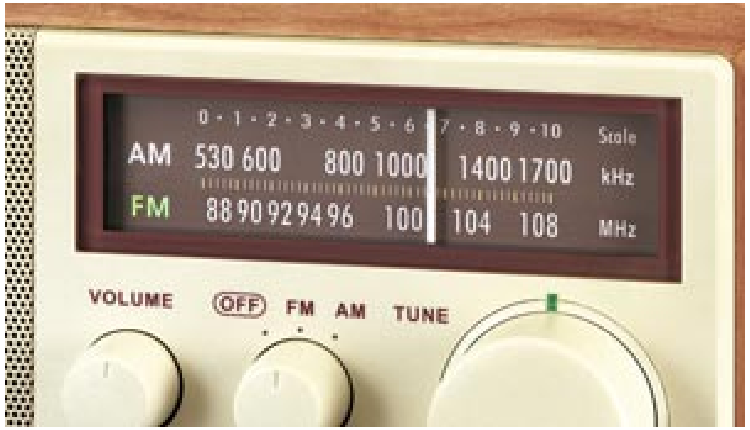
no overlap of frequency components

AM spectrum for voice signal

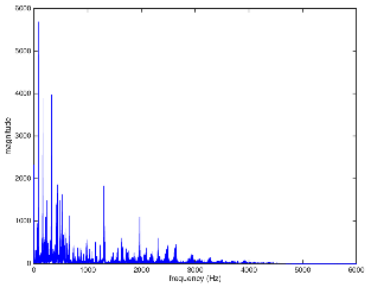
AM Carriers Separated by 10kHz



FCC allows carrier frequencies: 530 kHz, 550 kHz, ..., 1.59 MHz, 1.70 MHz



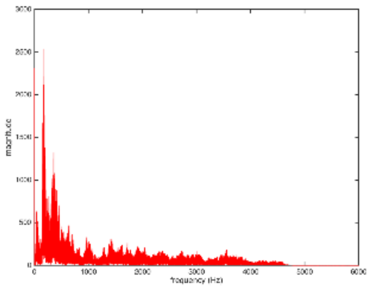
What about the Receiver ???



music

AM T_x #1

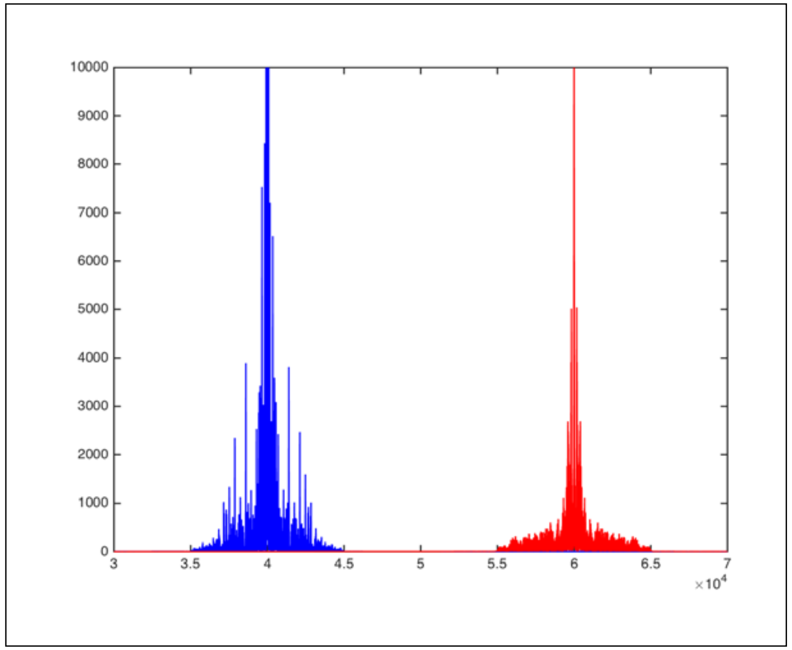
$f_{c1} = 40kHz$



voice

AM T_x #2

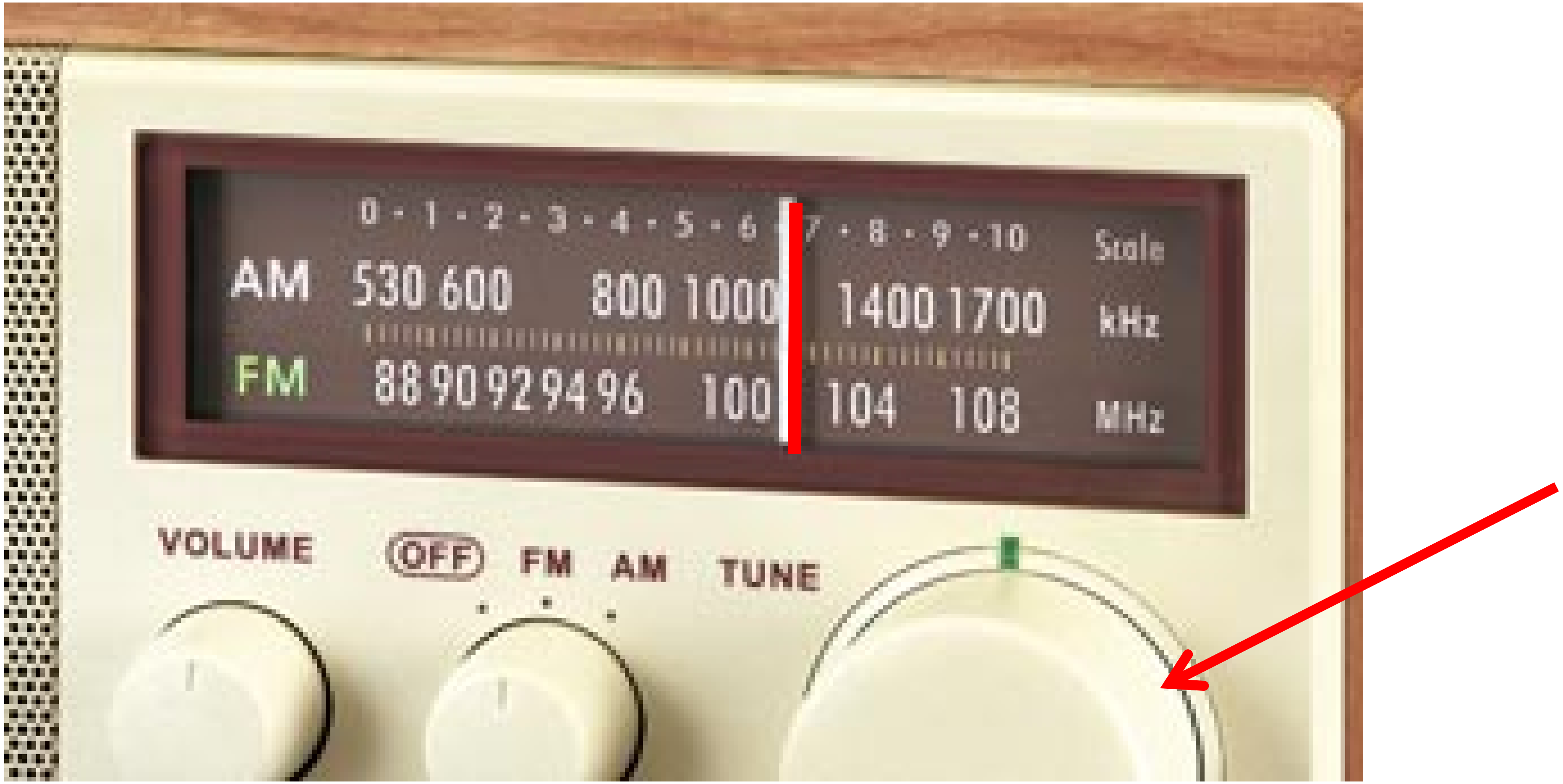
$f_{c2} = 60kHz$



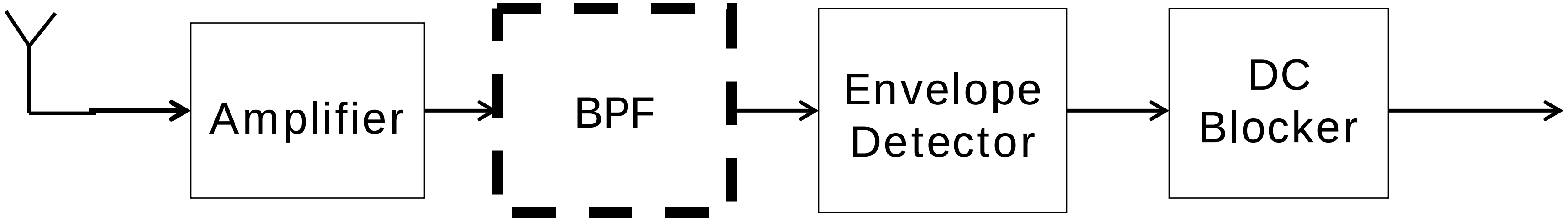
Channel

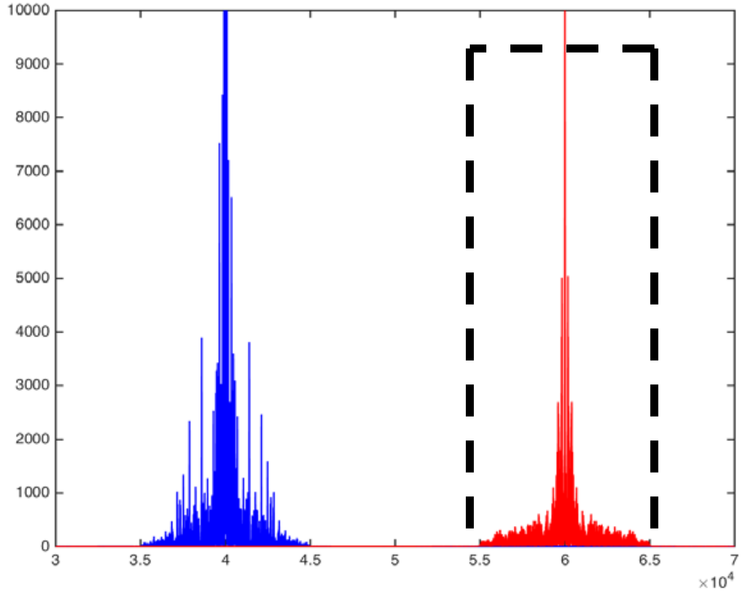
AM R_x

Give it a Tuning Knob!

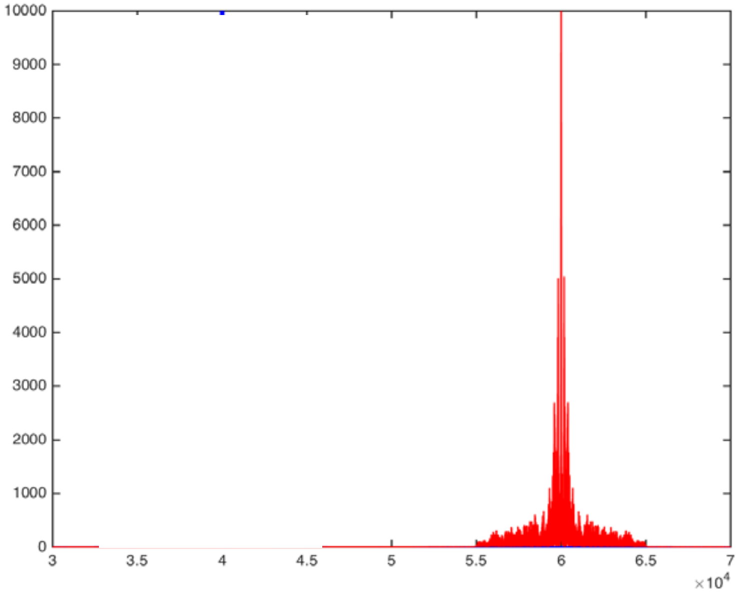


The Band Pass Filter (BPF)



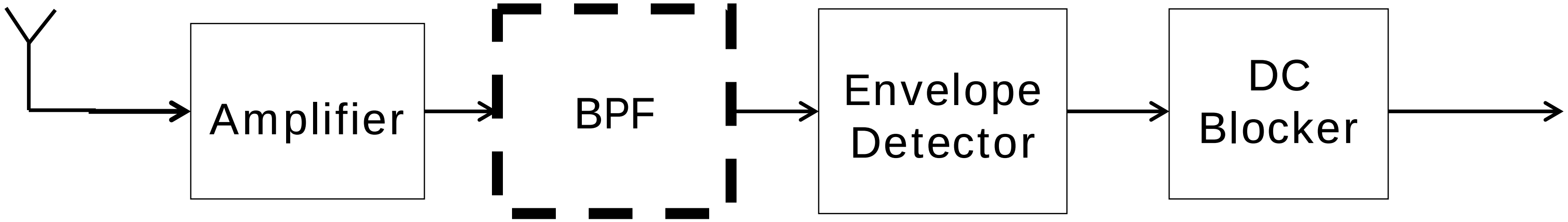


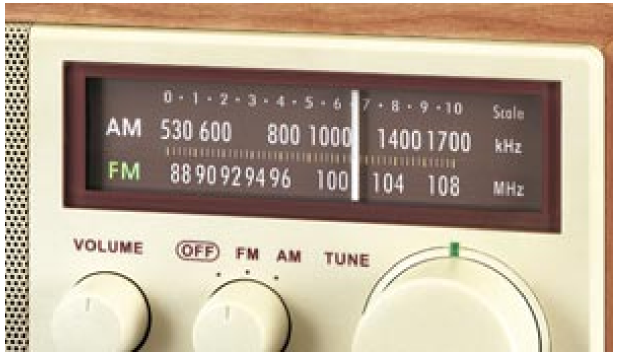
input to BPF

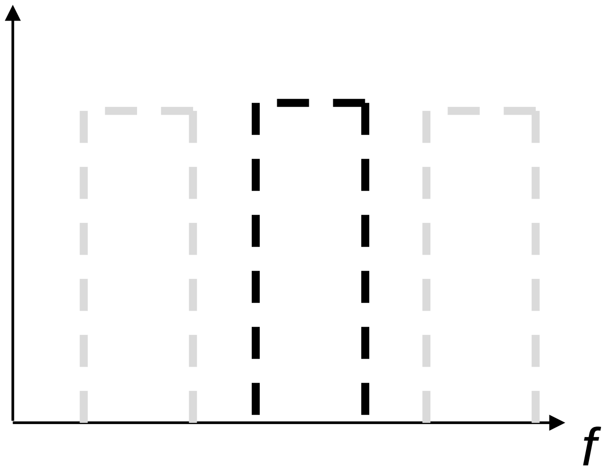


output of BPF

Tuner: Tunable Band Pass Filter

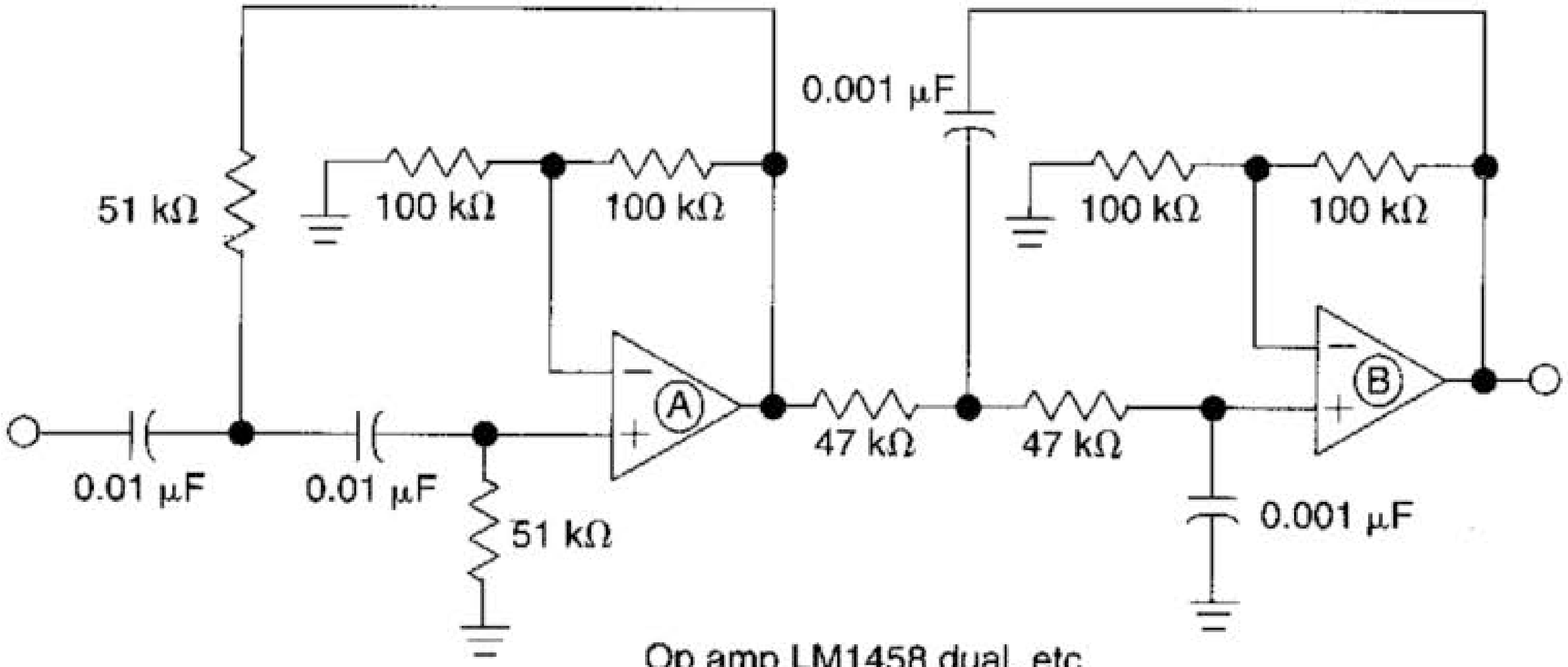




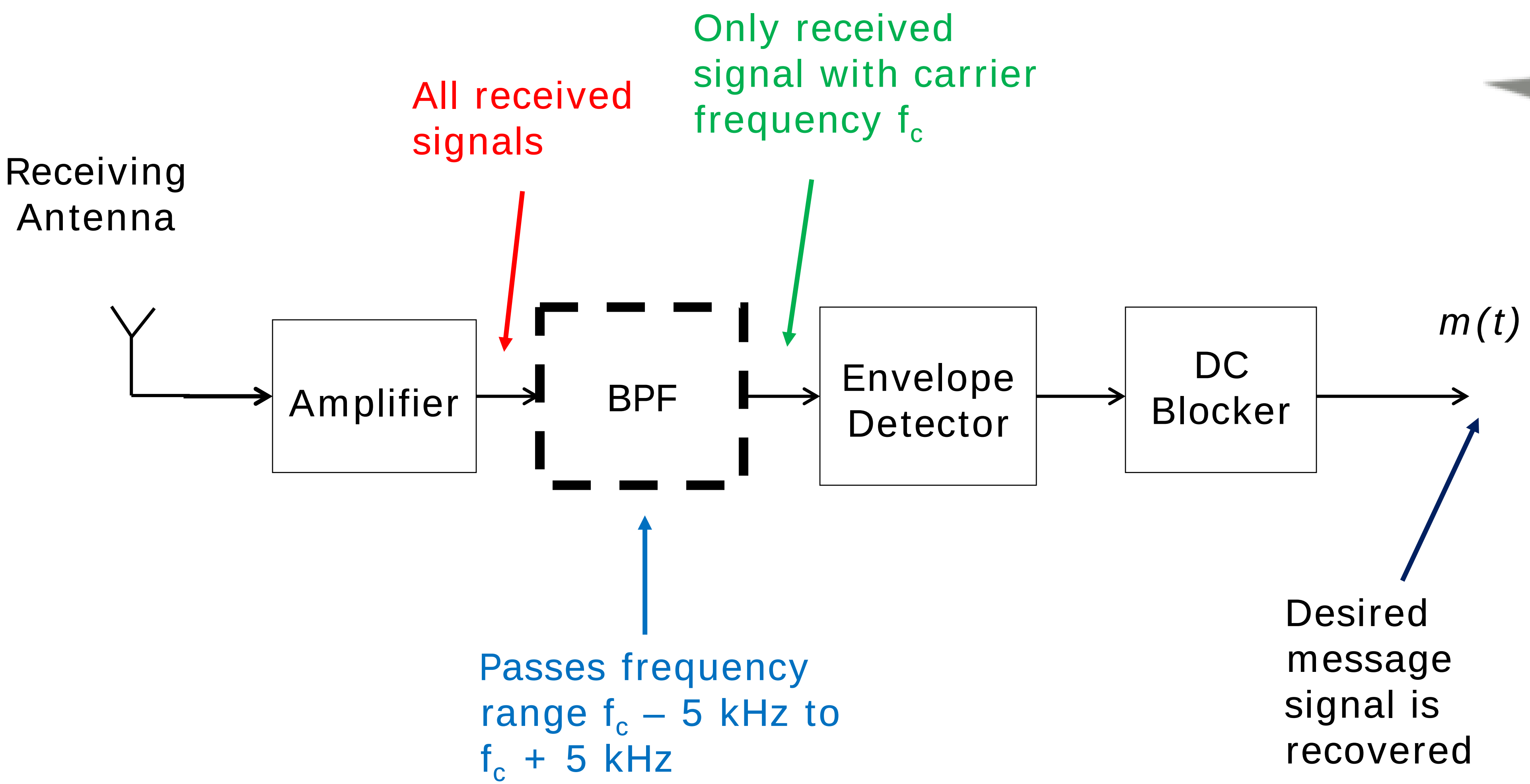


BPF example of Frequency Selective Filter

BPF: Analog Hardware



AM Receiver (Tunable BPF)



Maxwell's Equations (1831-1879)

$\nabla . E = \frac{\rho}{\epsilon_0}$	(1)	Gauss' law
$\nabla . B = 0$	(2)	Magnetic monopoles
$\nabla \times E = -\frac{\partial B}{\partial t}$	(3)	Faraday's law
$\nabla \times H = J + \frac{\partial D}{\partial t}$	(4)	Ampere-Maxwell law

Marconi

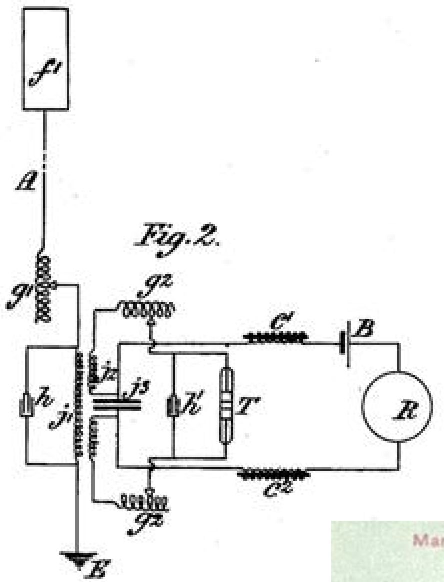
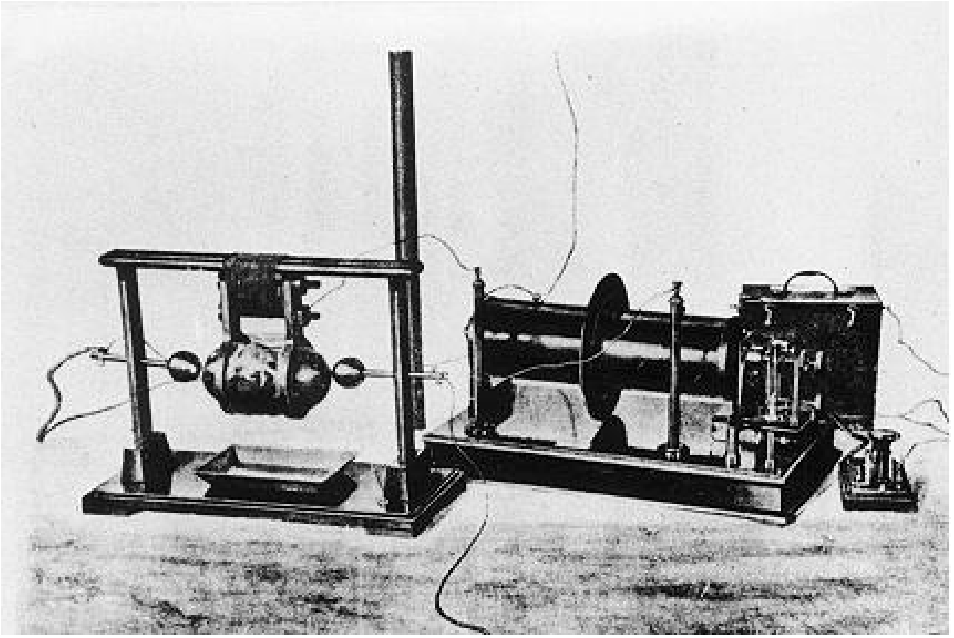
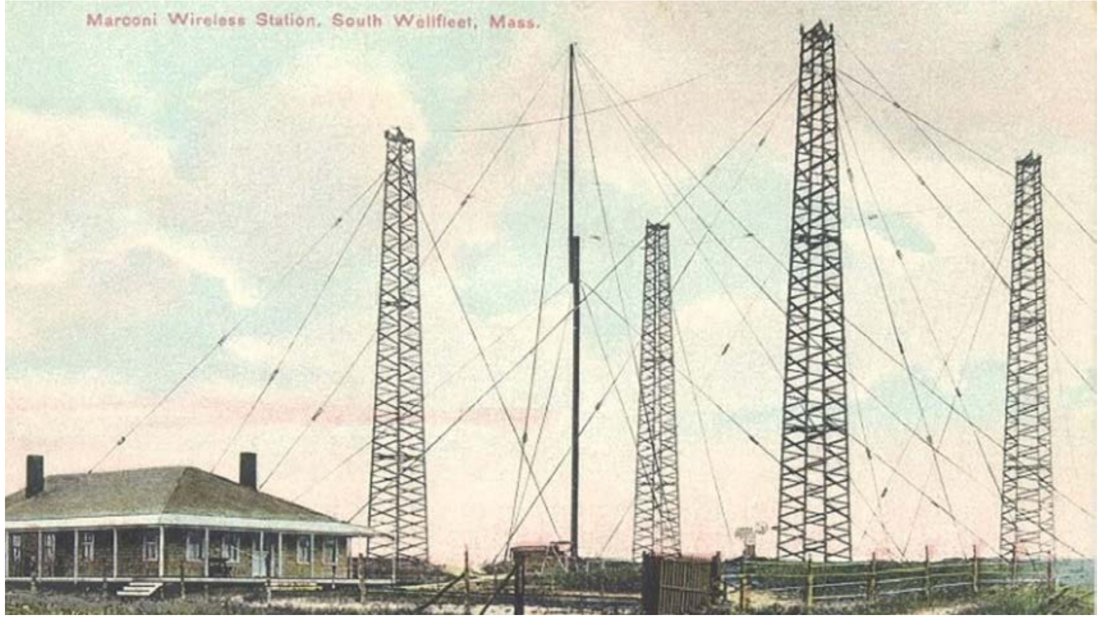


Fig. 2.
f¹
A
g¹
g²
C¹
B
h
j¹
j²
j³
k¹
T
R
C²
g²
E

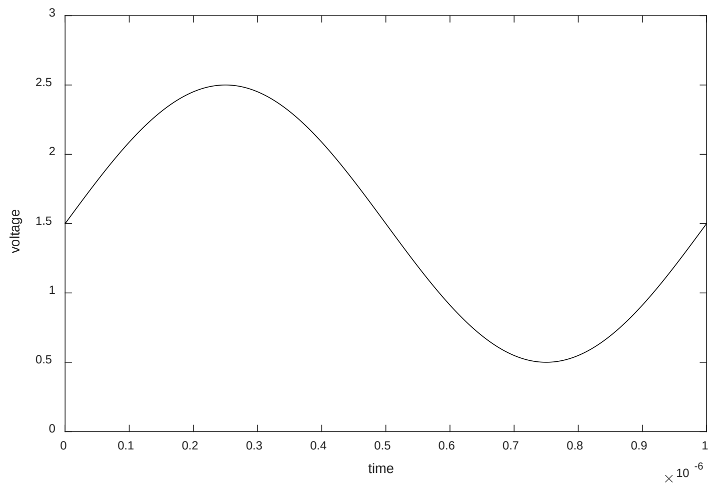



Marconi Wireless Station, South Wellfleet, Mass.

Main Concepts

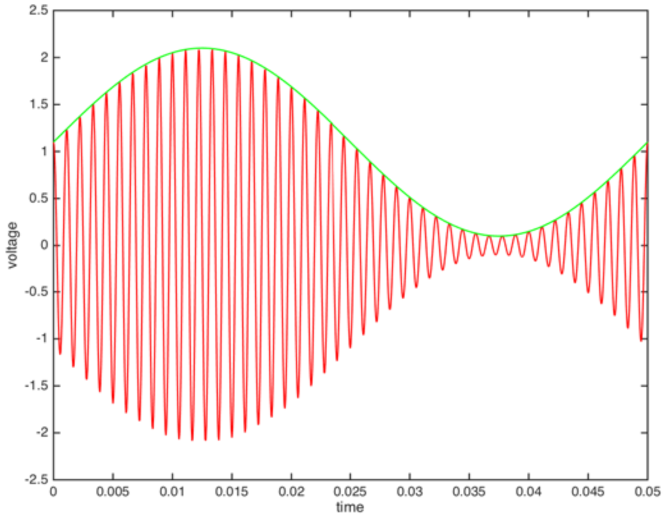
- EM Waves & Antennas ✓
- Amplitude Modulation ✓
- Frequency Division Multiplexing ✓
- Frequency Selective Filtering ✓
- Digital Communication Systems

Frequency Modulation (FM)

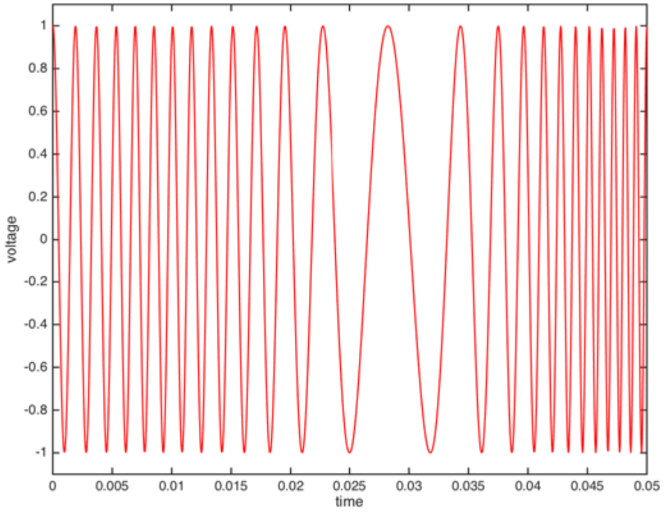


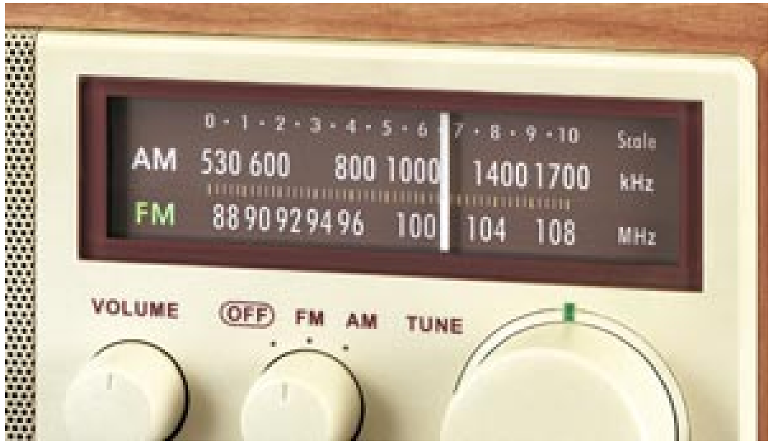
message signal

AM signal

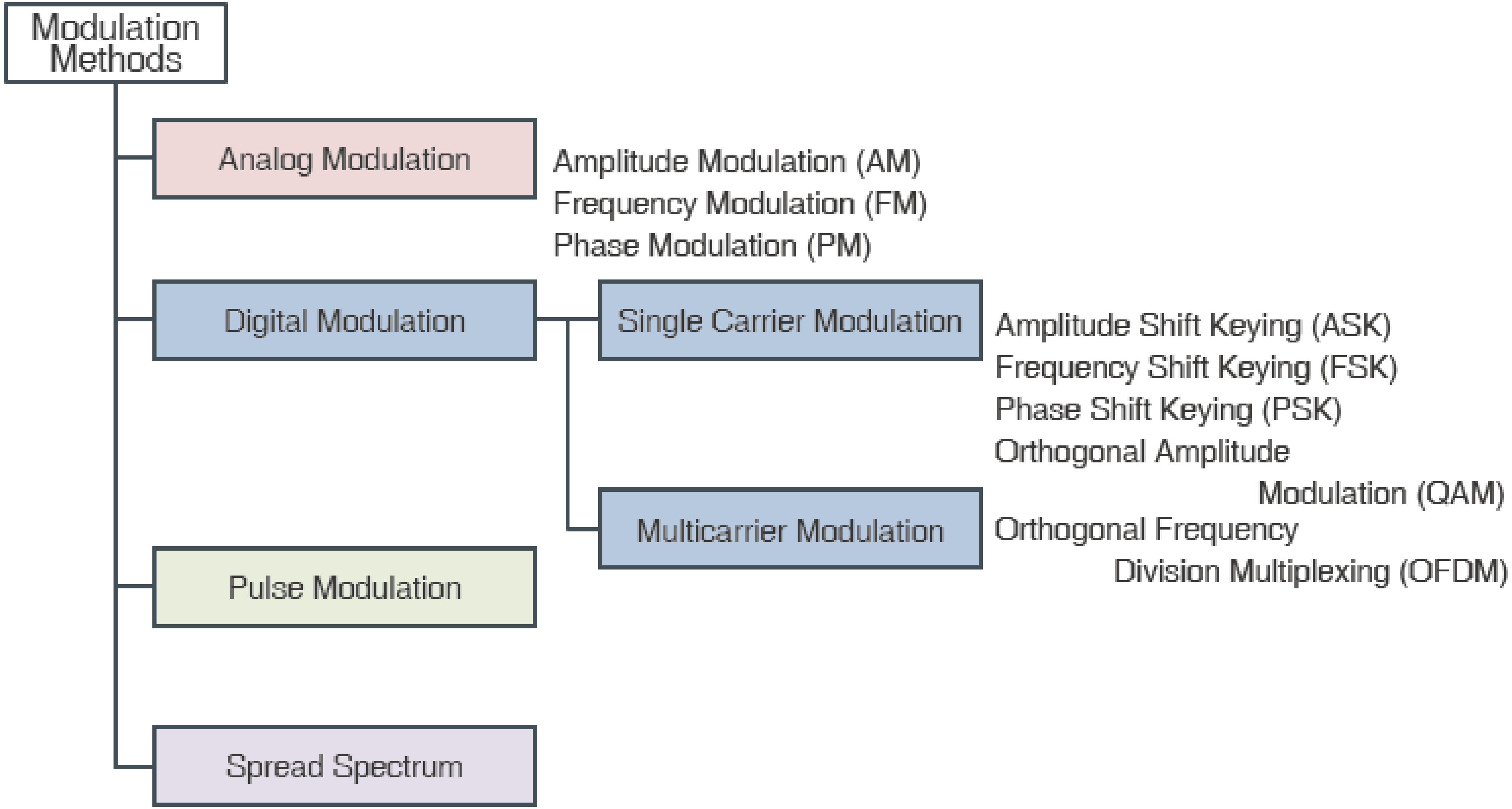


FM signal





Modulation Methods



from: *Modulation Methods*, https://www.rohm.com/electronics-basics/wireless/modulation-methods

Digital Communications

0111000011110010
1000111101001001
0111100111100010
...

Binary Phase Shift Keying (BPSK)

- Bit stream (R_B bits/sec = bit rate)

  1 0 0 0 1 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 ...

- T_B = $1/R_B$ sec = bit interval= time to transmit one bit

- carrier

$$c(t) = A\cos(2\pi f_c t)$$

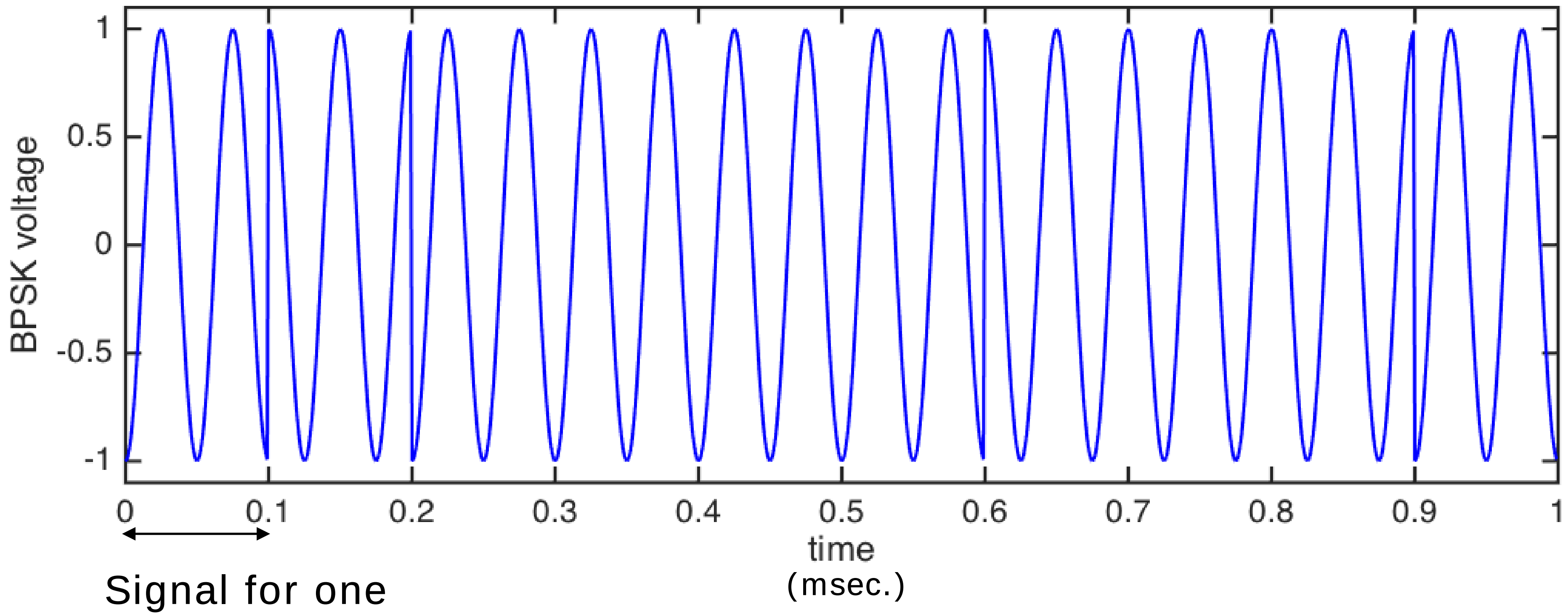
- BPSK:

  bit = 1, transmit $c(t)$ for T_B sec
  bit = 0; transmit $-c(t)$ for T_B sec

BPSK Example

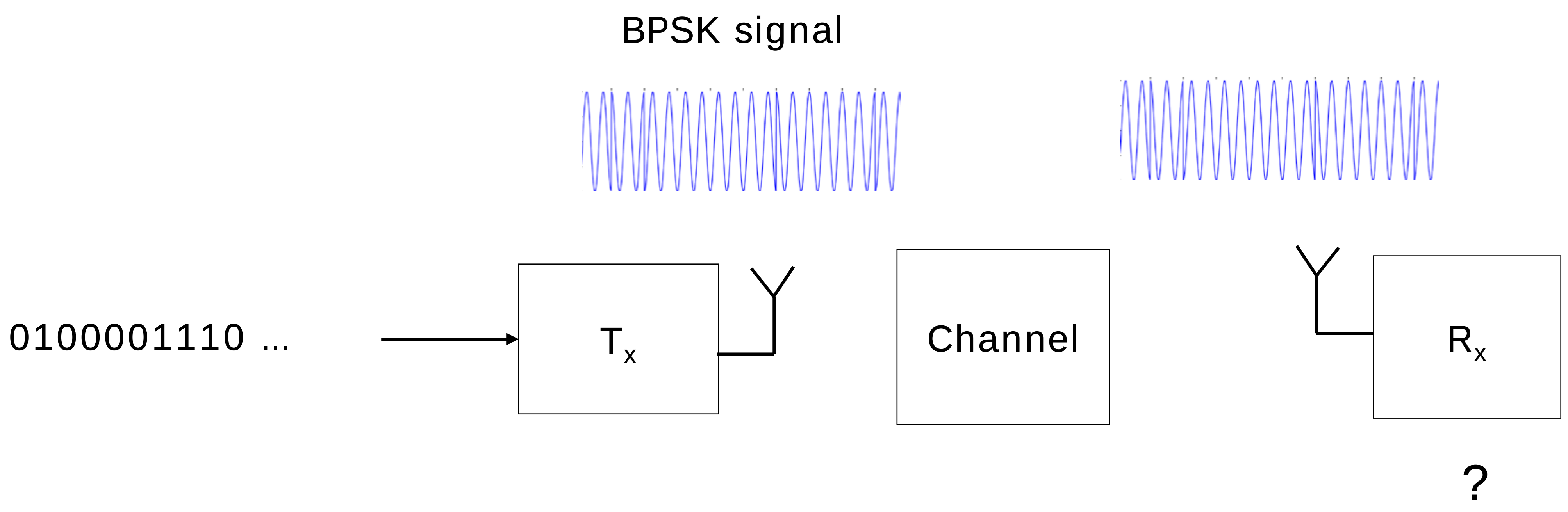
$$R_B = 10\,\text{kbits/sec}; \quad T_B = 0.1\,\text{msec}; \quad f_c = 20\,\text{kHz}; \quad 1/f_c = 0.05\,\text{msec}$$

0	1	0	0	0	0	1	1	1	0
$-c(t)$	$c(t)$	$-c(t)$	$-c(t)$	$-c(t)$	$-c(t)$	$c(t)$	$c(t)$	$c(t)$	$-c(t)$



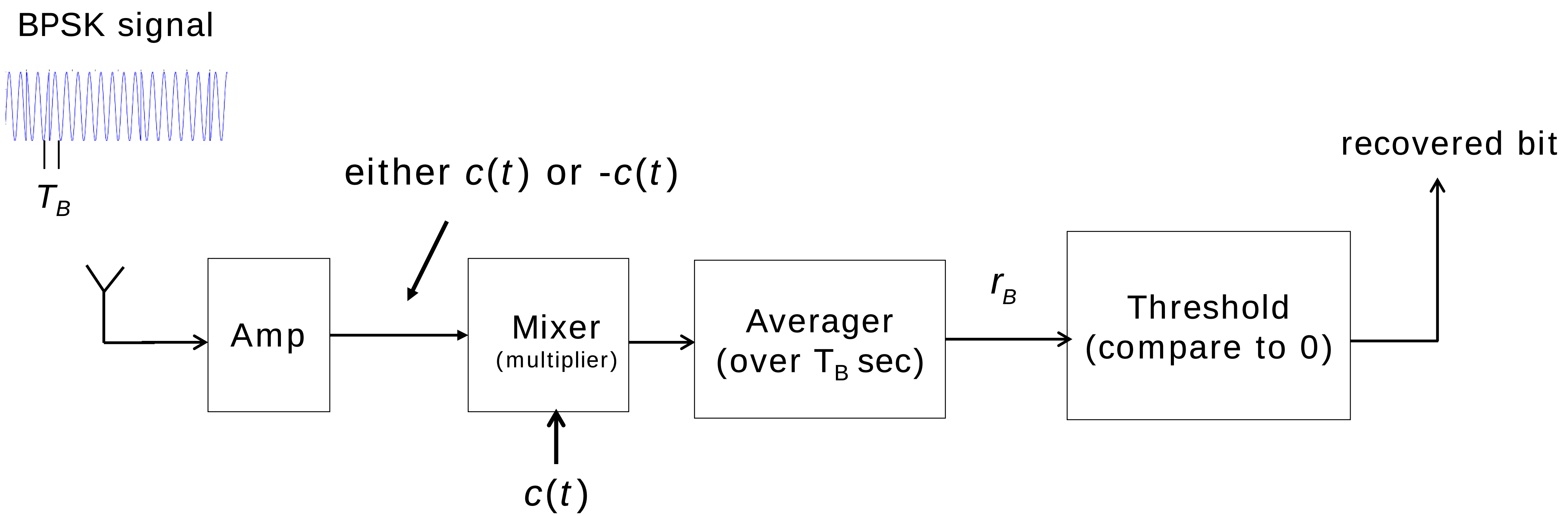
Signal for one transmitted bit

Receiving a BPSK Signal



Correlation Receiver - 1

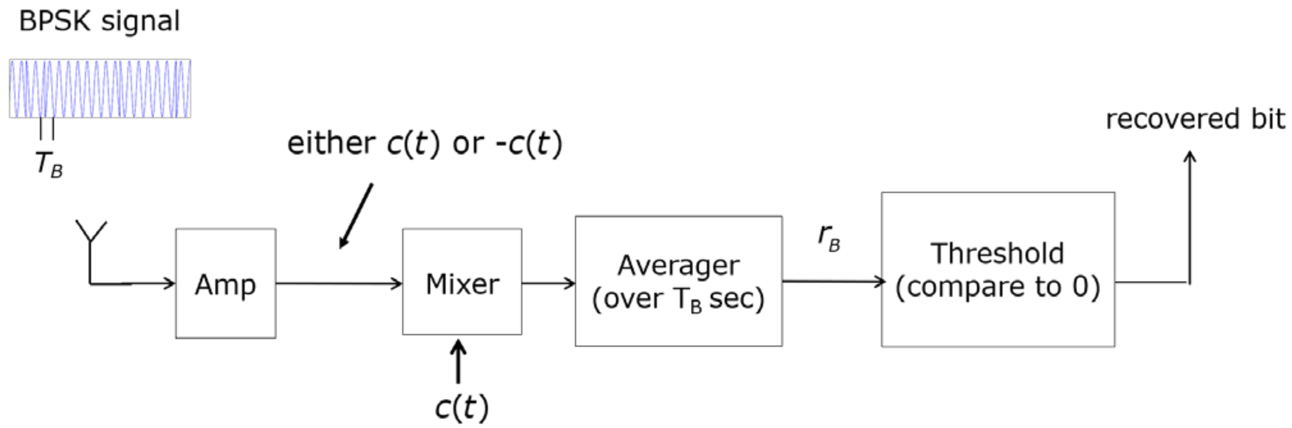
(operation over one-bit interval, T_B sec)



r_B = receiver's "decision variable"

Correlation Receiver - 2

(operation over one-bit interval, T_B sec)

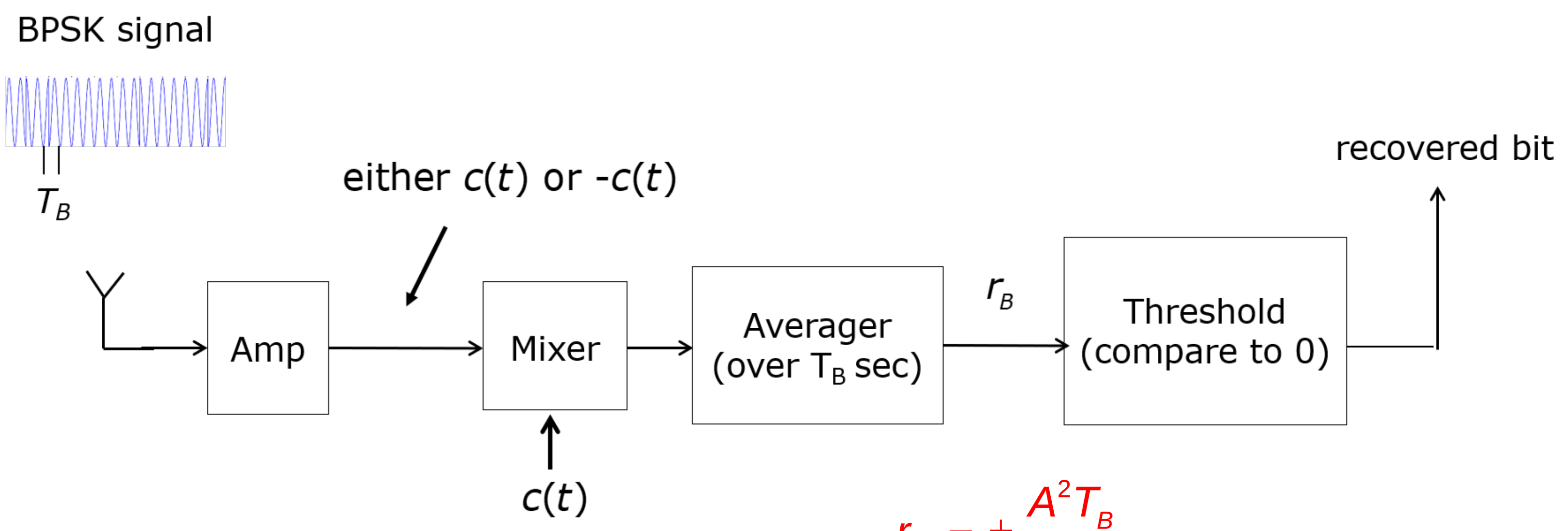


$$c(t)\cdot c(t) = \left[A\cos(2\pi f_c t)\right]^2 = \underbrace{\frac{A^2}{2} + \frac{A^2}{2}\cos(4\pi f_c t)}_{r_B = \text{ average over bit interval } = \frac{A^2 T_B}{2} > 0} \quad ; \quad r_B > 0 \text{ when received bit } = 1$$

$$-c(t)\cdot c(t) = -\left[A\cos(2\pi f_c t)\right]^2 = \underbrace{-\left(\frac{A^2}{2} + \frac{A^2}{2}\cos(4\pi f_c t)\right)}_{r_B = \text{ average over bit interval } = \frac{-A^2 T_B}{2} < 0} \quad ; \quad r_B < 0 \text{ when received bit } = 0$$

Correlation Receiver - 3

(operation over one-bit interval, T_B sec)



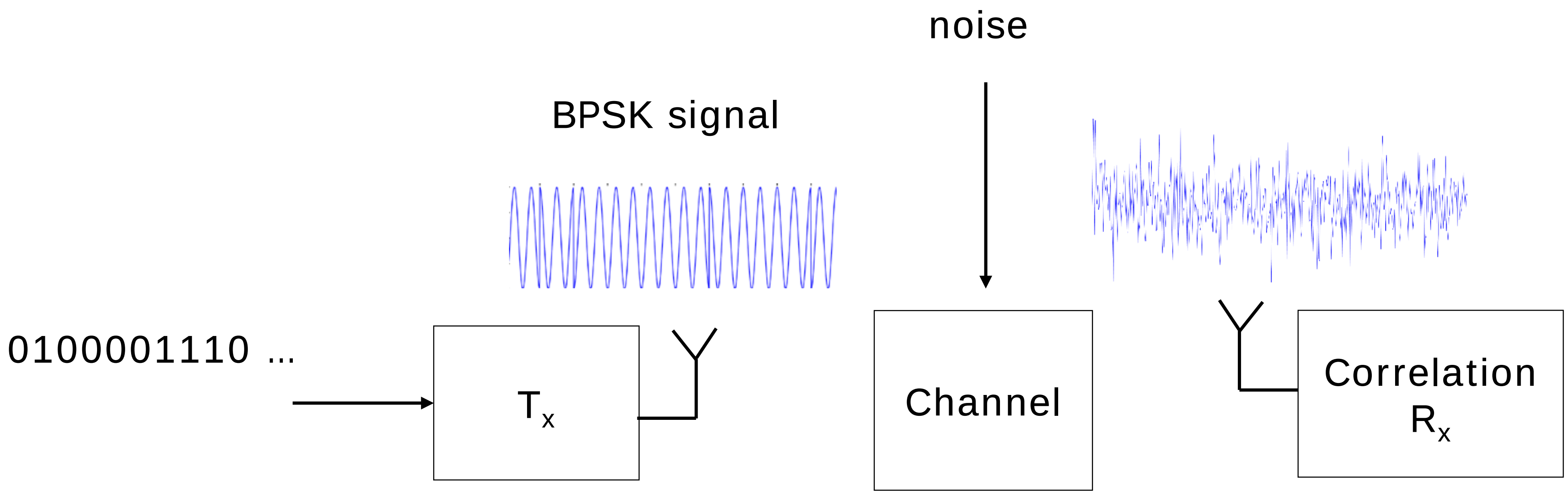
$$r_B = \pm \frac{A^2 T_B}{2}$$

Threshold:

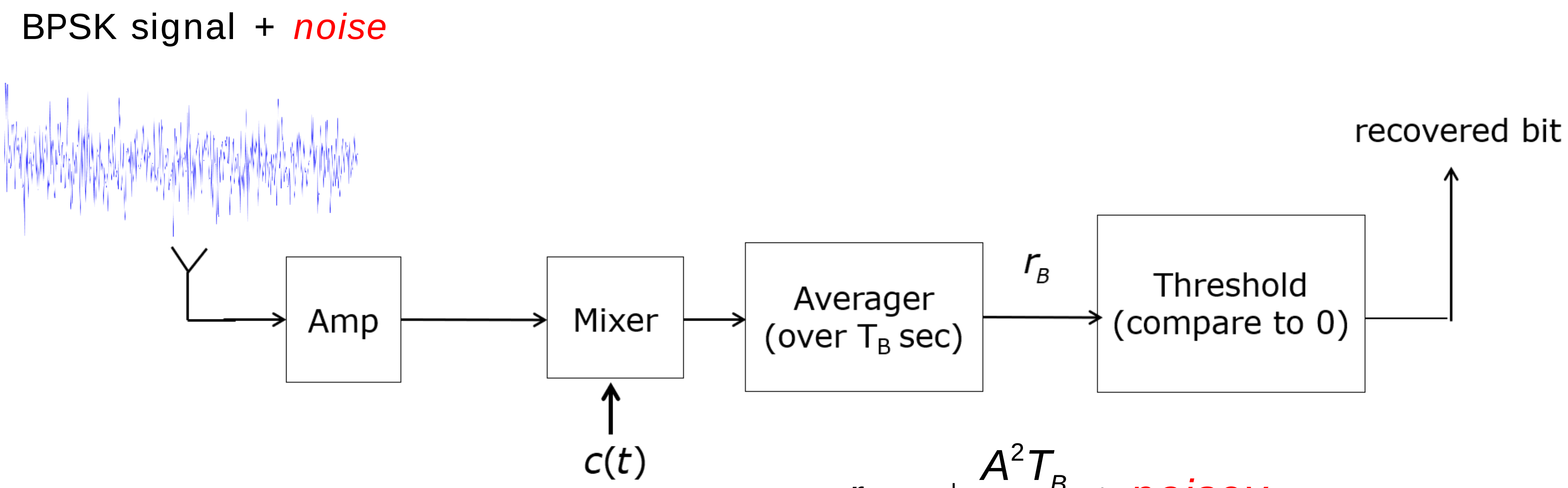
recovered bit = 1 when $r_B > 0$;

recovered bit = 0 when $r_B < 0$

Noisy Channel



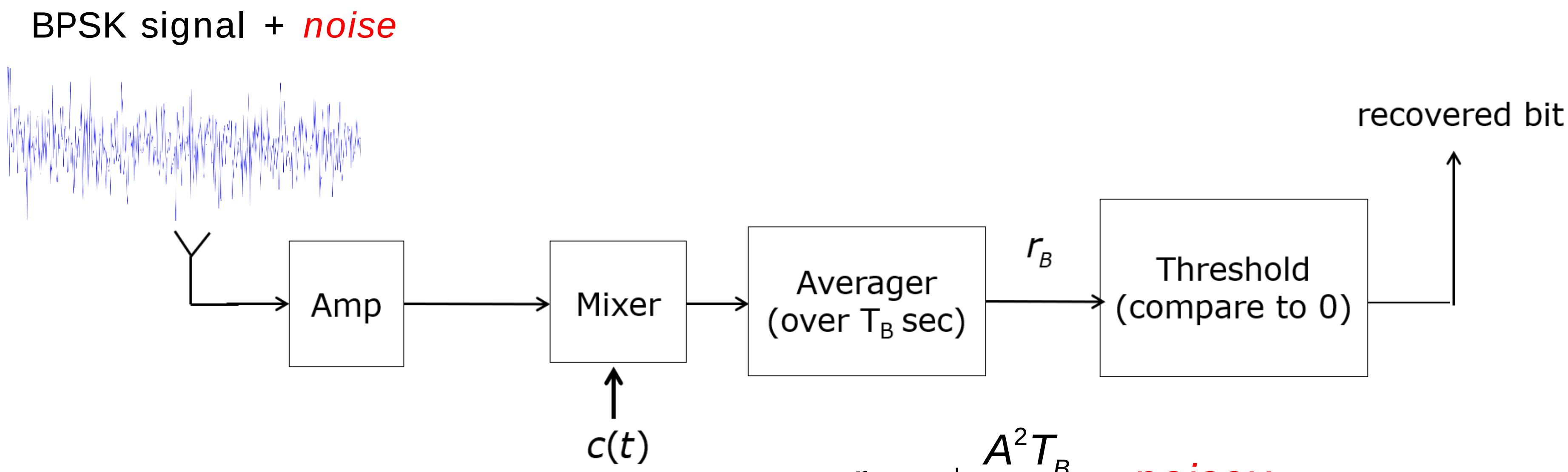
Bit Errors - 1



$$r_B = \pm \frac{A^2 T_B}{2} + noisey$$

Big noisey can change sign of r_B ! ("Bit Error')

Bit Errors - 2



$$r_B = \pm \frac{A^2 T_B}{2} + noise_y$$

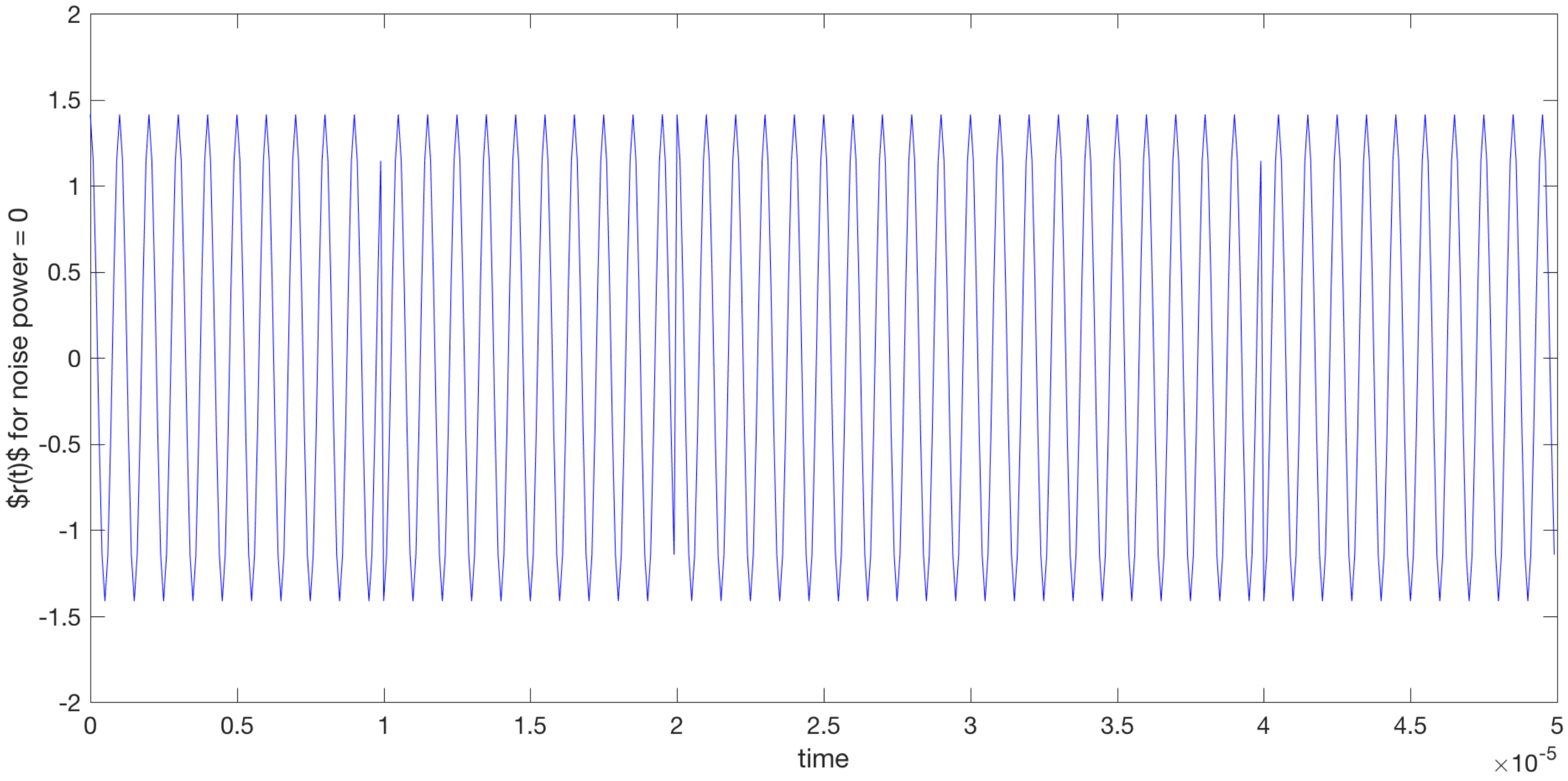
- bit error rate (ber) = (#bit errors)/(#transmitted bits)
- ber is a function of the signal-to-noise ratio (SNR)
- BPSK: SNR = $\frac{A^2 T_B}{2} / noise_y$

Example (like Question 6 in Homework 4)

- Transmit the set of bits 10110 using BPSK
- Bit interval T_B = 1 x 10^{-5} sec (bit rate R_B = 100 kbits/sec).
- Carrier frequency f_c = 1 MHz = 10 R_B
- Simulate the operation of a correlation receiver in MATLAB for different values of SNR:

Case 1: Noise Power = 0 (SNR = ∞)

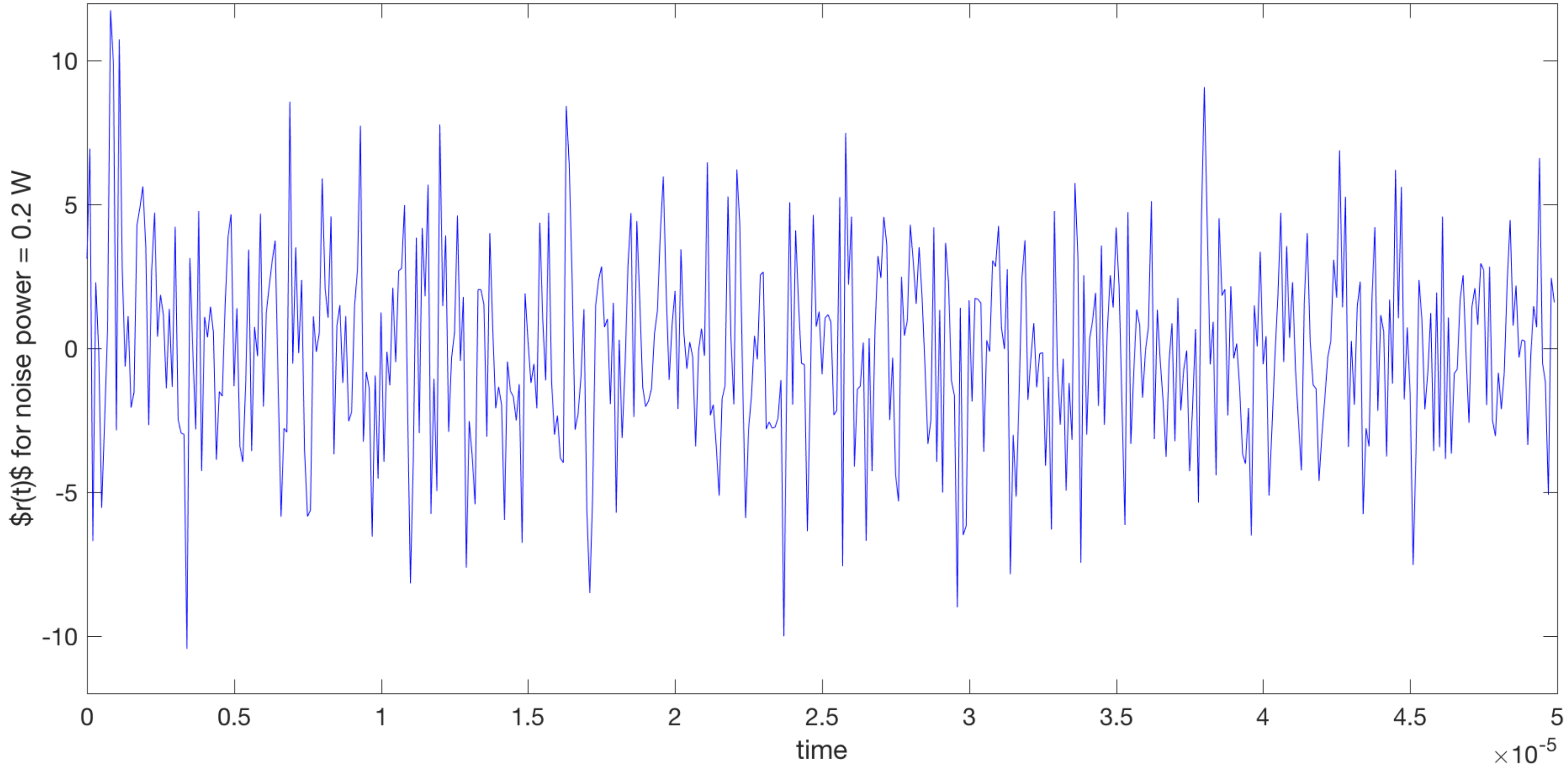
Received signal



Bits recovered by receiver: 10110 (no bit errors)

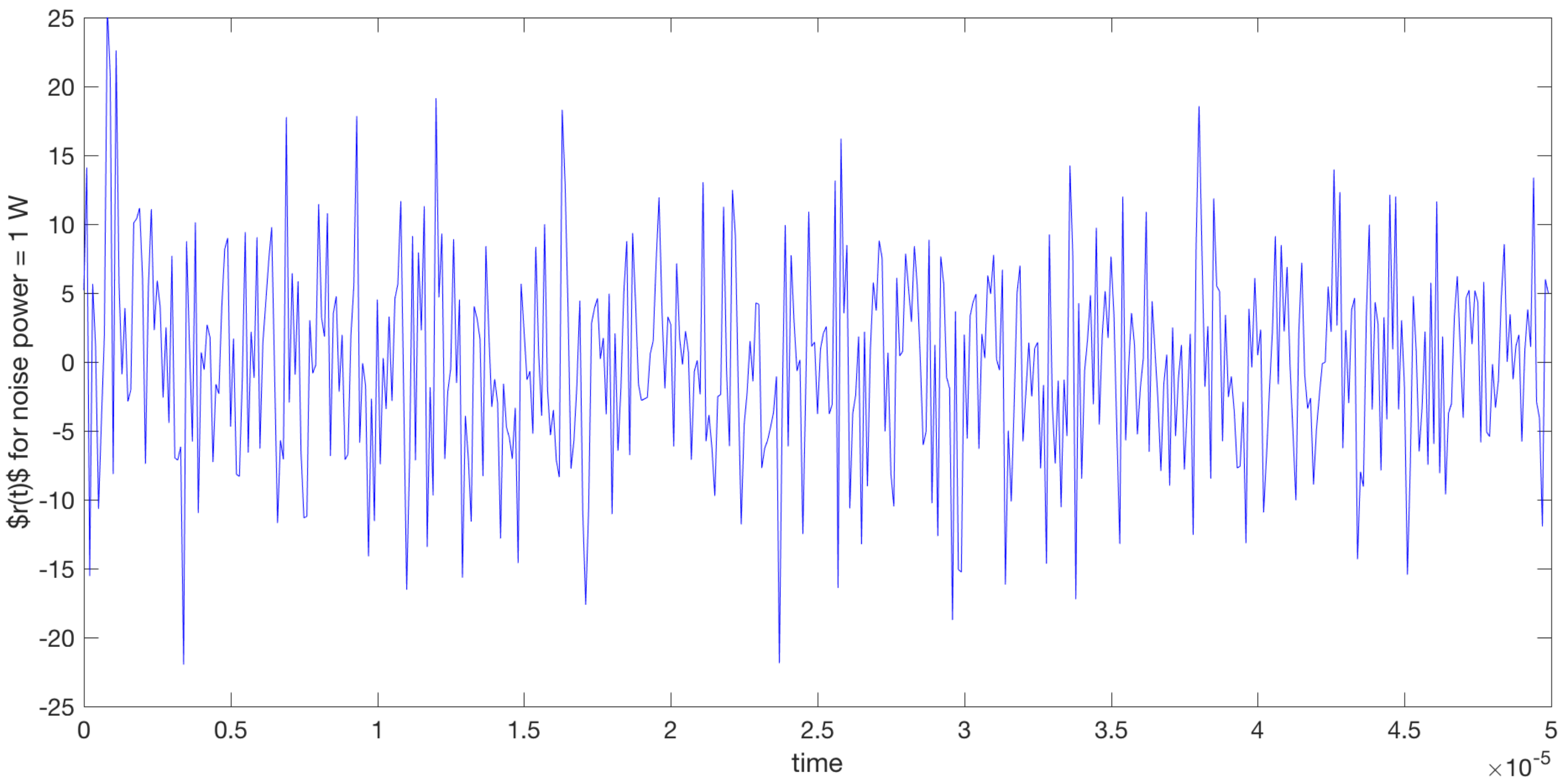
Case 2: SNR = 5; $(\text{SNR})_{\text{dB}} = 10\log_{10}(5) = 7$ dB

Received signal



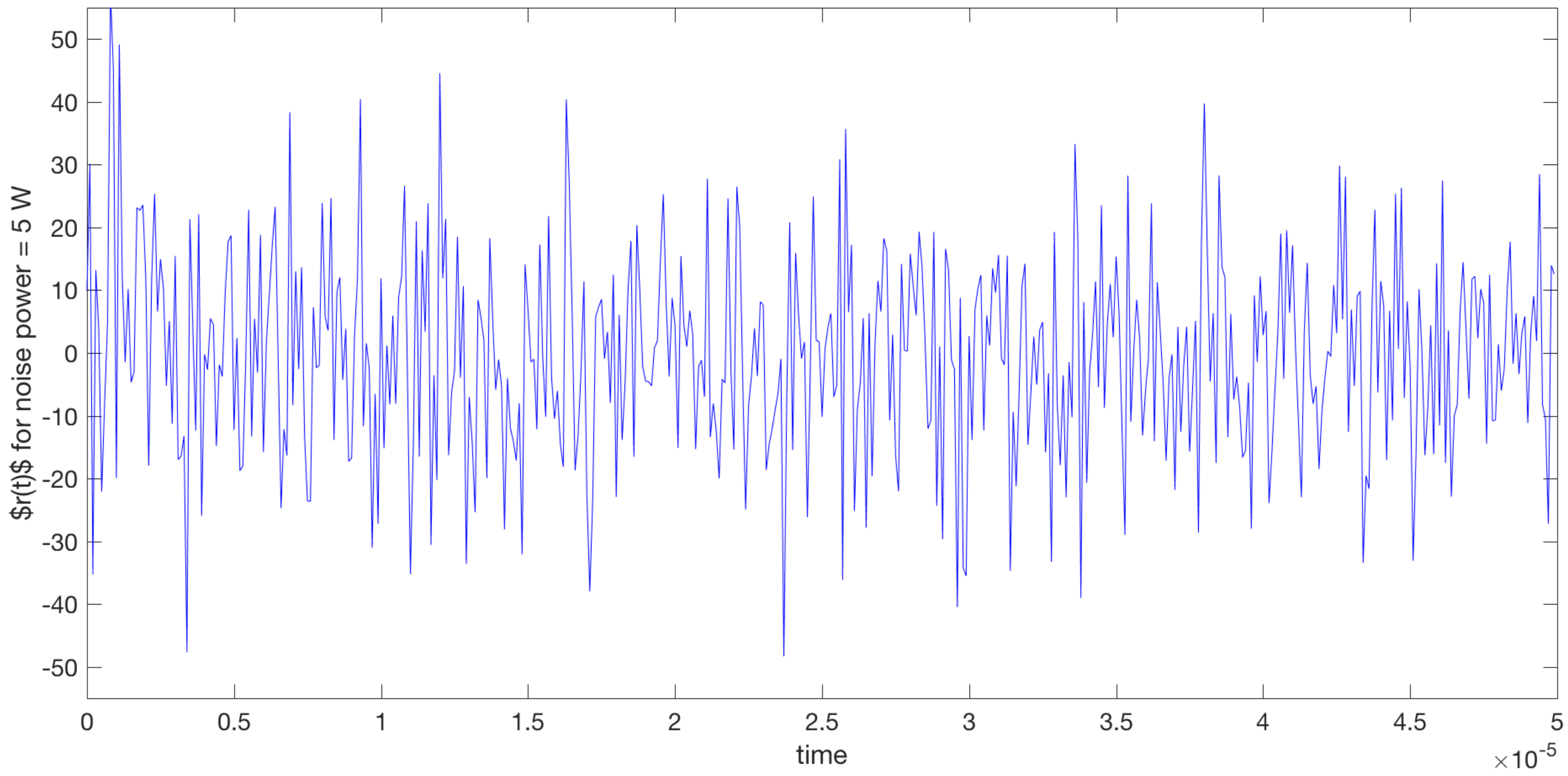
Bits recovered by receiver: 10110 (no bit errors)

Case 3: SNR = 1; $(\text{SNR})_{dB} = 10\log_{10}(1) = 0$ dB



Bits recovered by receiver: 10110 (no bit errors) !!!

Case 4: SNR = 0.2; $(SNR)_{dB}$ = -7 dB



Bits recovered by receiver: 1011**1** ← ***Bit error***

(r_B: 1.8, -2.54, 2.31, 0.88, **0.23**)

Correlation receiver is "optimal"

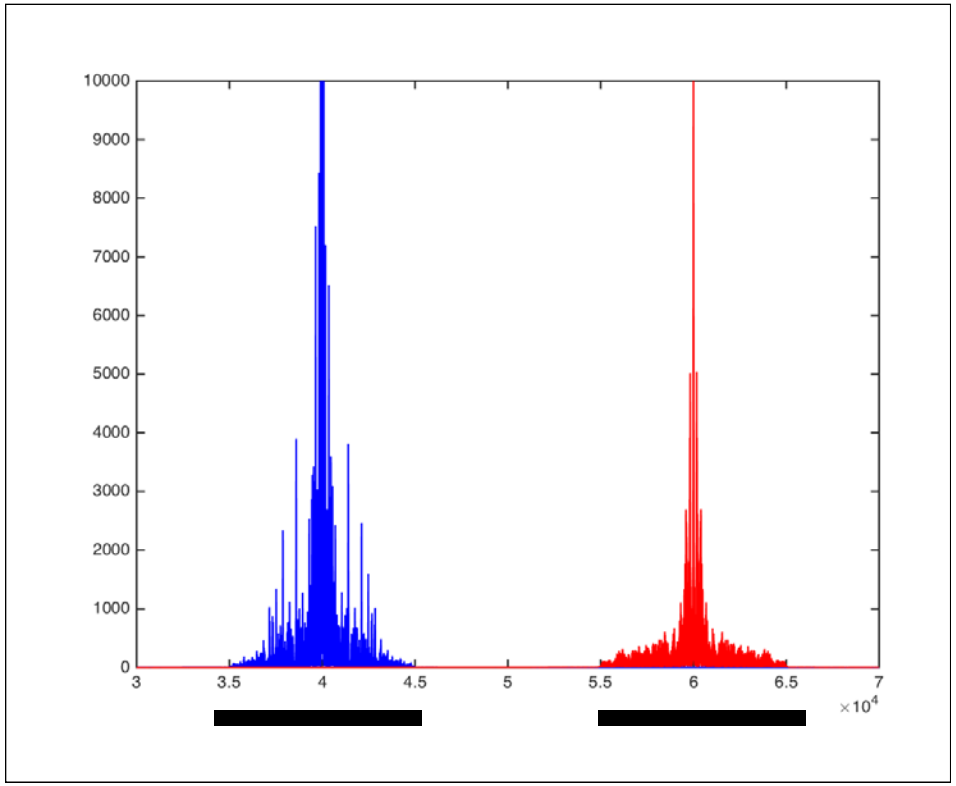
- Correlation receiver optimal - the receiver having the highest probability of recovering the correct bits !!!

$$SNR = \frac{A^2 T_B}{2\ \textit{noisey}}$$

- To decrease ber, increase
  - increase A
  - increase T_B; decrease R_B

Real Estate

Spectral Real Estate for AM

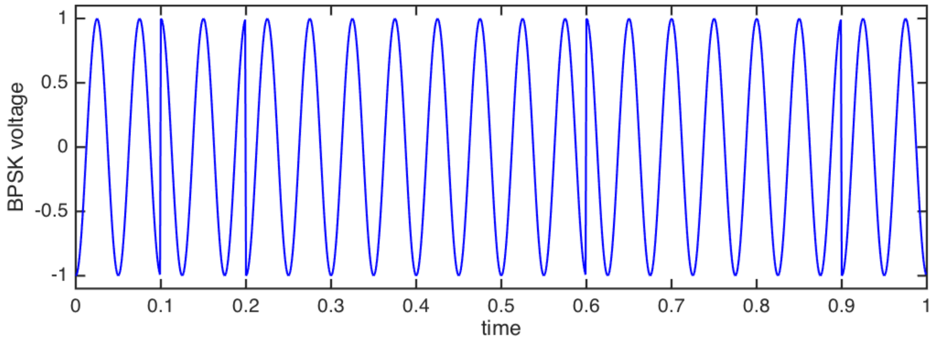


10 kHz

10 kHz

transmission bandwidth

Spectral Real Estate for BPSK ?

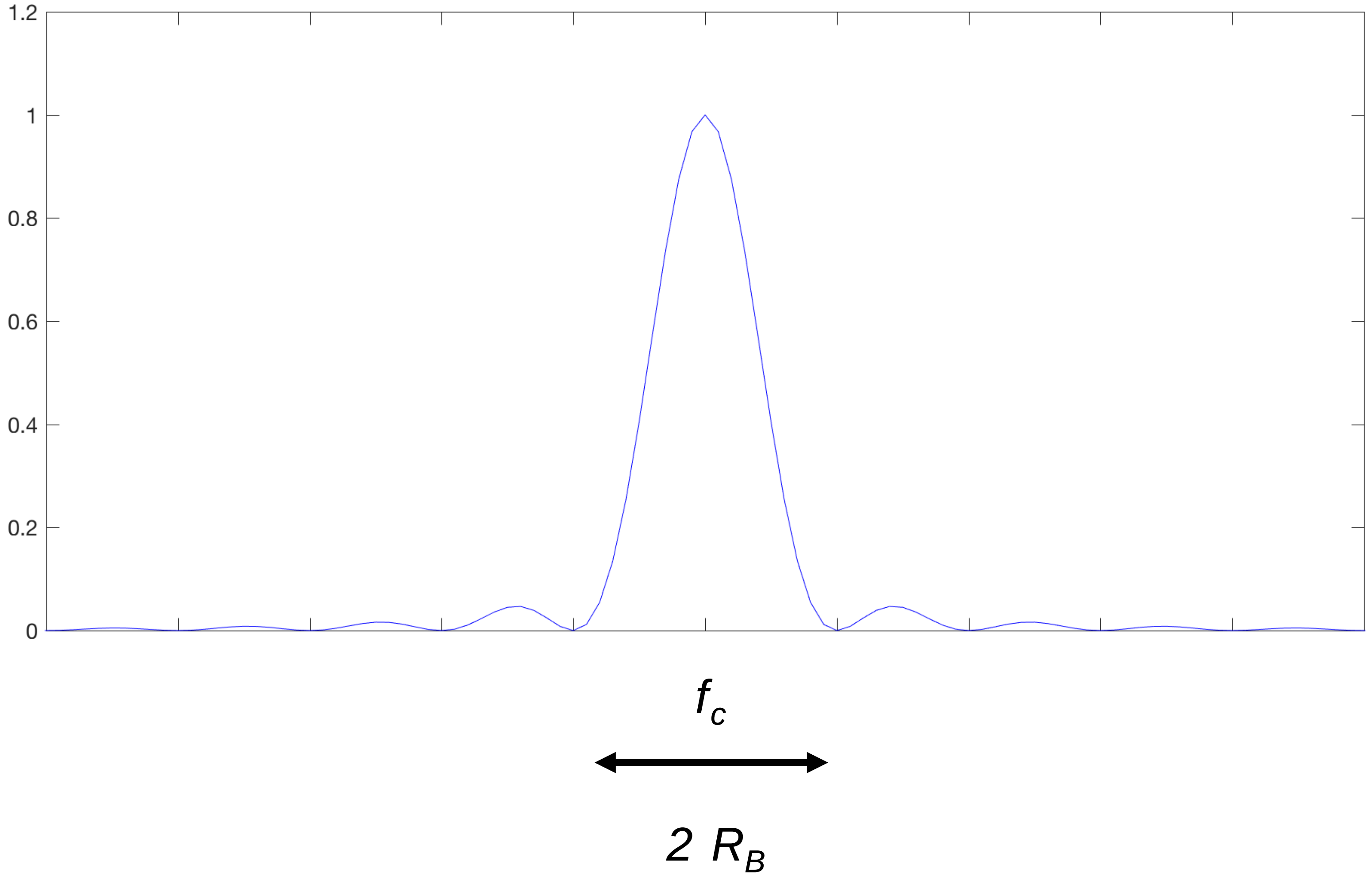


$\longleftrightarrow$ BPSK Spectrum?

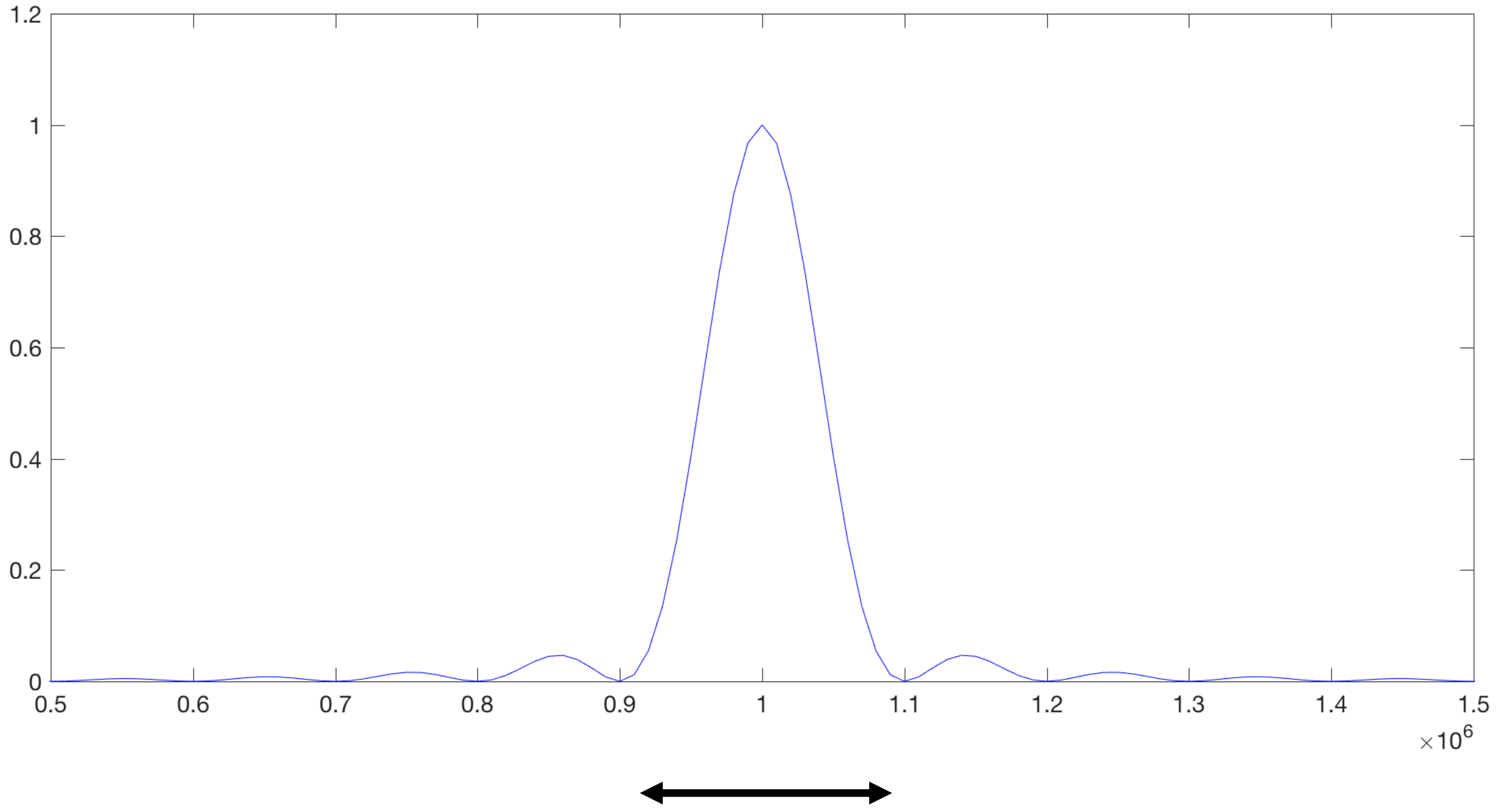
$$c(t) = \pm A\cos(2\pi f_c t)\,,0 \ \le t \le T_B$$

$$R_B = 1/T_B$$

BPSK Spectrum

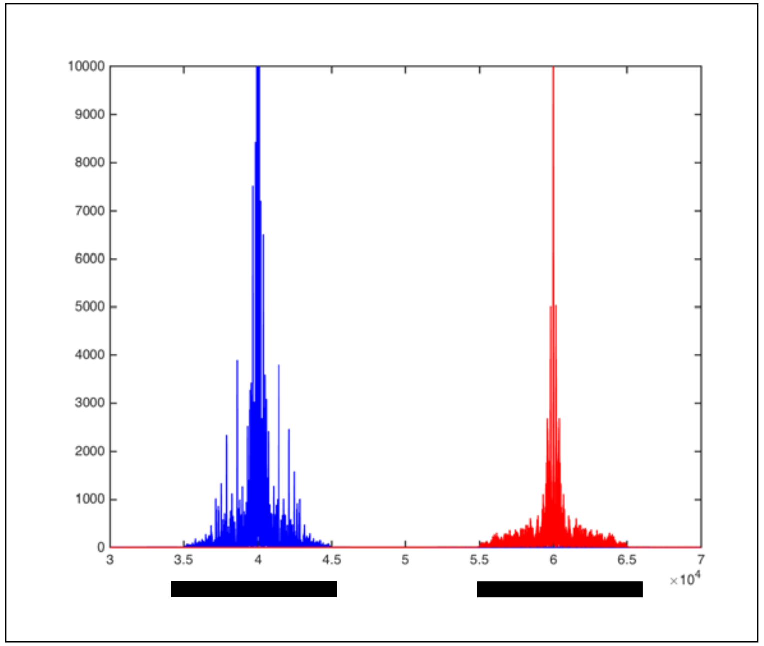


Example: R_B = 100 kbits/sec and f_c = 1 MHz



Transmission bandwidth = 200 kHz = 2 R_B

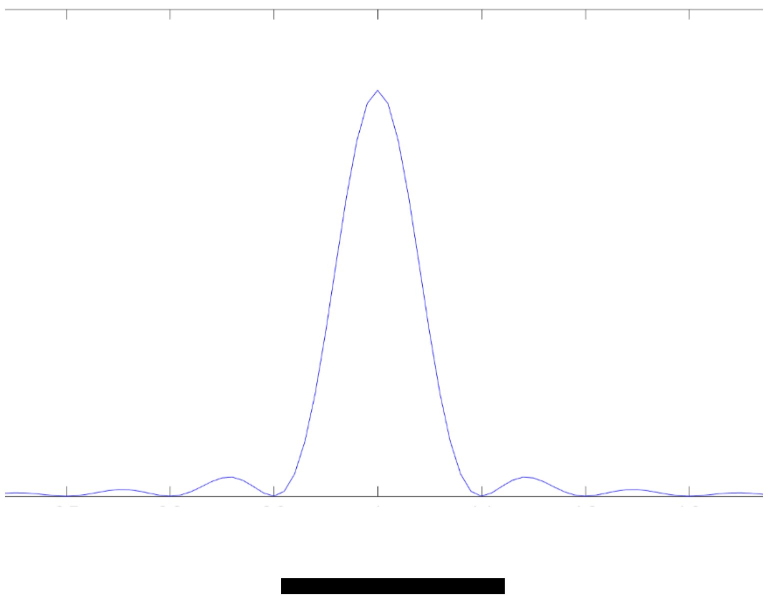
AM



10 kHz 10 kHz

WiFi

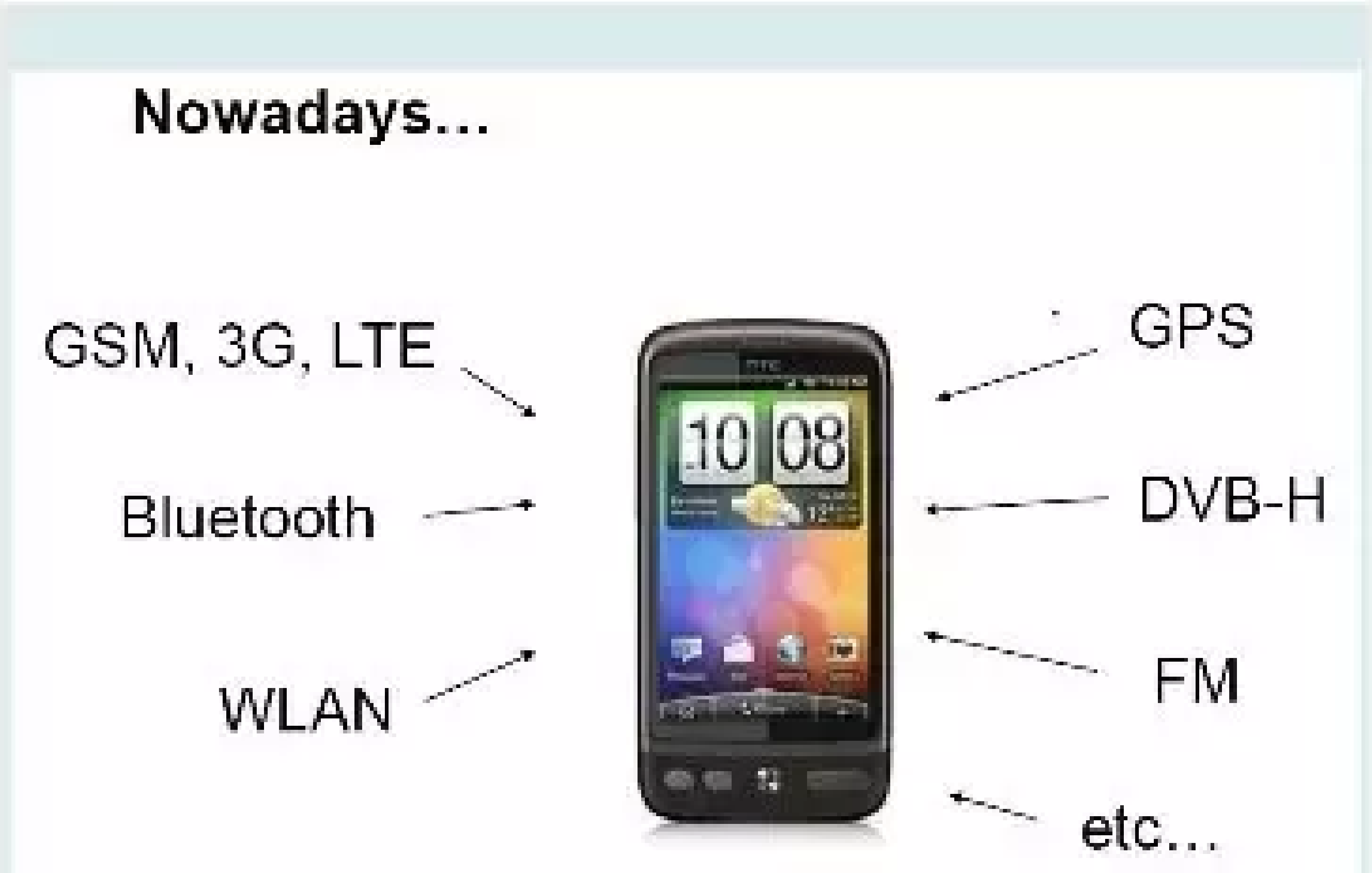
$$f_c = 2.4GHz, \quad R_B > 150 \text{ Mbits / sec}$$



300MHz

Main Concepts

- EM Waves & Antennas ✓
- Amplitude Modulation ✓
- Frequency Division Multiplexing ✓
- Frequency Selective Filtering ✓
- Digital Communication Systems ✓


Nowadays…
GSM, 3G, LTE
Bluetooth
WLAN
GPS
DVB-H
FM
etc…