

Chapter 5

Communication theory

ADVANCED TOPICS IN DATA SCIENCE

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Outline

I. Communication theory

Radio Frequency

Link budget

II. Information Theory

Modulation

Sampling

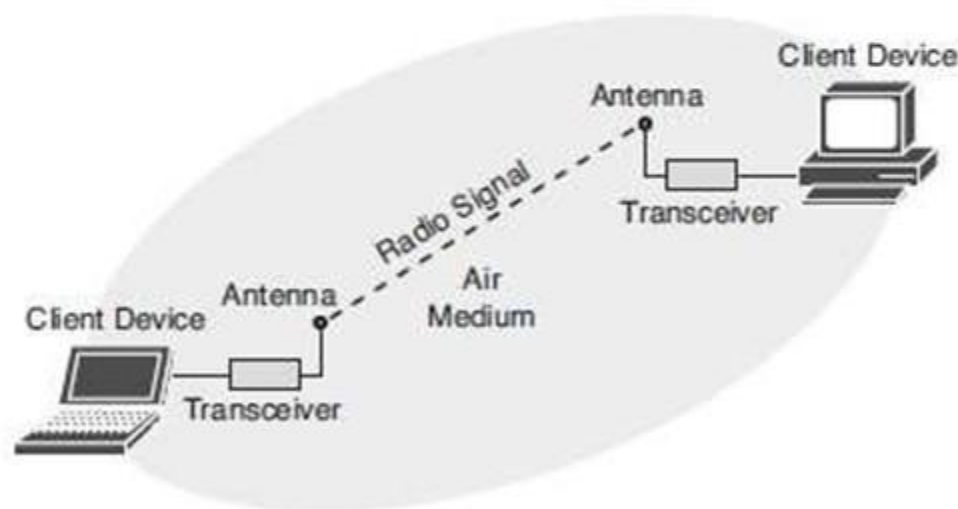
Bit error rate

Motivation

- IoT is more than simply data from a sensor. We must first understand and architect the transport of moving sensor data from the remotest places on Earth to the cloud. There are a significant number of technologies and data paths to move data.
- IoT brings with it an increase in the demand for wireless technologies. From beginning of connecting systems to the final outcome it is imperative to understand RF fundamentals. This will ensure proper application and implementation of wireless systems.
- We begin with a review of wireless RF signals and the contributing factors that impact signal quality, limitations, interference, models, bandwidth, and range.

Radio Frequency (RF)

- Wireless transmissions are radio frequency (RF) signals which travel based on behaviors called propagation characteristics. RF radiates from an antenna on the transmitter end and is received by an antenna on the receiver end. The actual data being carried is modulated on one end, which is transmitted over the air. Then the data is demodulated on the other end. The RF signal's propagation characteristics are dictated by frequency, wavelength, and amplitude.



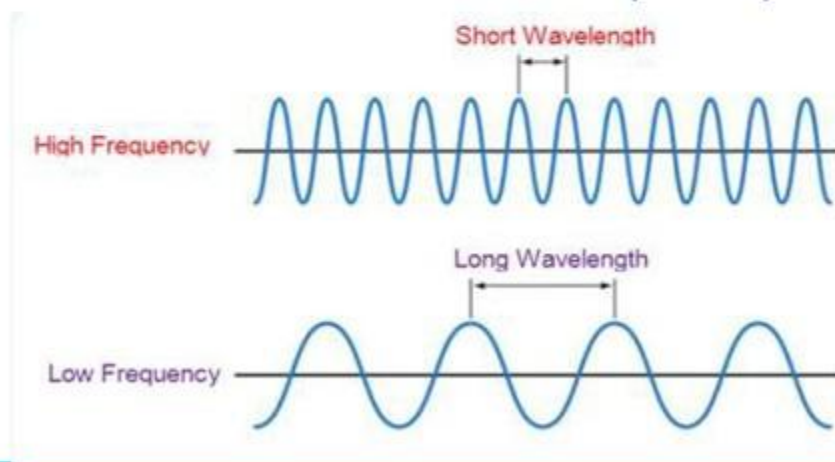
Transceiver turns electrical signals into radio waves so they can travel sometimes thousands of kilometers around the Earth or even into space and back. (or vice versa, from radio waves to electrical signals). Antennas and transmitters are the key to all forms of modern telecommunication.

Radio Frequency (RF)

- Radio frequency (RF) is the oscillation in the frequency range from around 20 kHz to around 300 GHz.
- It is important when talking about any RF wireless protocol, to consider the range of transmission. **Competing protocols use range, speed, and power as differentiators.**
- We need to consider different protocols and design choices when implementing a complete solution. **The range of transmission is based on the distance between transmitter and receiver antennas, the frequency of transmission, and the power of transmission.**
- The best form of RF transmission is unobstructed line-of-sight in a radio signal- free area. In most situations, this ideal model will not exist. In the real world, there are obstructions, reflections of signals, multiple wireless RF signals, and noise.

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Radio Frequency (RF)

- Depending on the technology and the part of the world the system is being deployed, regulatory bodies for that country will govern the frequencies that can be used.

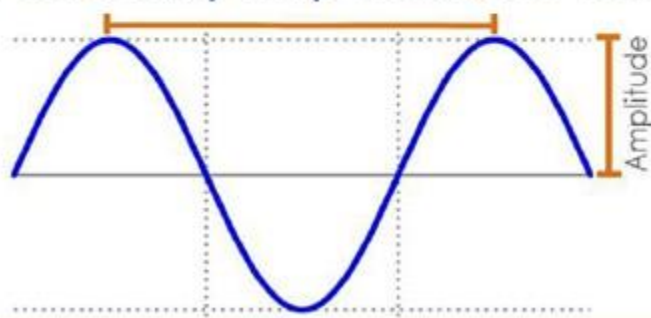
For instance, in the U.S., the Federal Communications Commission (FCC) allocated what is known as the Industrial, Scientific, and Medical (ISM) Band which allows license free operation in the 900MHz, 2.4GHz and 5.8GHz bands. However, other countries may use 900MHz for their national cellular band or even over the air television. In addition, there are also licensed bands used below 900MHz and above 5.8GHz.

- Hertz (Hz) simply means frequency or cycles per second.

Therefore, at 900 MHz, the frequency is 900 Million (900,000,000) cycles per second. Wi-Fi most commonly uses 2.4 GHz and 5.8 GHz, where the G is a prefix meaning Giga, denoting a factor of one Billion. Therefore, the frequency is 2.4 Billion (2,400,000,000) and 5.8 Billion (5,800,000,000) cycles per second respectively.

Radio Frequency (RF)

- Wavelength, represented lambda λ , is the distance between the starting point of one cycle and the starting point of the next cycle.
- Wavelength is inversely proportional to the frequency. The higher the frequency, the shorter the wavelength. Conversely, the lower the frequency, the longer the wavelength.
- Knowing the frequency allows calculation of the wavelength by dividing the speed at which RF signals travel (the speed of light, rounded up to 300,000,000 meters per second) by its frequency. At 900 MHz, the wavelength is 33.3 cm or approximately 13 inches.
- Knowing wavelength is critically important to antenna design.

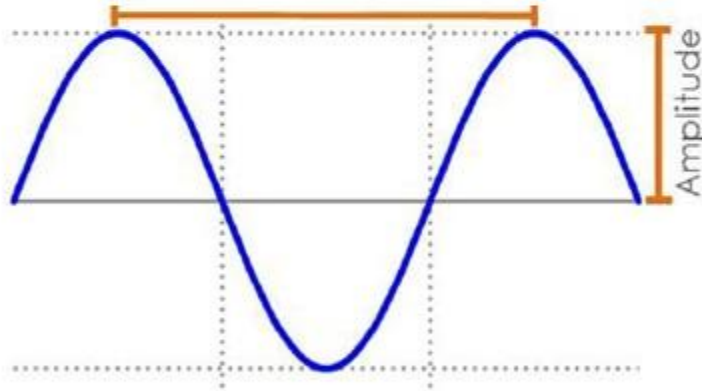


Calculating Wavelength for 900MHz

$$\begin{aligned}\text{Lambda (wavelength)} &= \text{Velocity} / \text{Frequency} \\ &= 300,000,000 \text{ (m/s)} / 900,000,000/\text{sec} \\ &= .33 \text{ m (33.3 cm) or approximately 13 inches}\end{aligned}$$

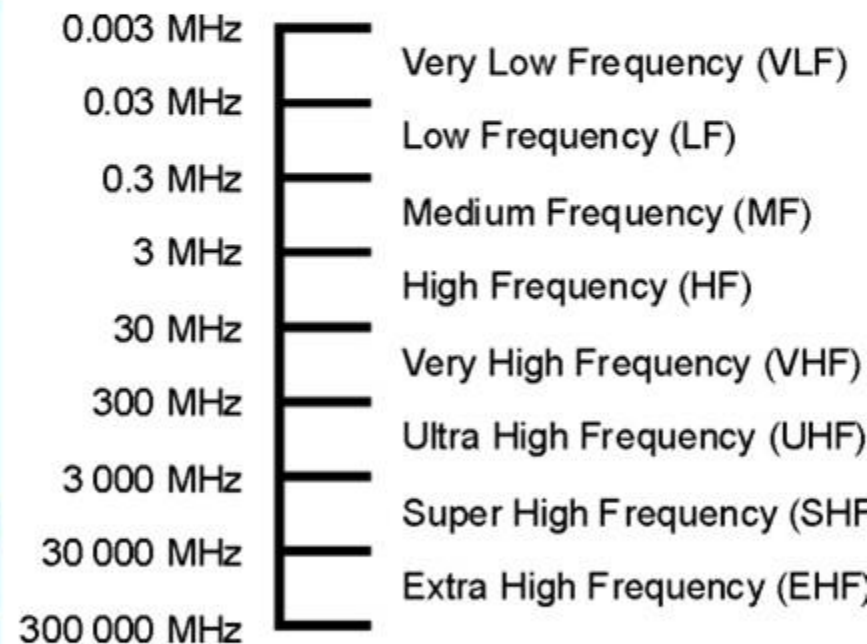
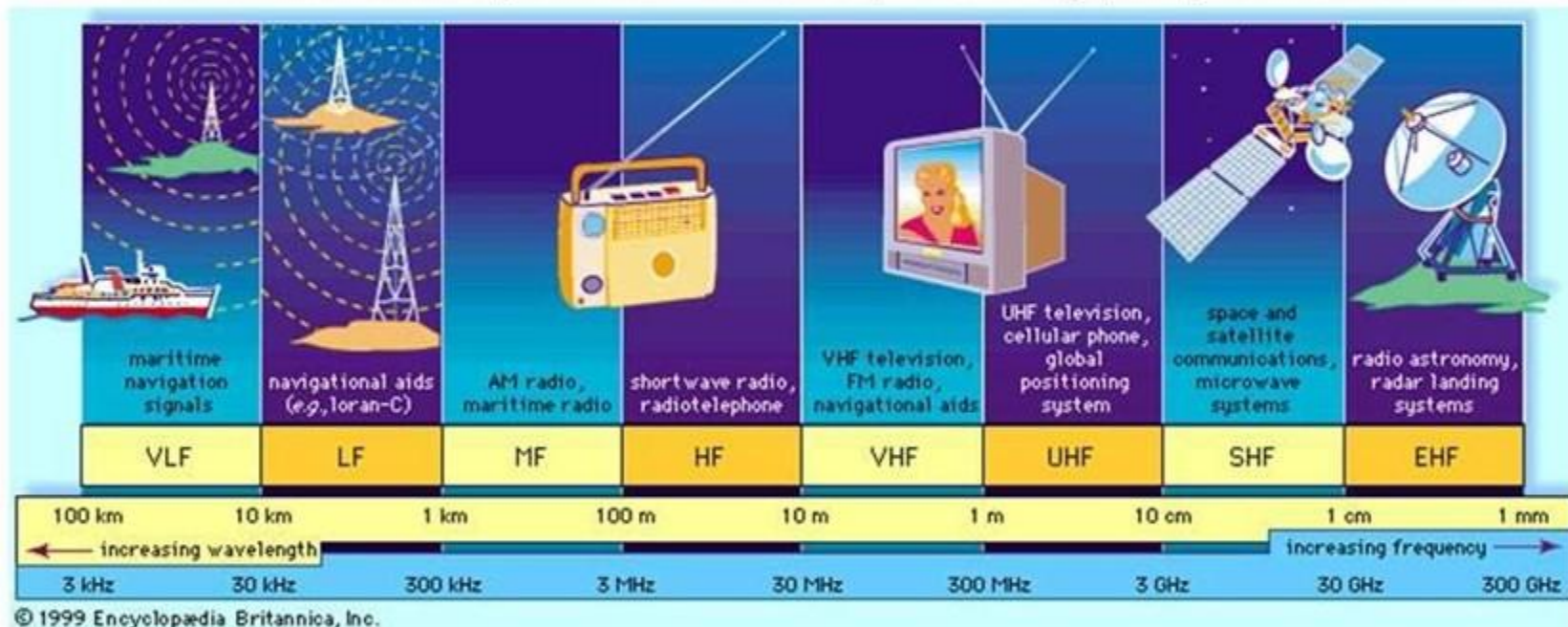
Radio Frequency (RF)

- The last of the RF propagation characteristics is amplitude. Amplitude, as illustrated in the figure, is the height or peak of the wave and is a function of power. The higher the output power or amplitude, the higher the peak.



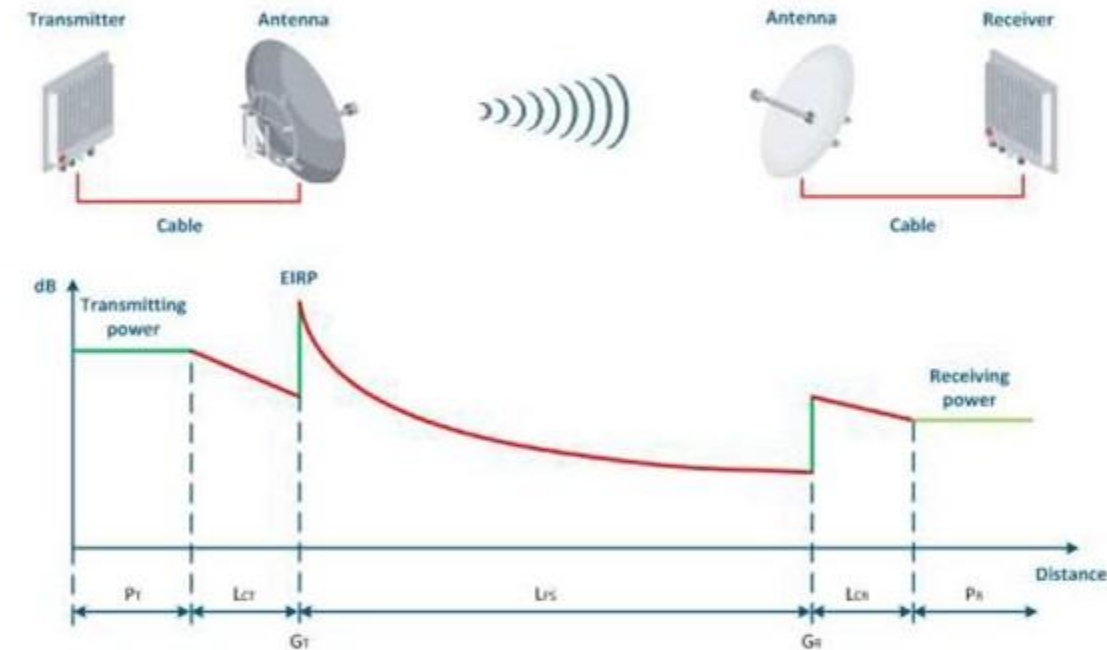
General RF Spectrum

General RF (Radio Frequency) Spectrum



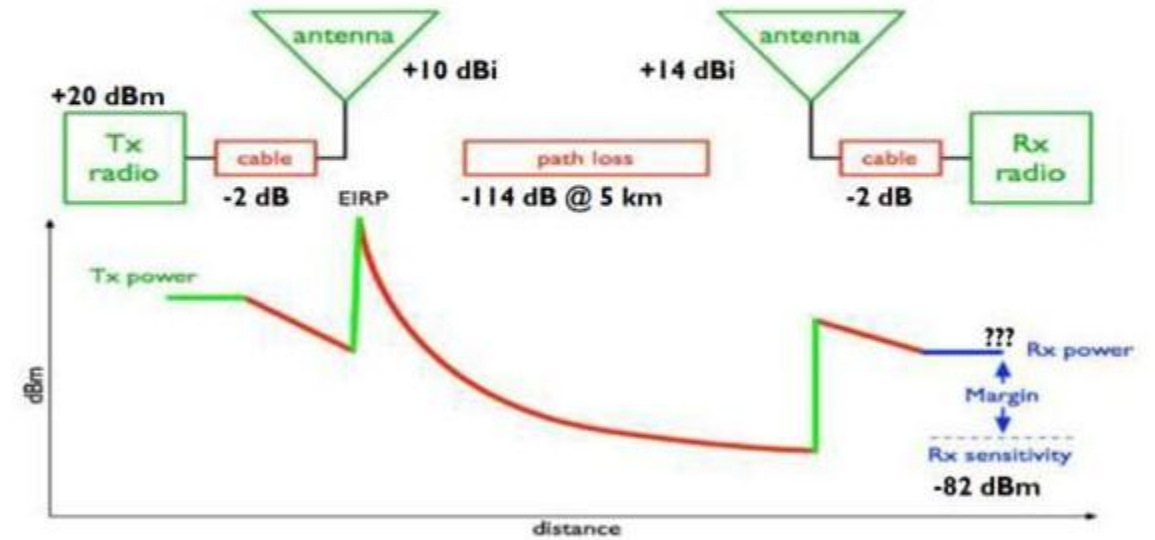
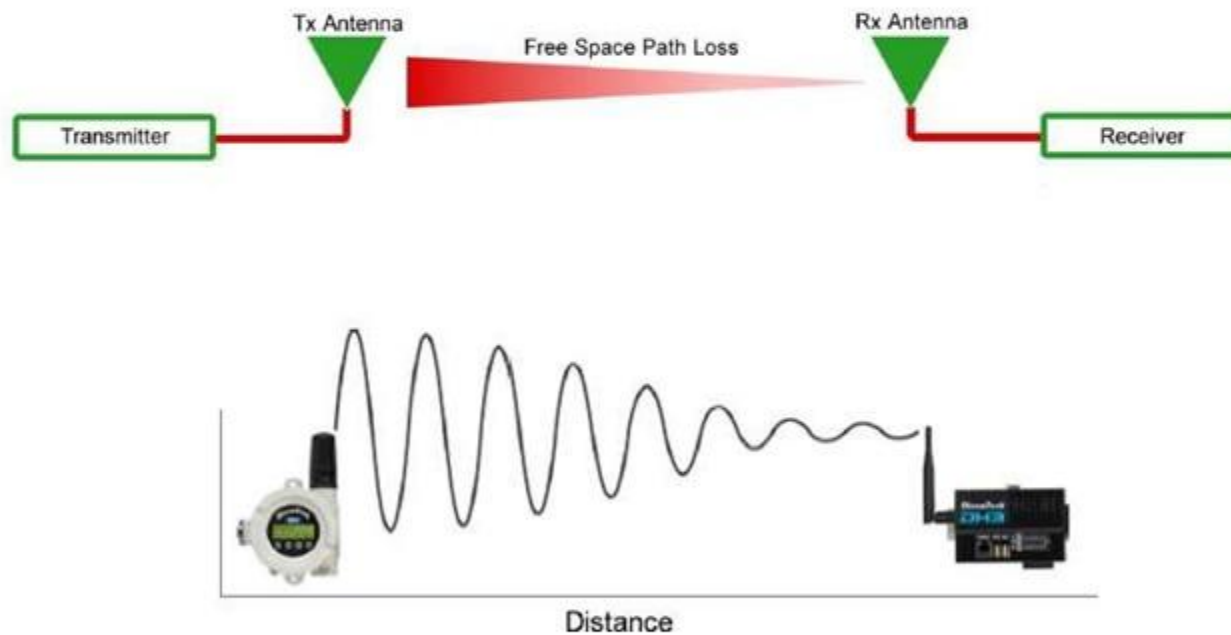
Link budget

- Regardless of the wireless technology being implemented, link budgets are key in determining whether a system will work.
- Link budget accounts for all of the gains and losses from the transmitter, through the medium (free space, cable, waveguide, fiber, etc.) to the receiver in a telecommunication system.
- It accounts for the attenuation of the transmitted signal due to propagation, as well as the antenna gains and various losses.



Link budget

- So how to do the calculations ?



Link budget

- ***Received Power (dBm) = Transmitted Power (dBm) + Gains (dB) – Losses (dB)***
- A link budget is the accounting of all gains and losses that occur in the wireless signal from the transmitting device as it is passed through various connectors, antennas, open air, etc. on its way to the receiver in a wireless communication system. In looking at the simple equation above, you can see how this is represented.

Link budget

- Decibels
- **Signal** strengths can range from approximately -30 **dBm** to -110 **dBm**. The closer that number is to 0, the stronger the cell **signal**. In general, anything **better** than -85 decibels is considered a usable **signal**.
- dBm = It's a logarithmic expression of signal power.

Sensitivity

- In our everyday conversations, we know that it is just not about how loud someone can talk but also how well we can hear and more importantly, be able to understand what they are saying. **Sensitivity provides this “hearing” specification. Receiver sensitivity is the lowest power level at which the receiver can detect a RF signal and just like being able to understand a conversation, demodulate the data.**
- When comparing a receiver sensitivity specification of -110dBm to that of one with a -107dBm, the first thought is that there is only a difference of 3dB. However, the receiver with the 110dBm specification can hear signals that are half as strong as the receiver with the -107dBm specification. Because receive sensitivity indicates how faint a signal can be successfully received, the lower the power level, the better. This means that the larger the absolute value of the negative number, the better the receive sensitivity.

Link budget

- **1. Transmitter Output Power** – The transmitter output power will be based on the technology being deployed and the country it is being deployed in. With intrinsically safe, battery-powered wireless sensor networks, minimizing energy use is a primary goal to maximize battery life. As such, output power could be as low as 10 dBm. However, for other systems such as licensed radio systems, output power can be significantly higher.
- The transmit power is related to the distance that the wifi signal can reach. the higher the transmit power, the more distance that a signal can travel.
- *Hypothetical Example: 30dBm*

Link budget

- **2. Transmitter Loss** - from the RF connector of the transmitter to the antenna, the system will experience losses from the coaxial cable as well as insertion loss resulting from adapters/connectors, etc. It is very important when remote mounting an antenna to consult the manufacturer's specifications for the coaxial cable being used.
- *Hypothetical Example: 4.3 dB of loss*

Link budget

- **3. Antenna Gain** - an antenna is an electromagnetic radiator converting electrical currents to radio waves at the transmitting end and back to electrical currents on the receiving end. The most common types of antennas are omni-directional and directional antennas. Omni-directional antennas radiate its energy in a 360° pattern whereas a directional antenna will focus its energy in one direction.
- All antennas have a gain specification typically expressed in dBi which is referenced to a hypothetical isotropic antenna.
- ***Hypothetical Example: 3 dBi of gain*** if we will use an antenna with a gain of 3dBi.

Link budget

4. Free Space Path Loss – Just like our voices attenuate over distance (the further you get from someone the harder it is to hear them), so does RF. Essentially, signal power is diminished by geometrically spreading of the waveform over distance.

- $FSPL = 92,45 + 20 \cdot \log(d) + 20 \cdot \log(f)$
- where FSPL is expressed in dB, d is in kilometers and f is in GHz.
- **$FSPL = 36.56 + 20\log_{10}(\text{Frequency in MHz}) + 20\log_{10}(\text{Distance in miles})$.**

➤ ***Hypothetical Example: 110dB of Loss (5 miles at 900MHz)***

Link budget

- **5. Receiver Antenna Gain**

Hypothetical Example: 3dBi of gain

- **6. Receiver Loss**

Hypothetical Example: 4.3dB of loss

- **7. Received Signal Strength** – this is the received signal strength at the Receiver after all the gains and losses (Free Space Path loss of -110 dBm plus 27.4dB of system gain).

➤ *Hypothetical Example: -82.6dBm (the expected received strength level)*

Link budget

- **8. Receiver Sensitivity** –Receiver sensitivity is the threshold or lowest power level at which the receiver can detect an RF signal. Having a received signal strength (from number 7) equal to or less than the receiver is not desirable and will not produce a reliable link. Therefore, contingency or margin must be factored in and will be covered in number 9.
- ***Hypothetical Example: -110dBm*** (Receiver Sensitivity, specified from manufacturer)

Link budget

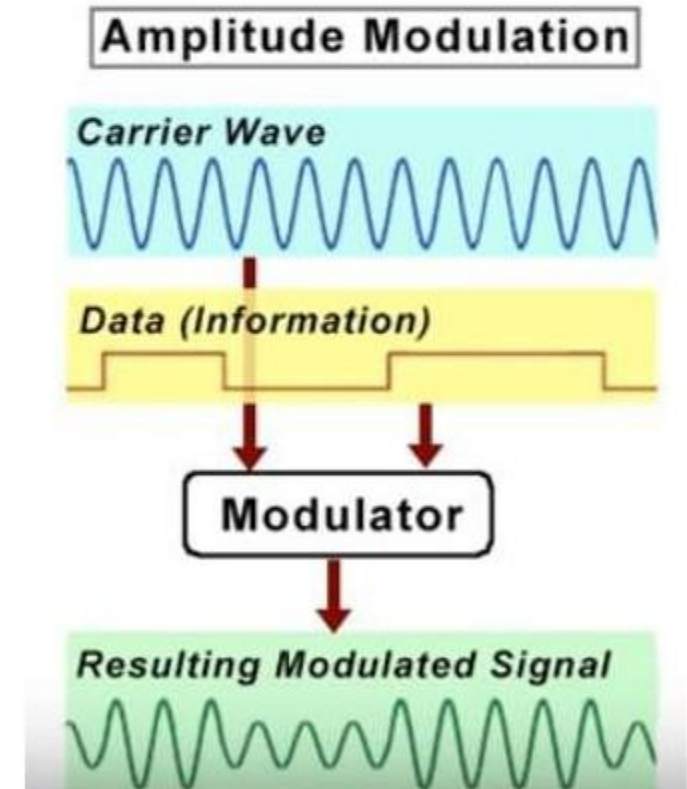
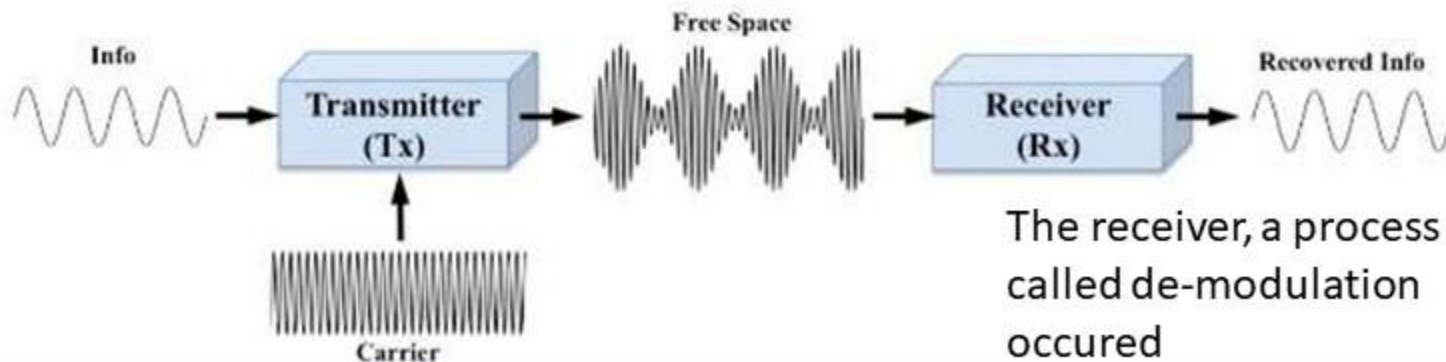
- **9. Fade Margin** – Finally, the margin is just how much margin (expressed in dB) there is between the received signal and the receiver sensitivity. This margin can help overcome the attenuation through obstacles, attenuation from rain and atmospheric conditions as well as challenges faced with terrain. Like most RF parameters, there are differing opinions of recommended fade margins. However, designing systems with **20 dB of margin will leave you with a robust system with a high degree of reliability.**

Transmitter

- A transmitter can be a separate piece of electronic equipment, or an electrical circuit within another electronic device. A transmitter and a receiver combined in one unit is called a transceiver. The term transmitter is often abbreviated "TX" in technical documents. The purpose of most transmitters is radio communication of information over a distance.
- The information is provided to the transmitter in the form of an electronic signal, such as an audio (sound) signal from a microphone, a video (TV) signal from a video camera, or in wireless networking devices, a digital signal from a computer. The transmitter combines the information signal to be carried with the radio frequency signal which generates the radio waves, which is called **the carrier signal**. This process is called **modulation**.
- The information can be added to the carrier in several different ways, in different types of transmitters. In an amplitude modulation (AM) transmitter, the information is added to the radio signal by varying its amplitude. In a frequency modulation (FM) transmitter, it is added by varying the radio signal's frequency slightly. Many other types of modulation are also used.

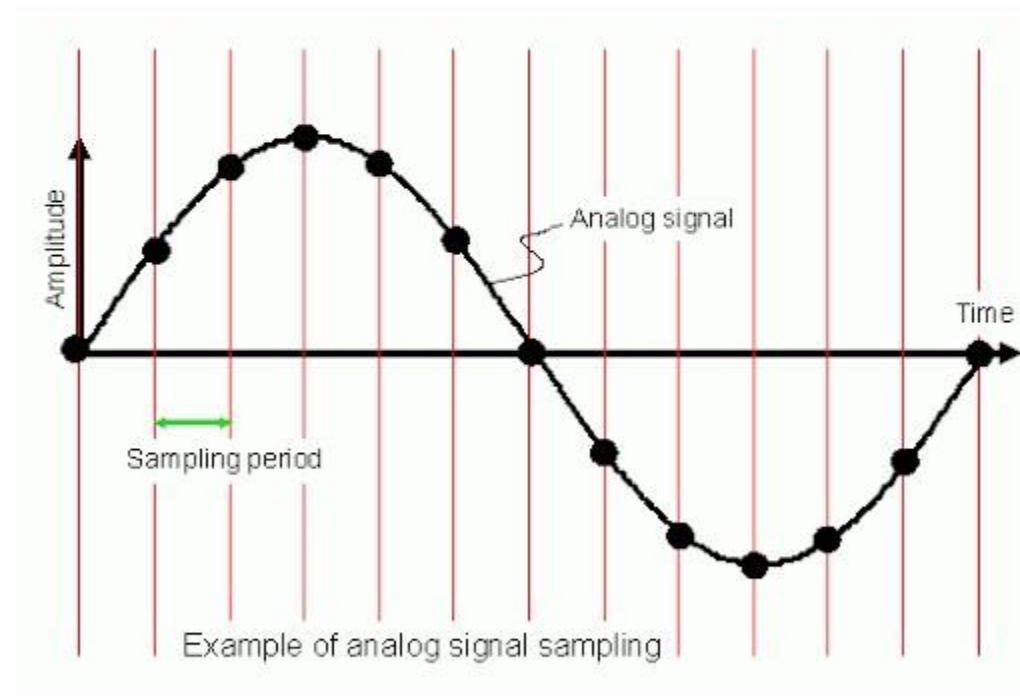
Modulation / Demodulation

- Modulation is a process of mixing a signal with a sinusoid to produce a new signal. This new signal, conceivably, will have certain benefits over an un-modulated signal. Mixing of low frequency signal with high frequency carrier signal is called modulation.
- The two basic components of an RF communication:
 - The carrier wave
 - The information sent (data)



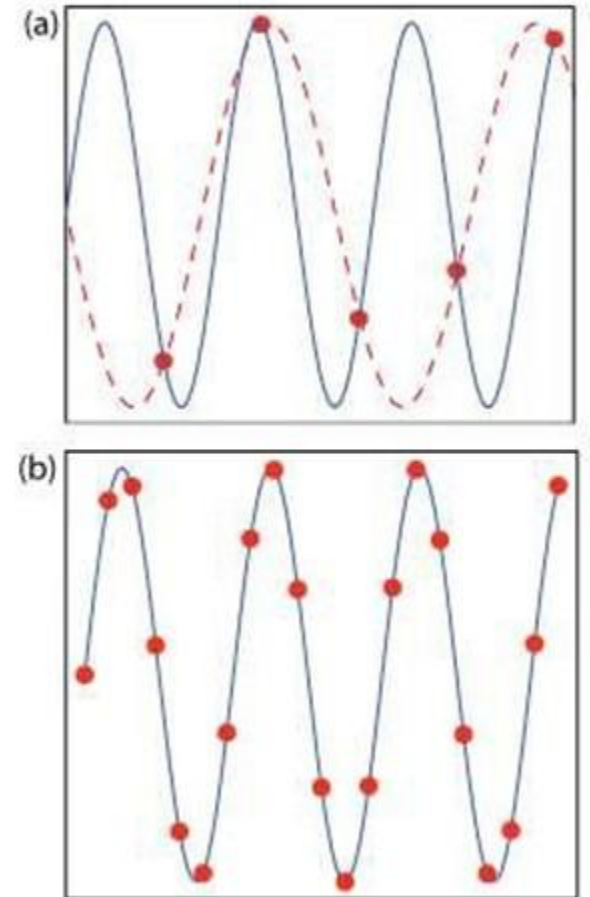
Sampling

- Sampling means instead of transmitting the analog signal as it is, few samples of it will be transmitted and observed at the receiving side to judge the actual signal.



Sampling rate

- Essentially, Nyquist's theorem states that a periodic signal must be sampled at more than twice the highest frequency component of the signal.
- As an example, humans can detect or hear frequencies in the range of 20 Hz to 20,000 Hz. If we were to store sound, like music, to a CD, the audio signal must be sampled at a rate of at least 40,000 Hz to reproduce the 20,000 Hz signal. A standard CD is sampled at 44,100 times per second, or 44.1 kHz.



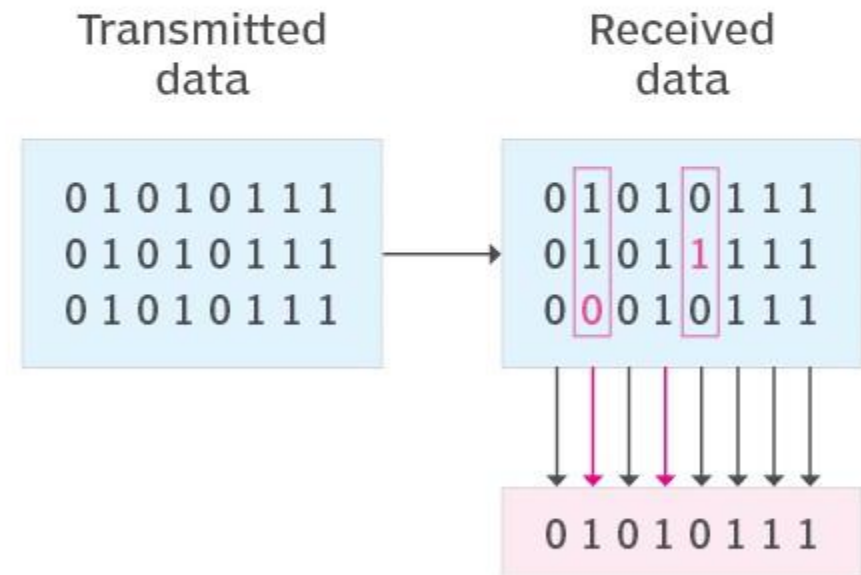
Bit error rate

- Another important characteristic of data transmission is the Bit error rate (BER). BER refers to the number of bit errors received over a communication channel. BER is a unitless measurement expressed as a ratio or percentage.
- For example:
If an original transmission sequence is: 1 0 1 0 1 1 0 1 0 0
And the received sequence is: **0** 0 1 0 1 **0** **1** **0** **1** 0 (differences in bold)
Then the BER is 5 errors / 10 bits transferred = 50%
- BER is affected by channel noise, interference, multipath fading, and attenuation.

Bit error rate

- Techniques to improve BER include increasing transmission power, improving receiver sensitivity, or adding more redundant data. The last technique is typically referred to as forward error correction (FEC).
- FEC simply adds extra information to a transmission. In the most basic sense, one would add triple redundancy and a majority vote algorithm; however, this would reduce bandwidth by 3x.

How forward error correction works



Questions