PART III: WIRELESS FROM THE PHYSICAL LAYER, UP

Preliminaries: Radio Communication, Modulation, and Filtering

COS 463: Wireless Networks
Lecture 11

Kyle Jamieson

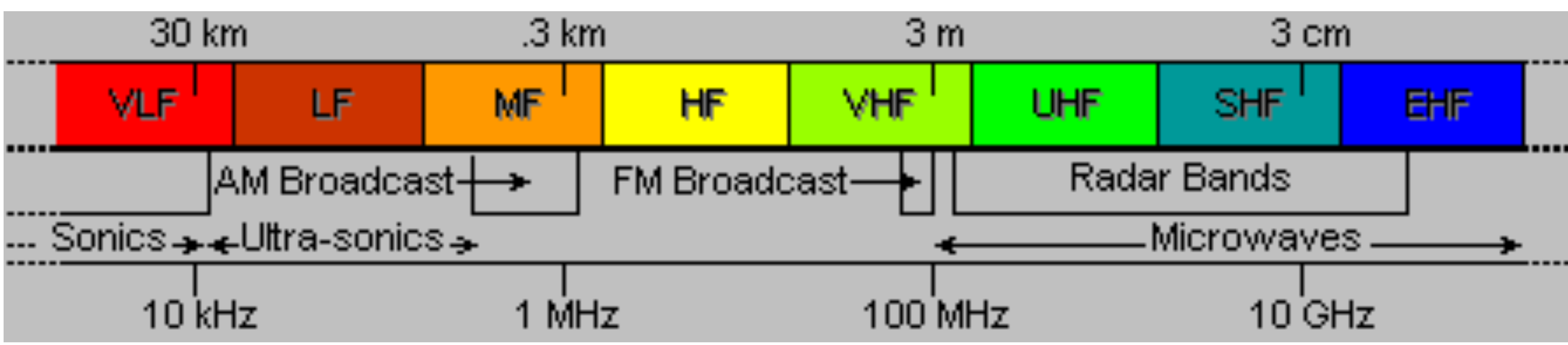
[Parts adapted from H. Balakrishnan, M. Perrot, C. Sodini , P. Steenkiste]

Radio Frequency (RF)

- Electromagnetic signal that propagates through space
  - Transmitted at some **carrier frequency** f_c
  - Travels at the **speed of light** (c)

- **Wavelength** in air: $\lambda = c/f_c$

- f_c range: (beyond) 3 KHz to 300 GHz (or, λ = 100 km to 1 mm)

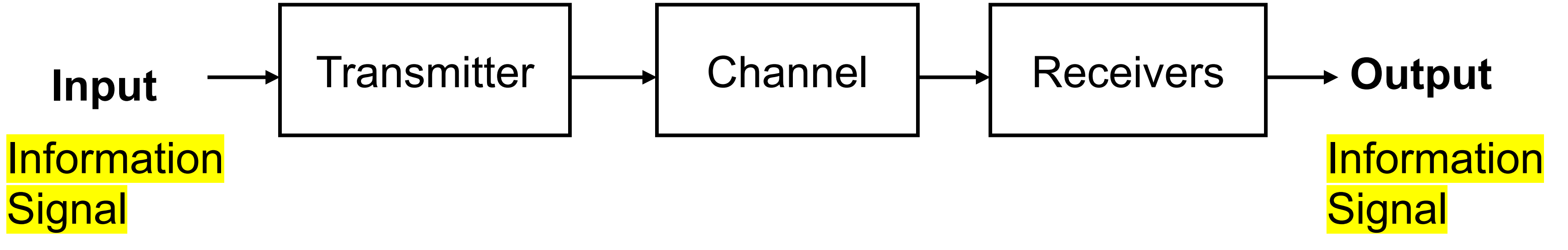


Today

- **Introduction to Signals: The Frequency Domain**
  - Modulation and Demodulation
- Introduction to Filtering
- AM Radio
- Signals and Noise

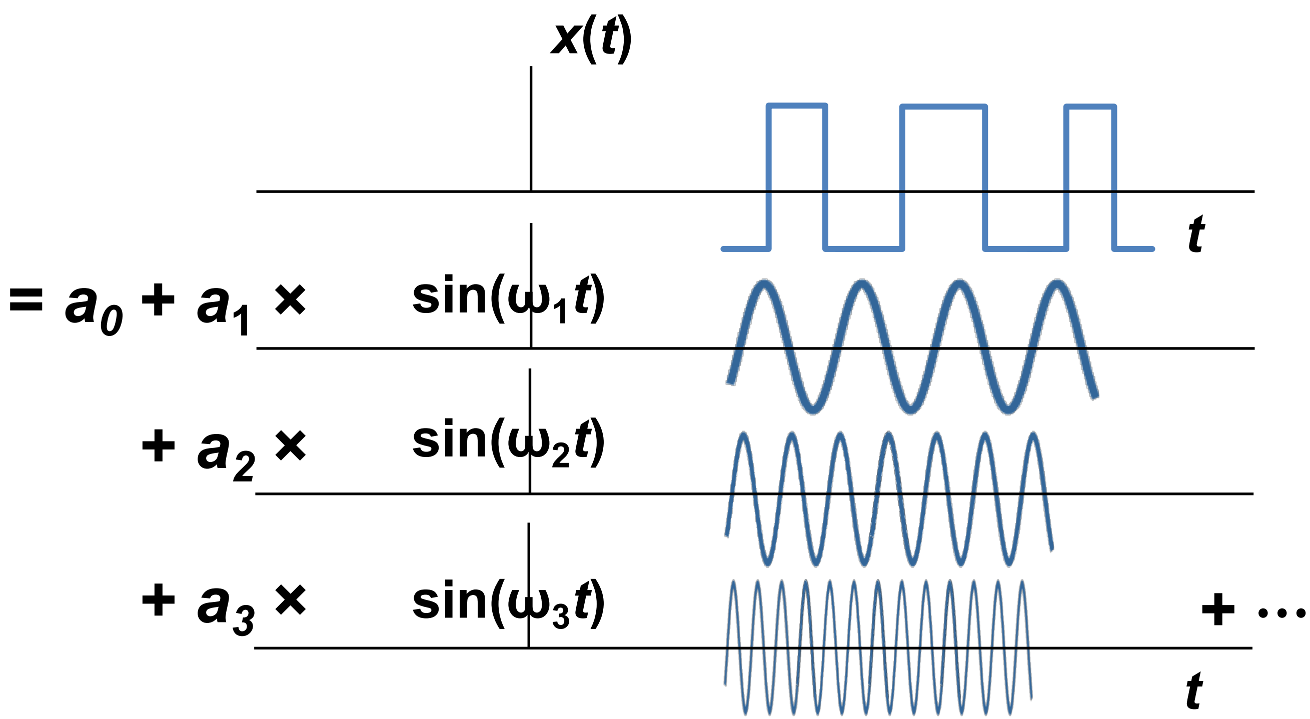
Information Transmission

- **Goal: Move information** (voice, video, data *etc.*), encoded in **signals** (*e.g.,* electromagnetic, optical, acoustic)
  - Over some ***channel*** (physical medium, *e.g.,* free space, fiber, coax)



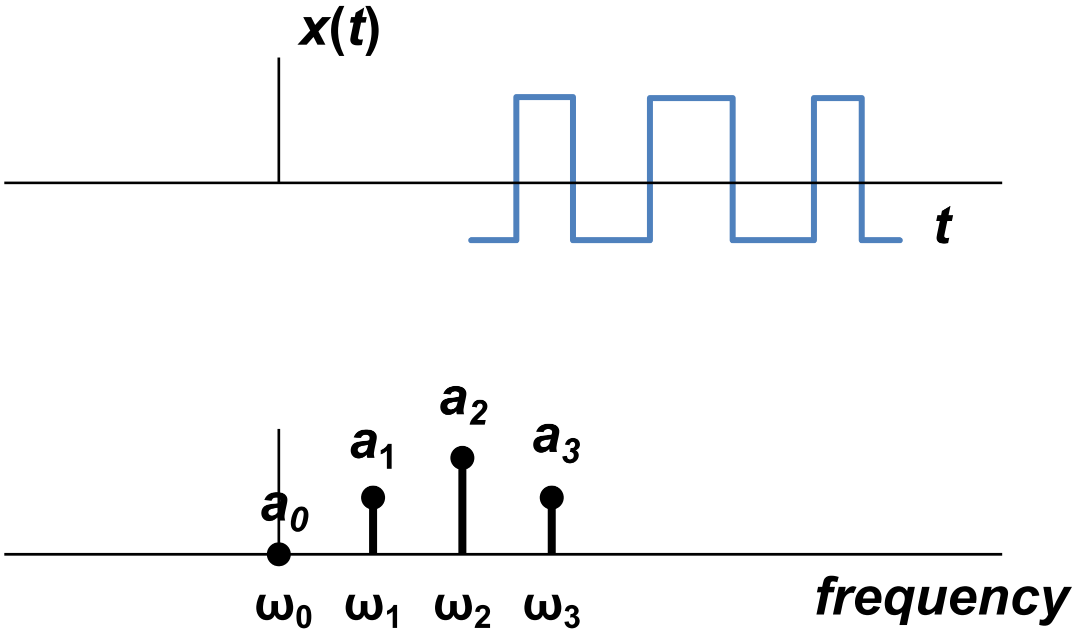
Key Tool: Fourier Series

- Suppose $x(t)$ is our ***information signal***
- A periodic waveform $x(t)$ can be **represented** as a **sum of *weighted* (a_n) sinusoids of different *frequencies* ω_n:**



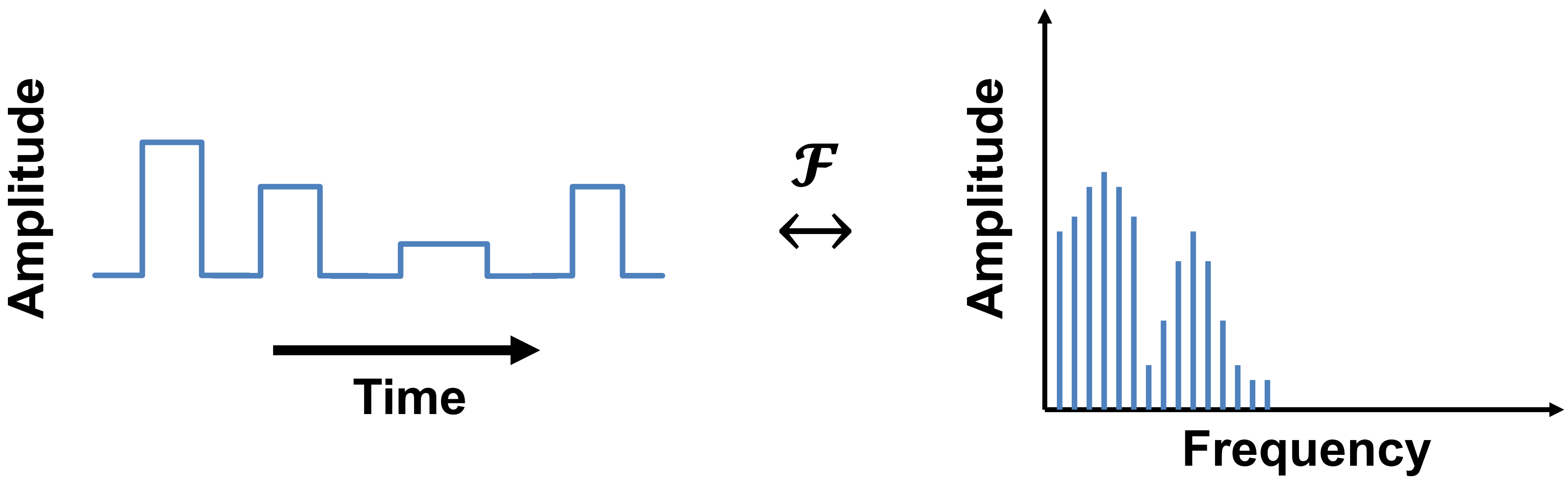
Frequency Domain View

- **Idea: plot** the weights a_n **versus** the frequencies ω_n:

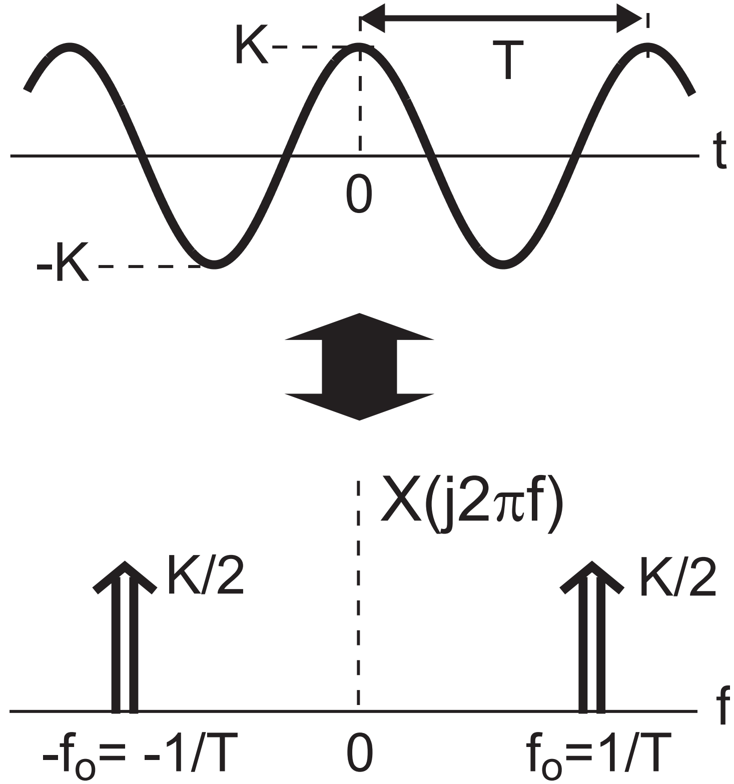


Fourier Transform

- **Fourier series** deals with **periodic signals**
- **Fourier transform** deals with **non-periodic signals**
- **Notation:** $x(t) \overset{\mathcal{F}}{\leftrightarrow} X(f)$

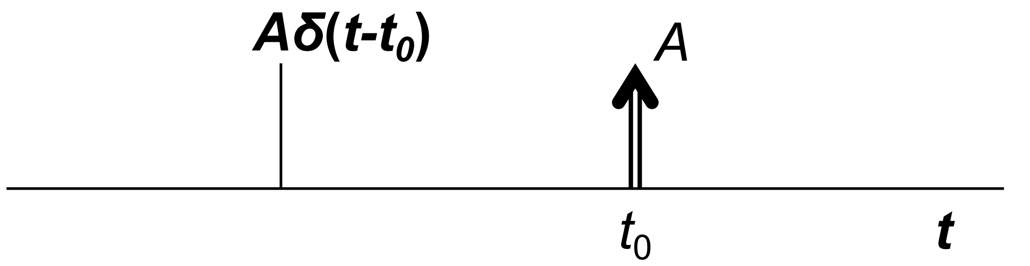


Fourier Transform of cosine wave



Key Tool: The Impulse Function

- An ***impulse*** of area *A* at time t_0 is denoted:



- Defined in terms of its **properties** when combined with other (information carrying) signals

Today

- Introduction to Signals: The Frequency Domain
  - **Modulation and Demodulation**
- Introduction to Filtering
- AM Radio
- Signals and Noise

Motivation for Modulation

- **Physical medium** of wireless channel usually **free space**

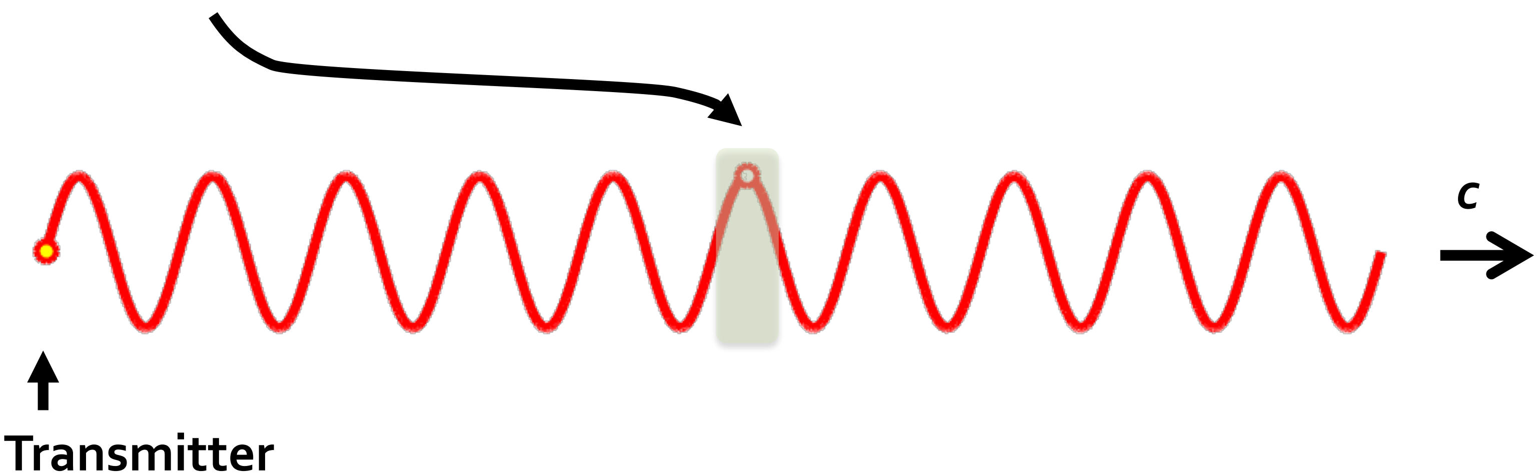
- Radio wavelength ***inversely*** proportional to frequency (1 GHz → 30 cm, while 1 KHz → **30 km wavelength**)

1. Since **antenna, component size** related to wavelength:
   - Want to **move signal to higher frequency** for **smaller** devices

2. Higher frequency signals can **send more data, further**

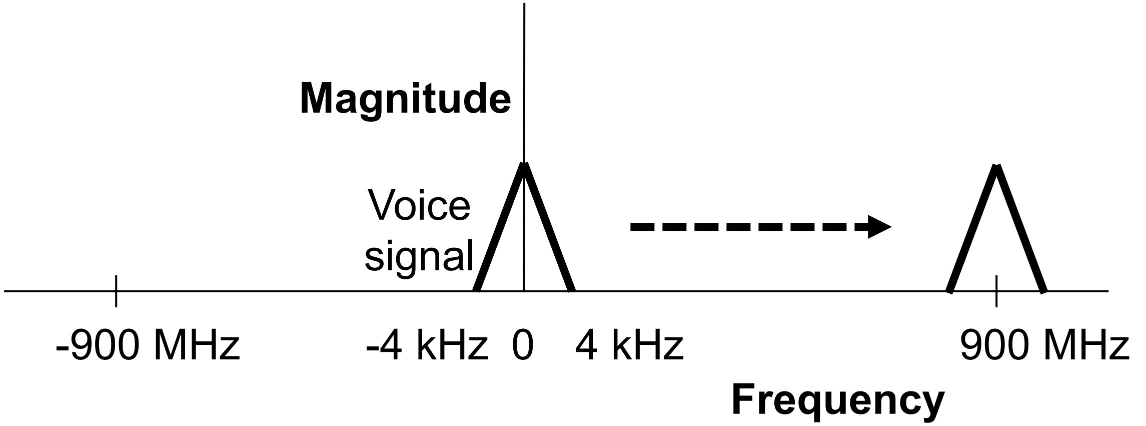
Sinusoidal *carrier signal*

- RF signal propagates away from transmitter at light speed *c*
- At an **instant in time:** signal "looks" sinusoidal **in space**
- At a **point in space**: signal **oscillates sinusoidally in time**



Goal of Modulation

Given an ***information signal***
Example: Voice signal with 4 KHz ***bandwidth***

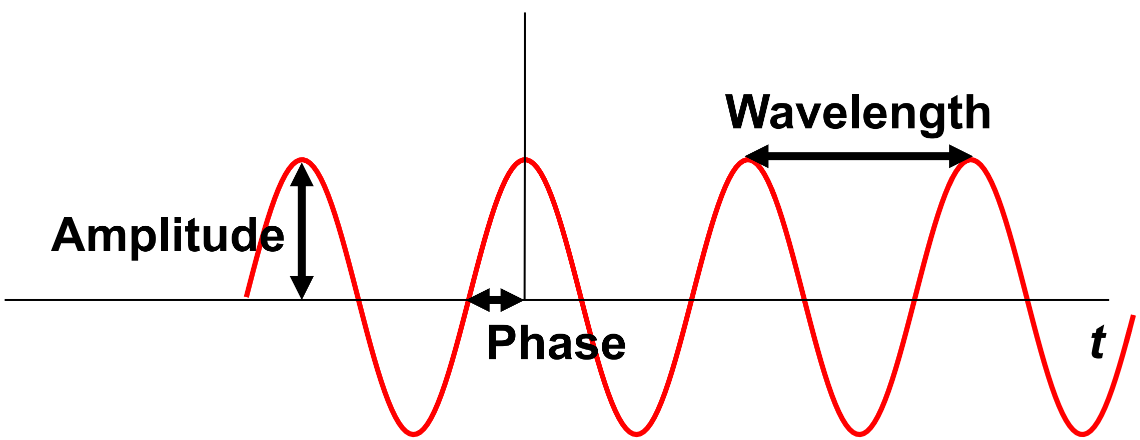


Shift information signal to the ***carrier frequency***
Example: 900 MHz carrier frequency

→ Information signal ***modulates*** (changes) the carrier signal

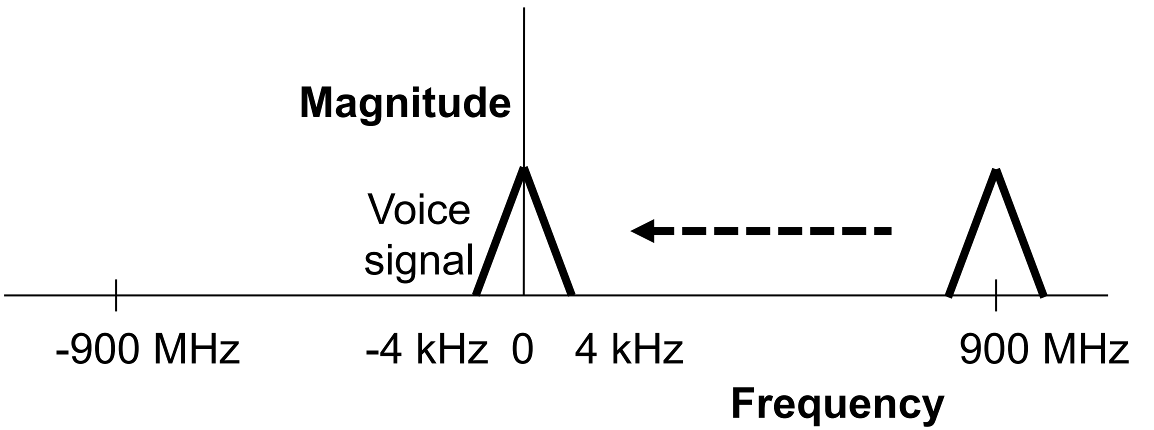
Carrier signal parameters

- The **information signal** **modulates** the **carrier's parameters:**



Goal of Demodulation

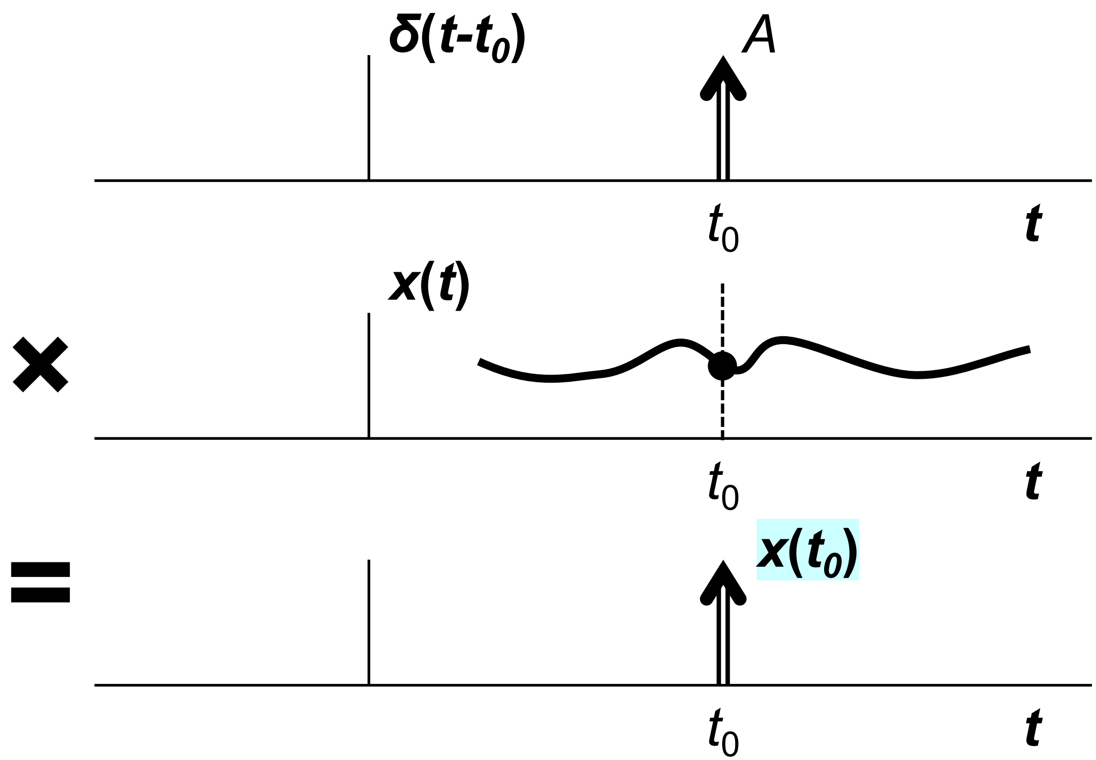
Given a transmitted signal,
Example: Voice signal centered at 900 MHz



Recover the **original signal** from the transmission.
Example: 4 KHz bandwidth voice signal centered at 0 Hz

Impulse: Sampling Property

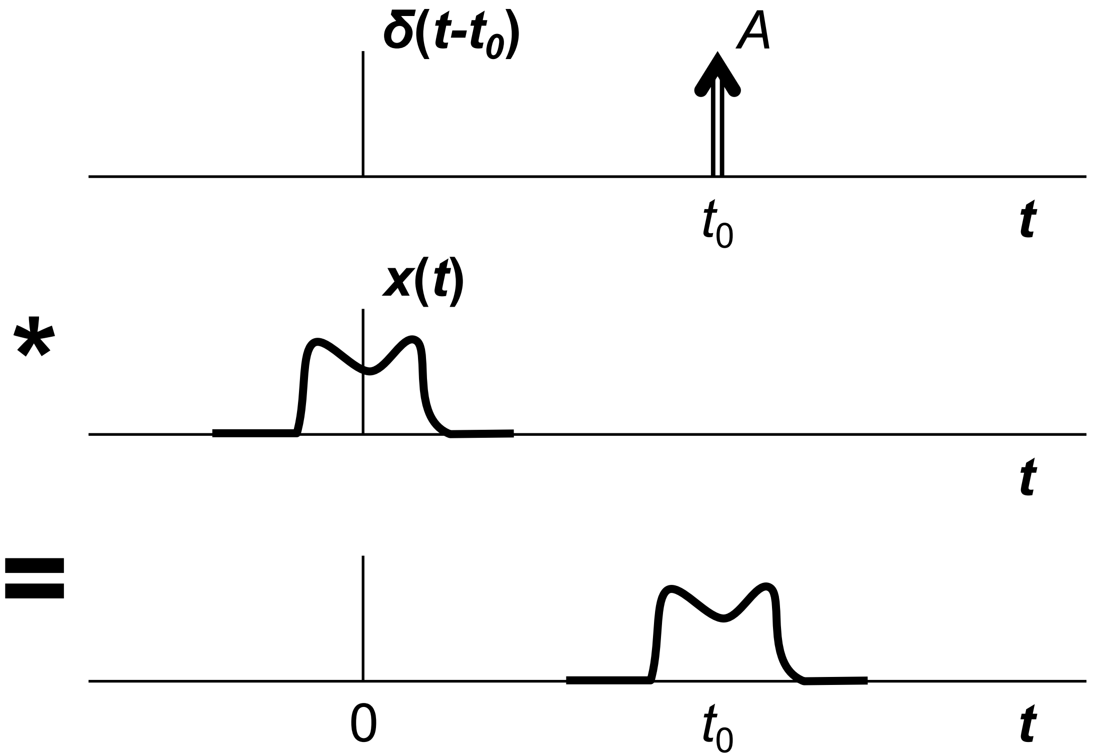
- **Multiplication** of a **function $x(t)$** with an impulse at time t_0:



- Results in **scaling** the impulse **by the value of $x(t)$ at t_0**

Impulse: Convolution in Time

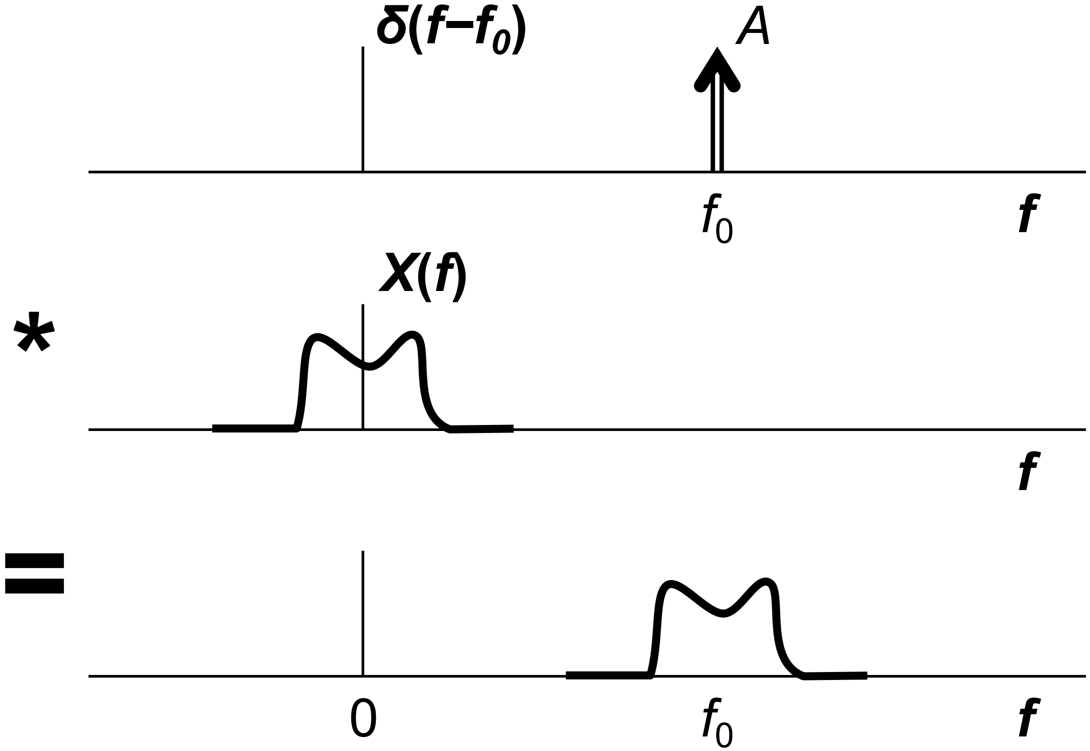
- Convolution of a **function $x(t)$** with an impulse at time t_0:



- Results in a **time shift of** $x(t)$ **by t_0**

Impulse: Convolution in Frequency

- Convolve **function *X*(*f*)** with impulse at frequency f_0:



- Results in a **frequency shift of** $X(f)$ **by** f_0

Duality of Convolution and Multiplication

- **Multiplication** in time leads to **convolution** in frequency:

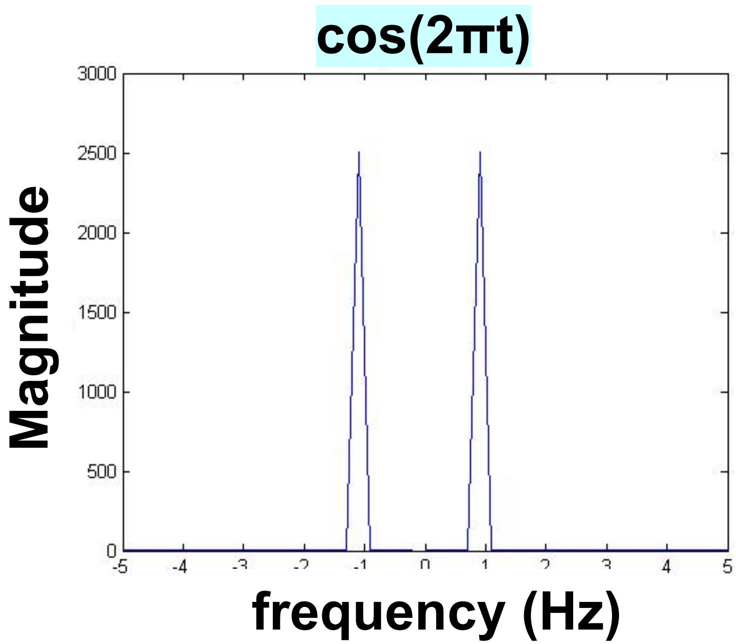
$$x(t)y(t) \overset{\mathcal{F}}{\leftrightarrow} X(f) * Y(f)$$

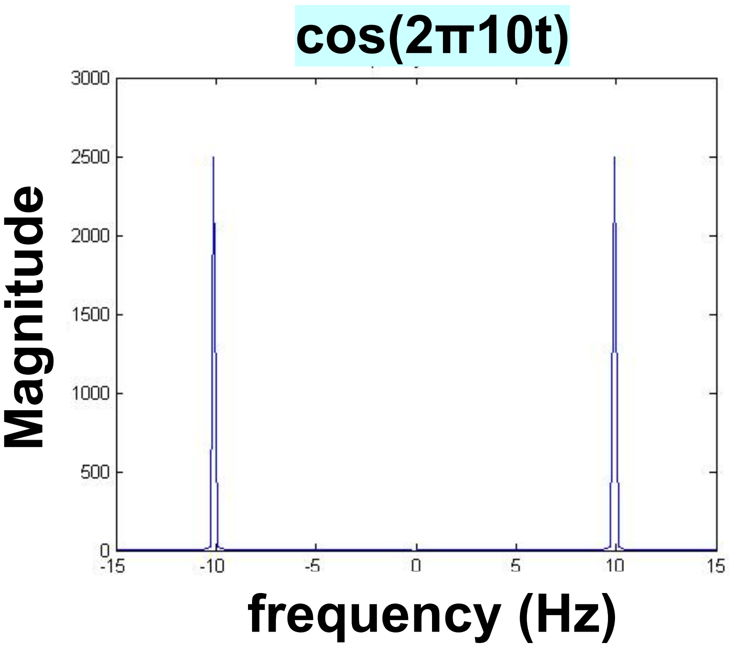
- **Convolution** in time leads to **multiplication** in frequency:

$$x(t) * y(t) \overset{\mathcal{F}}{\leftrightarrow} X(f)Y(f)$$

Modulation: Introduction

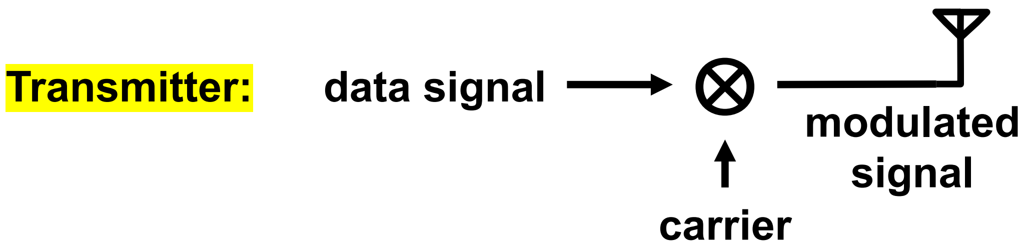
- Given a ***data signal*** (e.g. cosine wave) at frequency $\boldsymbol{f_1}$ (*e.g.,* 1 Hz)
- ***Modulate*** it with carrier at frequency f_2 (*e.g.,* 10 Hz)

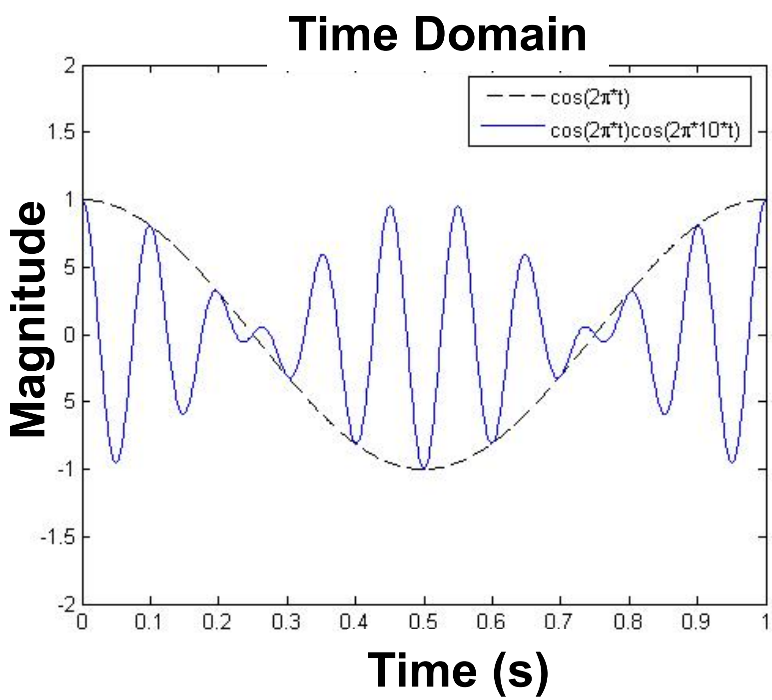


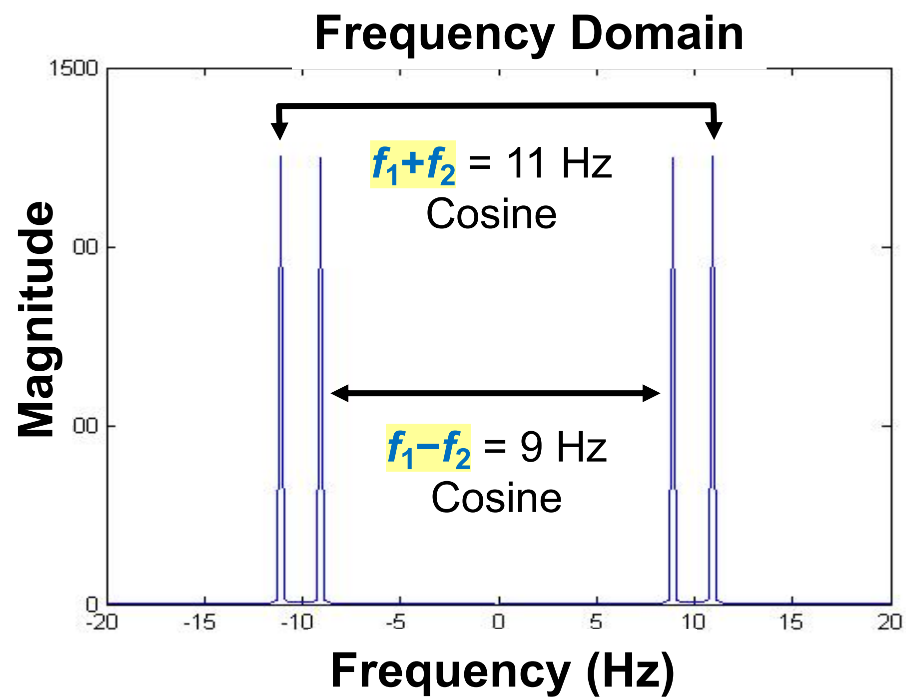


Transmitter: Principle of Modulation

- **Modulate** the carrier with the data: $\cos(2\pi t) \times \cos(2\pi 10t)$

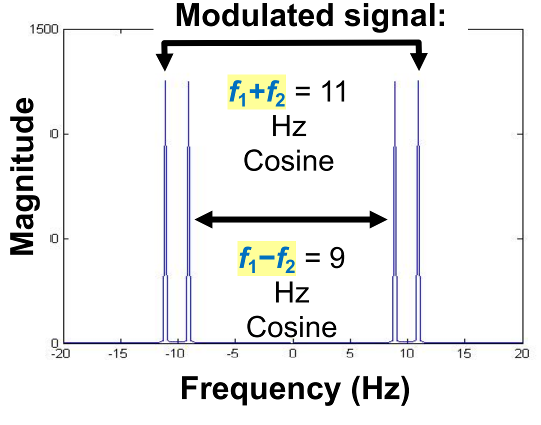


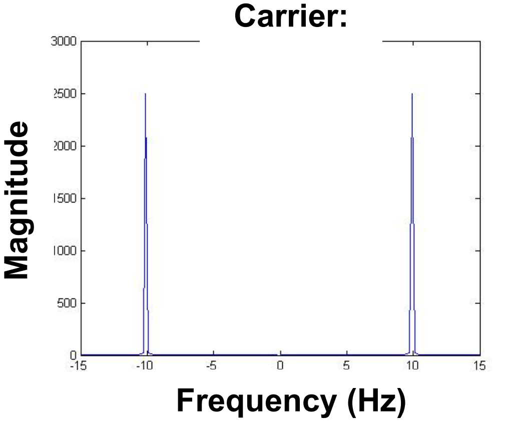




Demodulation: Motivation

- Receiver wants to **recover the original data signal**
  - Multiplies modulated signal containing $f_1 - f_2$ and $f_1 + f_2$ by **copy of carrier**

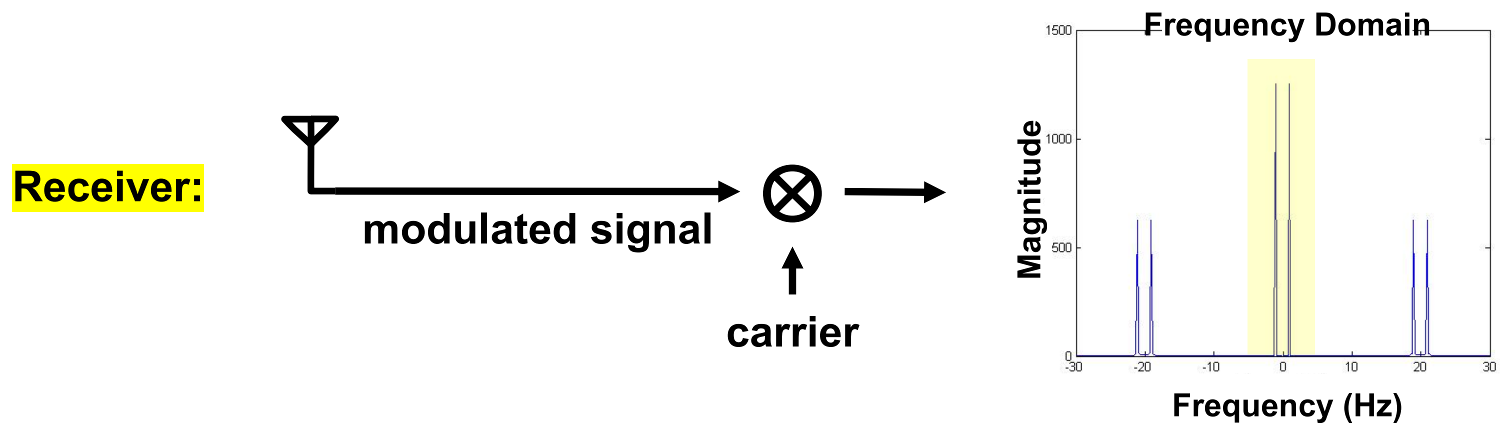




Receiver: Principle of Demodulation

- Receiver **multiplies** modulated signal by **copy of carrier signal,** $\cos(2\pi f_2 t)$
  - Frequency shift of $\pm f_2$ by the convolution property

- Result contains **original signal** and higher frequency sinusoids:



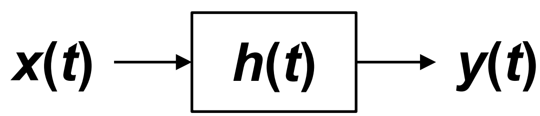
- How to **remove the higher frequency sinusoids?**

Today

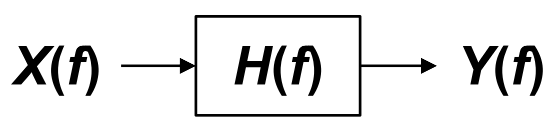
- Introduction to Signals: The Frequency Domain
- **Introduction to Filtering**
- AM Radio
- Signals and Noise

The Concept of Filtering

- With input, filter produces **output signal $y(t)$** by **convolution** with a **filter response $h(t)$**

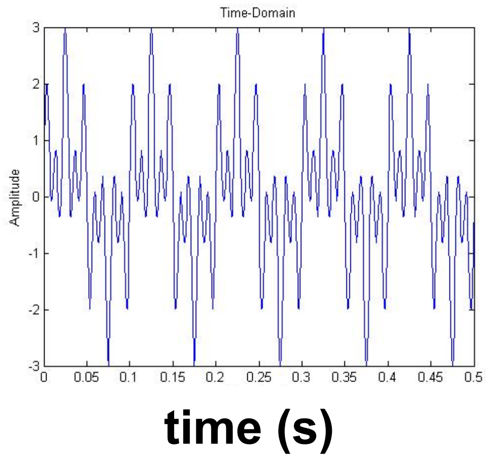


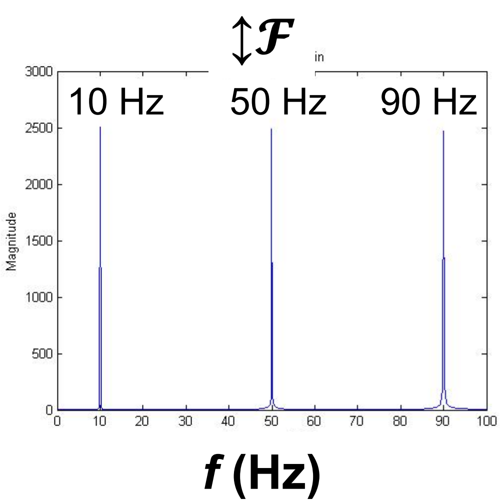
- So, in the frequency domain, the filter **multiplies** each input frequency f by $H(f) \overset{\mathcal{F}}{\leftrightarrow} h(t)$
  - $Y(f) = X(f)H(f)$

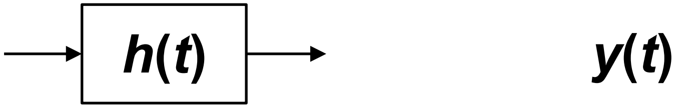


Example Input Signal to Filter

- **Input signal:** Sum of three sinusoids (10, 50, 90 Hz)

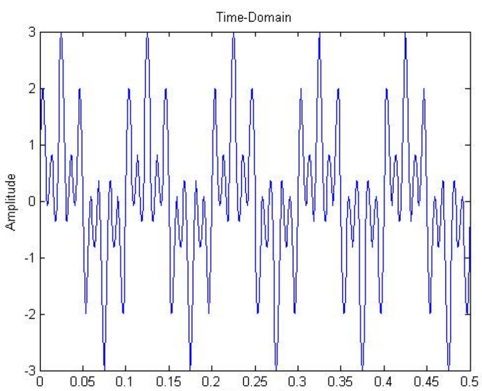




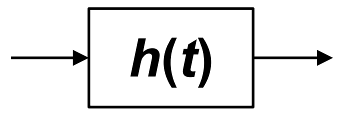


Low Pass Filter Example

- $H(f)$ = 1 below 20 Hz, approaches 0 above 20 Hz

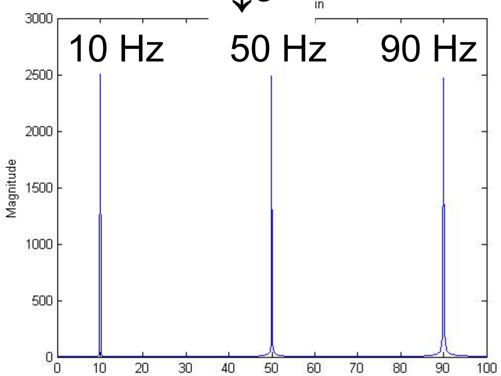


time (s)



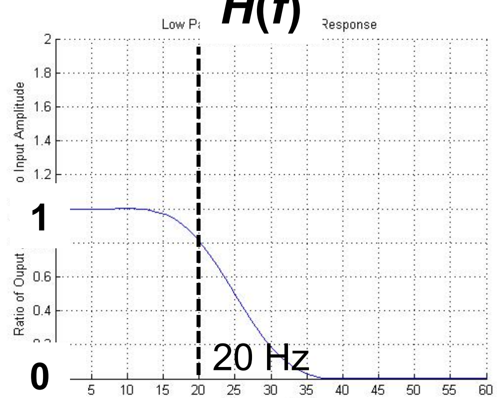
***y*(*t*)**

↕ $\mathcal{F}$



***f* (Hz)**

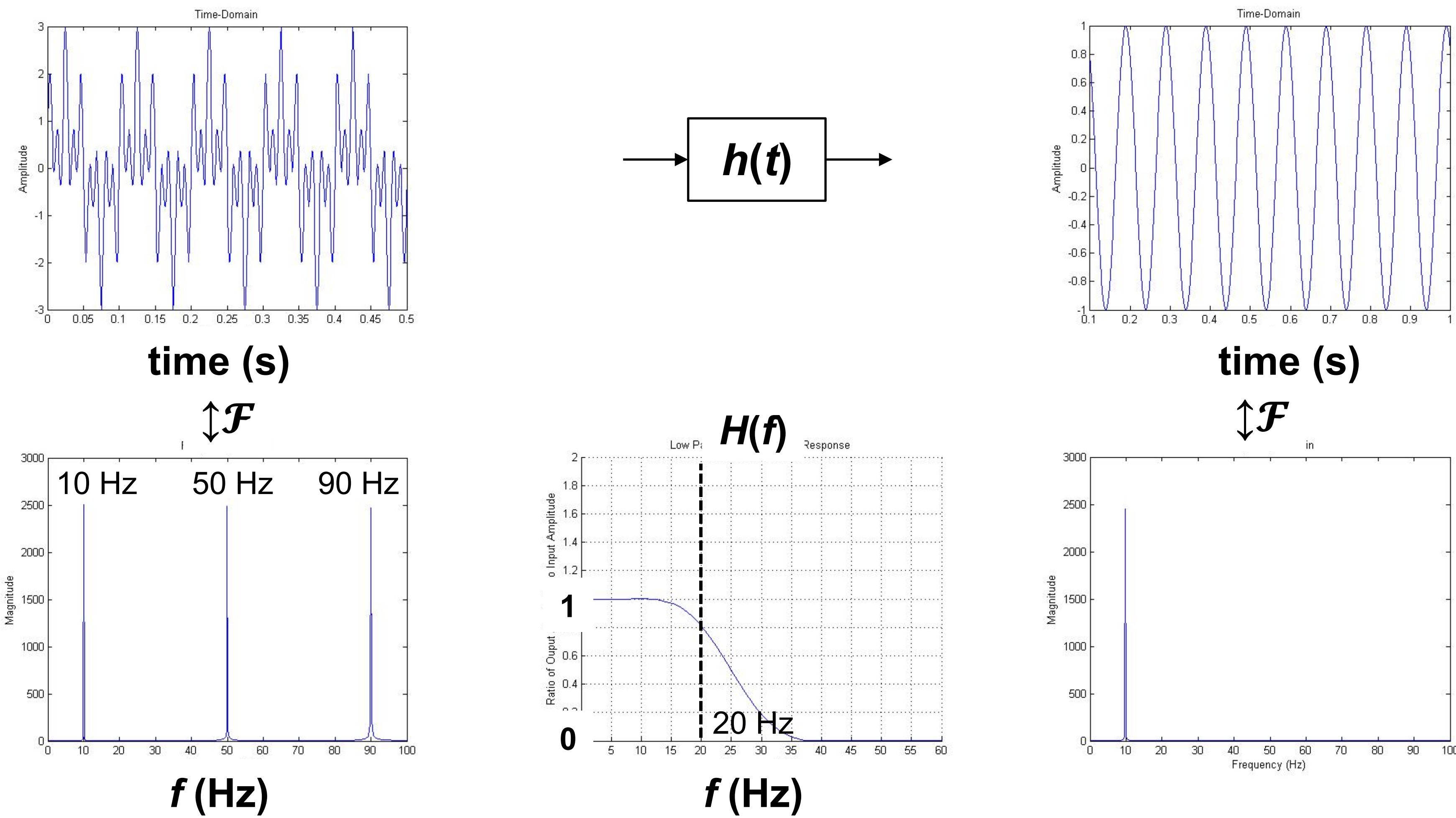
***H*(*f*)**



***f* (Hz)**

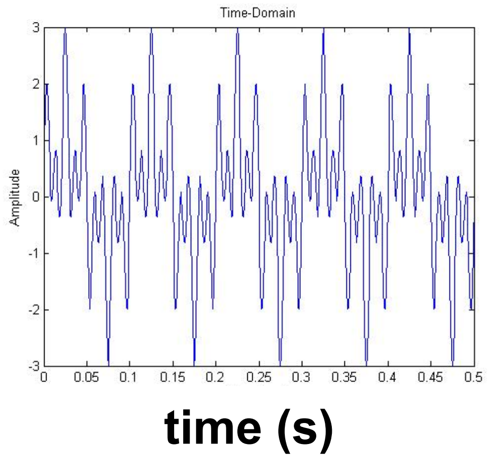
Low Pass Filter Output

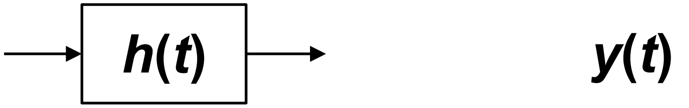
- *H*(*f*) = 1 below 20 Hz, approaches 0 above 20 Hz

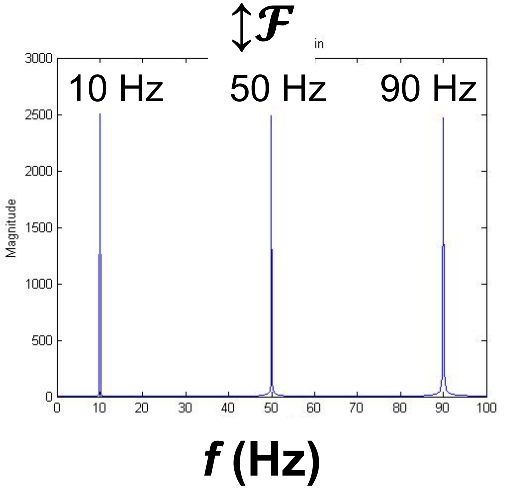


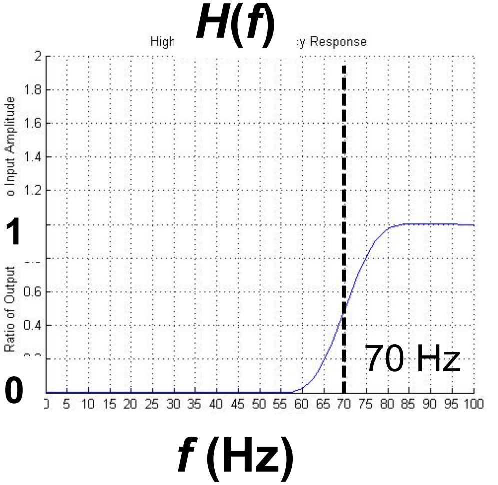
High Pass Filter Example

- $H(f)$ = 0 below 70 Hz, approaches 1 above 70 Hz



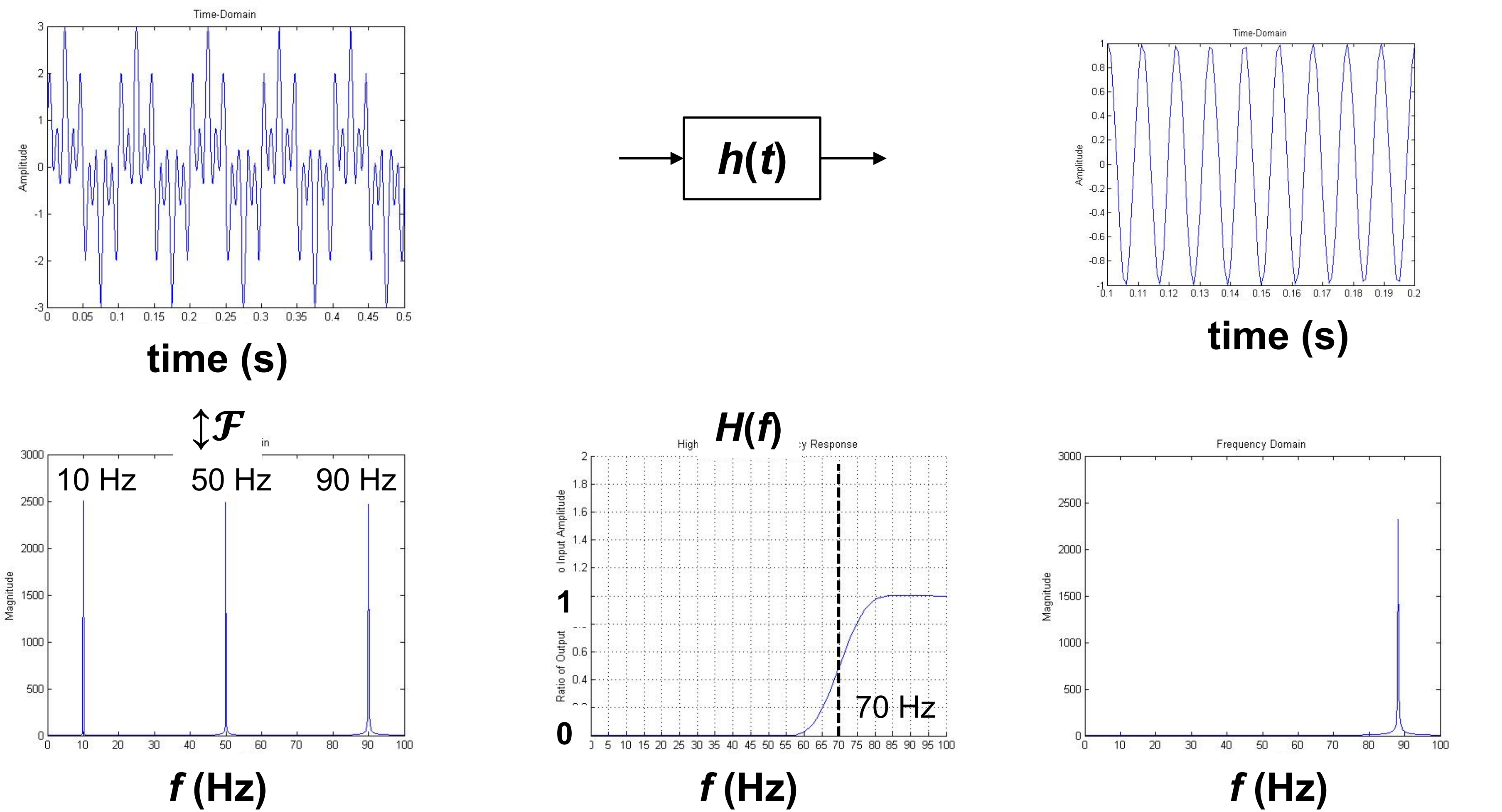




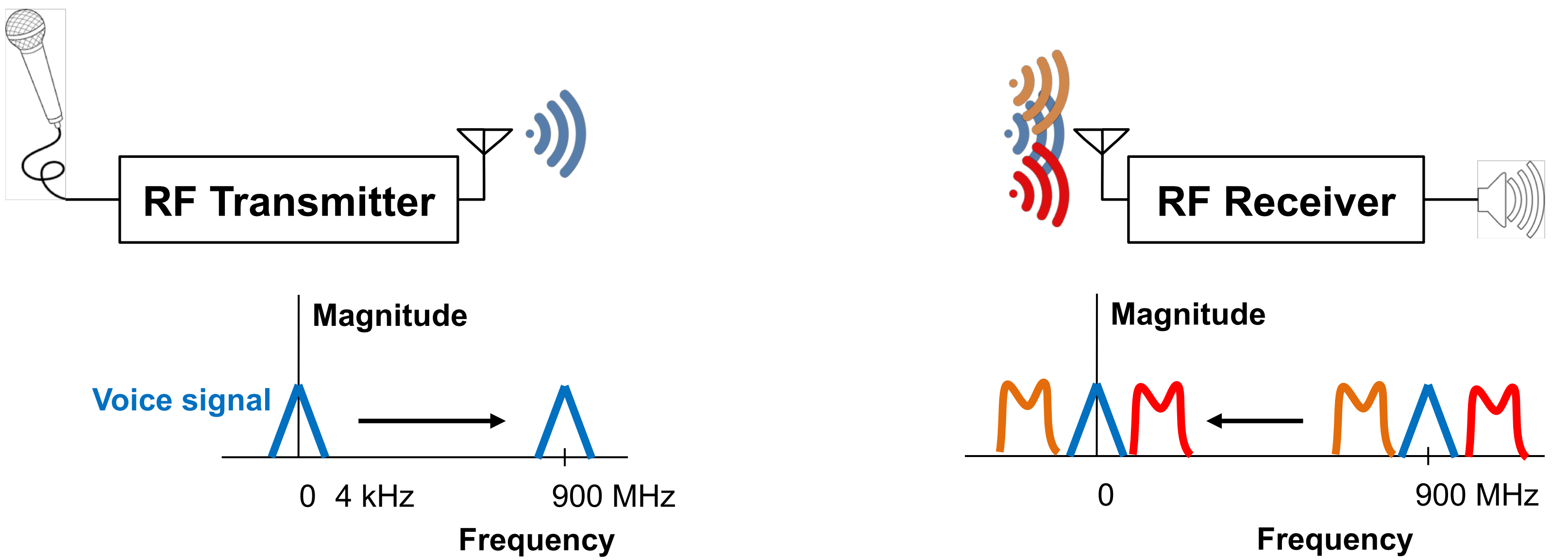


High Pass Filter Output

- *H*(*f*) = 0 below 70 Hz, approaches 1 above 70 Hz



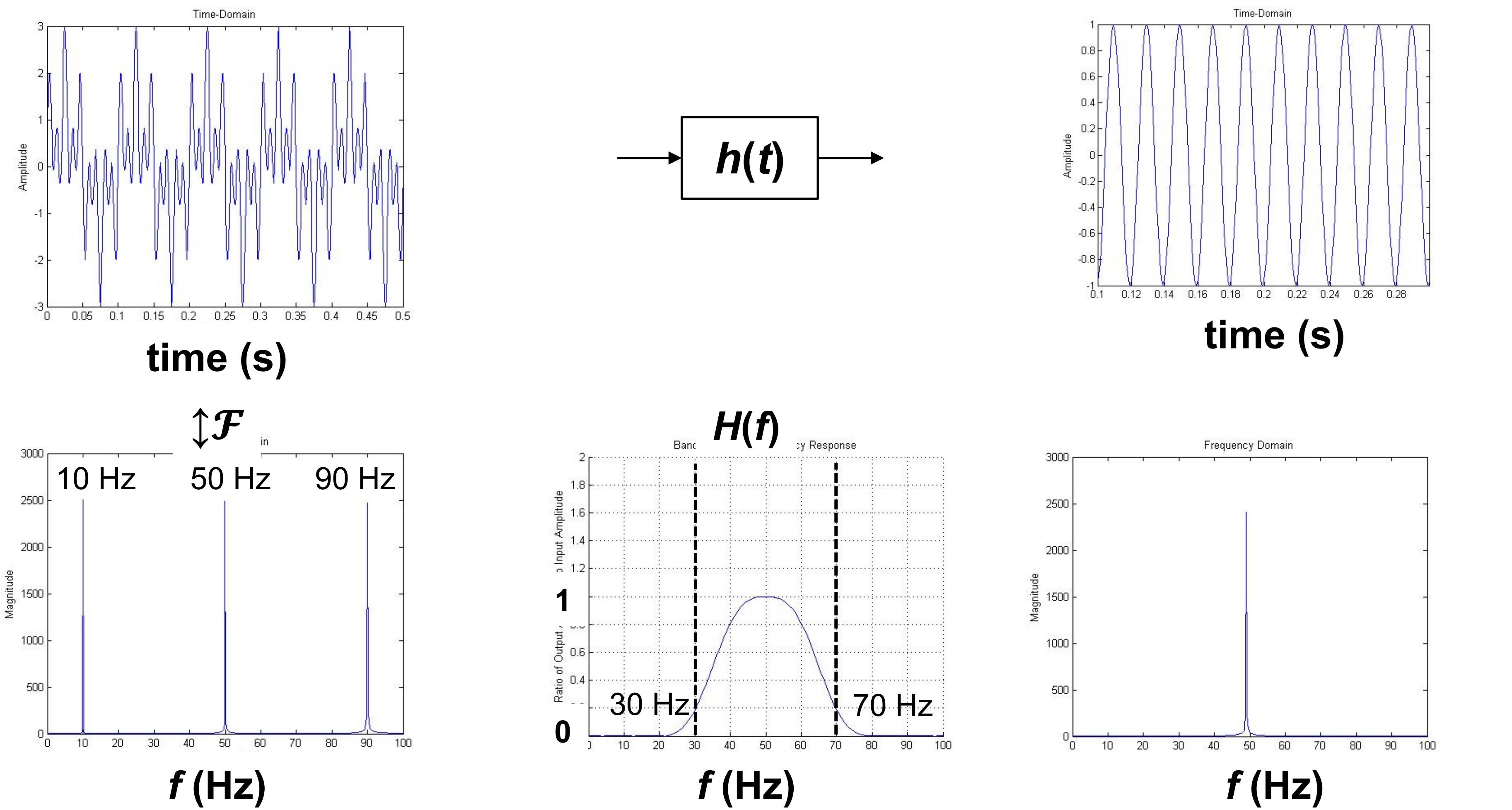
Bandpass Filter: Motivation



- Want to **receive** exclusively a certain **frequency band** of interest
  - In presence of other communication on **adjacent channels**

Bandpass Filter Output

- *H*(*f*) = 0 below 30 Hz, above 70 Hz, approaches 1 elsewhere



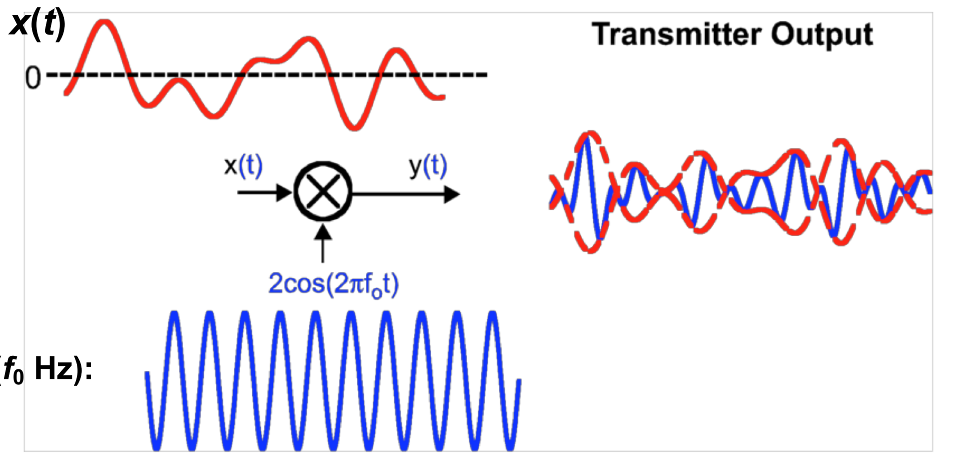
Today

- Introduction to Signals
- Introduction to Filtering
- **AM Radio**
- Signals and Noise

AM Radio Transmitter

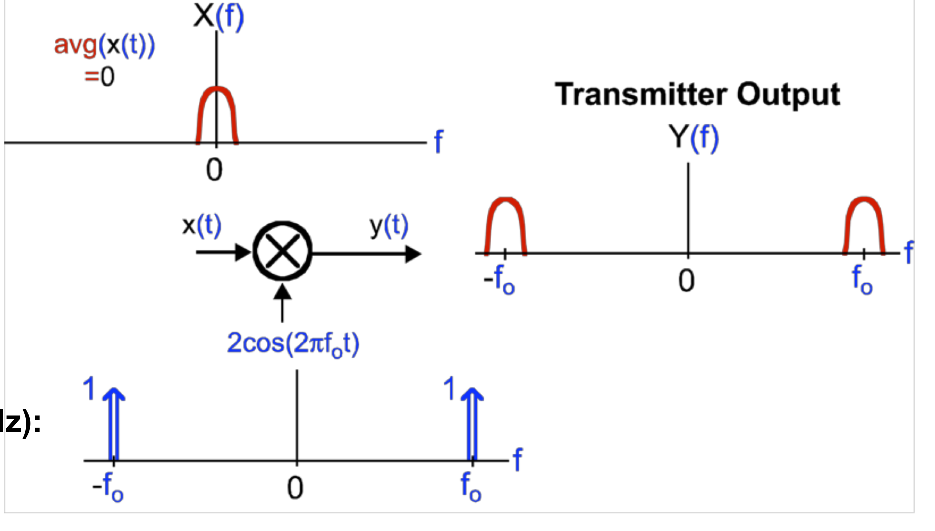
Time domain view:

Carrier signal (f_0 Hz):

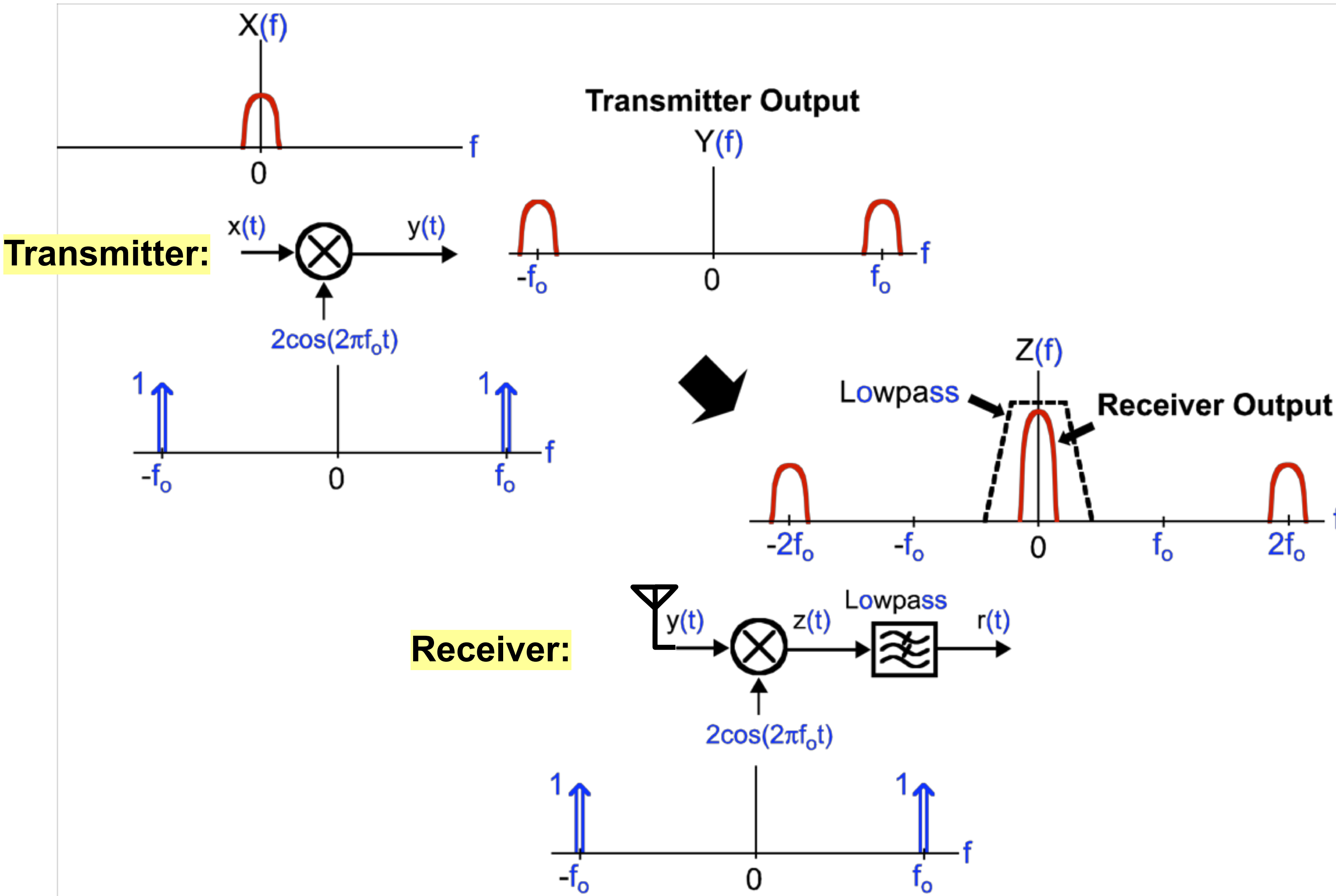


Frequency domain view:

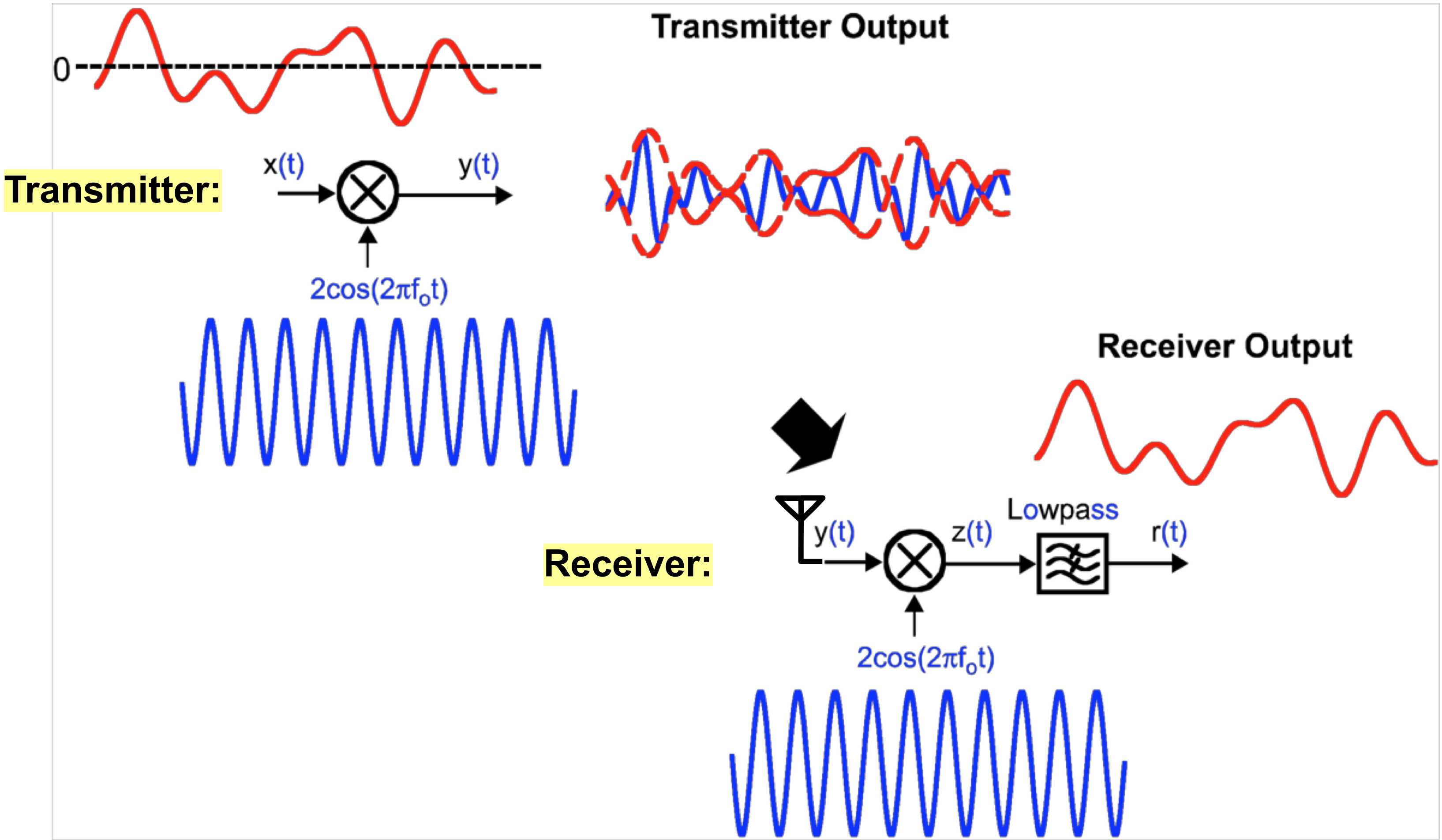
Carrier signal (f_0 Hz):



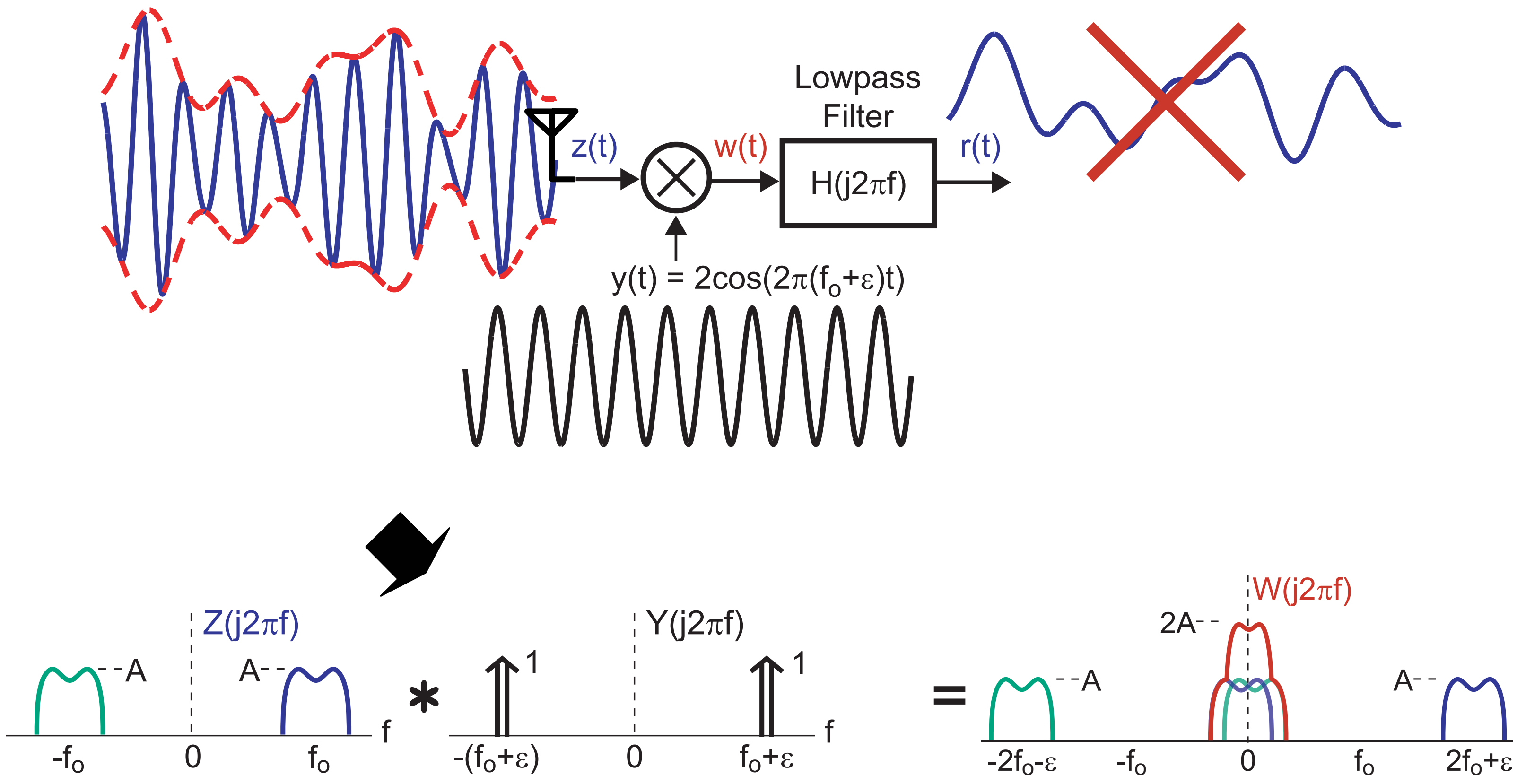
Demodulation: Frequency Domain View



Demodulation: Time Domain View



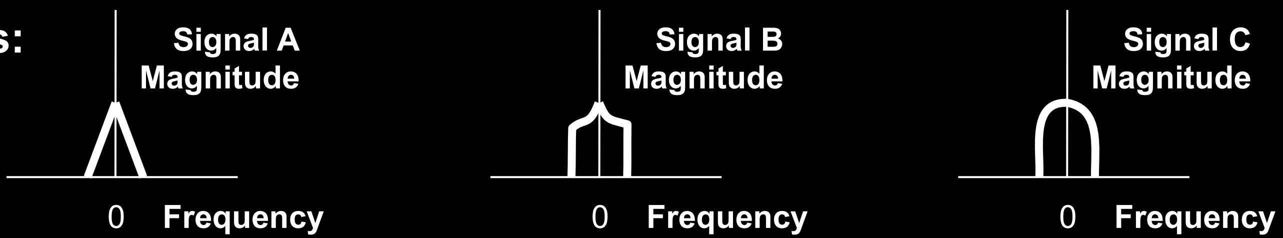
Impact of a frequency offset



Frequency offset ε at receiver corrupts the output signal *r*(*t*)

Stretch Break and Partner Exercise: FDM-AM

Voice signals:



- Using the principle of superposition and the AM radio circuits we've just seen:

  1. Draw a circuit to transmit **frequency division-multiplexed** amplitude modulation (FDM-AM) of the voice signals A, B, and C at frequencies f_A, f_B, and f_C, respectively

  2. Plot the **radio-frequency spectrum** of your circuit's output (the transmitted FDM-AM signal)

  3. Describe how **a receiver** would tune in to and demodulate just Signal B

Today

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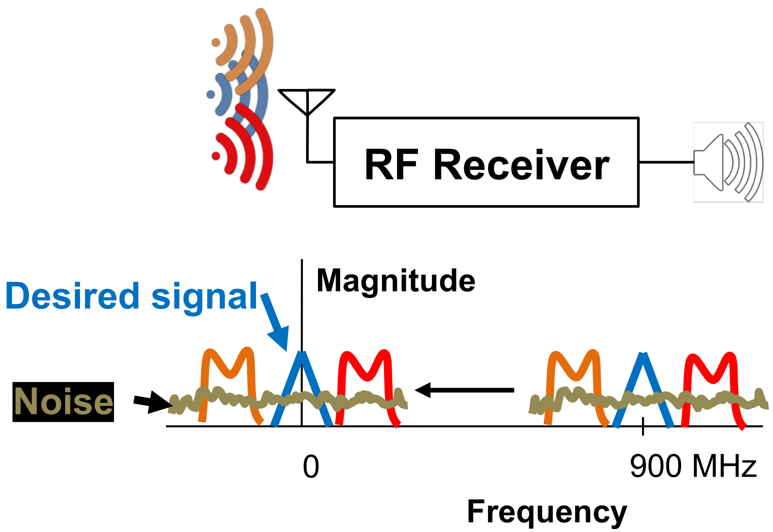
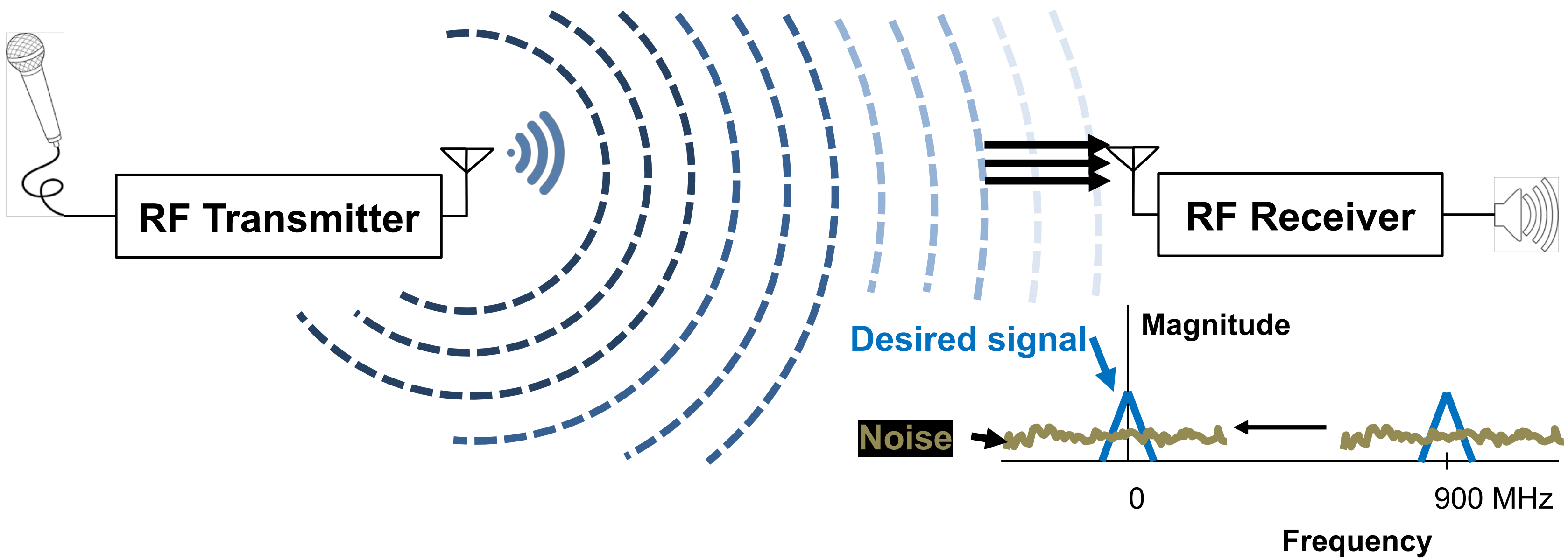
The Issue of Noise



- ***Noise:*** **Unpredictable, corrupting** signal that **adds** to desired signal
  - For RF receiver, mostly comes from analog receiver amplifier circuitry

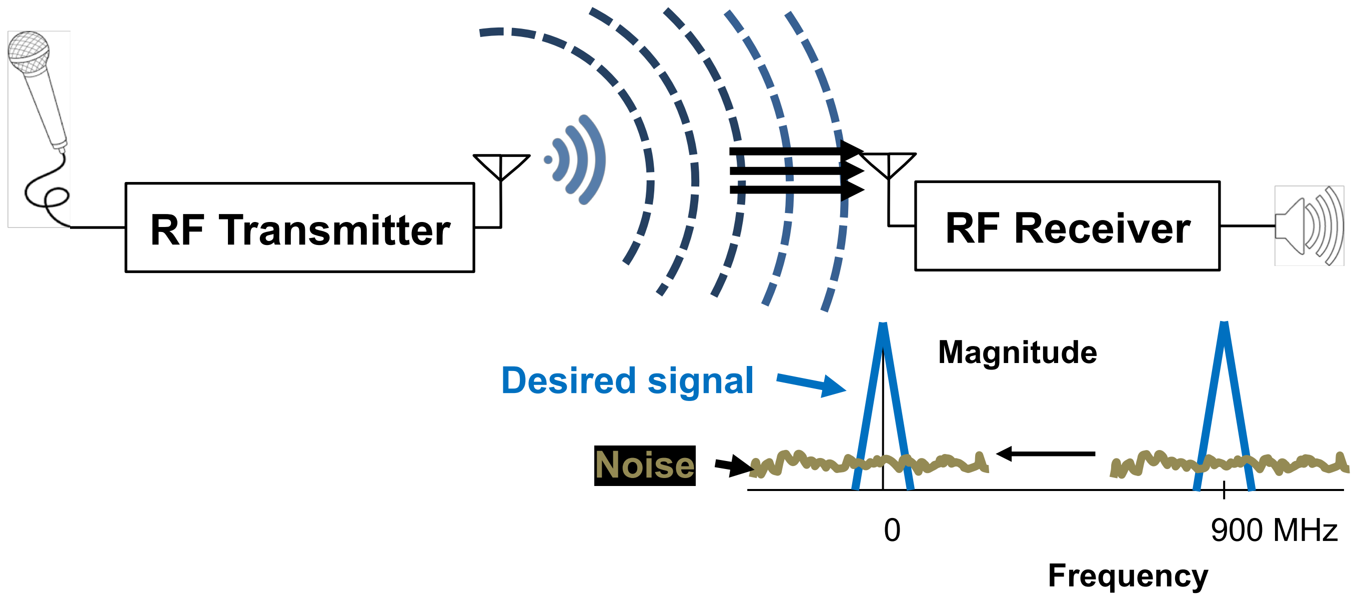
- **Undesired signals** also add to and corrupt desired signal

Energy Transfer in Wireless Communication



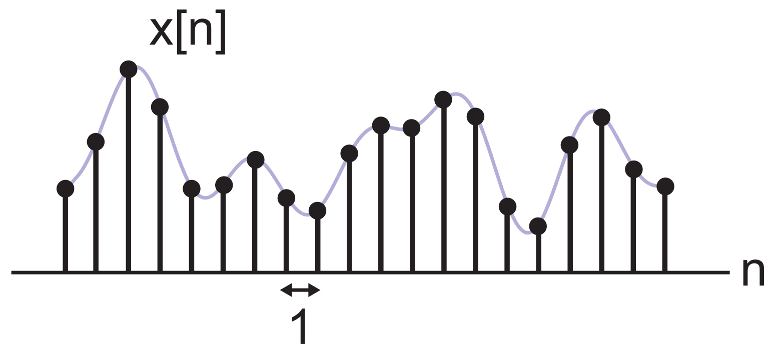
- Receiver antenna captures a **limited amount** of **desired signal's energy**
  - Depending on antenna size, distance, environment

Signal versus Noise



- Moving transmitter closer to receiver generally **increases desired signal energy**
- Noise from analog receiver circuitry **remains unchanged**
- **Next few lectures:** *How is system performance impacted?*

Definition of Power, Energy



- Given a signal x[n]:
- ***Energy*** $E_x = \sum_{k=0}^{N-1}(x[k])^2$
- ***Power*** $P_x = \frac{1}{N}\sum_{k=0}^{N-1}(x[k])^2$

Signal to Noise Ratio (SNR)

- ***Signal-to-Noise Ratio*** (SNR) measures power ratio between a signal of interest and background noise: $\mathrm{SNR} = \frac{P_{signal}}{P_{noise}}$

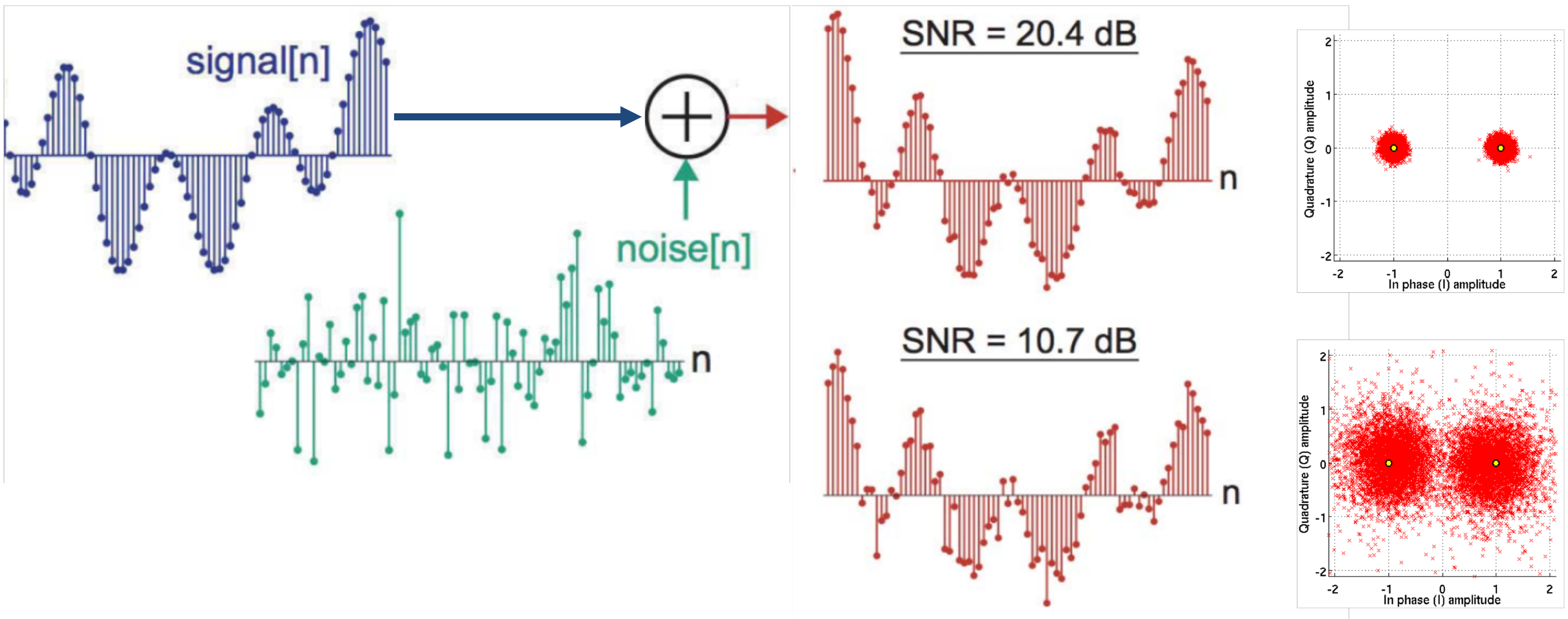
- SNR is often expressed in ***decibels*** (dB), 10 times the base-10 logarithm of a quantity: $\mathrm{SNR}\ (\mathrm{dB}) = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$

SNR (dB)	SNR
30	1,000
20	100
10	10
0	**1 (equal)**
-10	0.1
-20	0.01
-30	0.001

Visualizing Signal to Noise Ratio

Signal view:

Constellation view:



Summary

- **Impulse function** is an important concept for frequency domain **"picture" analysis**
  - **Shifting, sampling properties** of impulse explain modulation and demodulation

- "Picture analysis" of modulation and filtering
  - **Modulation *shifts*** in frequency (convolution with impulses)
  - **Filtering *multiplies*** in frequency

Good luck with the remainder of your midterms!

Tuesday, March 25 lecture:
From AM Radio to Digital I/Q Modulation