EE194-EE290C

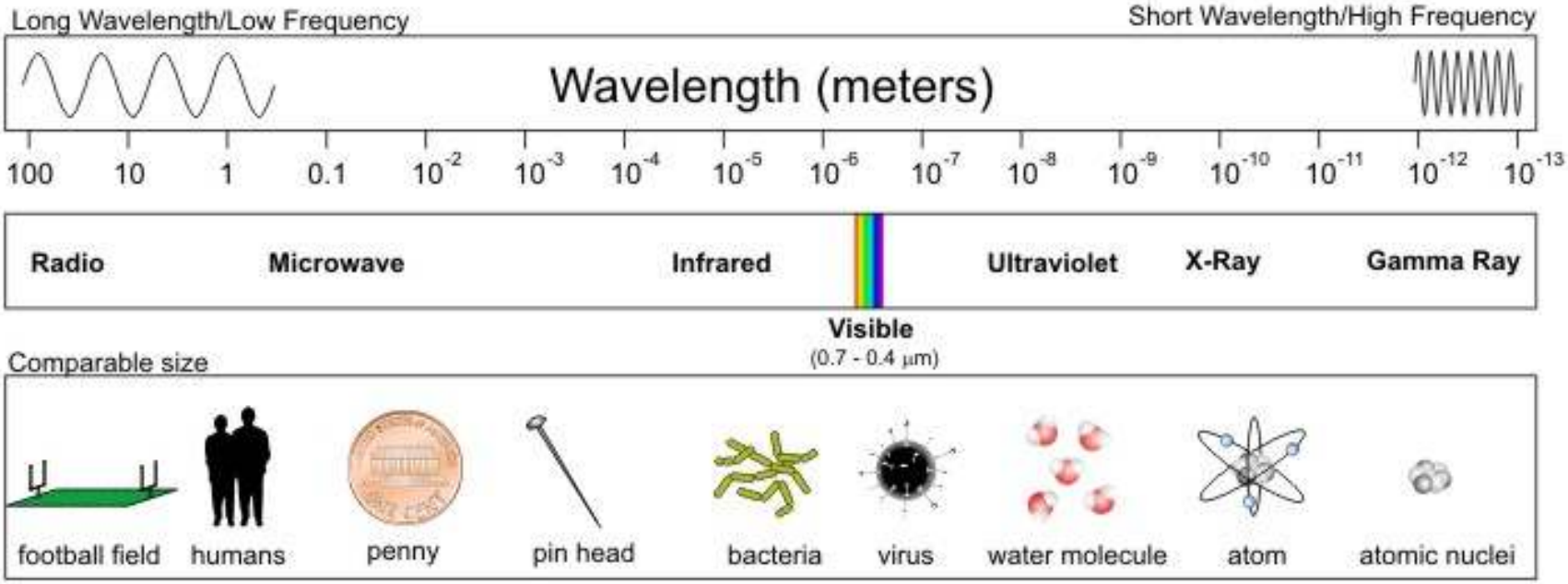
28 nm SoC for IoT

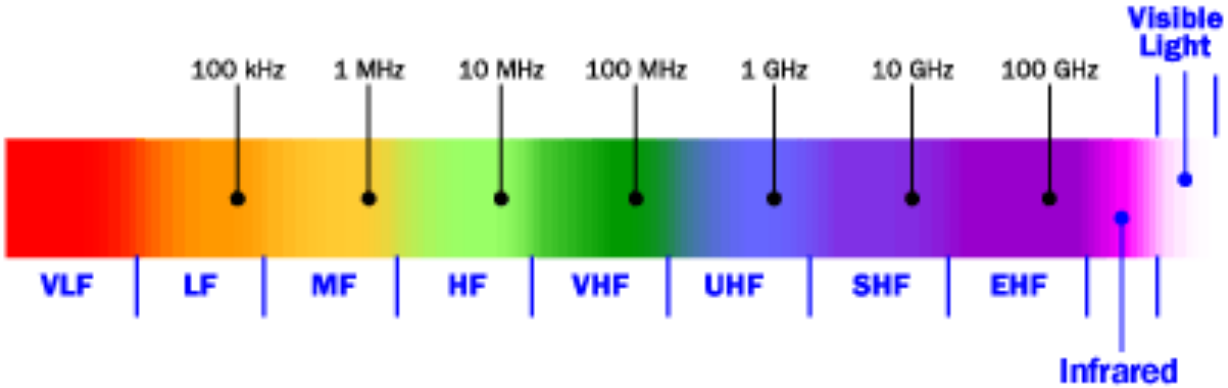
Acknowledgement: Wayne Stark EE455 Lecture Notes, University of Michigan

Lecture 1:Goals

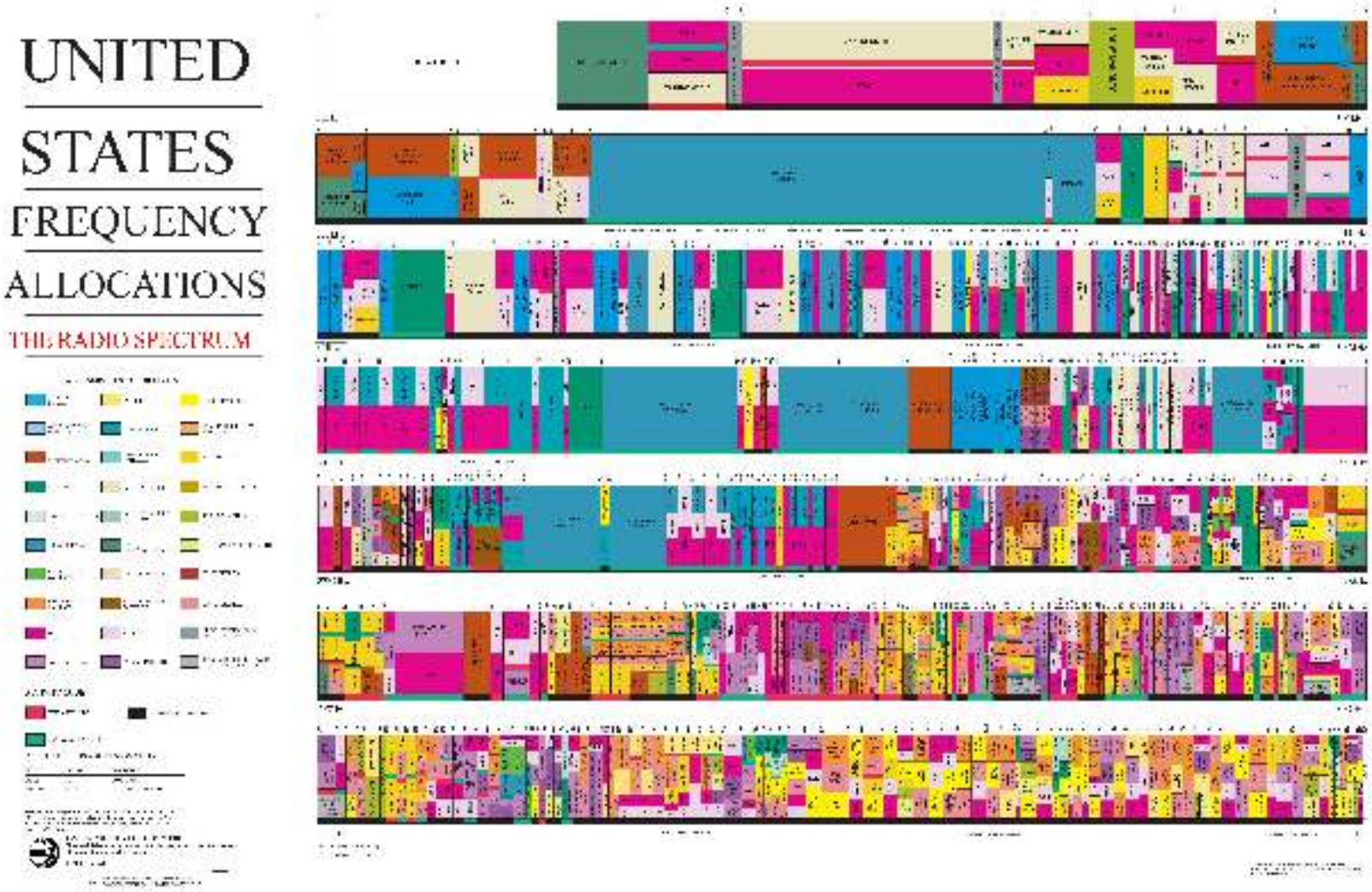
- Know the difference between analog and digital communications
- Know the fundamental tradeoff between data rate, bandwidth, signal power and noise power in communicating binary information (bits) from a source to a destination

EM Spectrum


Long Wavelength/Low Frequency
Short Wavelength/High Frequency
Wavelength (meters)
100
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
Radio
Microwave
Infrared
Ultraviolet
X-Ray
Gamma Ray
Visible
(0.7 - 0.4 μm)
Comparable size
football field
humans
penny
pin head
bacteria
virus
water molecule
atom
atomic nuclei


100 kHz
1 MHz
10 MHz
100 MHz
1 GHz
10 GHz
100 GHz
Visible Light
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
Infrared

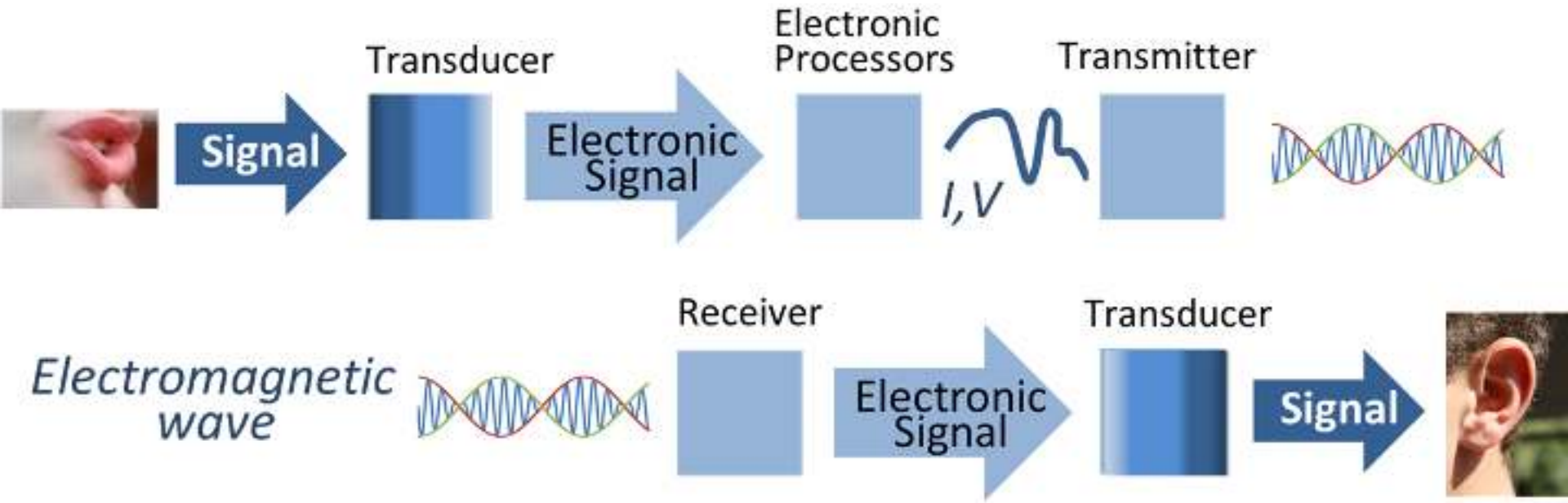
US Radio Spectrum



https://www.nasa.gov/sites/default/files/thumbnails/image/january_2016_spectrum_wall_chart.jpg

Communication System

The goal of communication systems is to transfer information from one location to another at a distance away.

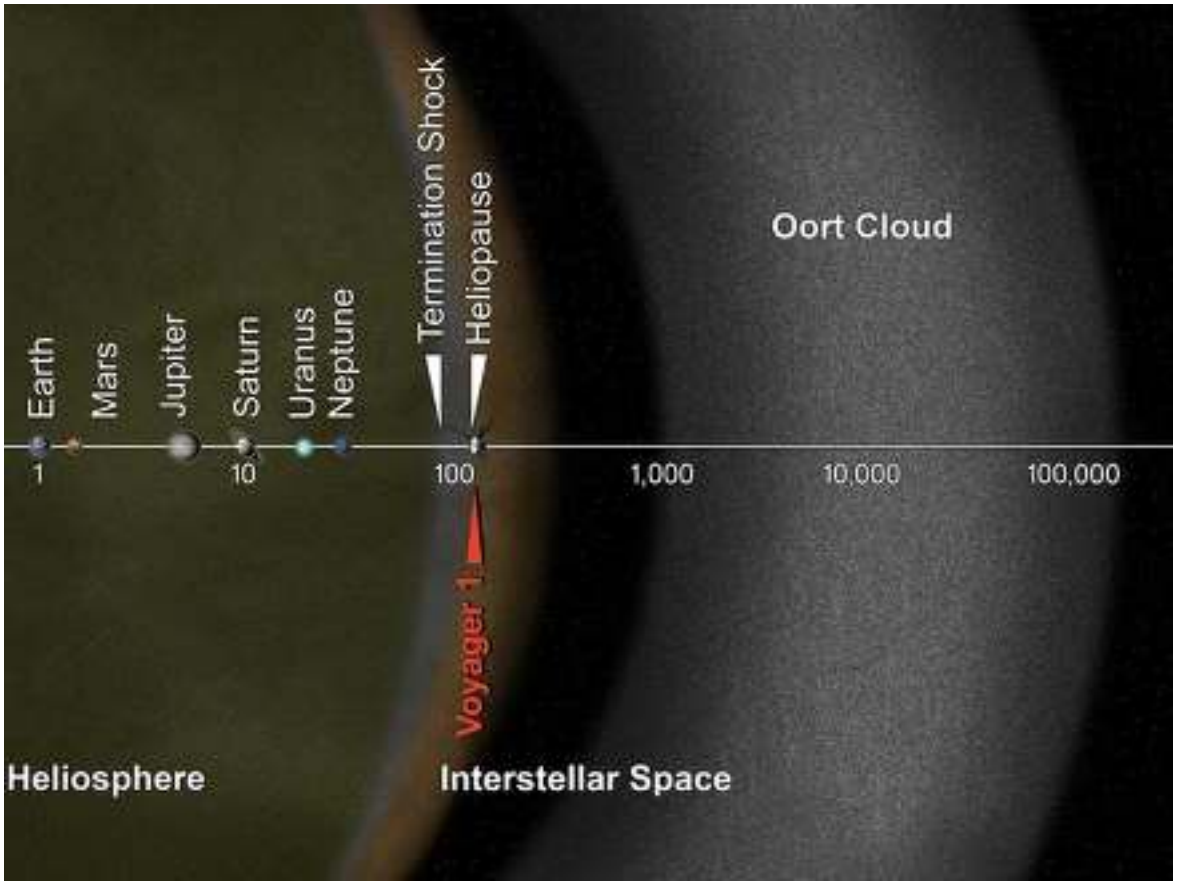


Circuits, electromagnetics, signal processing, microprocessors, and communication networks, …

Source: Wikipedia

Communication Range

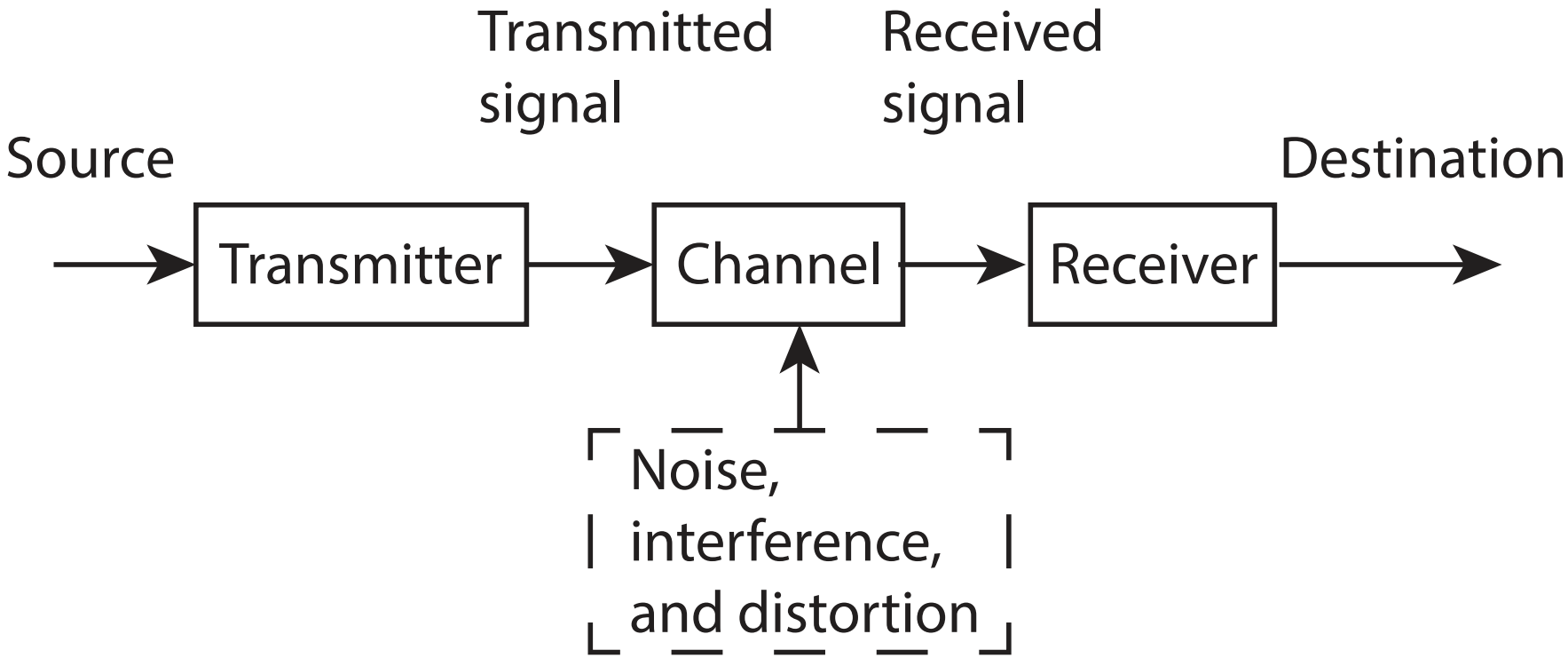
1cm, 1m, 10m, 1Km, 10Km,…, 20 billion Km, ...



An AU is just the distance from Earth to the Sun, about 13 billion miles.

http://voyager.jpl.nasa.gov/where/

Communication System



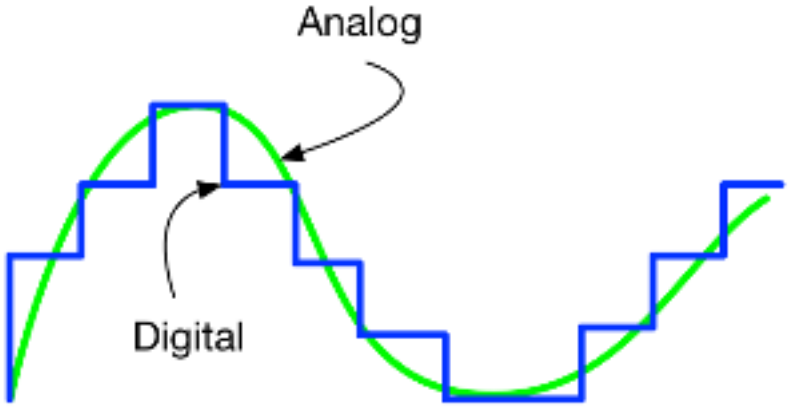
Important Parameters

- The goal of communication systems is to transmit information from one location to another.
- This can be done in various ways which depends on certain resources.
- These include the energy, the noise, the channel conditions among others.
- Parameters: Power/Energy, Data Rate, Bandwidth, Distortion, Bit Error Probability

Digital vs. Analog Message

- An analog message is a physical quantity that varies with time, Usually in a smooth and continuous fashion. An analog communication system should deliver this waveform with a specified degree of fidelity.

- A digital message is an ordered sequence of symbols selected from a finite set of discrete elements. Since the information resides in discrete symbols, a digital communication system should deliver these symbols with a specified degree of accuracy in a specified amount of time.



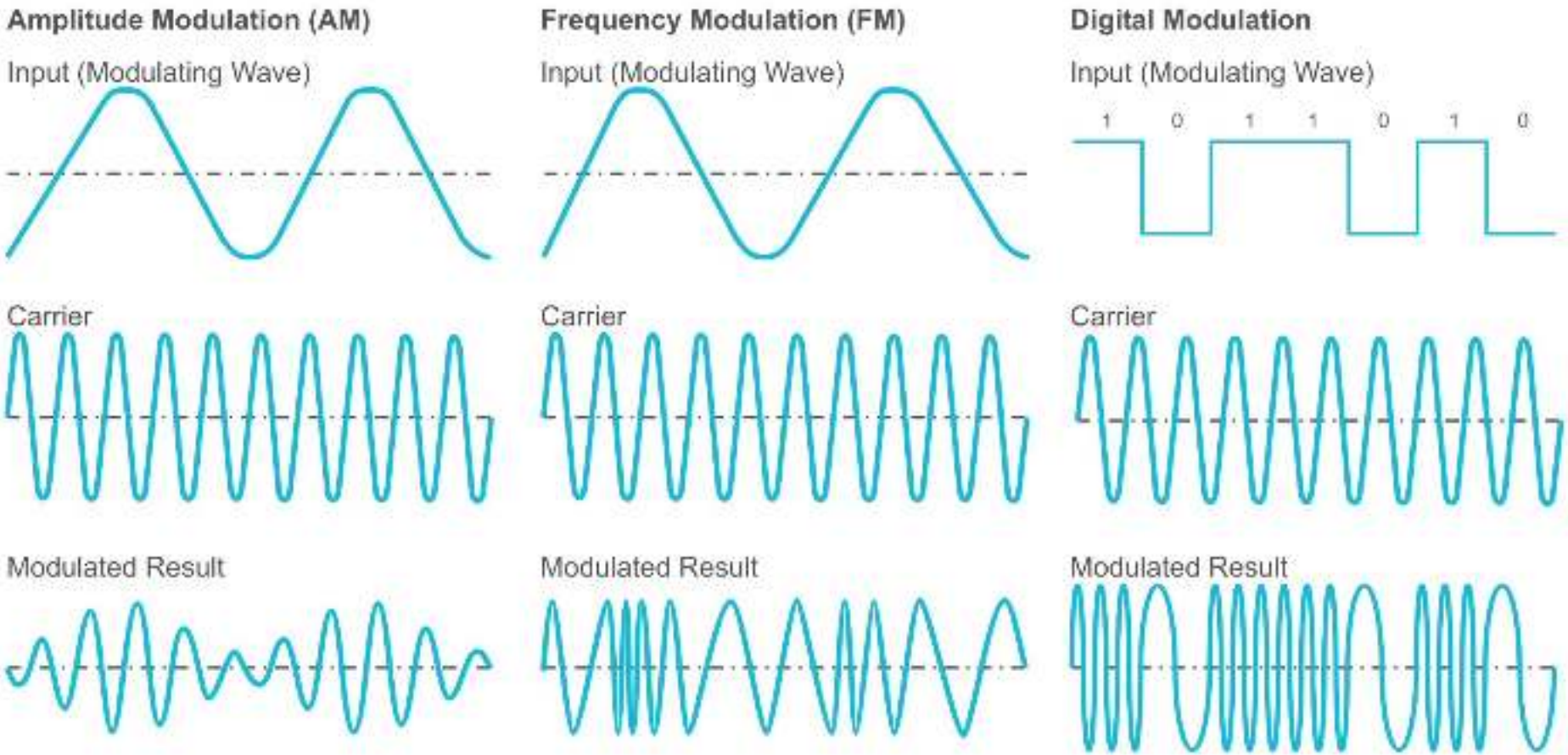
Modulation

- Modulation involves two waveforms:
  A modulating signal that represents the message.
  A carrier wave that suits the particular application.

- A modulator systematically alters the carrier wave in correspondence with the variations of the modulating signal.

- The resulting modulated wave thereby “carries” the message information. We generally require that modulation be a reversible operation, so the message can be retrieved by the complementary process of demodulation.

Modulation



http://www.taitradioacademy.com/topic/how-does-modulation-work/

Why Modulation?

- Efficient Transmission:
  Efficient radiation requires antennas whose physical dimension are at least $1/10^{th}$ of the signal's wavelength.

- Un-modulated transmission of an audio signal containing frequency components down to 100Hz would require antennas ~300 km long. Modulated transmission at 100MHz, as in FM broadcasting, allows a practical antenna size of about one meter.

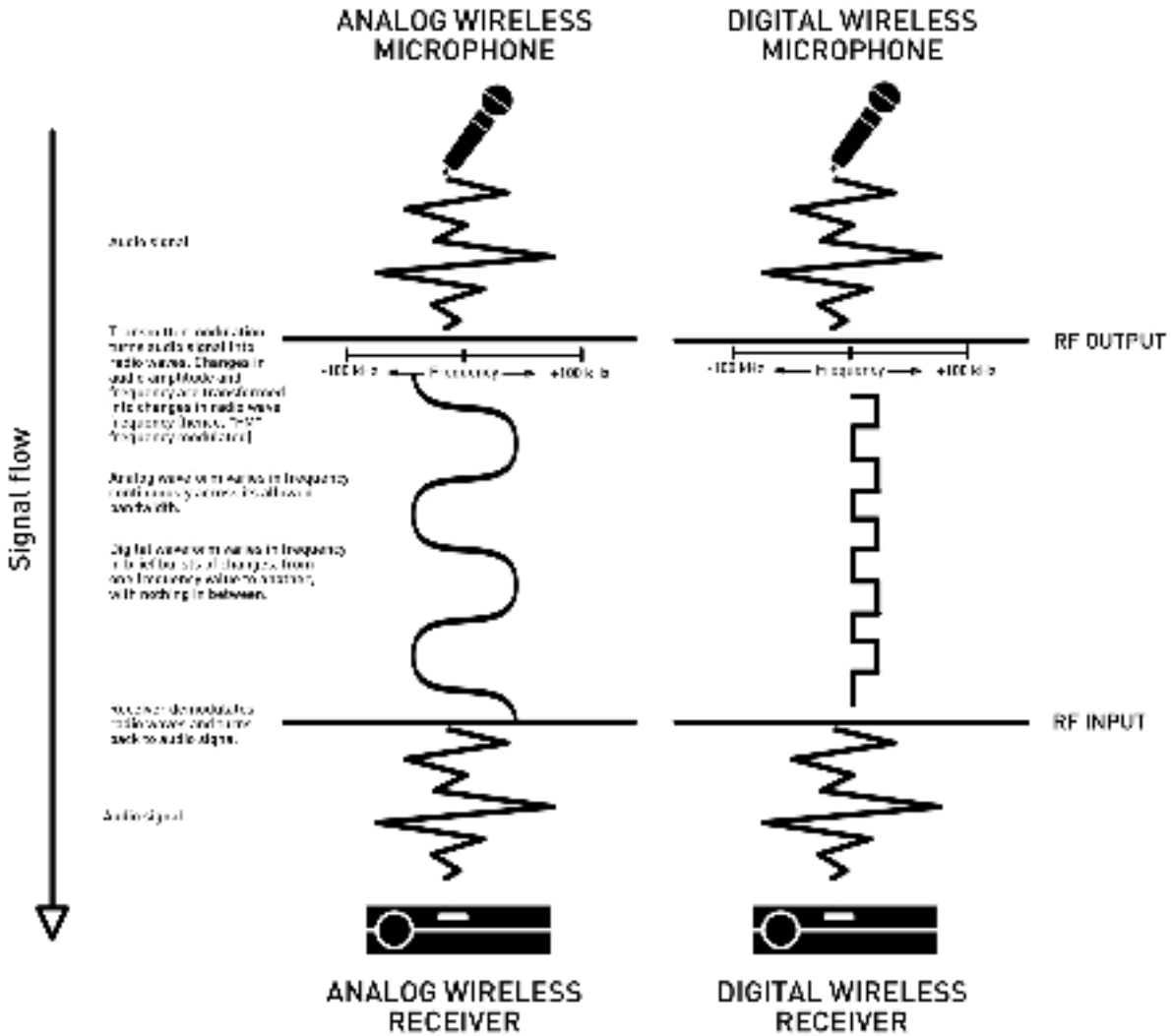
- Hardware limitations
- Noise and interference
- Frequency assignments

Digital vs. Analog Communication

- Digital communication differs from analog communication in that in a digital communication system during any finite time interval there is a finite number of possible transmitted waveforms.

- In an analog communication system during any finite time interval there are a potentially infinite number of possible waveforms transmitted.

Digital vs. Analog



http://blog.rfvenue.com/digital-wiireless-explored/

Digital vs. Analog Receiver

- In a digital communication system the receiver needs to decide, based on the received signal, which of the finite number of transmitted signals was sent.

- In an analog communication system the receiver needs to estimate, based on the received signal, what was the transmitted signal.

- The performance measure for digital communication systems is usually the probability of making an error in deciding which waveform was transmitted.

Advantages of Digital

- Ease of regeneration of signals in a series of regenerative repeaters,

- The flexibility of circuitry available for processing digital signals (DSPs, VLSI),

- The ability to store information in digital format in various media (e.g. DVD, CD, RAM, Hard Disk),

- Many source are digital (e.g. data files).

Power

- Clearly the more power available the more reliable communication is possible.
- However, the goal is to reduce the required transmission power so that talk time is maximized.
- Power levels of radios vary from less than a milliWatt to 1MWatt.
- Performance generally depends on the received power (not the transmit power) which depends on how far apart the transmitter and receiver are located.

Data Rate

- The goal is large data rates.

- For a fixed amount of power as the data rate increases the energy transmitted per bit will decrease because of decreased transmission time for each bit.

- The data rate can be as low as several kbps to transmit speech to 10's of Gbps for data.

Data Rate

- If the data rate increases then the amount of intersymbol interference will increase.

- A wireless channel typically has an impulse response with some delay spread. That is, the received signal is delayed by different amounts on different paths. The signal corresponding to a particular bit received with the longest delay will interfere with the signal corresponding to a different bit with the shortest delay. The larger the number bits that are interfered with the more difficult it is to correct for this interference.

Bandwidth

- The bandwidth is the amount of frequency spectrum available for use.

- Generally the FCC allocates spectrum and provides some type of mask for which the radios emissions must fall within.

- The larger the bandwidth the more independent fades across frequencies and thus better averaging is possible.

- The available bandwidth might be 3kHz for voice-band telephone lines and as high as 10’s of GHz.

Distortion

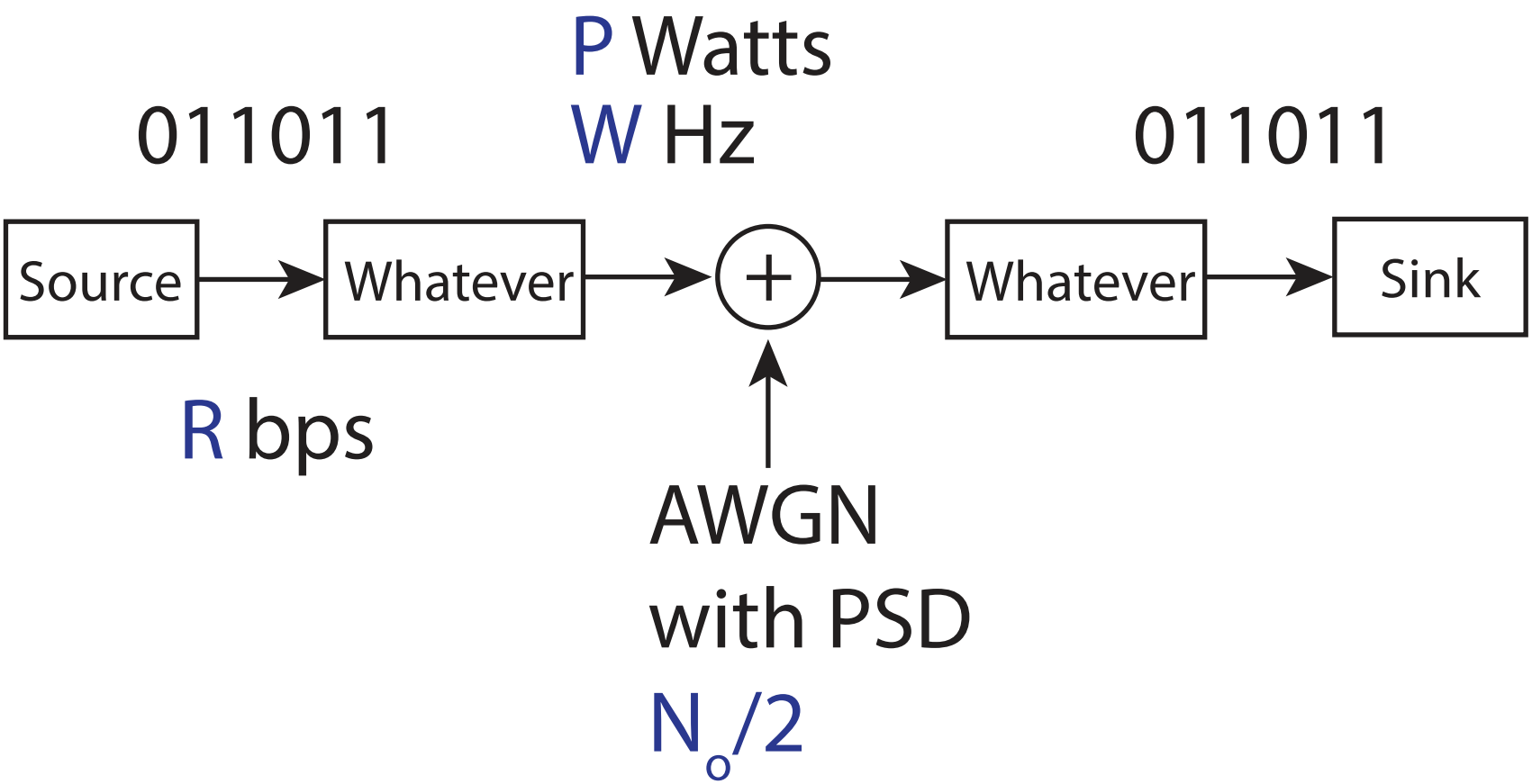
- For analog sources such as speech or video the distortion between the original source and the reproduction of the original signal at the destination is often a performance measure of interest.

- The mean-squared error is one often used performance measure for distortion.

Bit Error Probability

- Different sources require different error probabilities (also call bit error rates).
- Bit error rates vary between 10^{-2} and 10^{-4}

First Fundamental Tradeoff



Assumptions

- The source produces equally likely data bits (0s and 1s) at rate **R** bits/second.
- We transmit a signal (waveform) such that the received power is **P**.
- The transmitted signal has bandwidth **W** (Hz).
- Noise is added to the transmitted signal. The noise is white (power at all frequencies of interest), Gaussian and has power spectral density **N0/2** Watts/Hz. This is called an additive white Gaussian noise channel.
- We can allow any delay or complexity.

First Fundamental Tradeoff

- In 1948 Claude Shannon (U of M EE/Math graduate) published a paper in which he determined the tradeoff between data rate, bandwidth, signal power and noise power for reliable communications for an additive white Gaussian noise channel. Let
- **W** be the bandwidth (in Hz),
- **R** be the data rate (in bits per second),
- **P** be the received signal power (in Watts),
- **$N_0/2$** the noise power spectral density (in Watts/Hz).
- Then reliable communication is possible provided

$$R < W \log_2 \left(1 + \frac{P}{N_o W} \right)$$

Capacity

For large values of **W** the maximum rate (capacity) approaches

$$\lim_{W \to \infty} W \log_2\left(1 + \frac{P}{N_o W}\right) = \frac{P}{N_o \ln(2)} = 1.4426\left(\frac{P}{N_o}\right)$$

Let $\mathbf{E_b}$ be the energy transmitted per bit of information. Then

$$E_b = \frac{P}{R} \qquad \text{or} \qquad P = E_b R$$

Using this relation we can express the capacity formula as

$$\frac{R}{W} < \log_2\left(1 + \frac{E_b}{N_o}\frac{R}{W}\right)$$

Capacity

$$\frac{R}{W} < \log_2\left(1 + \frac{E_b}{N_o}\frac{R}{W}\right)$$

Inverting this we obtain

$$\frac{E_b}{N_o} > \frac{2^{\frac{R}{W}} - 1}{\frac{R}{W}}$$

Capacity

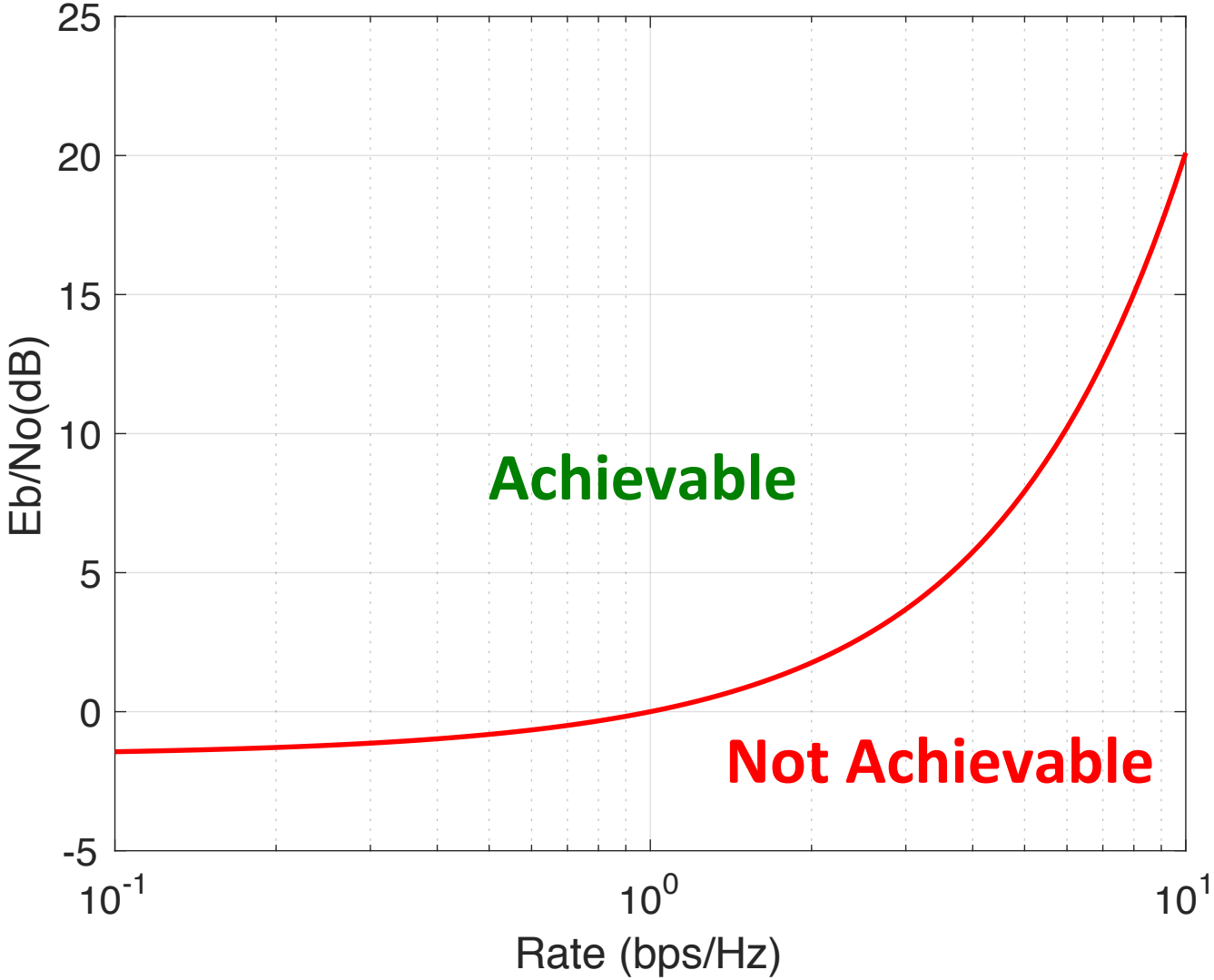
$$\frac{E_b}{N_o} > \frac{2^{\frac{R}{W}} - 1}{\frac{R}{W}}$$

- Reliable communication is possible with bandwidth efficiency **R/W** provided that the signal-to-noise ratio, **E_b/N_o**, is larger than the right hand side of the equation.

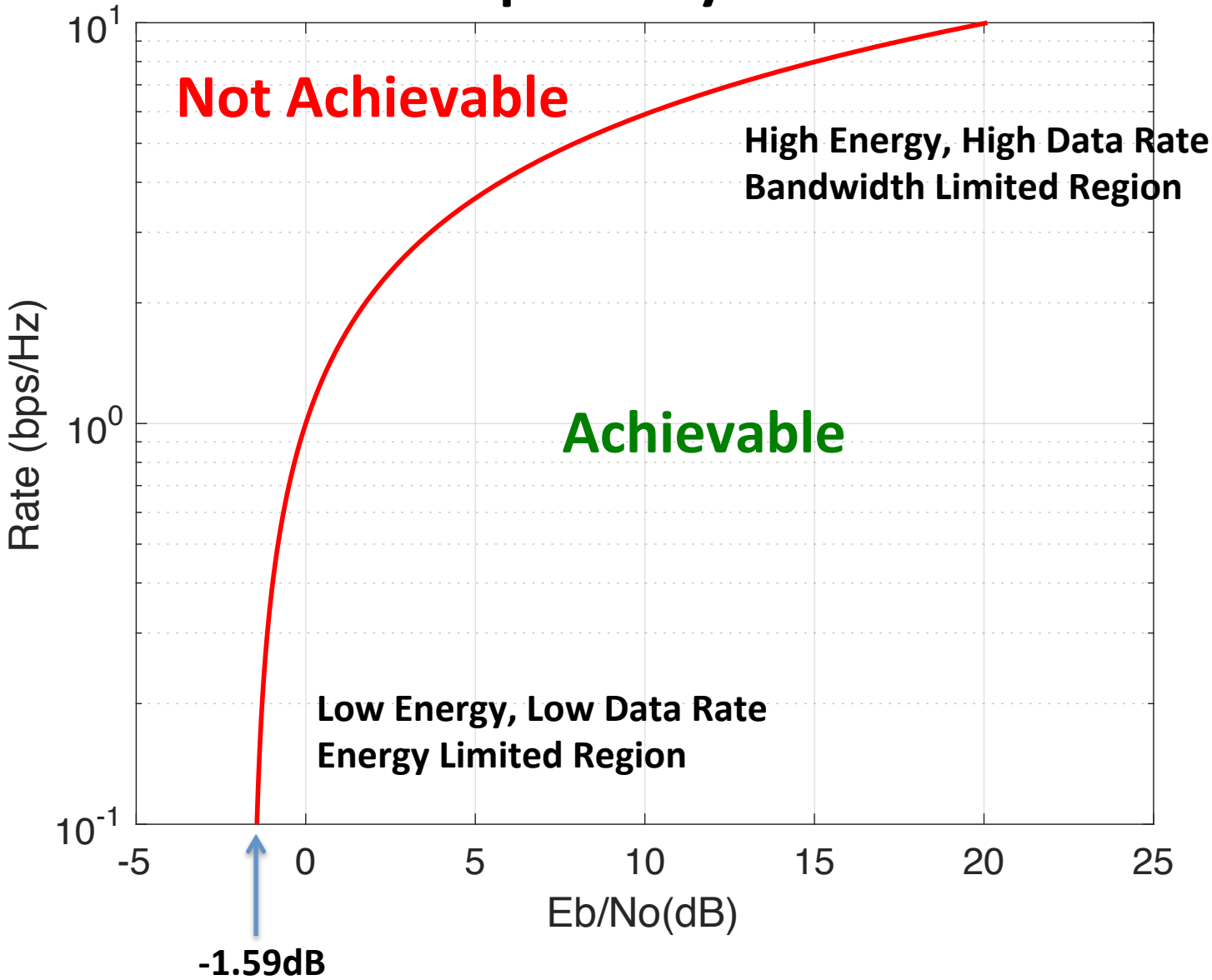
- For small values of **R/W** the smallest value of **E_b/N_o** where reliable communication is Possible is **ln(2)=0.693**. That is,

$$\lim_{\frac{R}{W} \to 0} \frac{2^{\frac{R}{W}} - 1}{\frac{R}{W}} = \ln(2)$$

Capacity


25
20
15
10
5
0
-5
Eb/No(dB)
Achievable
Not Achievable
10^{-1}
10^{0}
10^{1}
Rate (bps/Hz)

Capacity


Not Achievable
High Energy, High Data Rate
Bandwidth Limited Region
Achievable
Low Energy, Low Data Rate
Energy Limited Region
Rate (bps/Hz)
10^1
10^0
10^{-1}
-5
0
5
10
15
20
25
Eb/No(dB)
-1.59dB

dB or not dB?

When the range of values for energy or power are vast we usually employ a dB scale. The conversion is

$$\frac{E_b}{N_o}(dB) = 10\log_{10}\left(\frac{E_b}{N_o}\right)$$

The smallest signal-to-noise ratio for reliable communication (at low rates) is

$$\frac{E_b}{N_o} > \log(2) = 0.693$$

$$\frac{E_b}{N_o}(dB) > 10\log 10\left(0.693\right) = -1.59dB$$

dBW, dBm

Sometimes absolute power levels are also expressed in dB's by referencing them to either 1W or 1mW. When referencing to 1W the dB units are written as dBW. When referencing to 1mW the dB units are written as dBm. So, for example

$$100Watts = 10\log_{10}(100Watts/1Watt) = 20dBW$$

$$= 10\log_{10}\left(100Watts/1mWatt\right) = 50dBm$$

$$10Watts = 10\log_{10}(10Watts/1Watt) = 10dBW$$

$$= 10\log_{10}\left(10Watts/1mWatt\right) = 40dBm$$

dBW, dBm

$$1Watts = 10\log_{10}(1Watts/1Watt) = 0dBW$$
$$= 10\log_{10}\left(1Watts/1mWatt\right) = 30dBm$$

$$0.1Watts = 10\log_{10}(0.1Watts/1Watt) = -10dBW$$
$$= 10\log_{10}\left(-0.1Watts/1mWatt\right) = 20dBm$$

$$0.01Watts = 10\log_{10}(0.01Watts/1Watt) = -20dBW$$
$$= 10\log_{10}\left(0.01Watts/1mWatt\right) = 10dBm$$

$$0.001Watts = 10\log_{10}(0.001Watts/1Watt) = -30dBW$$
$$= 10\log_{10}\left(0.001Watts/1mWatt\right) = 0dBm$$

Notes

- The capacity formula only provides a tradeoff between energy efficiency and bandwidth efficiency. Complexity is essentially infinite, as is delay. The model of the channel is rather benign in that no signal fading is assumed to occur.

- The capacity theorem says that we can communicate with error probability near zero at rates below the capacity or equivalently at values of $\mathbf{E_b/N_0}$ above a threshold.

Example

Telephone modems use about 3000Hz and have P/No of 74dB. What rate is possible?

$$\frac{P}{N_o} = 10^{\left(\frac{74}{10}\right)} = 23829000$$

$$C = 3000\log_2\left(1 + 23829000/3000\right)$$

$$= 3000\log_2\left(1 + 7943\right)$$

$$= 38.867kbps$$

Wireless Applications

- Paging
- Digital Cordless Phones
- Digital Cellular
- Packet Radio
- Wireless Local Area Networks
- Low Earth Orbit Satellites (e.g. GPS)

Generally these systems are power or energy limited rather than bandwidth limited in that they must operate on batteries.

Wired Applications

- Telephone Modems
- DSL (Digital Subscriber Loop)
- Cable Modems
- Ethernet
- Optical Fiber

Generally these systems are bandwidth limited rather than power or energy limited since they are typically powered from an AC power source.

Analog Cellular

- Analog cellular systems were in widespread use from the early 1980's to the mid 1990's. but are not being used anymore (in the US).
- All of these systems used FM (frequency modulation) with FDMA (frequency division multiple access).

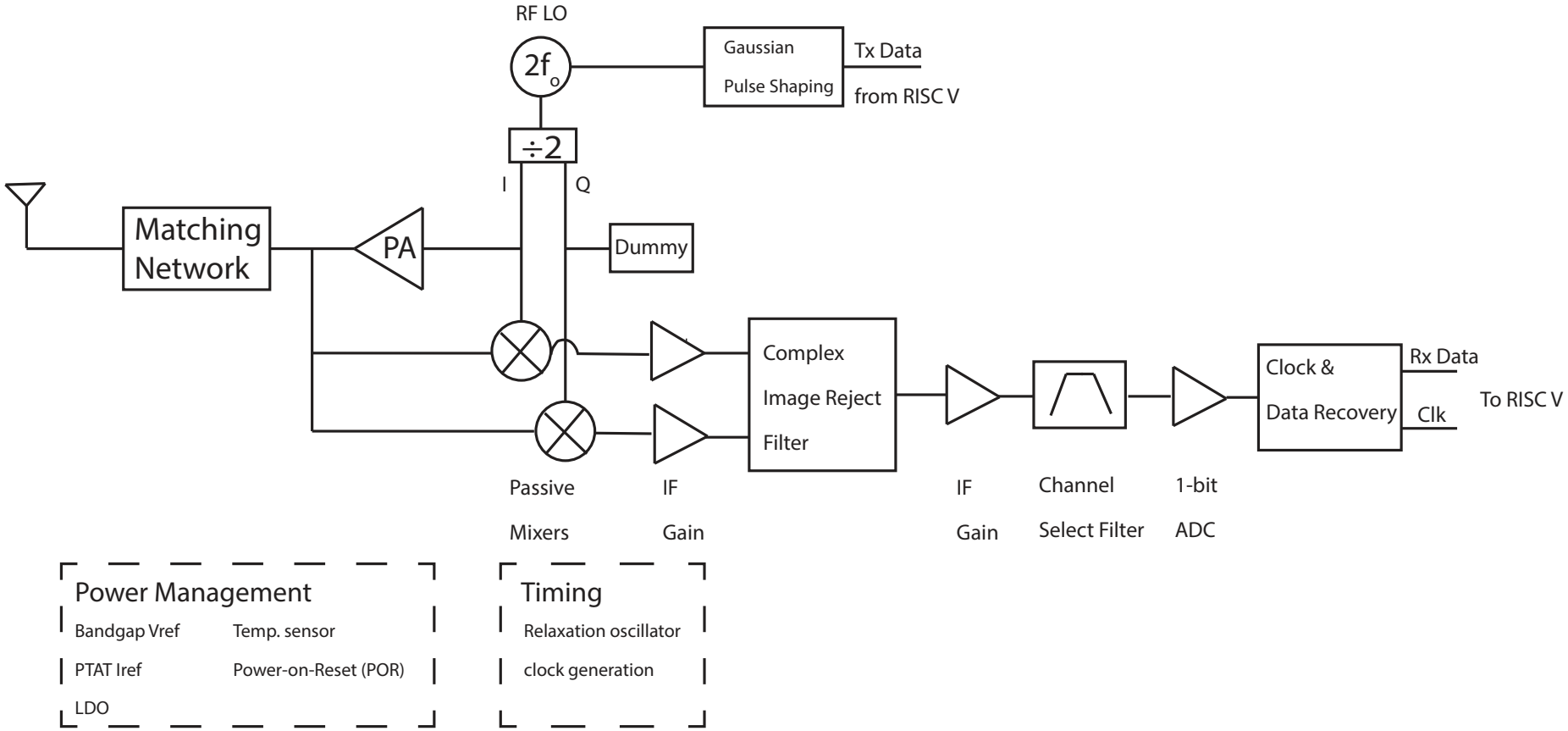
Industrial Scientific and Medical(ISM) Bands

- Frequencies:
  - 902-928 MHz,
  - 2400-2483 MHz,
  - 5725-5850MHz
- The data rates vary from around 10 kbps to 100 Mbps.

Other wireless systems

- IEEE 802.11 a,b,g,n,h
- WiMax
- UWB
- GPS
- LTE
- **BLE**
- IEEE 802.15.4

SoC Block Diagram



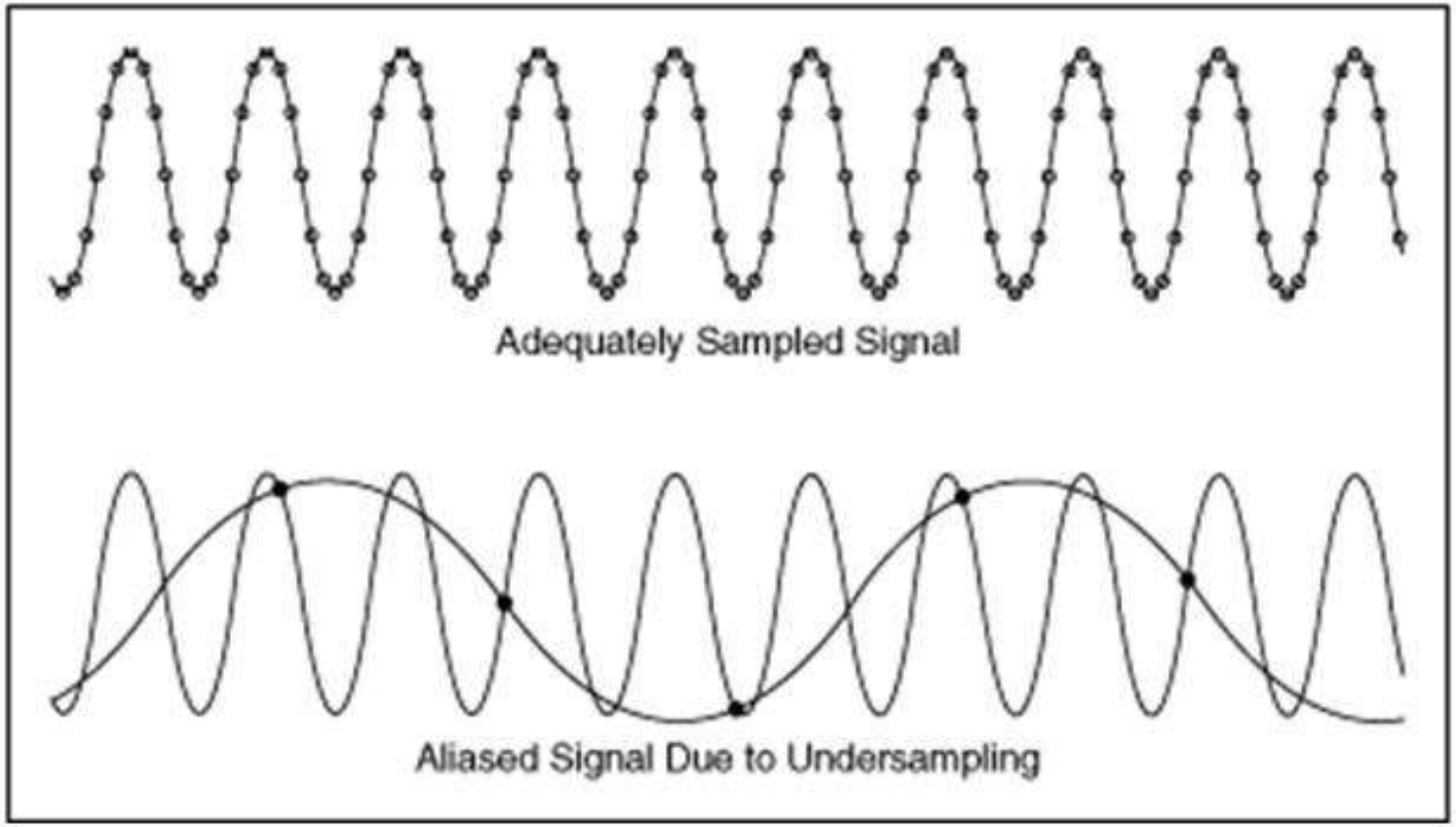
Lecture 2: Goals

Wireless Standard: BLE
Frequency Band: 2.4 GHz ISM
Modulation: GFSK
Data Rate: 1 Mbps

Sampling Theorem

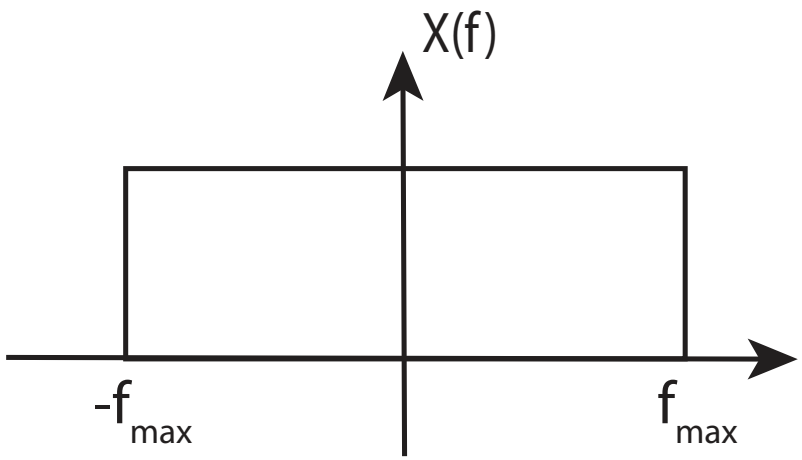
We can represent a continuous-time signal of finite bandwidth with a sequence of samples without losing any information. If a signal has a maximum frequency of $\mathbf{f_{max}}$ then sufficient sampling rate is > $\mathbf{2f_{max}}$

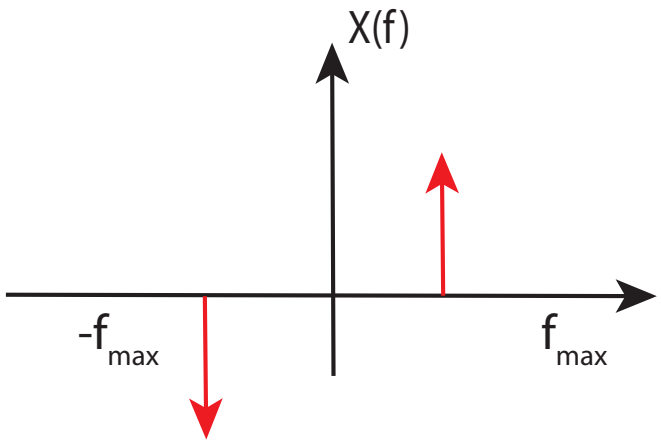
Bridge between discrete-time and continuous-time signals

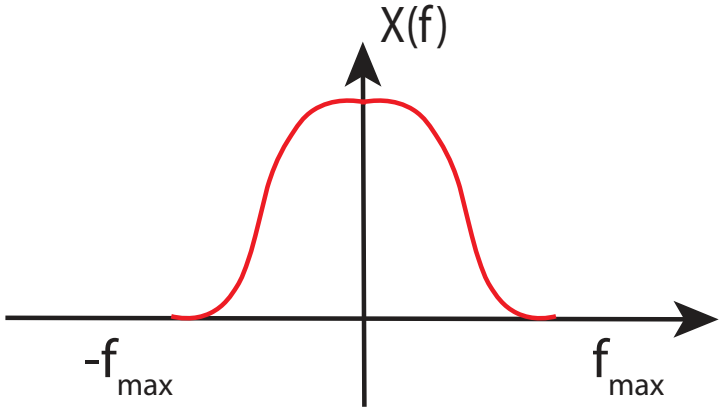


Bandwidth of Signals

Consider a signal **x(t)** with Fourier Transform **X(f)**. Suppose **X(f)** is zero for $|f| > f_{\max}$

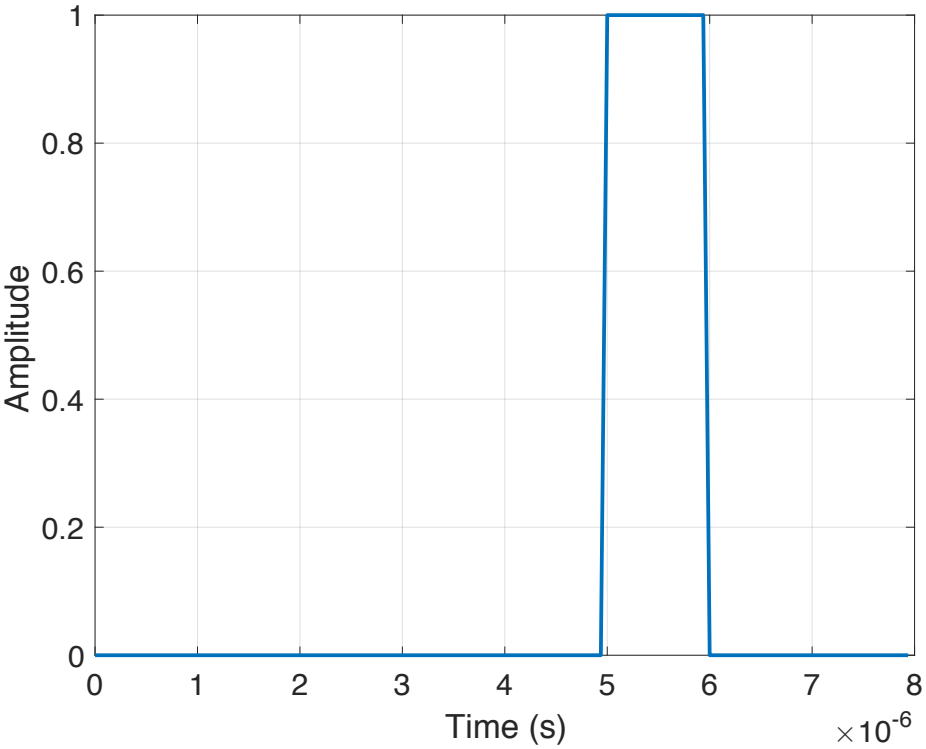


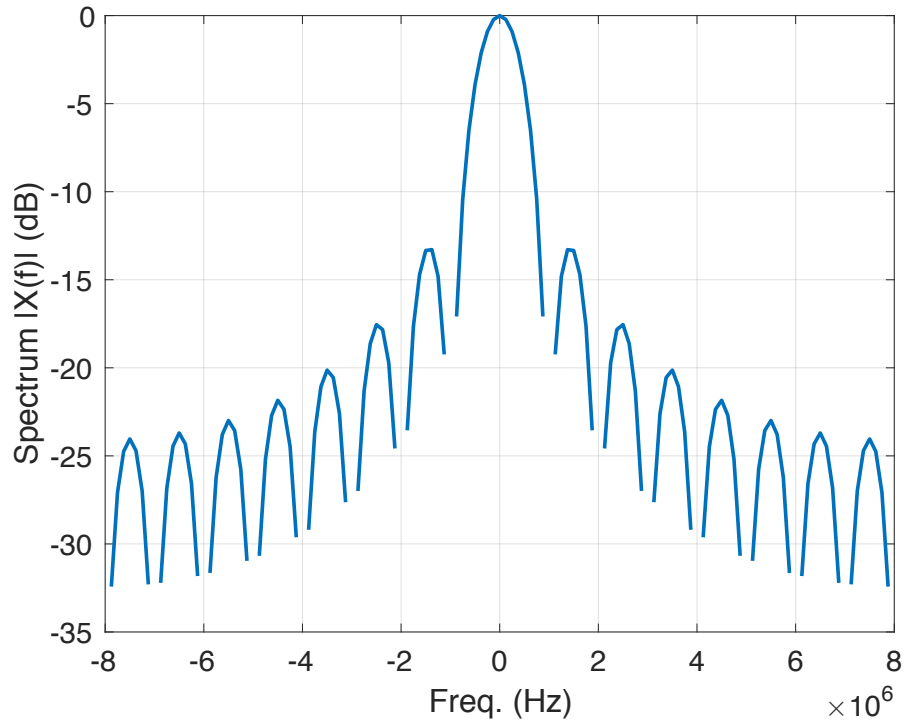




Rectangular Pulse

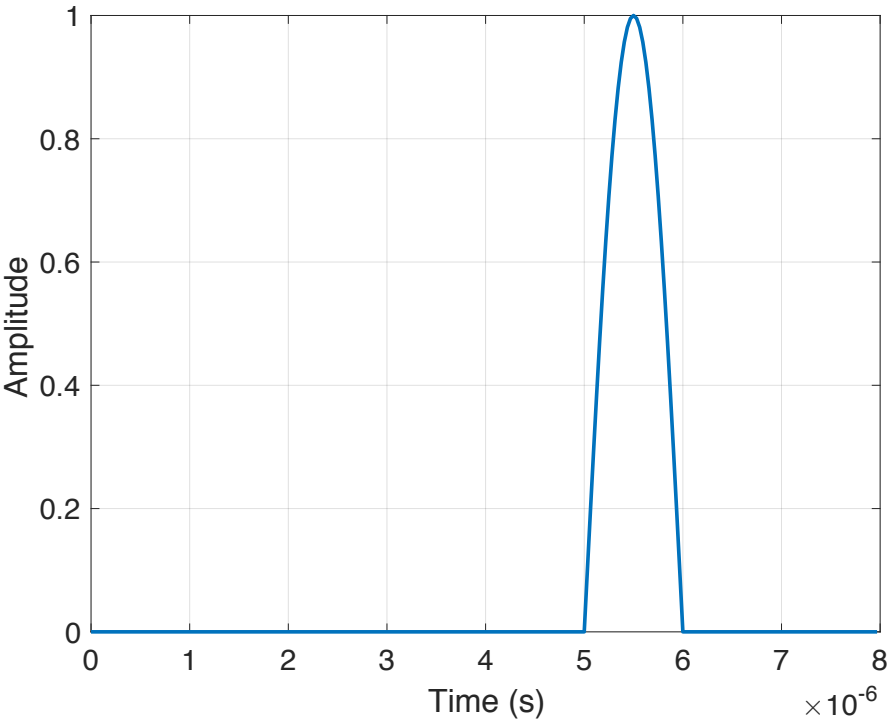
$$x(t) = \sqrt{P}\, p_T(t) = \begin{cases} \sqrt{P} & 0 \le t \le T \\ 0 & \text{elsewhere} \end{cases}$$

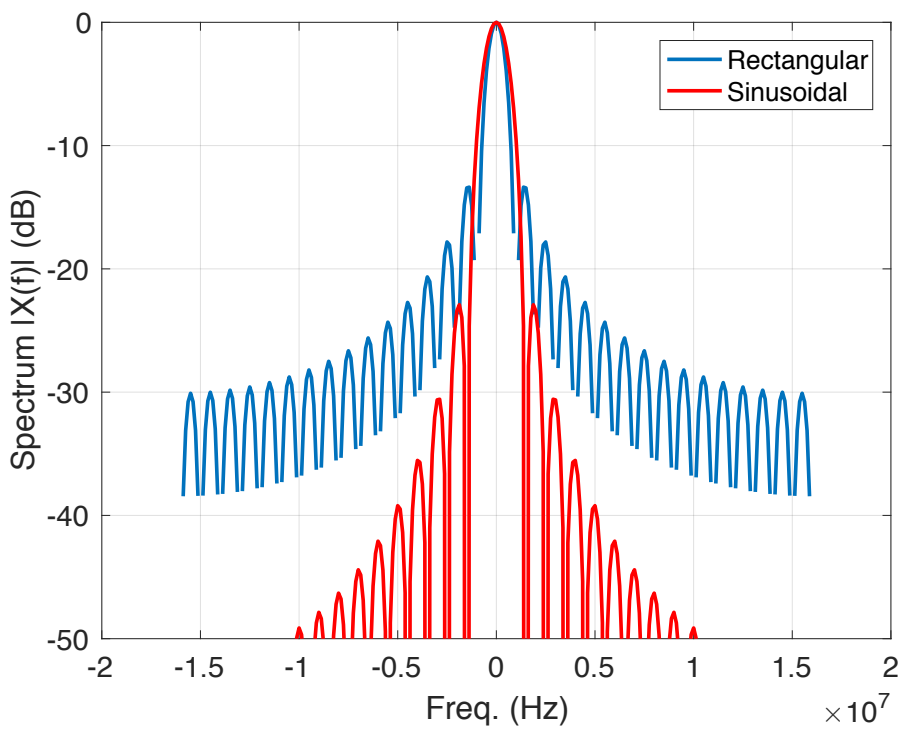




Sinusoidal Pulse

$$x(t) = \sqrt{2P}\sin\left(\frac{\pi t}{T}\right)p_T(t)$$





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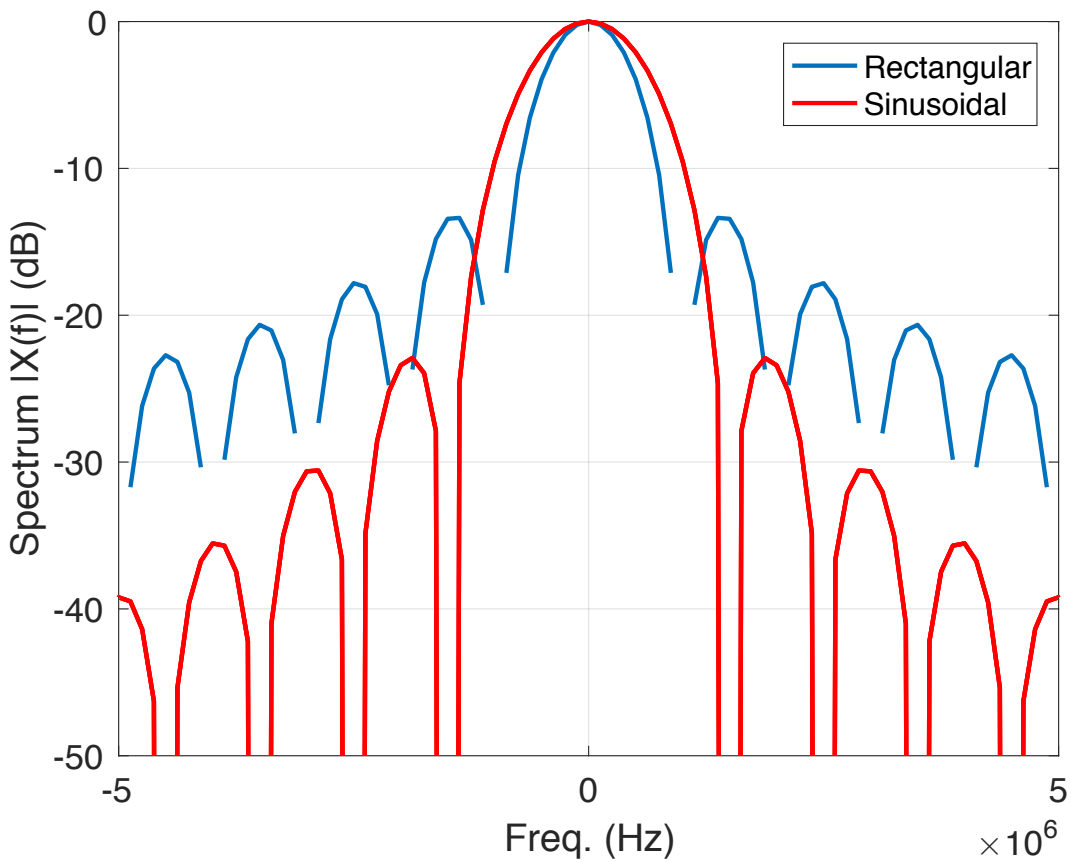

Bandwidth for Digital Signals

- Null-to-Null bandwidth == bandwidth of main lobe of power spectral density
- 99% power bandwidth containment == bandwidth such that ½% of power lies above upper band limit and 1/2% lies below lower band limit.
- x dB bandwidth == bandwidth such that spectrum is x dB below spectrum at center of band (e.g. 3dB bandwidth)
- Absolute bandwidth == $W_A = \min\{W : S(f) = 0 \forall |f| > U\}$