Radio Frequency (RF) and Antenna Fundamentals

- Wireless Communications has evolved in leaps and bounds since the first radio transmission by **Marconi** 100 years ago.

- **Cellular service** has pushed this technology into every person's working and home lives.

- The infrastructure currently utilizes old and new technology:

- **Old Technology**:

    - Two-way Radio
    - Mobile Radio Packet Data
    - Specialized Mobile Radio (SMR)
    - Cellular Radio
    - Microwave
    - Satellite
    - Cellular Digital Packet Data (CDPD)
    - PCS/PCN

- **New Technology:**

    - 3G, 4G, EDGE, LTE
    - Spread-Spectrum Radio
    - Infrared and Millimeter Wave
    - Wireless LANs (802.11)
    - Wireless data devices (Bluetooth)
    - Radio Frequency Identification (RFID)

Advantages of Wireless Communications

- The main advantage of wireless is the fact that there are no installation issues of a physical medium (channels).

- Communication over difficult geographical terrain is achieved without expensive cable costs.

- Interconnections with local Telcos and other telecommunications service providers are bypassed.

- Users can access information without necessarily being tied to their offices (mobility).

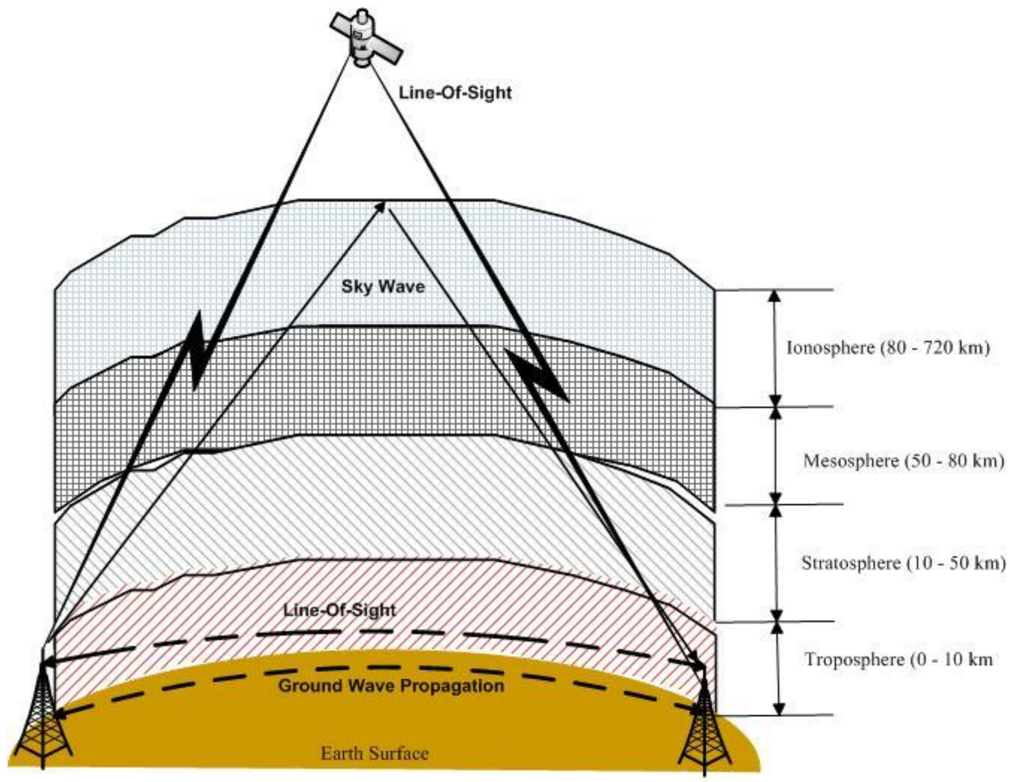
Disadvantages of Wireless Communications

- Lack of spectrum space.
- High user costs.
- Systems are susceptible to noise and interference.
- Security can be a major issue.

RF Spectrum

- Electromagnetic waves propagate through space at the speed of light (186,000 mph).
- Wireless signals travel between two points in one of three propagation modes:
- **Ground-wave propagation**
  - Propagates along the curvature of the earth by virtue of inducing currents in the earth. The imperfectly conducting earth leads to some of its characteristics.
  - Waves can propagate over very long distances.
  - Range depends upon: Frequency, Polarization, Location and Ground Conductivity.
- **Sky-wave propagation**
  - The signal is reflected by the ionosphere layer back down to earth.
  - Waves can travel a number of hops, back and forth between ionosphere and earth's surface (skip).
- **Line-Of-Sight Propagation**
  - VHF signals propagate between two points in straight lines between the two antennae.
  - Any obstructions in the communication path will result in blocked signals.

- The following diagram illustrates the three modes of wave propagation:



RF Wave Propagation Modes

- The table below shows the Radio Frequency Bands from 1 Hz to 3000 GHz.

DESIGNATION	FREQUENCY RANGE	WAVELENGTH RANGE	Propagation Mode
ELF (Extremely Low Frequency)	1 - 3000 Hz	300,000 - 100 Km	Ground Wave
VLF (Very Low Frequency)	3 - 30 KHz	100,000 - 10,000 m	Ground Wave
LF (Low Frequency)	30 - 300 KHz	10,000 - 1000 m	Ground Wave
MF (Medium Frequency)	300 - 3000 KHz	1000 - 100 m	Ground/Sky Wave
HF (High Frequency)	3 - 30 MHz	100 - 10 m	Sky Wave
VHF (Very High Frequency)	30 - 300 MHz	10 - 1 m	Line-Of_sight
UHF (Ultra High Frequency)	300 - 3000 MHz	100 - 10 cm	Line-Of_sight
SHF (Super High Frequency)	3 - 30 GHz	10 - 1 cm	Line-Of_sight
EHF (Extremely High Frequency)	30 – 300 GHz	1 cm – 0.1 cm	Line-Of_sight
THF (Tremendously High Freq)	300 – 3000 GHz	0.1 cm – 0.1 mm	Line-Of_sight

- The next table provides some typical applications of the frequency bands:

FREQUENCY BAND	TYPICAL APPLICATION
ELF	Submarine Communication
VLF	Time signals, standard frequencies
LF	Fixed, maritime mobile, navigational, radio broadcasting
MF	Land mobile, maritime mobile, radio broadcasting
HF	Fixed, land, maritime and aeronautical mobile, amateur, radio broadcasting
VHF	Fixed, land, maritime and aeronautical mobile, amateur, radio and television broadcasting, radio navigation
UHF	Fixed, Land, maritime and aeronautical mobile, amateur, television broadcasting, radio location and navigation, meteorological, satellite communications
SHF	satellite communication
EHF	Radar, Satellite
THF	Satellite, Space, Radio Astronomy

- The next table provides a general guide to area coverage capability for the Low, High, and UHF bands:

Feature	Low band	High Band	UHF
Use category:	Rural	Suburban	Urban & Suburban
Range:			
Base to Mobile	56 Km	40 Km	37 Km
Mobile to Mobile	21 - 48 Km	8 - 16 Km	6 - 14 Km
Antenna Elevation	Minimal	Medium	Maximum
Shadowing	Low	Medium	Maximum
Building Penetration	Poor	Fair	Best
Transmission Path Loss	Least	Moderate	Most
Vegetation Absorption	Least	Some	Noticeable
Multipath fading	Negligible	Noticeable	Pronounced
Interference	Skip and Cochannel	Cochannel	Fairly Clear
Noise	Maximum	10 dB less than Low Band	20 dB less than low band

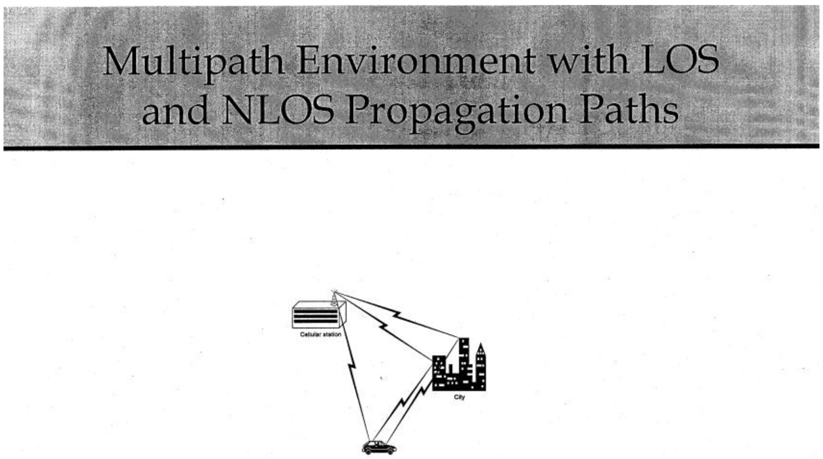
- Different portions of the RF spectrum are affected differently by terrain, vegetation, climatic conditions and ambient noise levels.

- System design engineering practices have to address the issue of different operating frequencies.

Multipath Fading

- Multiple copies of the transmitted signal arrive at the receiver from multiple paths.

- These received copies consist of **direct** Line of Sight (**LOS**) and **reflected** Non Line of Sight (**NLOS**) paths.



- The phase and amplitude of each LOS or NLOS signal are dependent on the **path length**, **frequency** of the carrier, and **environmental factors**.

- At the receiver, these multiple copies of the transmitted signal will combine **constructively** or **destructively** and result in a significant **fluctuation** of the received power level.

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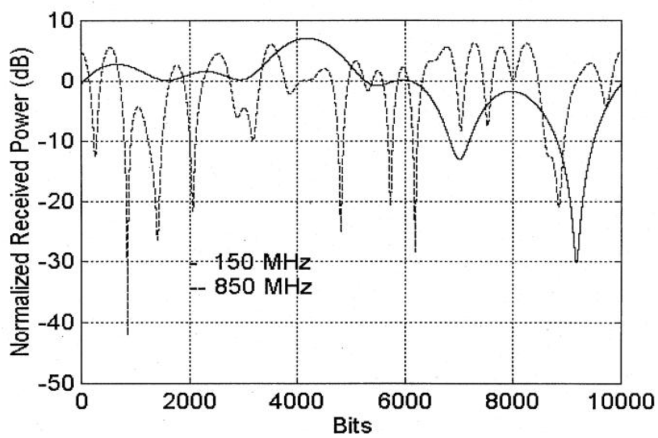
- This fluctuation of the received power level as a function of distance is know as **Multipath Fading.**

- At certain locations the signals will be in **phase alignment**, resulting in a relatively **high received power level**; and in some locations the phases will be **out of phase**, resulting in a **cancellation of the signals** and a relatively low received power level.

- **Multipathing** causes significant power fluctuations in the received signal, causing **deep fades** at certain locations. The diagram below illustrates this phenomenon.

Normalized Signal Power versus Bits Transmitted



- The **frequency** and **duration** of these fades is **carrier frequency dependent**.
- The **rate** at which fades are encountered and the **duration** of the fades **increases** with **frequency**.

Antenna Principles

- In any wireless communication system, the performance of the antennae has a very significant and fundamental impact on the entire communication link.

- An **antenna** is an electronic component that is designed to transmit or receive electromagnetic signals or energy.

- Antenna analysis is usually done using one of the following three fundamental antennae (radiators):

- **Isotropic Radiator**:

  - This is a hypothetical, lossless antenna having equal power radiation in all directions (spherical radiation pattern).
  - It represents an ideal antenna and it is used as reference to which other antennae are compared.

- **Omni-directional**:

  - Radiates EM energy equally in all directions.

- **Directional**:

  - Radiates more EM energy in one direction than in the other. All antennas radiate some energy in all directions but careful construction results in large directivity in certain directions and negligible energy radiated in other directions.

  - By adding additional conducting rods or coils (called *elements*) and varying their length, spacing, and orientation, an antenna with specific desired properties can be created, such as a **Yagi-Uda** Antenna.

Antenna Directivity and Gain

- Antennae do not radiate electromagnetic energy equally in all directions. It has been found that all radio antennae radiate more in some directions than others.

- The actual pattern depends on the type of antenna, its size, the environment and a variety of other factors.

- This directional pattern can be used to ensure that the power radiated is radiated in the desired directions. We refer to the directional patterns and gain in terms of the transmitted signal.

- It is often easier to visualize the antenna directivity is terms of its radiated power, however the antenna performs in an exactly equivalent manner for reception, having identical directivity and gain.

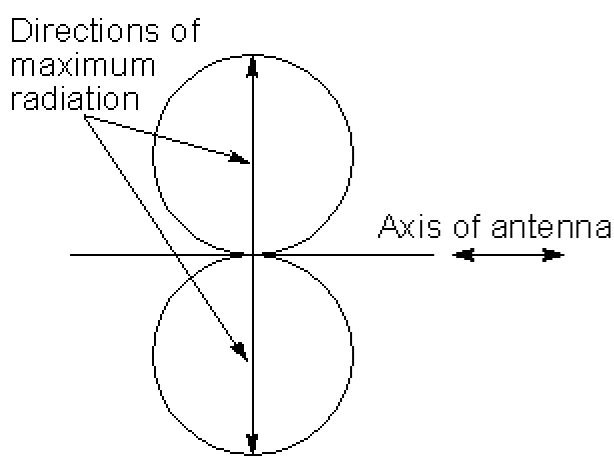
- In order to visualize the way in which an antenna radiates a diagram known as a polar diagram is used.

- This is normally a two dimensional plot around an antenna showing the intensity of the radiation at each point for a particular plane.

- Normally the scale that is used is logarithmic so that the differences can be conveniently seen on the plot.

- Although the radiation pattern of the antenna varies in three dimensions, it is more convenient to plot the pattern in a particular plane, usually the horizontal or vertical planes.

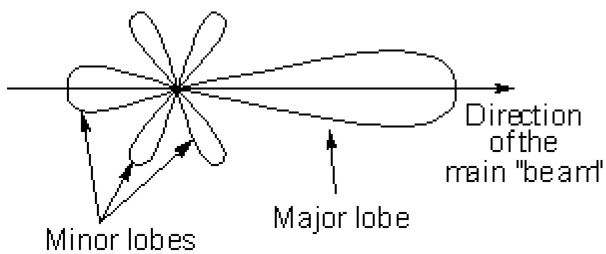
- The following is an example radiation pattern for a simple dipole antenna:



- Antennae are often categorized by the type of polar diagram they exhibit. For example an omni-directional antenna is one which radiates equally (or approximately equally) in all directions in the plane of interest.

- An antenna that radiates equally in all directions in all planes is called an isotropic antenna. As mentioned earlier it is not possible to produce one of these in reality, but it is useful as a theoretical reference for some measurements.

- Other antennas exhibit highly directional patterns and these may be utilized in a number of applications. The Yagi antenna is an example of a highly-directional antenna:



- There are a number of key features that can be seen from this polar diagram. The first is that there is a **main beam** or **lobe** and a number of **minor lobes**.

- It is often useful to define the beam-width of an antenna. This is taken to be angle between the two points where the power falls to half its maximum level, and as a result it is sometimes called the half power beam-width.

Units, Measurements and Link Budget Calculations

- The term **dB** or **decibel** is a relative unit of measurement used frequently in electronic communications to describe power gain or loss.

- Decibels are used to specify measured and calculated values in audio systems, microwave system gain calculations, satellite system link-budget analysis, antenna power gain, light-budget calculations and in many other communication system measurements.

- In each case the dB value is calculated with respect to a standard or specified reference.

- The dB value is calculated by taking the log of the ratio of the measured or calculated power (P2) with respect to a reference power (P1).

- This result is then multiplied by 10 to obtain the value in dB. This is commonly referred to as the power ratio form for dB:

$$dB = 10\log\left(\frac{P_1}{P_2}\right)$$

- The above equation can be used in any application that requires a relative measure of signal strength.
- For example, noise and other transmission media impairments tend to distort or attenuate the original signal.

- For a given level of noise, we would expect that a greater signal strength would improve the ability to correctly receive data in the presence of noise.

- The **Signal-to-Noise** (S/N) ratio is the ratio of the power in a signal to the power contained in the noise that is present at a particular point in the transmission.

$$\frac{S}{N} = 10\log\left(\frac{Signal\ Power}{Noise\ Power}\right)\ \ [\text{dB}]$$

- This expresses the amount, in decibels, that the intended signal exceeds the noise level.

- The logarithmic scale provides us with a very convenient way of expressing very large and very small ratios.

- Signal levels were normally quoted as power ratios and a reference point of 1 mW was chosen as a convenient size. The unit was named **dBm** with the `m' indicating a **reference point of 1 mW** and is therefore a measurement of power.

- For example, consider the case where the received signal power at a distance of 45m from an access point was measured to be 0.000000000316 mW. This can be more conveniently represented as **-95.2 dBm**.

- Another application where this type of measurement is convenient is in the performance specifications of different types of wireless equipment.

- The term "**sensitivity**" is a receiver parameter that indicates the **minimum signal level** required at the antenna terminals in order to provide **reliable communications**.

- Fore example, a manufacturer might specify that their PCMCIA 802.11 adapter has a receiver **sensitivity** of **"-84 dBm** at 11 Mbps**".** What this means is that the receiver in the card has to have a minimum signal power of **4 pW** in order for it to successful decode the 11 Mbps bit stream.

- The wavelength (λ) is related to the frequency of operation is as follows:

$$\lambda = \frac{c}{f}$$

- Where,

  λ = wavelength in meters
  c = The speed of light in free space, $3 \times 10^8 m/s$
  f = Frequency of operation in Hertz (Hz)

- The parameter L_p can be written in terms of λ as:

$$L_P = \left(\frac{4\pi f d}{c} \right)^2$$

The Friis Equation and Link Budget

- In case of non-isotropic antenna, the Free-Space loss relating the received and transmitted power is given the Friis equation:

$$P_R = P_T\left(\frac{G_T G_R}{L_P}\right)$$

- Where,

  G_R, G_T = Rx and Tx antenna gains.

- We want to obtain a link budget relationship from the above so it can be used in a practical application such as determining the performance parameters (in dB) of a system.

- Taking the logarithm of both sides of the equation and multiplying by ten we get:

$$10\log P_R = 10\log P_T + 10\log G_T + 10\log G_R - 10\log L_P$$

- Or more conveniently we obtain the **link-budget equation** in dB as follows,

$$P_R(dB) = P_T(dB) + G_T(dB) + G_R(dB) - L_P(dB)$$

- Where X(dB) = 10log(X).

- We observe from the above results that the transmitted power has the antennae gains applied to it, and then the path loss over the link is subtracted from the result, thus giving us the signal power at the receiver.

- The received power must be **equal to, or greater** than the receiver **sensitivity** specification in order for the data to be detected reliably.

- Note that the Friis equation (Link Budget), as presented does not include the effect of noise, e.g. receiver noise, antenna noise, artificial noise, multiple access interference, etc., which will cause a further degradation of the received signal.

- Also note that in a practical calculation the losses due to cables and connectors will also reduce the received signal strength.

- The system diagram shown illustrates a typical wireless link and all the individual components that would be considered in a link-budget calculation.

- We will analyze the link in five stages, each of which will contribute to the signal loss or gain:

- The transmitter: usually an access point, router or another station.

- The cabling and connectors at the transmitter end: These will attenuate the signal depending on the cable/connector types and the cable lengths.

- The wireless link: this will result in a free-space loss depending on the parameters described earlier.
- The cabling and connectors at the receiver end: These will attenuate the signal depending on the cable/connector types and the cable lengths.
- The receiver: usually an access point, station or another wireless device.
- The Tx and Rx antennae: Will contribute gains depending on the antenna at either end.
- Also shown in the diagram is an equation describing the system link budget or margin.
- Usually a minimum margin of **5 dB** is the **lowest level** that will provide acceptable results.
- This value provides us with a measure of much signal we have available (in dB) after going across the link and into the receiver.
- For a reliable link, the signal arriving at the receiver, the receive signal level (RSL) must be greater than the sensitivity of the wireless receiver. This is typically -82 dBm for 11 Mbps.
- We can rewrite the link budget equation as follows:

$$RSL_{\min} = P_T + G_T - L_P + G_R - L_{CT} - L_{CR}$$

- Where L_{CT} and L_{CR} are the cable and connector losses at the transmitter and receiver respectively.
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- So using the typical specification above, **RSL > -82 dBm** for the bits to be received and decoded reliably.

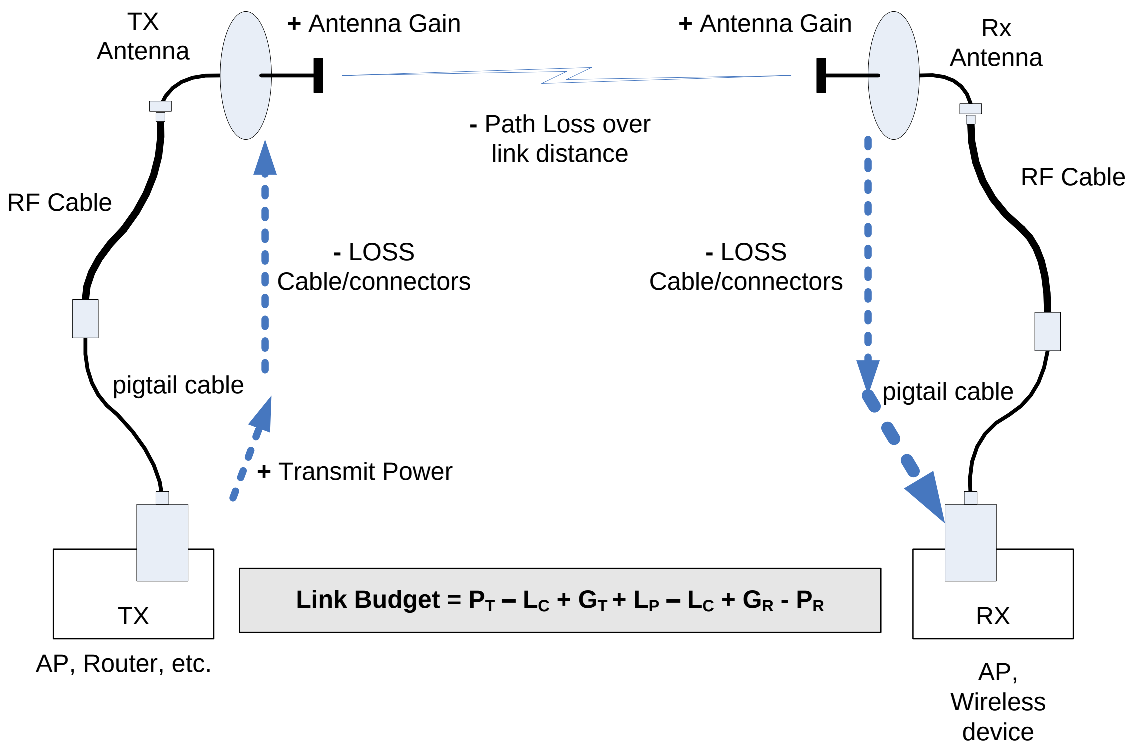
Example

A system has the following parameters:

RF cable: 3.4 dB (50 ft. LMR 400)
Pigtail and connectors: 2 dB
Tx/Rx Antennae: 24 dBi
Free-space path loss (16 Km) : 124 dB
Receiver sensitivity: -82 dBm
Tx power: -15 dB (32 mW)

RSL = -15 dB + 24 dBi – 124 dB + 24 dBi – 5.4 dB – 5.4 dB = -101 dB
RSL = -101 dB + 30 = -71 dBm > -82 dBm, therefore the system will work.

Note: If **RSL < -82 dBm**, then solutions such as higher gain antennae, lower loss cables or signal amplifiers will be required to maintain a reliable link.



TX
Antenna
+ Antenna Gain
+ Antenna Gain
Rx
Antenna
- Path Loss over
link distance
RF Cable
RF Cable
- LOSS
Cable/connectors
- LOSS
Cable/connectors
pigtail cable
pigtail cable
+ Transmit Power
TX
AP, Router, etc.
Link Budget = PT – LC + GT + LP – LC + GR - PR
RX
AP,
Wireless
device