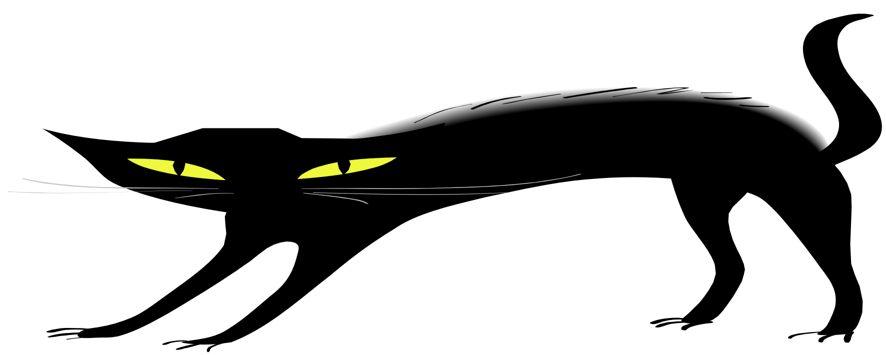
Introduction to Communication Systems
- Analog and Digital -

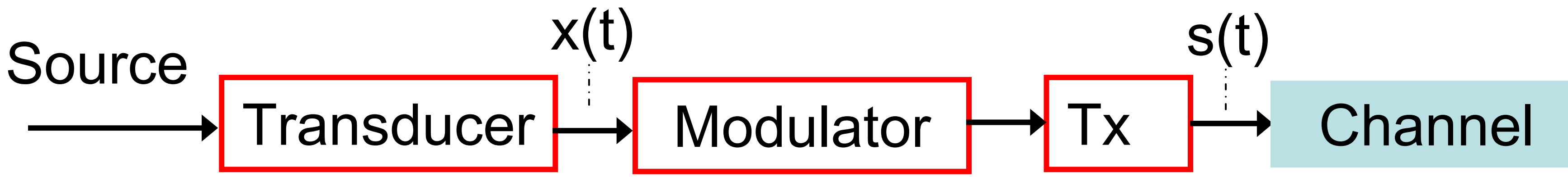
Albert Einstein: *"The wireless telegraph is not difficult to understand. The ordinary telegraph is like a very long cat. You pull the tail in New York and it meows in Los Angeles. The wireless is the same, only without the cat."*



Overview

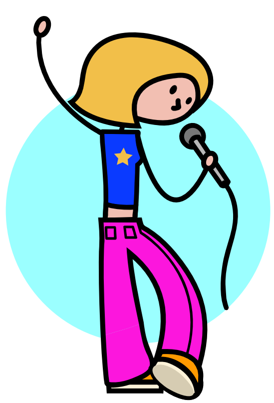
- A Typical Communications Link
- Signaling Categories
- Communication Channels
- The EM Spectrum and Propagation
- Modulation Techniques
- Digital Communication Systems
- What's Next? - Software Radio

Typical Communications Link: Transmitter Side



e.g., a microphone: changes sound waves to electrical signals

Includes high-power amplifier, filter, and antenna



Changes x(t) to a waveform suitable for transmission over the given channel
(antenna length ≈ .1 λ)

Typical Communications Link: Receiver Side

$s(t) + n(t)$

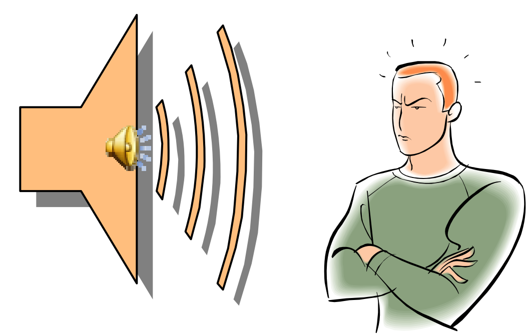
Channel → Rcv → Demodu-lator → Transducer → Sink

$\approx x(t)$

Rcv: Includes antenna, filter, & low-noise amplifier

Demodulator: (Approximately) recovers $x(t)$, by undoing what the modulator did

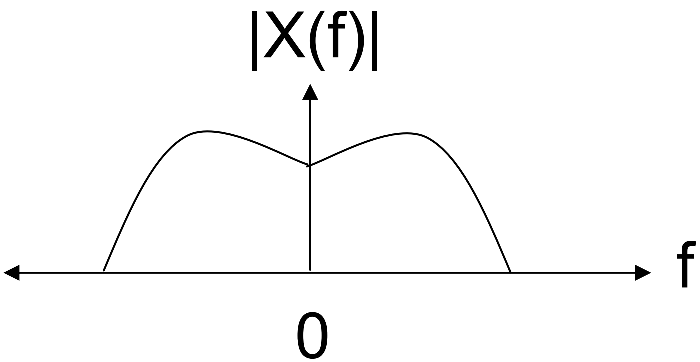
Transducer: e.g., a speaker: changes electrical signals to sound waves



Signaling Categories

Baseband Signals, x(t)

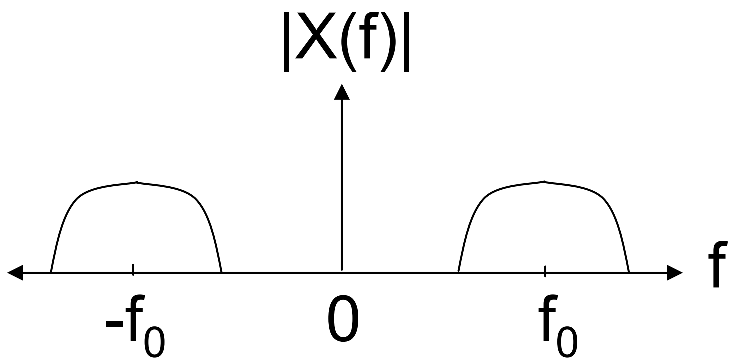
- Spectrum is centered at the origin



- Suitable for transmission over guided transmission media (e.g., phone signals over land lines)

Bandpass signals, x(t)

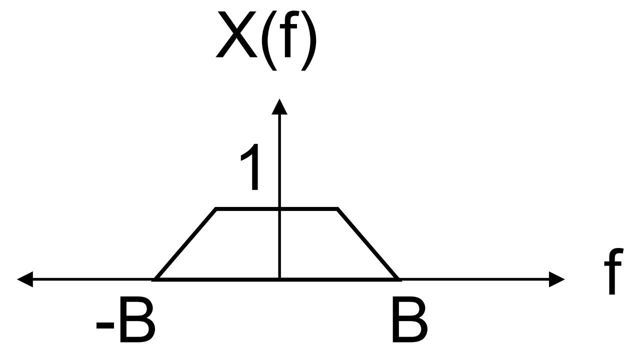
- Spectrum is centered at frequencies $\pm f_0 \neq 0$



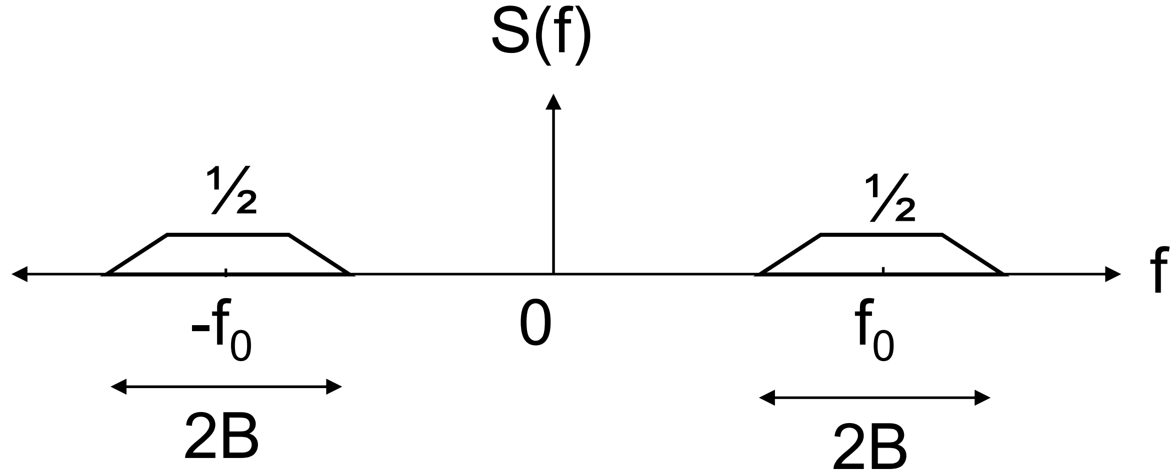
- Suitable for transmission over air waves (e.g., radio signals)

Getting the Signal Where We Want It: Fourier Transform Modulation Property

- Say $x(t) \rightarrow X(f)$



- Then if $s(t) = x(t)\cos(2\pi f_0 t) \rightarrow S(f)$



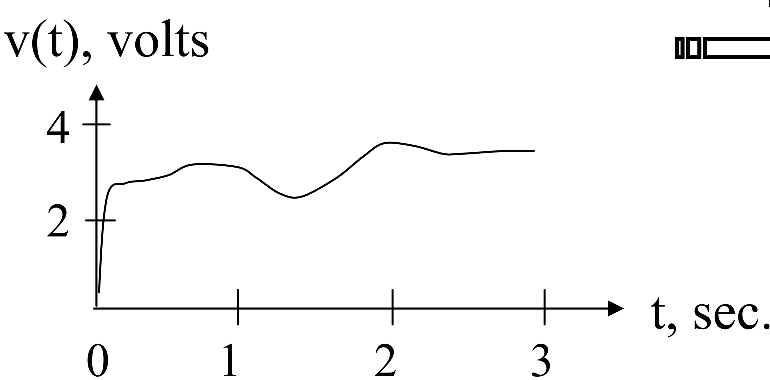
Signaling Categories

- **<u>Continuous-time Signals</u>**: value is **specified for all time, over some range** of time; e.g., voltage, v(t), at some point in a circuit, say for 3 sec.)

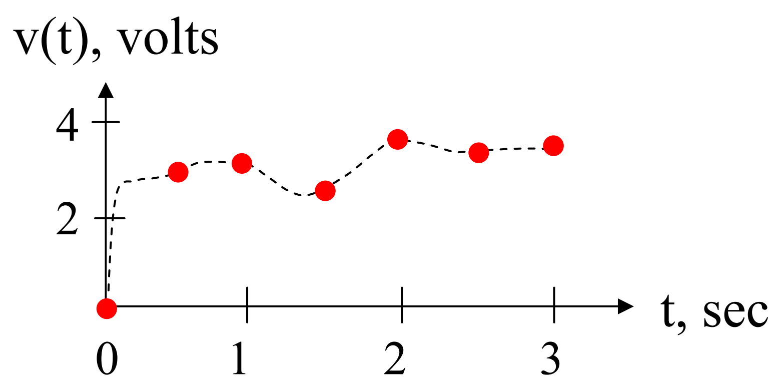
- **<u>Discrete-time Signals</u>**: value is **specified only at discrete points** in time:

  $t_0, t_1, t_2, \ldots, t_n, \ldots$

  - restricts set of values on horizontal axis



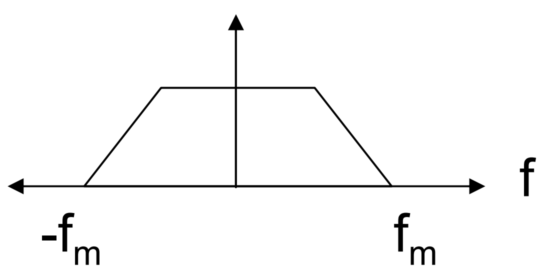
Sampling



Nyquist Sampling

- **Nyquist Sampling Theorem**: Signals **band-limited to f_m Hz** can be uniquely determined by values sampled at the **Nyquist rate $f_s > 2f_m$** (samples/sec)
- The time between samples is: $T_s = 1/f_s$.

$x(t) \longrightarrow X(f)$



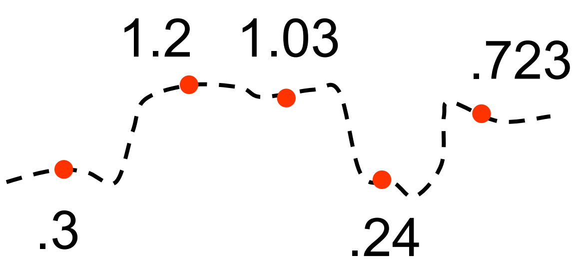
f_m: maximum frequency content of signal

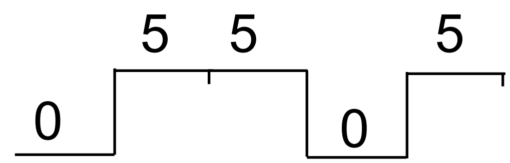
(band-limited to f_m Hz)

Signaling Categories

- **Analog Signals**: amplitude can assume any value over a **continuous range**
  - **∞ # of values** can be assumed by the signal

- **Digital Signals**: amplitude can assume only a **finite # of values**
  - restricts set of values on the vertical axis





Quantization

Real-World Parameters
- Sampling & Quantization -

Digital System	Frequency Band	Sample Rate, KHz	Quantization, Bits/Sample
Phone*	200 – 3.4K	8	8
CD	20 – 20K	44.1	16

- Voice Signals: Frequency content in range ~ (300 Hz, 4 KHz)
  - Quality: Intelligible speech
  - ~ 24 analog voice signals (say from home phones) digitized and combined and sent over a "T1" line (usually fiber optic)
- Human Hearing Range: ~ 15 Hz – 20 KHz

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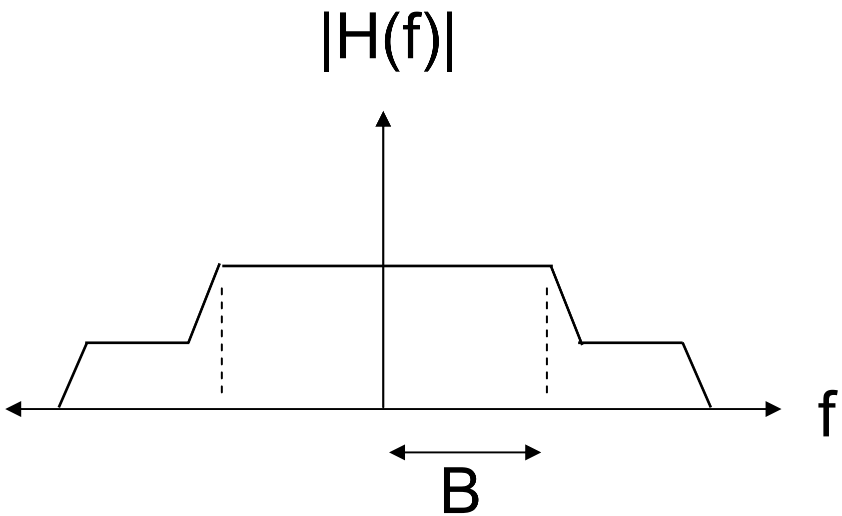
* POTS: plain old telephone service, via PSTN: Public Switched Telephone Network

Communications Link: the Channel

- Channel: Medium over which the transmitter output is sent to the receiver
- Channels types:
  - Guided: Signals confined to a closed path
    - Examples: Twisted pair, coaxial cable
    - Baseband signaling is (usually) suitable
  - Unguided: Signals radiate freely in all directions
    - Examples: atmosphere, ocean, outer space
    - Bandpass signaling is (usually) suitable

Communications Link: the Channel

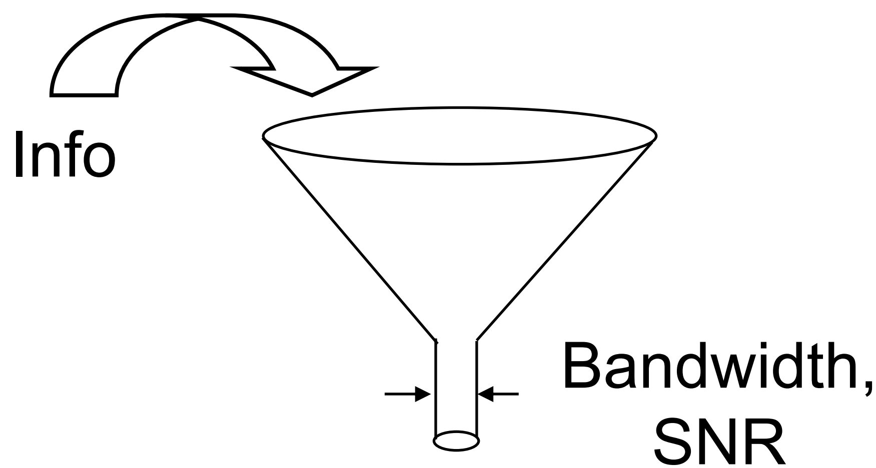
- Channels are characterized by a transfer function, H(f), the magnitude of which shows the **channel gain** as a function of frequency:



- Consider the range of frequencies over which the gain is relatively constant.
- The difference between the largest and smallest such frequencies is the **channel bandwidth**, B

Communications Link: the Channel

- Channels are characterized by their **capacity**
  - Capacity: An inherent limit on the rate at which information can be sent "error free"
  - Capacity increases with **bandwidth** (B) and **signal-to-noise ratio** (SNR or S/N)



$$C = B \log(1 + S/N)$$

Radio Frequency Bands

Band	Frequency	Typical Application
Extremely Low Frequency (ELF)	3 – 30 Hz	Submarine Comm
Super Low Frequency (SLF)	30 Hz – 300 Hz	Submarine Comm
Ultra Low Frequency (ULF)	300 Hz – 3 KHz	Telephone
Very Low Frequency (VLF)	3 KHz – 30 KHz	Navigation
Low Frequency (LF)	30 KHz – 300 KHz	Maritime
Medium Frequency (MF)	300 KHz – 3 MHz	AM Radio (535 KHz – 1.7 MHz)

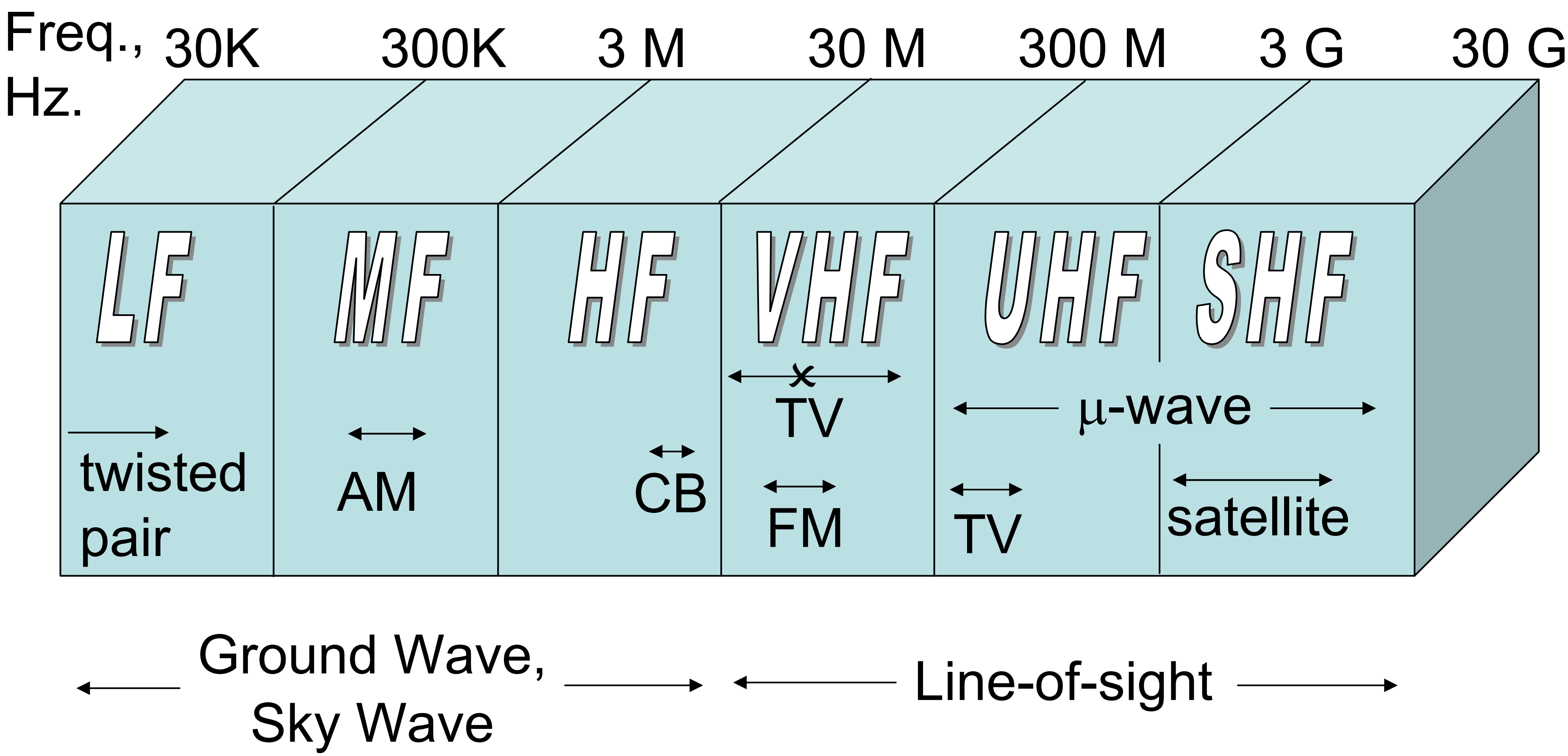
Band	Frequency	Typical Application
High Frequency (HF)	3 MHz - 30 MHz	Shortwave & Citizen Band (CB) Radio
Very High Frequency (VHF)	30 MHz - 300 MHz	FM Radio (88 MHz – 108 MHz), Broadcast TV (Ch. 2 – 13)
Ultra High Frequency (UHF)	300 MHz – 3 GHz	Broadcast TV, cell phones
Super High Frequency (SHF)	3 GHz - 30 GHz (Microwave Signals)	Satellite Bands
Extremely High Frequency (EHF)	30 GHz - 300 GHz (Millimeter Wave Signals)	Millimeter Wave Radar (35 GHz, 94 GHz, 140 GHz, 220 GHz)

Frequency Bands and Propagation

[Ref: *Now You're Talking*]

- **Ground-wave Propagation**: signal travels along the ground, following curvature of the Earth
  - Occurs mostly at lower frequencies (30 Hz - 3,000 KHz)
- **Sky-wave Propagation (Skip)**: signal is refracted by ionosphere (charged partical layer), returning to Earth
  - Occurs mostly at frequencies up to 15 MHz or 50 MHz (depending on solar activity)
- **Line-of-Sight (LOS) Propagation**: signal travels from one antenna to another, in a straight line
  - Occurs in VHF band and higher frequencies

The Radio Spectrum



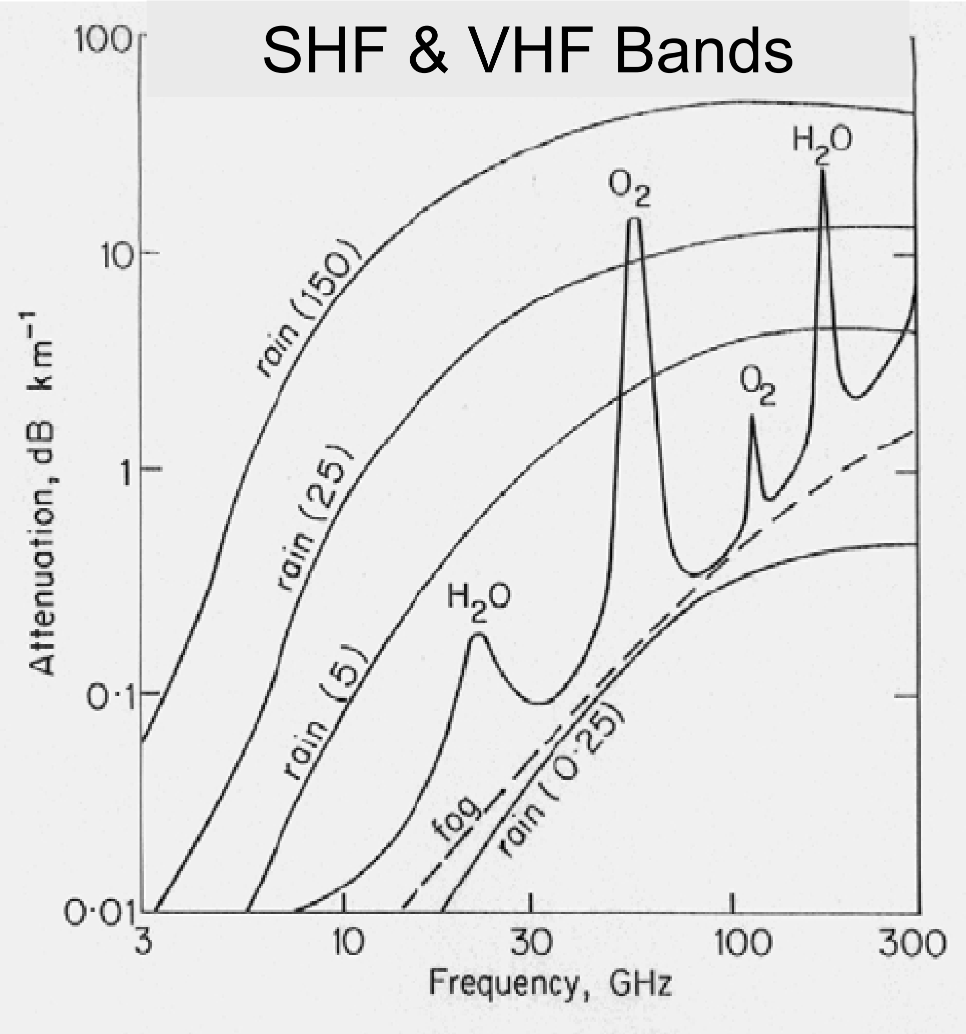
Free-Space Propagation

- Appropriate when a line-of-sight (LOS) path exists between the transmitter and receiver pair
- Received power at distance d (meters) from the transmitter

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 L}$$

  - λ: wavelength, meters $(c = \lambda f)$
  - P_t: transmitted power
  - G_t: gain of tx antenna
  - G_r: gain of rcvr antenna
  - L: system hardware losses

Propagation Effects vs. Frequency



- Water vapor and oxygen cause energy **absorption**
- Rain & fog cause energy **scattering**
- Absorption and scattering frequency dependent, and negligible for f < 5 GHz
- Ref: *Satellite Communications Tutorial*, J.P. Silver, http://www. odyseus. nildram.co.uk/Systems_And_ Devices_Files/Sat_Comms.pdf

Modulation Techniques [Ref: Martin Roden]

- Carrier signal: $s_c(t) = A \cos(2 \pi f_c t + \theta)$ (1)
  - Choose f_c for efficient transmission over the channel
- Modify (1), embedding the message x(t) in the signal
- **AM**: Embed x(t) in the amplitude of the carrier:

$$s(t) = x(t) \cos(2 \pi f_c t + \theta)$$

- **FM**: Embed x(t) in the frequency of the carrier

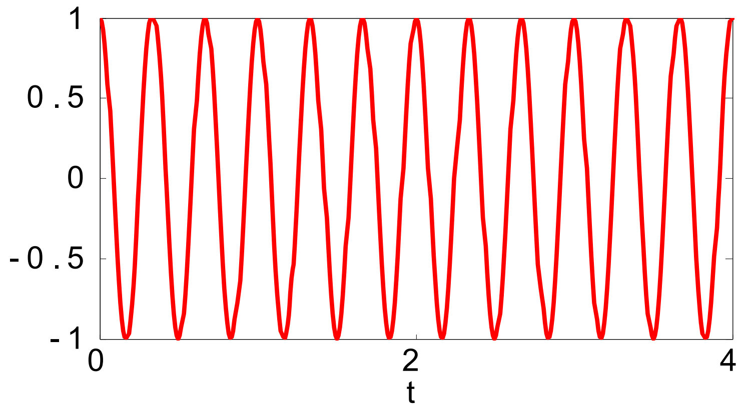
$$s(t) = A \cos\{ 2 \pi [f_c + k\, x(t)]\, t + \theta\}$$

- **PM**: Embed x(t) in the phase of the carrier:

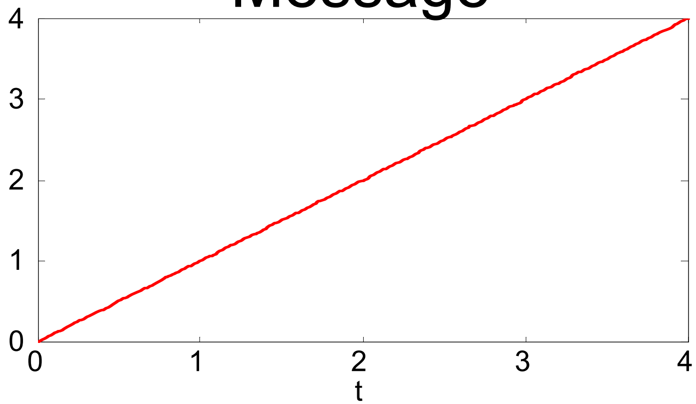
$$s(t) = A \cos\{ 2 \pi f_c t + k\, x(t)\}$$

AM & FM Transmitted Waveforms

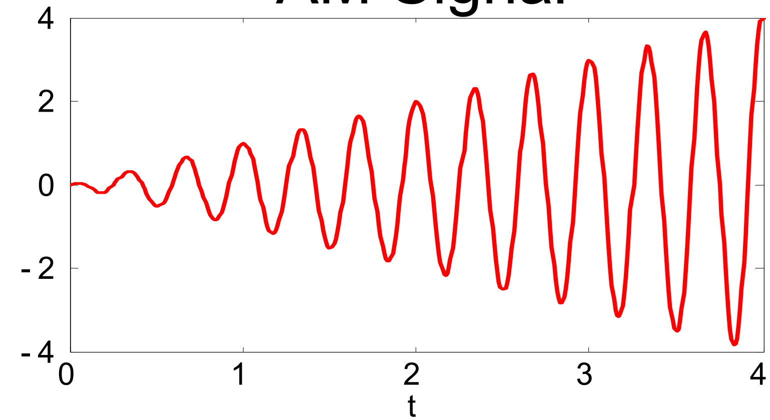
Unmodulated Carrier



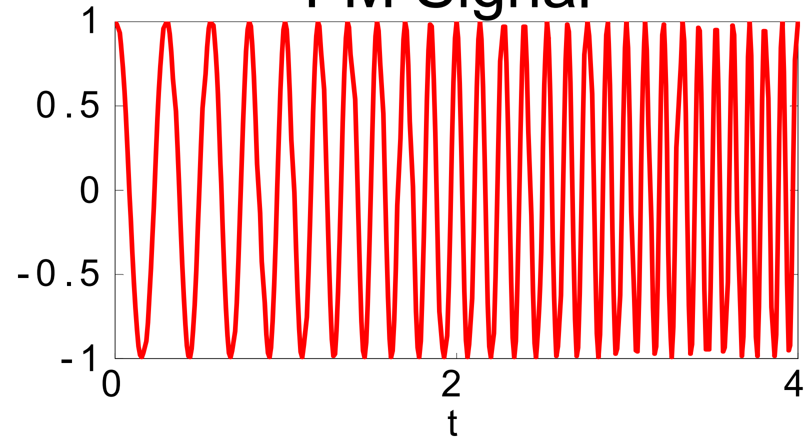
Message



AM Signal

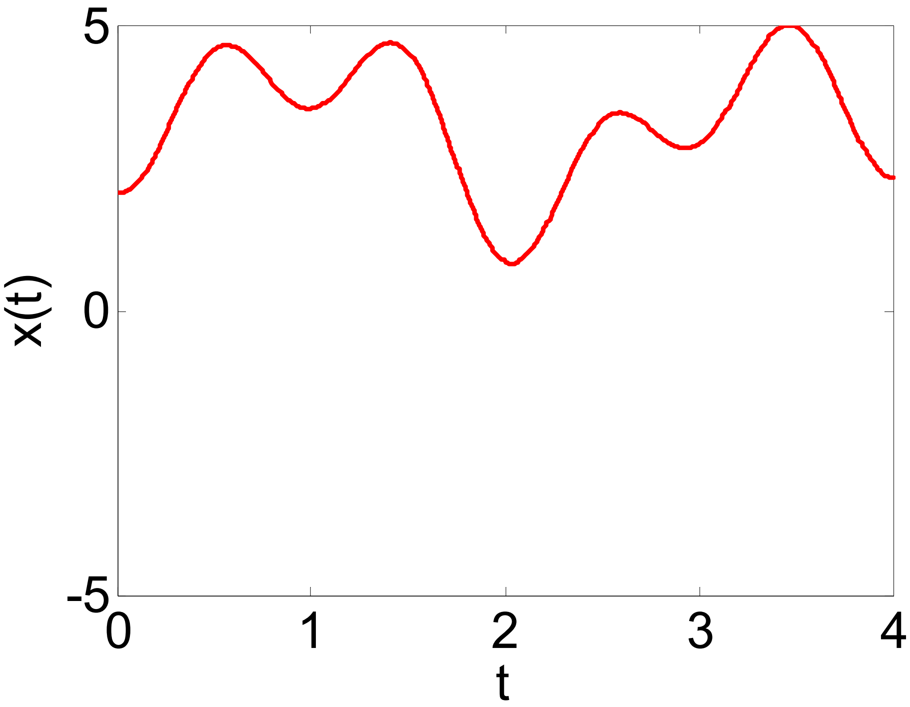


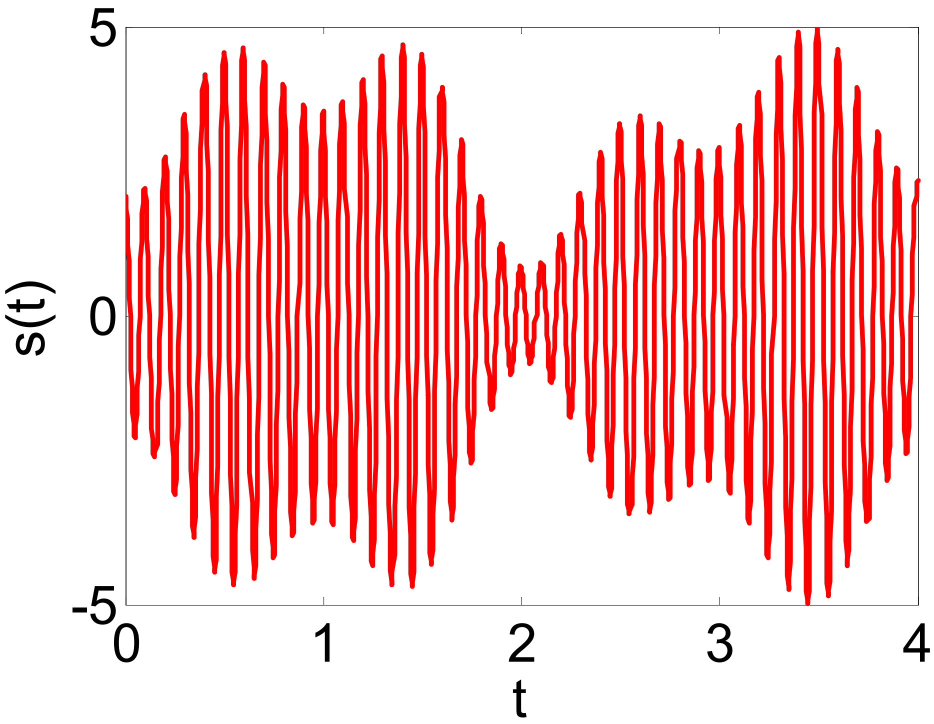
FM Signal



Amplitude Modulation (DSB-SC AM) – A Closer Look –

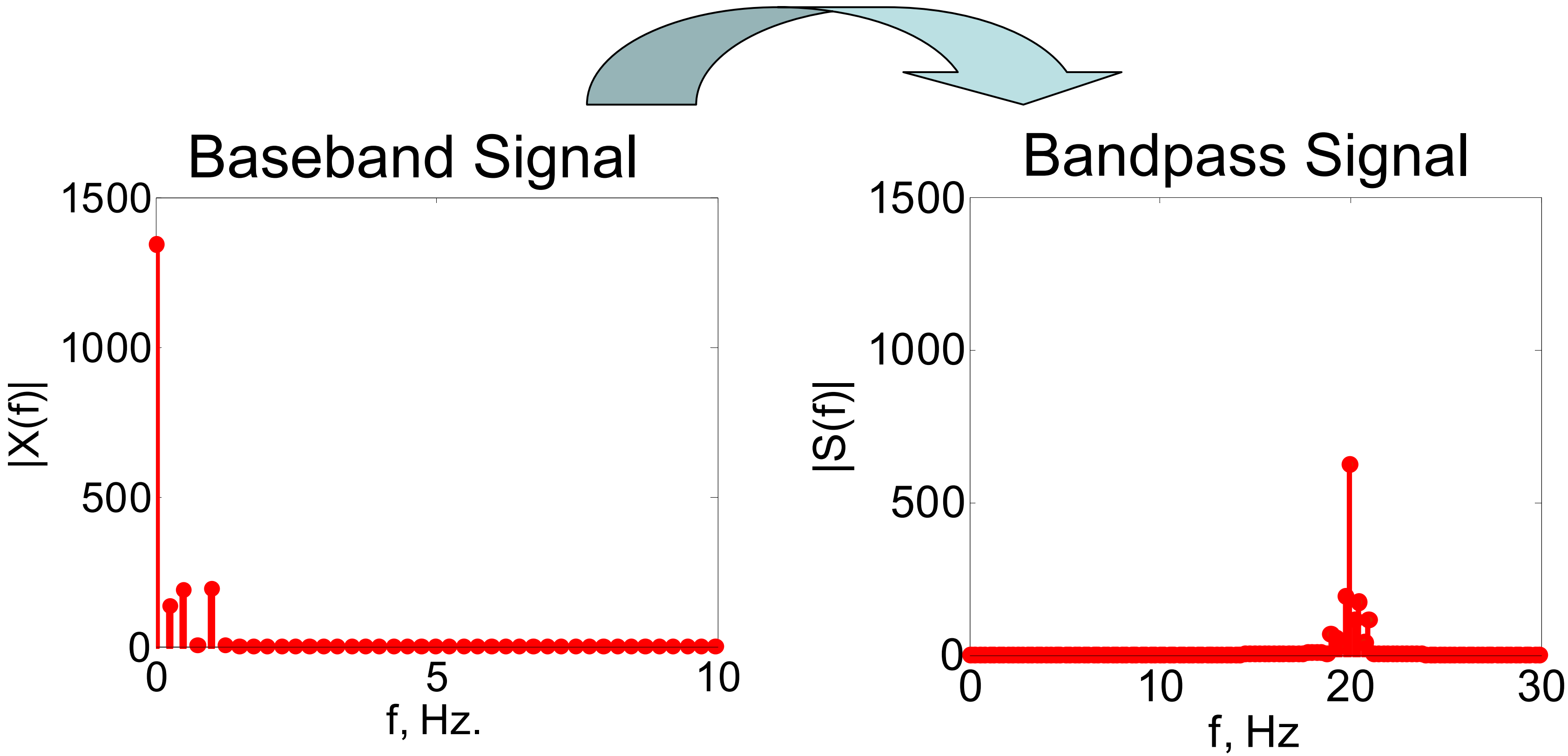
$s(t) = x(t) \cos(2 \pi f_0 t), \quad f_0 = 20$ Hz.





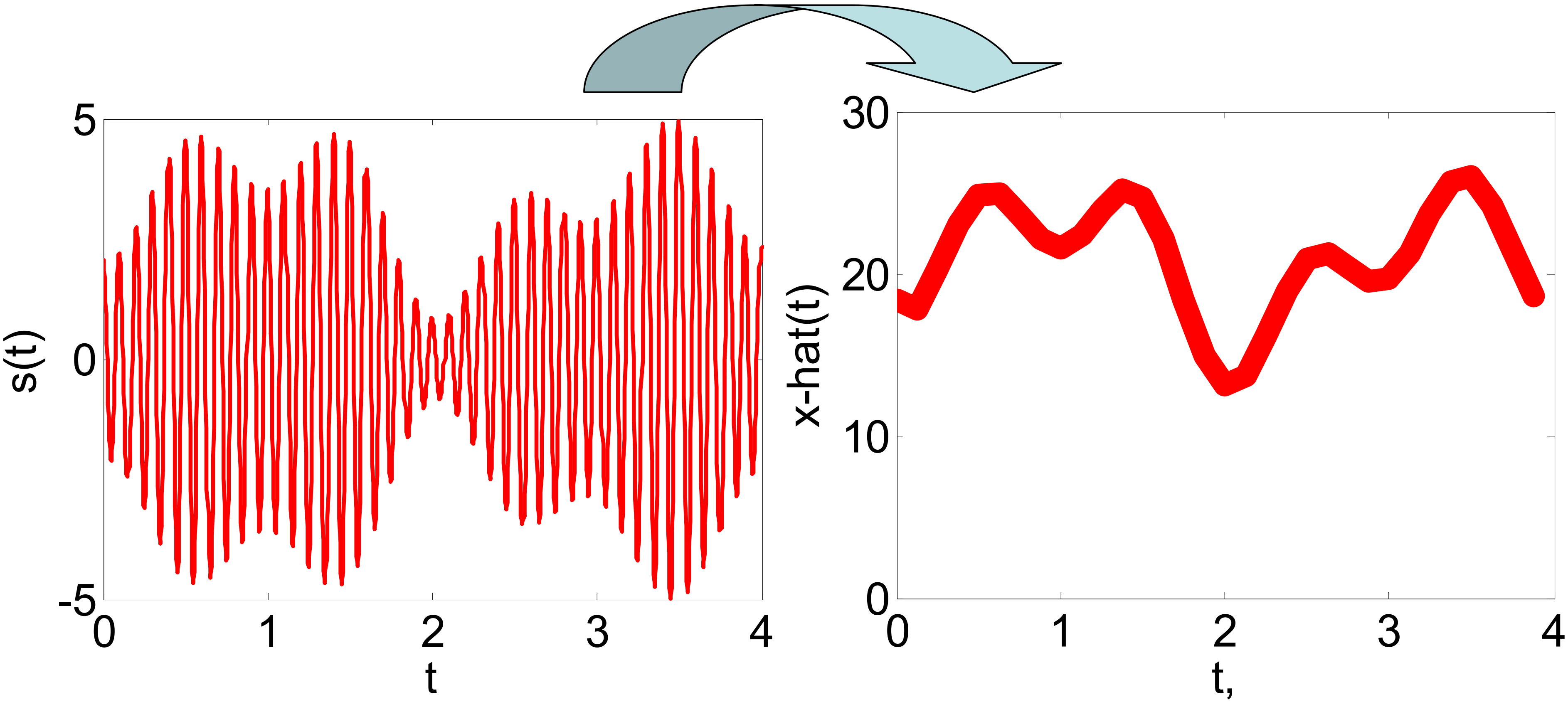
Amplitude Modulation in the Frequency Domain – FFT Magnitude Spectra

$$s(t) = x(t)\cos(2\pi f_0 t), \quad f_0 = 20 \text{ Hz.}$$

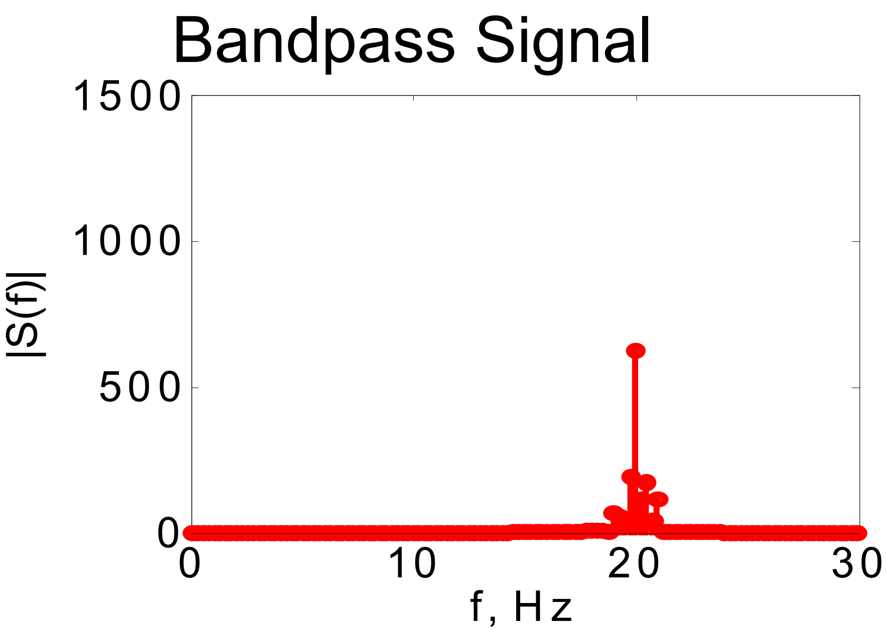


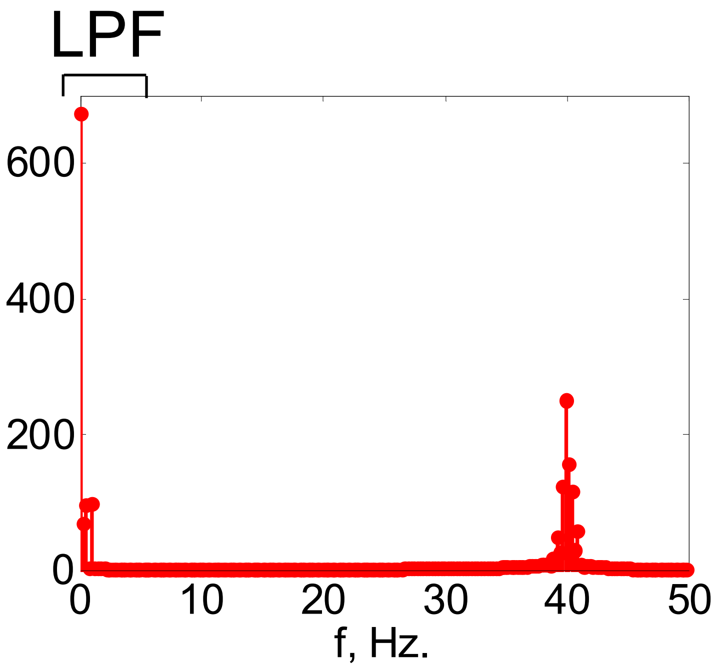
Demodulating the AM Signal

x-hat(t) = LPF'd { s(t) $\cos(2 \pi f_0 t)$ }



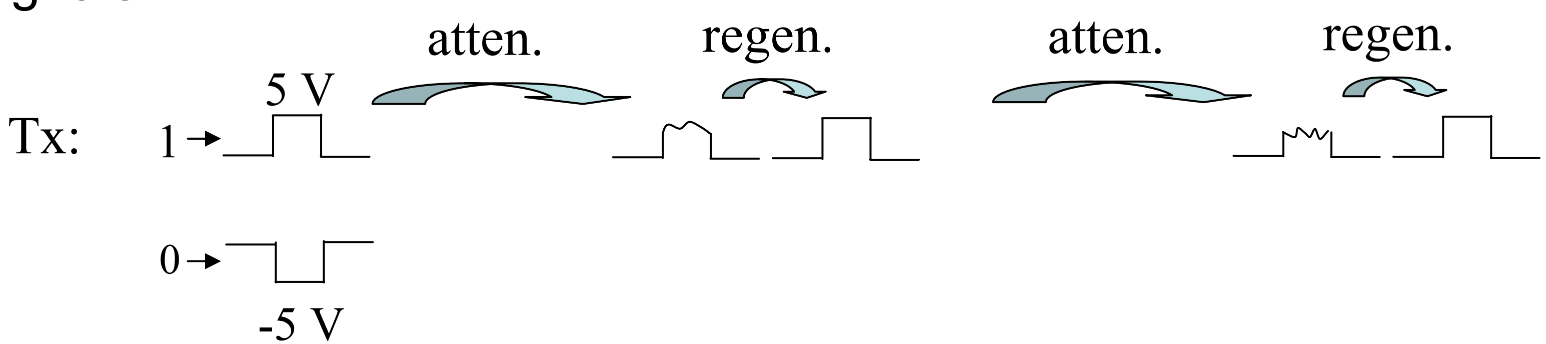
Demodulating DSB-SC AM in the Frequency Domain





Advantages of Digital Communication

- In “reasonable” noise environments, digital signals can be **regenerated** or cleaned up, eliminating the effect of noise; consider the antipodal signals:

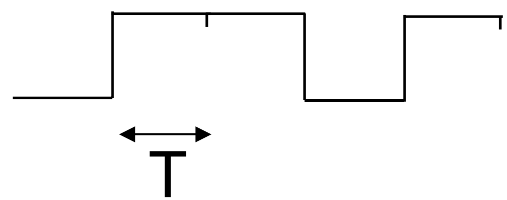


- Digital systems can be computer-controlled, with software. New features can thus be added remotely, even after the initial design.
- More digital circuitry can exist in a given unit of area on a chip.
- Error correcting codes can also be used with digital systems, further improving the noise immunity of digital systems over analog systems
- Elaborate digital signal processing (DSP) and image processing (IP) algorithms can be implemented in software.

Digital Transmission

- Transmit one waveform from a finite set of M possible waveforms every T seconds

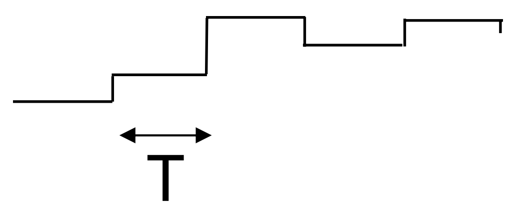
- M = 2: Binary



2 levels,

R = 1/T bps

- M = 4: Quaternary



4 levels,

R = 2/T bps

⋮

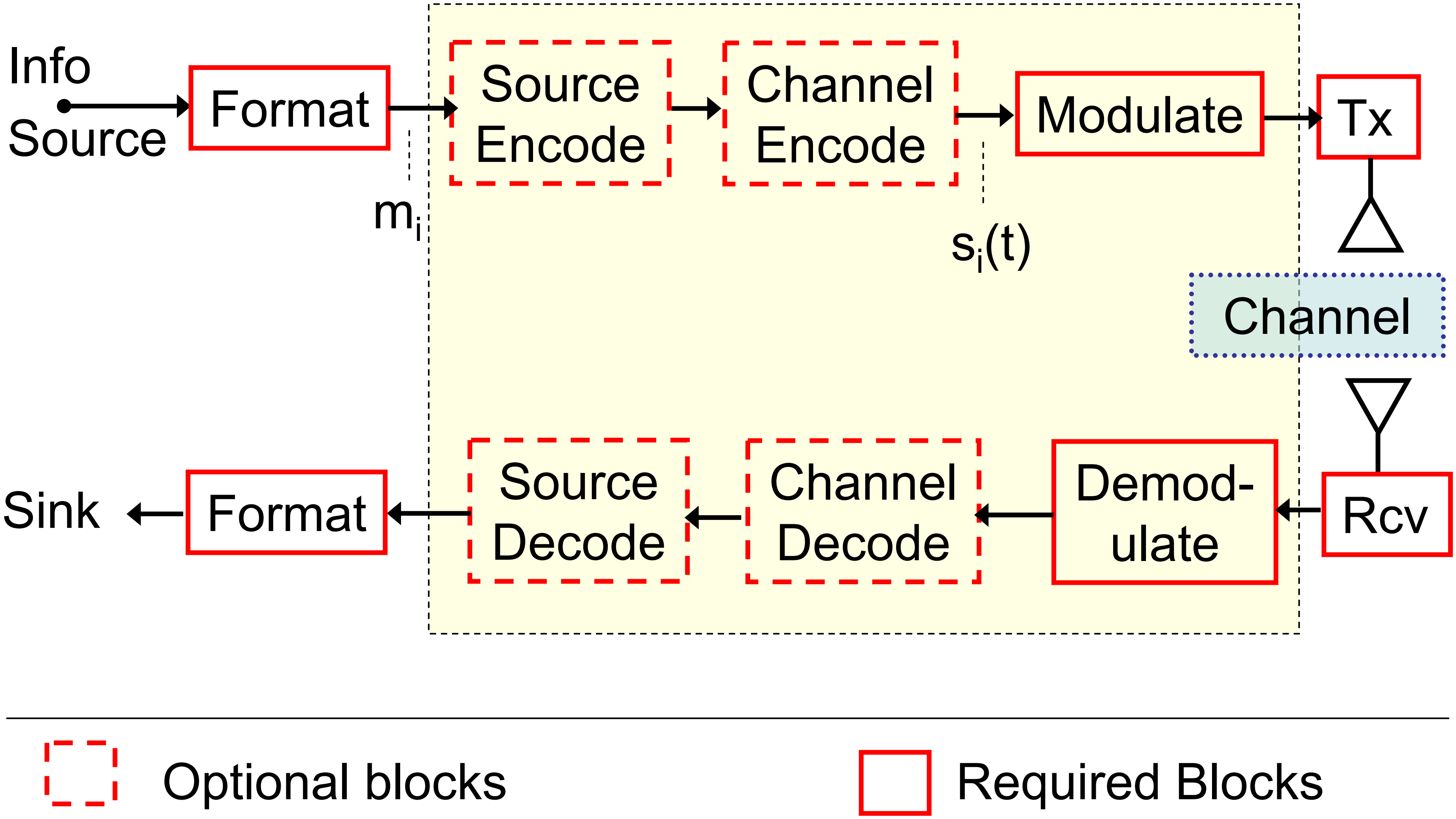
Data rate or throughput increases with alphabet size M

Digital vs. Analog Reception

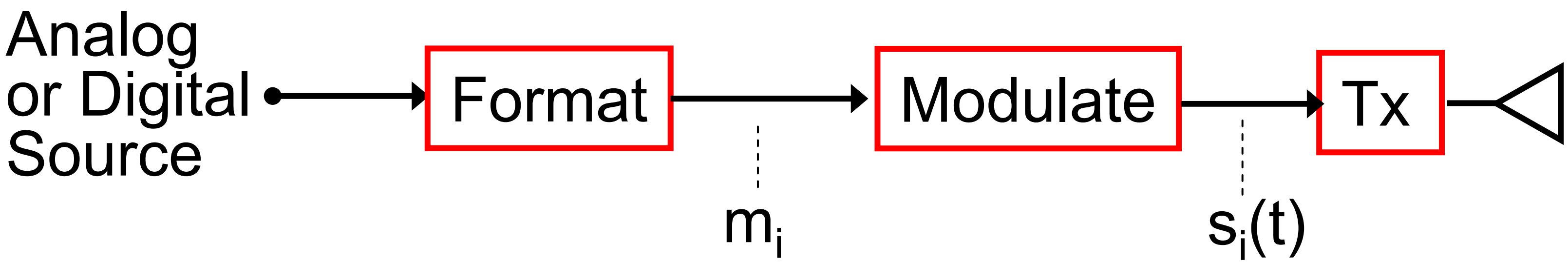
- **Digital Receiver**
- “Guesses” which of the possible waveforms was transmitted every T seconds
- Performance Measure: Pr(error) = Probability of guessing the incorrect waveform

- **Analog Receiver**
- Attempts to reproduce the transmitted waveform
- Performance Measure: measure of fidelity (e.g., mean squared error or % distortion between tx’d and rcv’d waveform)

(Typical) Digital Communication System
[Ref: Bernard Sklar]



The Transmitter Side



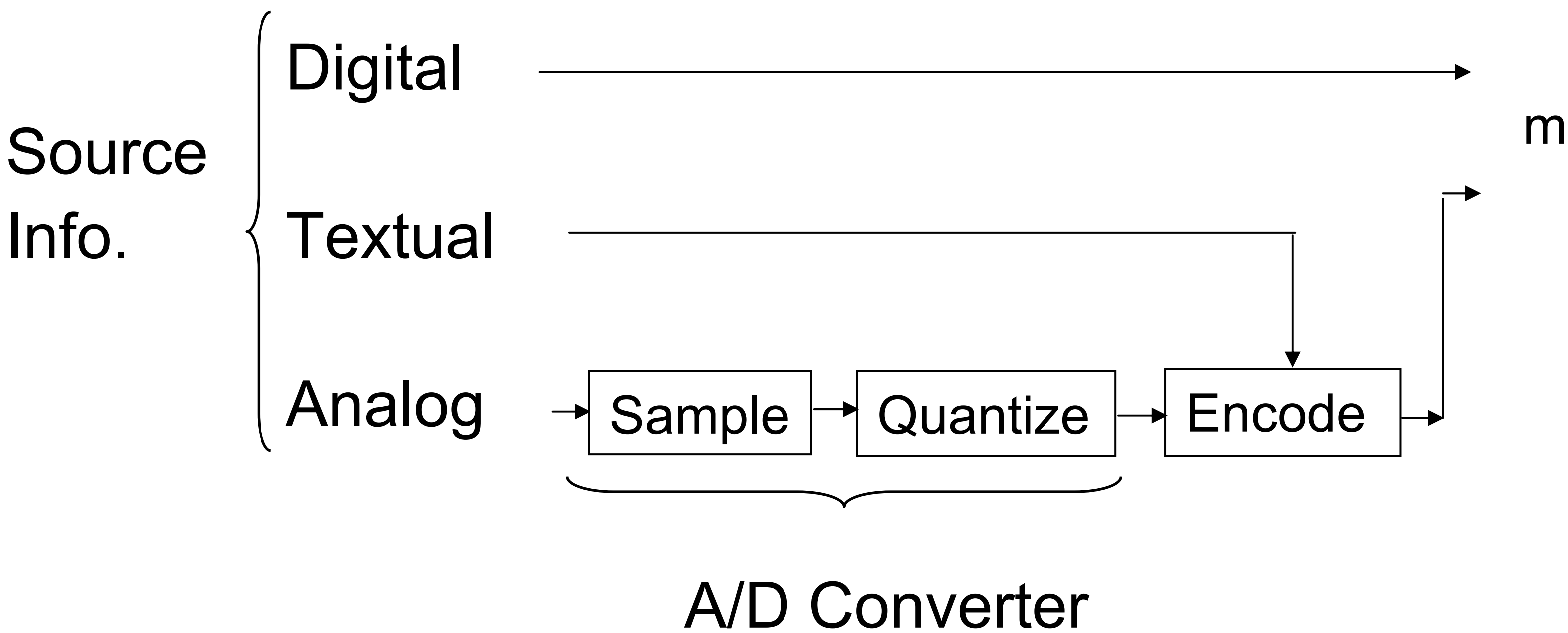
m_i : one of a finite # (2, for binary systems) of possible symbols or messages

$s_i(t)$: one of a finite # of possibly transmitted waveforms

Formatting: changes source information (digital, textual, or analog) to discrete-time digital information

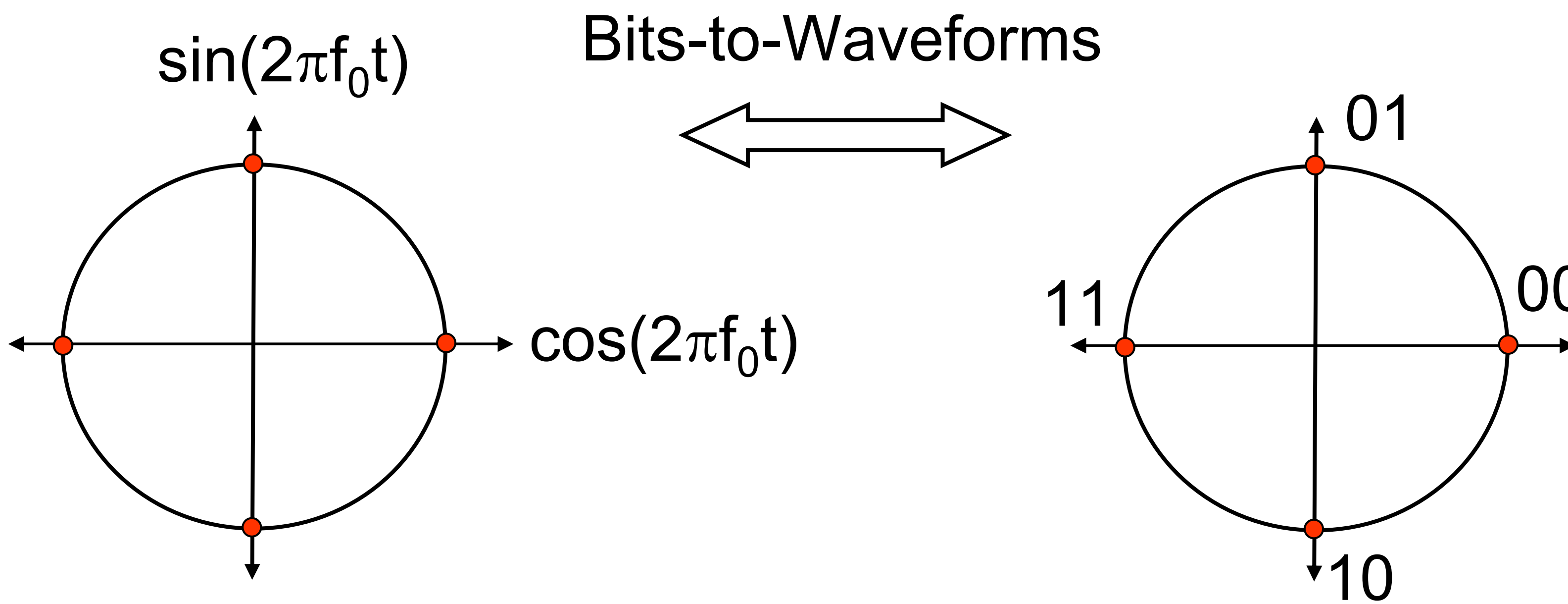
Modulator: maps each symbol to a waveform

Expanding the Formatting Block



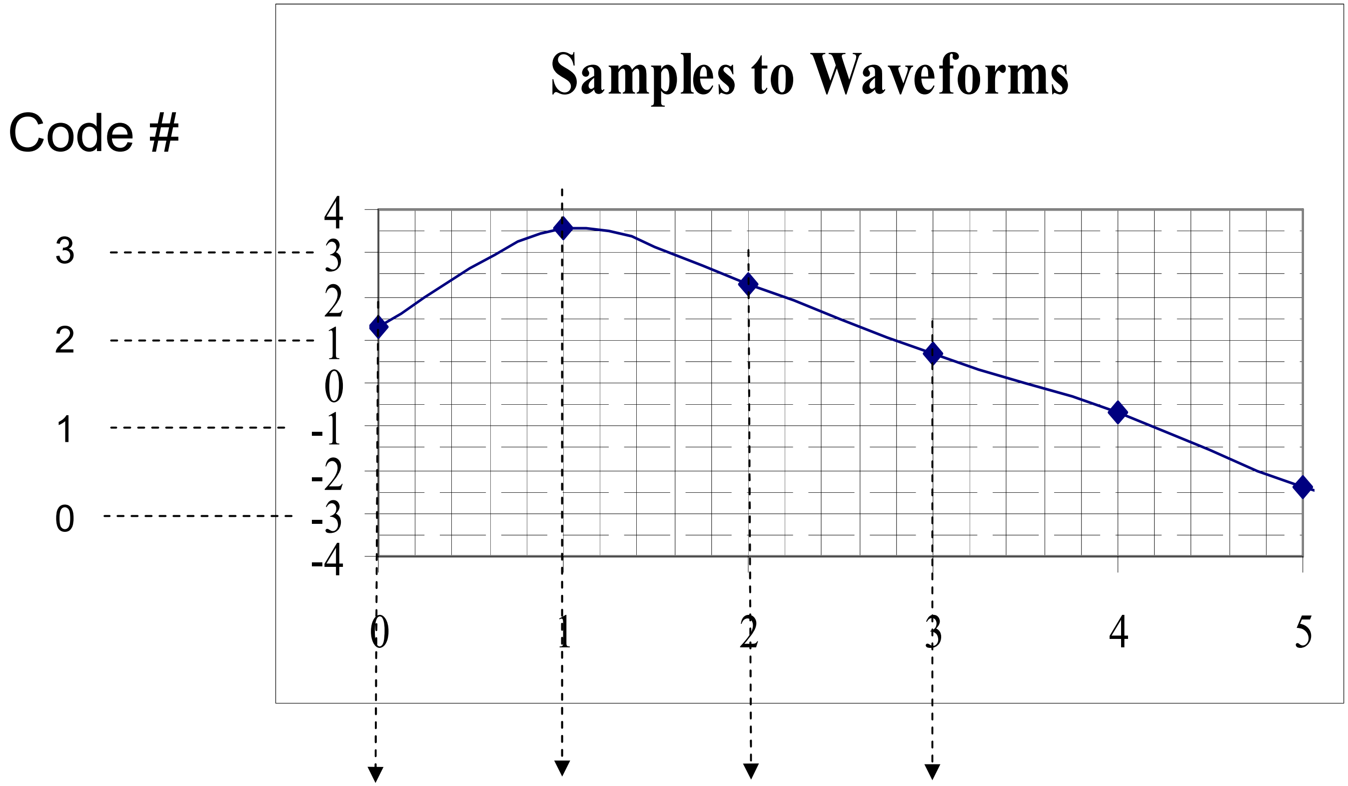
The Modulator Block

- Say we use Quadrature Phase Shift Keying (QPSK) as our modulation.
- We need M = 4 waveforms, with 4 different phase angles:



QPSK Example

Quantization Levels (-3, -1, 1, 3) Indicated by Horizontal Dotted Lines



Sample Value	1.3	3.6	2.3	.7	…
Quantized Value	1	3	3	1	…
Code #	2	3	3	2	…
Binary-Coded	10	11	11	10	

Quaternary Example, Continued

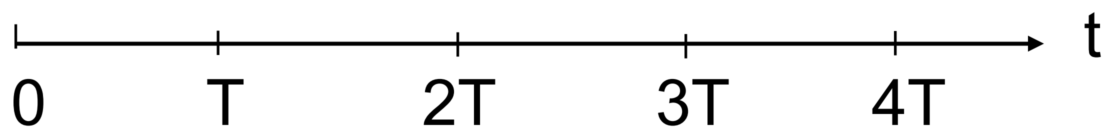
Bit Sequence 10 11 11 10

10 → $-\sin(2\pi f_0 t)$

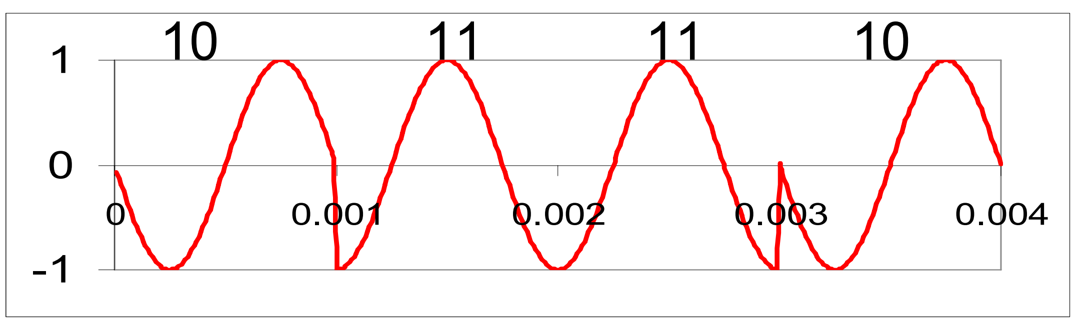
11 → $-\cos(2\pi f_0 t)$

11 → $-\cos(2\pi f_0 t)$

10 → $-\sin(2\pi f_0 t)$



Say f_0 = 1000 Hz, T = 1 ms



What's Next? - Software Radio

- Several key elements (e.g., modulator, codec for error correction, etc.) implemented in reconfigurable software
- Ideally: can operate in any radio frequency band and receive any type of modulation
  - Change from one mode to another by uploading software
- Major application areas, so far: military communications, cellular systems, and amateur radio

Questions?

- Claude Shannon, 1948: *"The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point."*