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Radio Transceiver System Design With Emphasis on Parameters Which Affect Range

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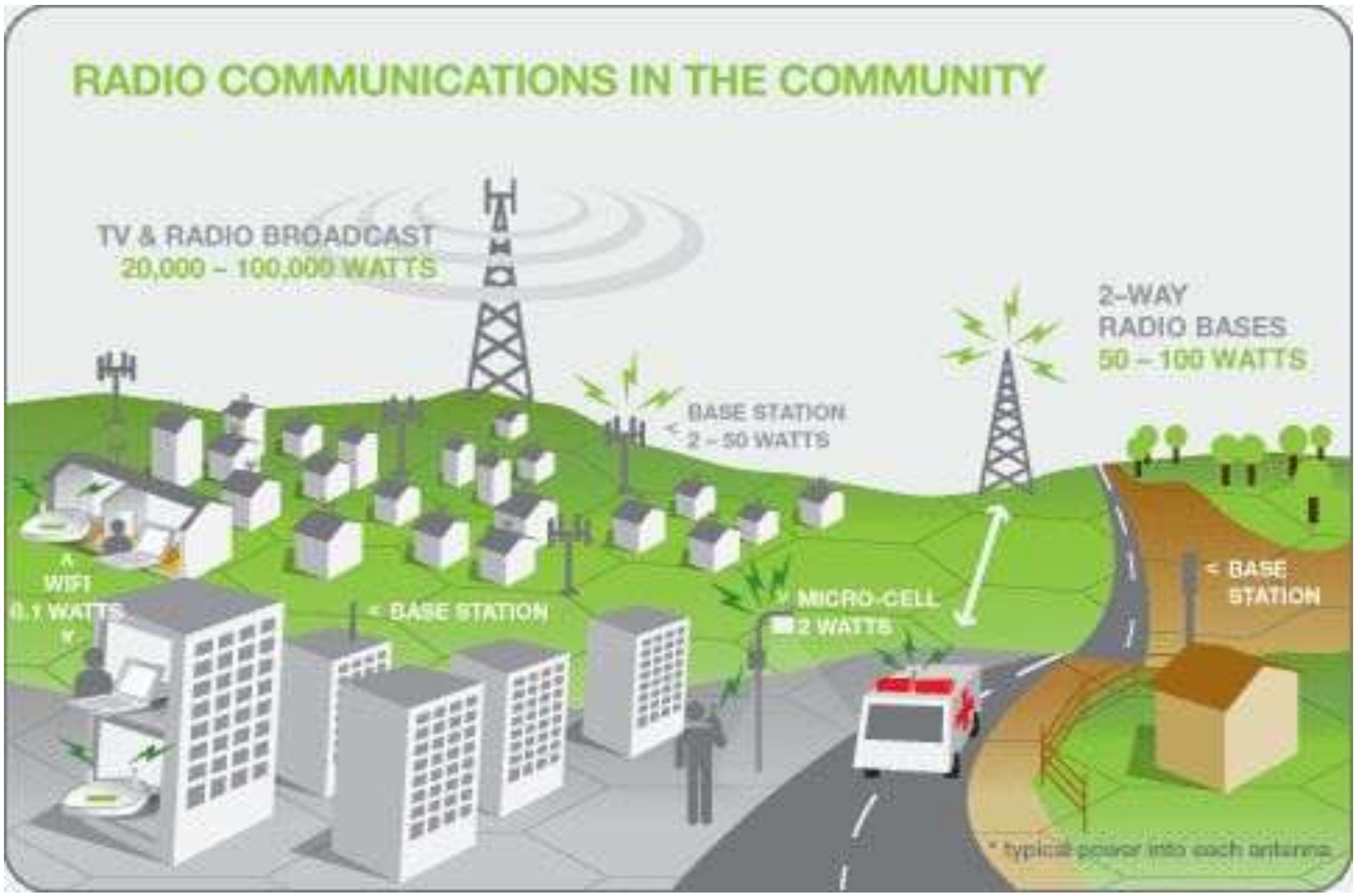


Fig 1

ABSTRACT

This paper will describe the basic impairments which reduce communications range in a radio system. Typically these are factors such as:

- Transmit Power and losses in the transmit chain, Power Amplifier non-linearity, etc.
- Receiver and Transmitter antenna choice, grounding, location, and impedance matching.
- Propagation path impairments such as Free Space Loss, Absorption (building materials, vegetation, moisture, etc), Multipath Destructive Interference, Fading, etc.
- Receiver Sensitivity and criteria which affect it such as Noise Figure, Bandwidth, Signal to Noise Ratio, Phase Noise, etc.

The ramifications of each of these effects would be discussed in terms of degradation to communications range as well as the "cost" of poor design practices.

The paper is aimed at people who currently use or need a radio communications system and want to learn many of the basic issues and constraints which affect communications range and radio design.

The discussion is presented in several parts:

- Antennas
- Propagation Path
- Transmitter issues
- Receiver issues
- Process Gain Enhancements
- Communications range estimation calculations using a 2.4 GHz radio as an example.

Some of the topics will be mentioned only briefly, as a full discussion is beyond the scope of this presentation, yet they are important issues that need to be touched on.

FUNDAMENTAL RADIO TRANSMISSION SYSTEM

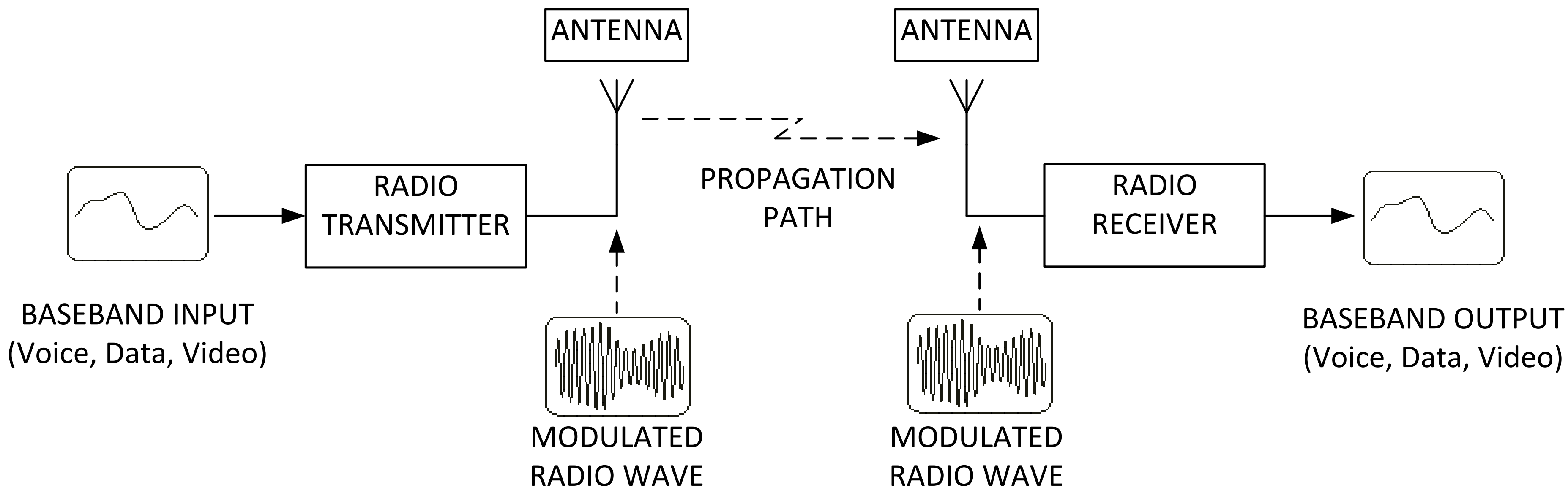


Fig 2
Fundamental Radio Transmission System

All Radio transmission systems require, at a minimum:

- A Radio Transmitter, which converts (modulates) lower frequency baseband signals (data, voice, video…) onto higher frequency radio waves.
- A Radio Receiver, which converts (demodulates) higher frequency radio waves back into lower frequency baseband signals (data, voice, video..)
- A Propagation Path to carry the signal from the Transmitter to the Receiver ("free space" in a wireless system).
- Antennas at the Receiver and Transmitter, which couple RF energy from the Transmitter or Receiver to free space.

There are potential impairments in each area which can degrade the quality of the signal and effective communications range.

ANTENNAS

Antennas affect both Receive and Transmit range; often the cheapest and easiest solution to a range problem is selection of the proper antenna and its location. Antennas are chosen based on the following characteristics:

- **Frequency of operation:**
  - No antenna works over all frequencies; the antenna must be chosen for the appropriate frequency band(s).

- **Gain:**
  - No antenna truly has “gain”; after all, they are just a pieces of metal attached together.
    But, there does exist a mathematically hypothetically perfect antenna called an “isotropic radiator” which in theory radiates equally well in all directions, with a spherical radiation pattern. The gain of this hypothetical antenna is deemed to be “1”, or 20 log (1) = 0 dB
  - Practical antennas do NOT radiate equally well in all directions; they will transmit more energy in some directions at the expense of other directions. In the direction in which they transmit more energy than an Isotropic antenna, we say the antenna has “X dB gain over an isotropic antenna”, or ”X dbi”. For example, a dipole antenna will have 2.15 dB more gain than an Isotropic in some directions.

Fig 3
Hypothetical Isotropic antenna radiation pattern
(Gain = 0 dBi)

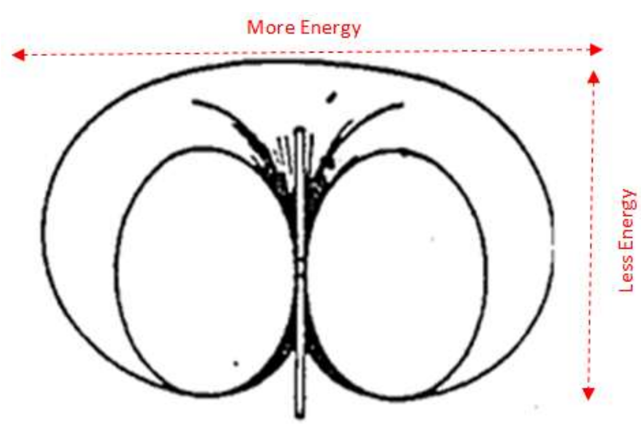
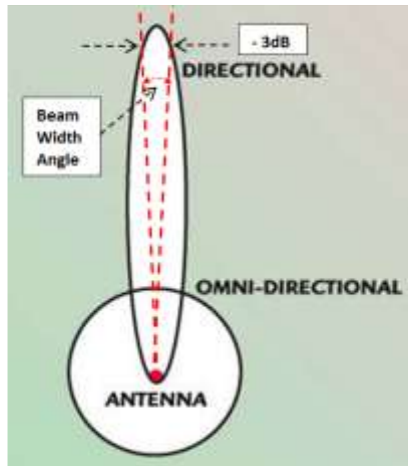
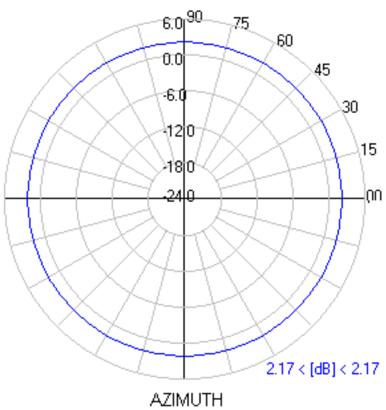


Fig 4
Dipole Antenna radiation pattern
(Gain = 2.15 dBi)

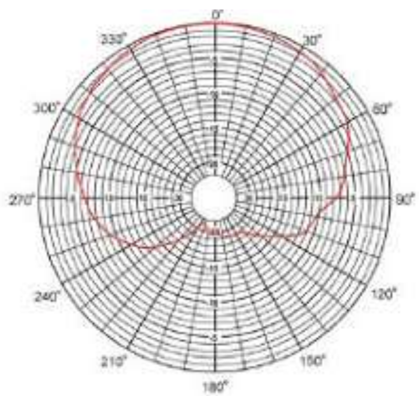
- **Directivity (Directionality) pattern:**
  - Range can be extended, and\or interference avoided, with Directional Antennas.
    - Antennas can be built with radiation patterns that concentrate energy in a specific direction, and decrease energy in other directions, like a garden hose which is changed from “mist” to “stream”.
    - The angle formed by the points on the radiation pattern where the pattern is down 3 dB (1/2 power point) is called the Beam Width.

Fig 5
Omni Directional
vs
Directional Radiation Patterns

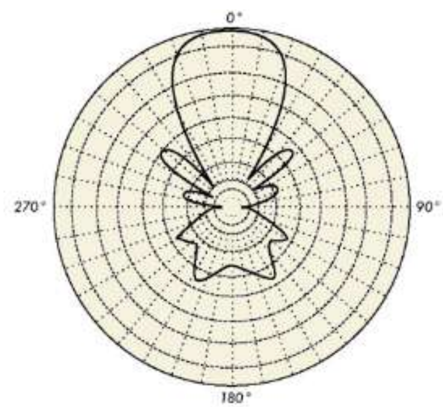




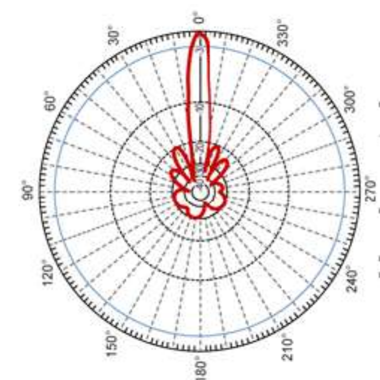
Omni-Directional
(360 deg Beam Width)
Fig 6



Moderately Directional
(120 deg Beam Width)
Fig 7



Very Directional
(30 deg Beam Width)
Fig 8



Highly Directional
(5 deg Beam Width)
Fig 9

- **Impedance (usually referred to as Voltage Standing Wave Ratio, or VSWR):**
  - A measure of how well the Antenna is "matched" (i.e., will transfer power) from free space to a radio.
  - Most common antennas, RF cables and radio antenna connections are nominally 50 Ohms.
  - VSWR is a measure of the antenna deviation from 50 Ohms.
    - A VSWR of 1:1 means the antenna system is exactly 50 Ohms, and the antenna system perfectly couples all the RF energy between the radio and free space.
    - A VSWR of 2:1 is good, but some energy will not be coupled to free space - it will be reflected back into the Power Amplifier.
    - High VSWR from the antenna system can damage a poorly designed power amplifier during Transmit.
      This results in power being reflected back into the PA, producing potentially high voltages or currents, and excess heat.
      Examples below assume a 10 Watt Transmitter.

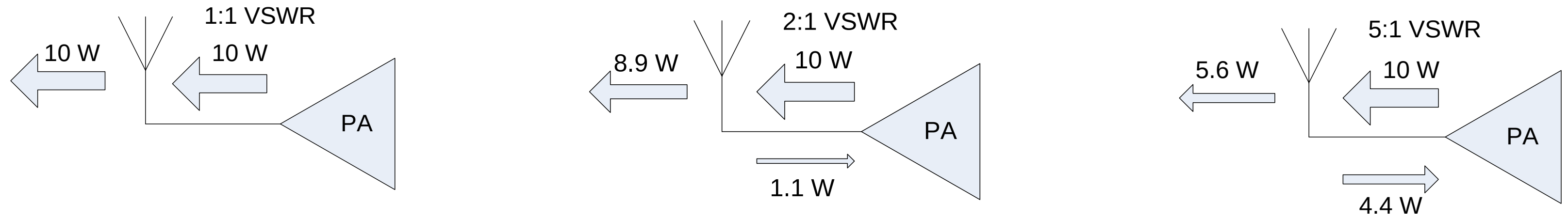


Fig 10 Example showing Antenna radiated power vs VSWR

- **Environment:**
  - Location: The higher the mounting location, free of nearby obstructions, the better.
  - Proximity to metallic surfaces:
    - No antenna wants to be mounted close to a metallic surface with the exception of 1 class of antenna:
      those types which specifically REQUIRE that a metal surface be directly BELOW the antenna. These antennas are referred to as antennas which require a "ground plane" or a "counterpoise". (The magnetic mobile mount on the next page is an example).
      They have certain benefits over other types of antennas, but the need for a ground plane *could* be a drawback in certain applications.
  - Rigidity:
    - Outdoor antennas can see a lot of wind and\or ice loading; make sure they are rigid and secure or the antenna can be damaged and become a poor radiator.
    - Use proper RF cabling that can sustain bending and other forms of "abuse".
    - Weatherproof the RF Connectors to prevent water from seeping in.

Examples of 2400 MHz Omni-Directional Antennas

Ceiling Mount
5 dBi 6.8 " 360 deg

Transceiver Mount
5 dBi 7"x 4" 360 deg

Desktop
5 dBi 9 ½ " 360 deg

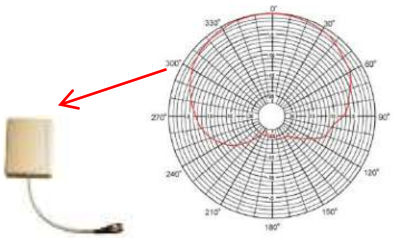
Car Magnetic Mobile Mount
7.8 dBi 12 " 360 deg

Vertical Pole Mount
11.8 dbi 36” 360 deg

Vertical Pole Mount
15 dBi 64” 360 deg

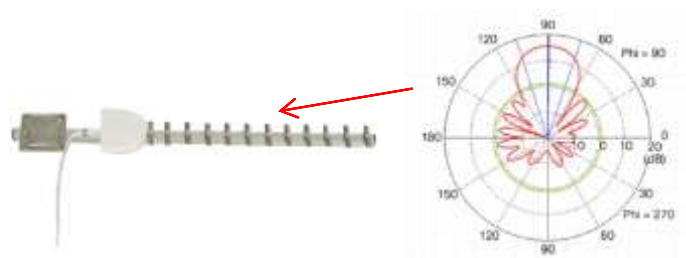
Figs 11-XX (Antennas courtesy of Radio Labs)

Examples of 2400 MHz Directional Antennas

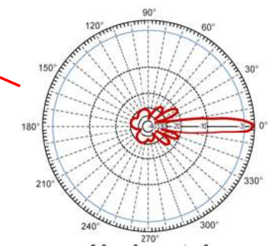


Wall Mount
7 dBi   5" x 4" 180 deg

Pole Mount Panel
19 dBi 15" x 10.5" x .8" 17.5 deg



Pole Mount 14 Element Yagi
14 dBi   24" 45 deg



Pole Mount Panel
15.5 dBi 5.5 “x 38” 7 deg

Pole Mount Parabolic Grid
24 dBi 34” x 28” 9 deg

Pole Mount Parabolic Dish
30 dBi 67 “ diameter 4.8 deg

Figs 11-XX (Antennas courtesy of Radio Labs)

PROPAGATION PATH

- **Propagation Path Impairments:**
  - Transmitted radio signals propagate through space.
    An RF signal emanating from the Transmitting antenna will be at a much lower level once it reaches the Receiving antenna.
    Three typical causes are:

  - **Energy spreading:**
    A fixed amount of radiated energy from a source spreads out over a wider and wider area at a distance, resulting in less energy at any point as the radio wave moves away from the source, similar to the light from a bare light bulb in a dark room.

  - **Energy absorption by objects**:
    Many objects will absorb RF energy, converting that energy into heat inside the object, similar to sunlight absorption on dark clothing. Examples are furniture, human body, dry wall, foliage, gaseous atoms, etc.

  - **Reflections off objects:**
    Many objects reflect RF energy off materials, and absorb little of that energy (although some materials can absorb and reflect energy), similar to a flashlight shining into a mirror. Examples are most metallic objects, concrete, bricks, etc.

  - The following pages describe some of the propagation impairments that reduce the received signal level.

- **<u>Free Space Path Loss (Line of Sight (LOS) loss):</u>**
  The RF signal leaving the antenna spreads out power over a wider area away from the source, resulting in weaker signals at any point.
  The Path Loss increases as the frequency increases, which is one reason why you want to operate at no higher a frequency than is necessary.
  However, high speed data requires large amounts of frequency spectrum, which is more plentiful at higher frequencies.
  So, a "Bandwidth/Data rate vs. Operating Frequency" balance must be made for each system.
  A simple formula to calculate Free Space Loss is shown below Fig 13.

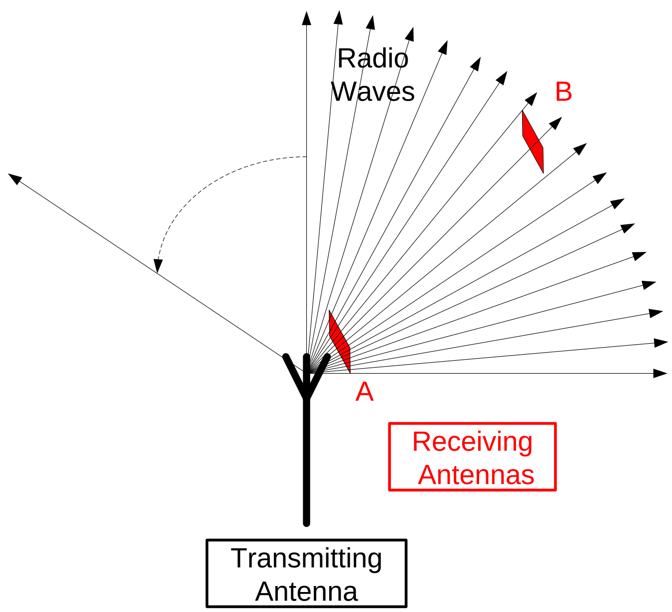


Fig 12 Power Density

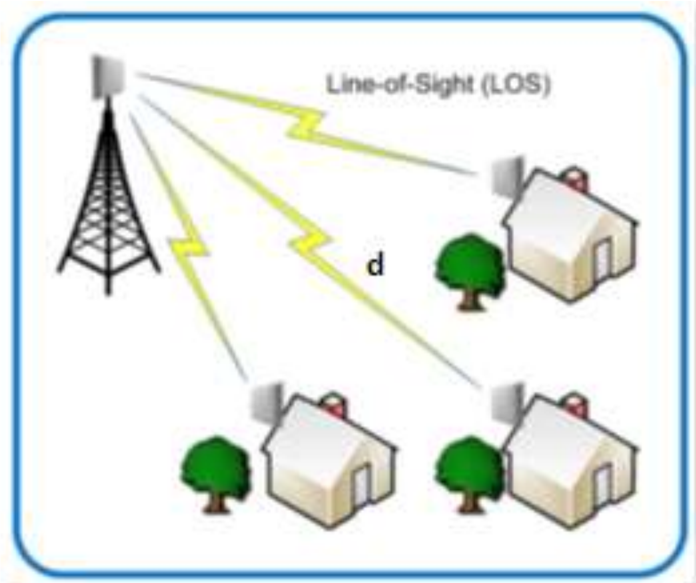


Fig 13 FSPL

Given 2 identical antennas A and B:
Antenna "A" captures more energy than Antenna "B" because it's closer to the Transmitter.

FSPL (dB) = 20 log (d) + 20 log (f) + 36.6

- d = distance between antennas, miles
- f = frequency, MHz
  For example, the path loss for a 2400 MHz signal at a distance of 10 miles is 124.4 dB

- **Multipath\Reflection:**
  Due to reflections off objects causing interference patterns. Signals arrive at receiver from multiple paths with multiple phases and time delays, which can cause cancellation of the desired signal at the receiver.
  The amount of cancellation depends upon the amplitudes, phases and time delays of the Direct Path and Multipath signals.
  Signal cancellation could easily be 20-40 dB; moving the receiver a small distance often can change the received signal level appreciably.

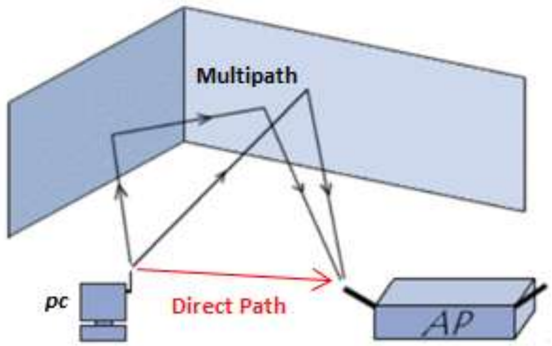


Fig 14 Multipath reflections in an office

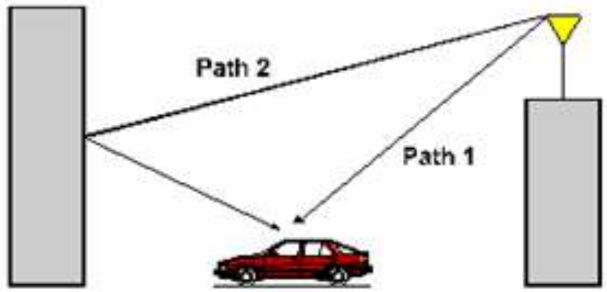


Fig 15 Multipath reflections in an urban environment

- **Fresnel zone clearance:**
  "Obstruction depth" at which reflections are generally not a problem. Objects less than 20% into the Fresnel zone will not affect the received signal appreciably.

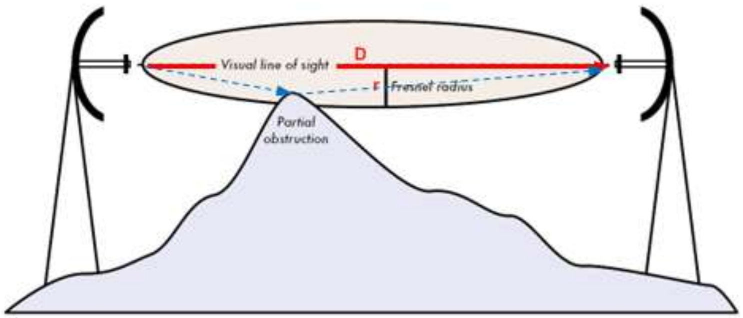


Fig 16 Fresnel Zone Clearance

$$r = 8.657\sqrt{(D \div f)}$$

r = radius in meters
D = total distance in kilometers

- **<u>Multipath Mitigation Techniques:</u>**

Two of the more common techniques to mitigate Multipath issues and increase range follow:

- **Antenna Spatial diversity**:
  Uses two or more antennas to improve the quality and reliability of a wireless link. Multiple antennas offer a receiver several observations of the same signal. Each antenna will experience a different interference environment. Thus, if one antenna is experiencing a deep fade, it is likely that another has a sufficient signal.

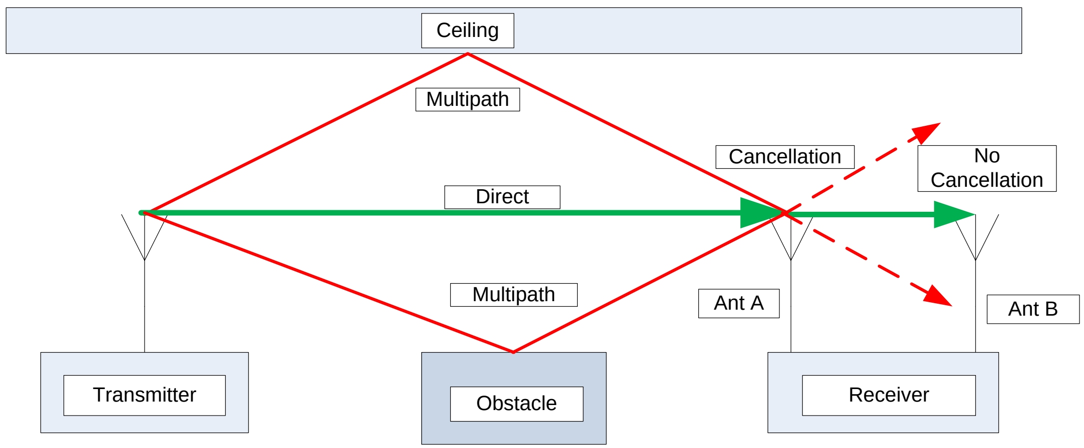


Fig 17 Antenna Spatial Diversity

- **Antenna Polarization diversity:**
  Often times only certain Electric Field polarizations will cause cancellation at the receiver while other polarizations could arrive at the receiver with a negligible phase shift due to reflections. The receiver would respond to the strongest of the polarized signals.

  - Orthogonally Polarized Antennas: Emits two Electric Field patterns, at 90 degrees relative to each other.

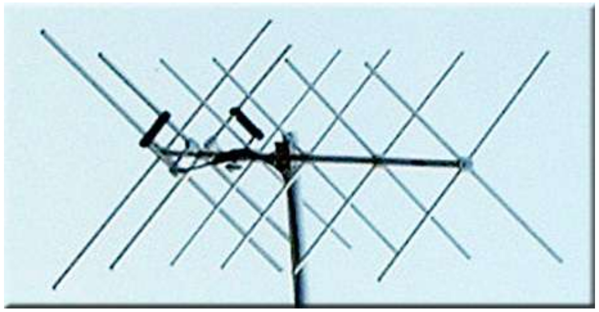


Fig 18

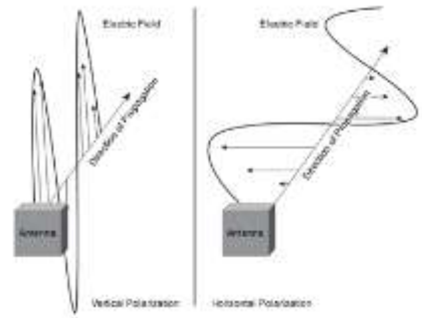


Fig 19

Orthogonally Polarized Antenna and Electric Field Patterns

  - Circularly Polarized Antennas: Emits a continuously rotating (360 deg) Electric Field pattern.

Fig 20

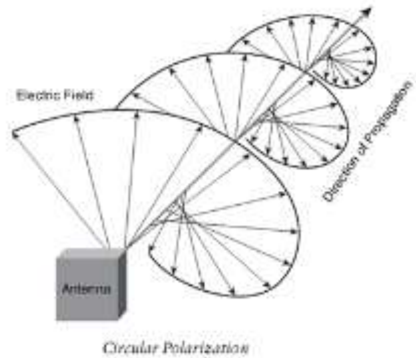


Fig 21

Circularly Polarized Antenna and Electric Field Pattern

- **<u>Construction Material Attenuation</u>:**
  Most building construction materials will absorb and/or reflect energy, thereby attenuating it.

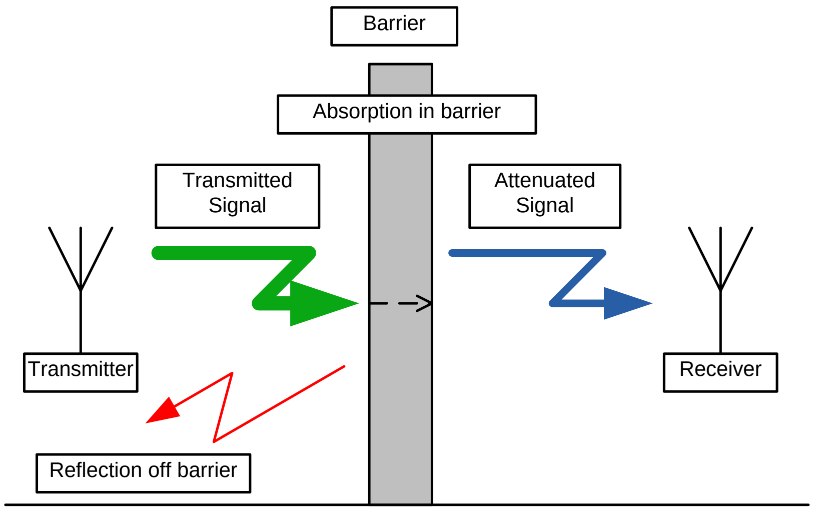
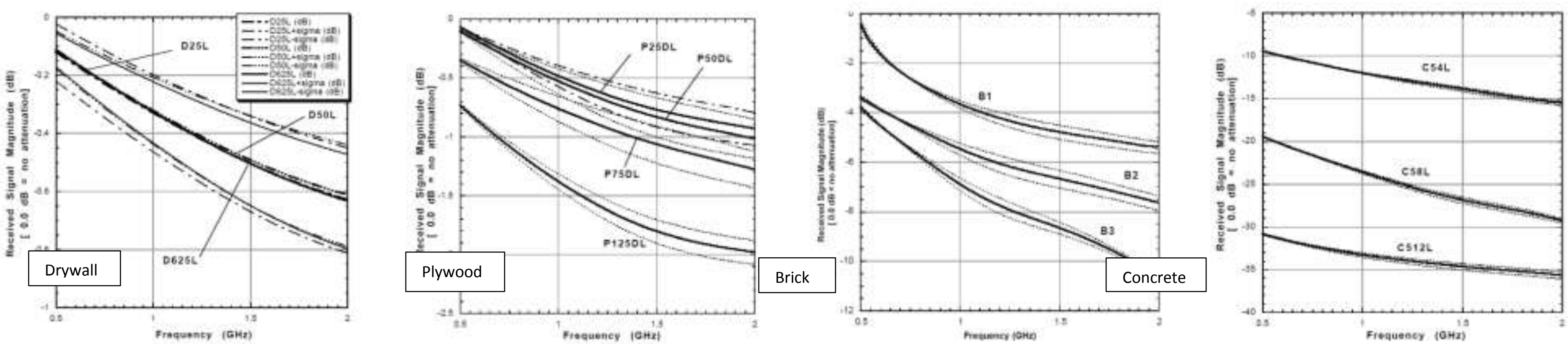


Fig 22 Barrier Attenuation

Materials	Degree of attenuation	Examples
Air	None	Open space, inner courtyard
Wood	Low	Door, floor, partition
Plastic	Low	Partition
Glass	Low	Untinted windows
Tinted glass	Medium	Tinted windows
Water	Medium	Aquarium, fountain
Living creatures	Medium	Crowds, animals, people, plants
Bricks	Medium	Walls
Plaster	Medium	Partitions
Ceramic	High	Tiles
Paper	High	Rolls of paper
Concrete	High	Load-bearing walls, floors, pillars
Bulletproof glass	High	Bulletproof windows
Metal	Very high	Reinforced concrete, mirrors, metal cabinet, elevator cage

Fig 23 Materials' Relative Attenuation



Figs 24-XX Examples of Measured Attenuations of Several Common Building Materials

- **Diffraction**:

A propagation mode in which radio waves will bend around "sharp" edges. Diffraction is not necessarily an impairment, unless the fact that it is happening is allowing unwanted signals to interfere with a desired signal.
Diffraction depends on the relationship between the wavelength and the size of the obstacle in wavelengths.

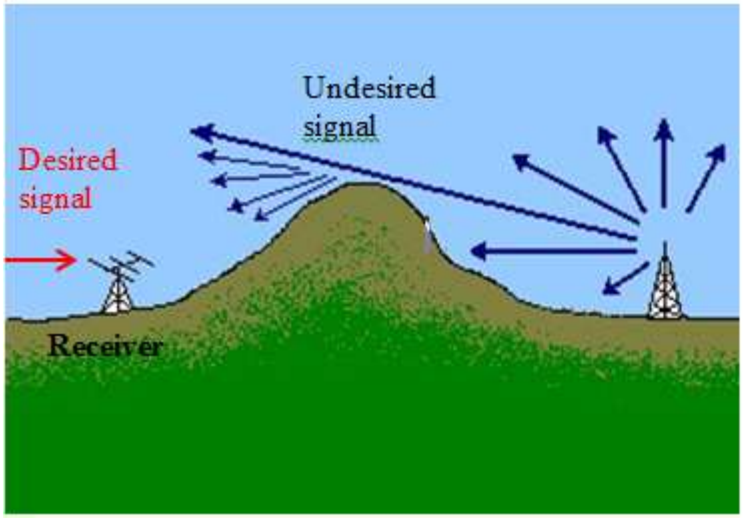


Fig 25
Mountain Peak Diffraction

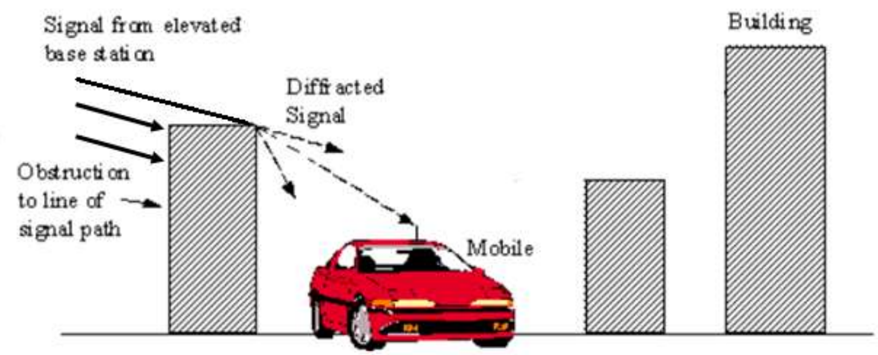


Fig 26
Building Diffraction in an urban environment

- Diffraction is sometimes purposely used to get signals into lower lying areas shadowed by a mountain.
  A receiver shadowed by a building may be able to receive a signal due to "bending" around an object.

- **<u>Foliage Absorption Losses</u>**
  Foliage losses are significant, starting at VHF. In fact, the foliage loss may be a limiting propagation impairment in some cases.

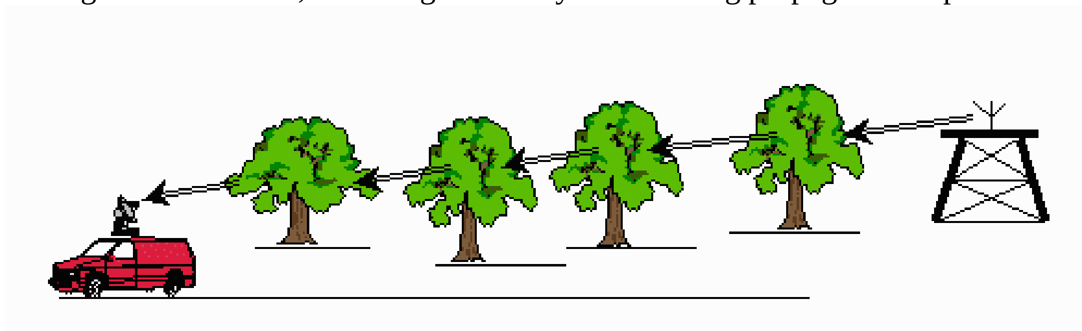
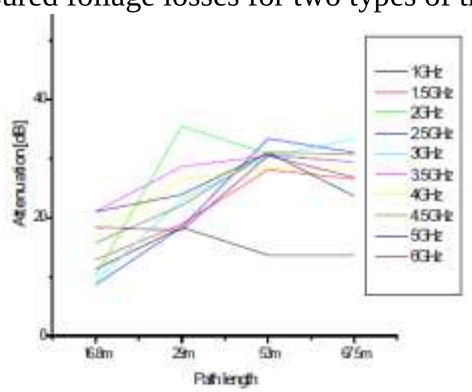


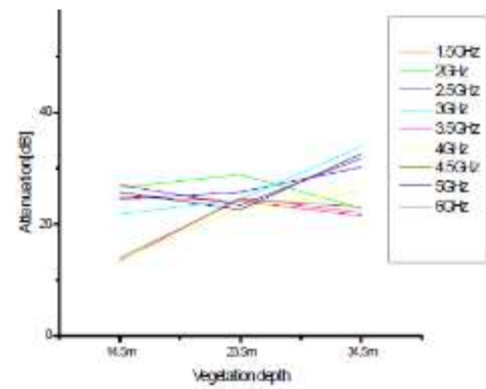
Fig 27 Foliage Attenuation

- An empirical relationship has been developed (CCIR Rpt 236-2), which can predict the loss:
  $\text{Loss} = 0.2 * f^{0.3} * R^{0.6}$ dB
  f = frequency in MHz
  R= depth of foliage transversed in meters (R< 400 meters)
  - Example: foliage loss at 2400 MHz for a penetration of 10 meters (equivalent to a large tree or two in tandem) is about 8.25 dB.

Measured foliage losses for two types of trees:



Stand of Fir Trees



Stand of Broad Leaf Trees

Fig 28-XX Examples of Measured Foliage Absorption vs Distance vs Frequencies for 2 Types of Trees

<u>Atmospheric Effects</u>:
Several conditions existing in the earth's atmosphere can impair radio propagation. Several common conditions follow:

- **Ionospheric Effects:**

  - <u>Below 30 MHz</u>:
    Ionized molecules in the upper atmosphere can create refractive "surface layers" for radio waves at frequencies below about 30 MHz. The height of these layers is determined by the types of gaseous molecules in those layers, and the layers' ability to reflect radio signals depends upon the ionizing energy supplied by the sun. Signals will reflect off lower layers during the day and higher layers at night, allowing for a longer night time reflection path and range. In so doing, radio waves can travel beyond the curvature of the earth. This can be an enhancement or an impairment, depending on whether these signals are desired or undesired.

  - <u>Above 30 MHz</u>:
    Radio waves generally have the energy to punch through the reflective layers, and will continue in a straight line. Consequently, the radio wave will not travel beyond the earth's curvature, and the only practical way to do so is to build taller towers or use air\space craft as relay stations.

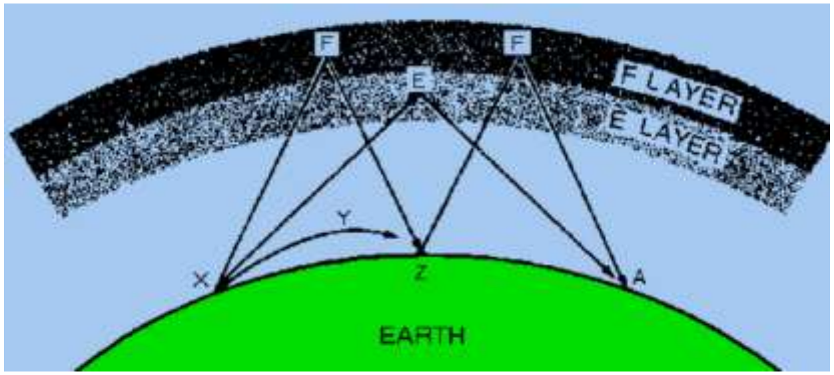


Fig 29 Multiple Hop HF Propagation

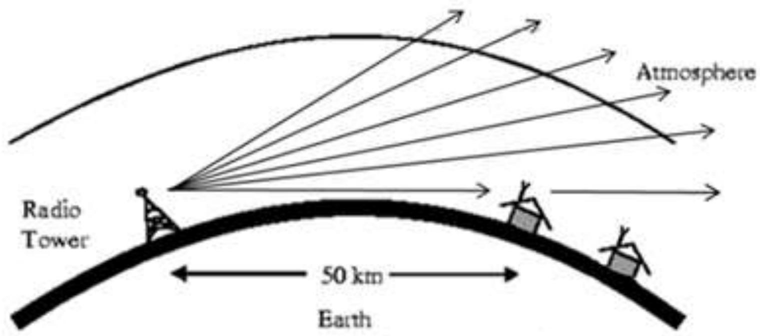


Fig 30 Line of Sight VHF Propagation

- **Tropospheric Effects:**
    - Above 30 MHz: air turbulence and/or temperature layers change the troposphere's refractive properties and allow radio "ducts" or "wave guides" to form. This is an unreliable mode, and can cease as quickly as it began. It can cause local interference.

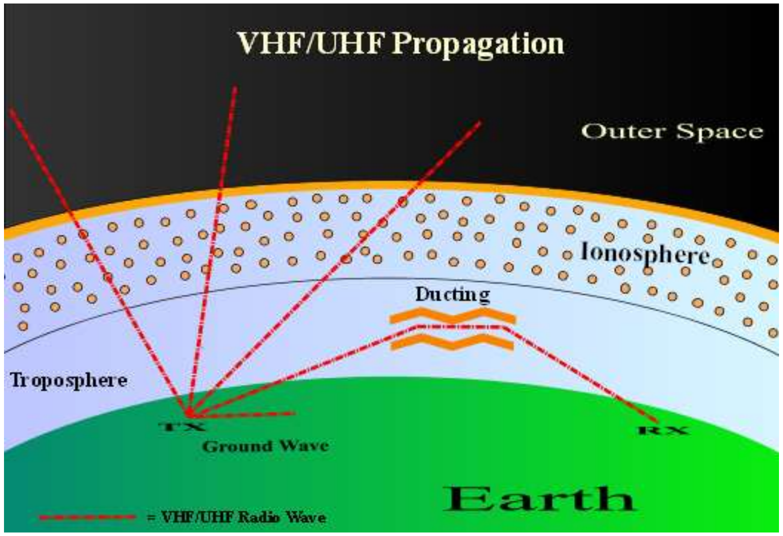


Fig 31 VHF Tropospheric Ducting

- **Attenuation due to Atmospheric Moisture (rain, snow, etc)**
  Water in the atmosphere will absorb and attenuate radio signals. The amount of attenuation depends on the rate of water fall, distance, and radio signal frequency. Absorption of radio signals is greatest for signals higher than several GHz, particularly at very long distances.

- **Oxygen attenuation**
  Oxygen in the atmosphere will absorb RF energy and attenuate the signal. The loss is highest around the 60 GHz oxygen absorption peak.

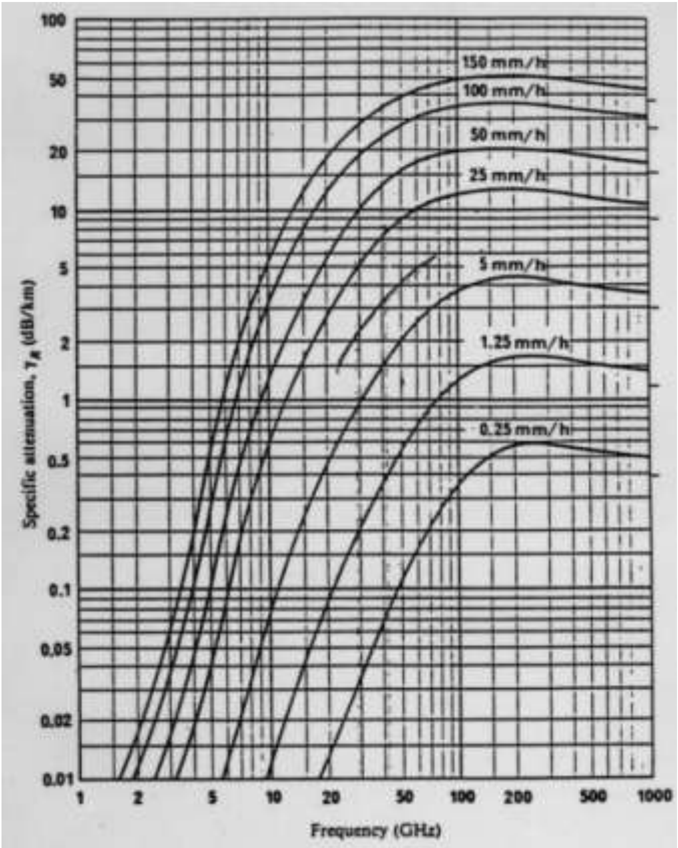


Fig 32
Measured Water Attenuation Rates; dB/km vs mm/hr

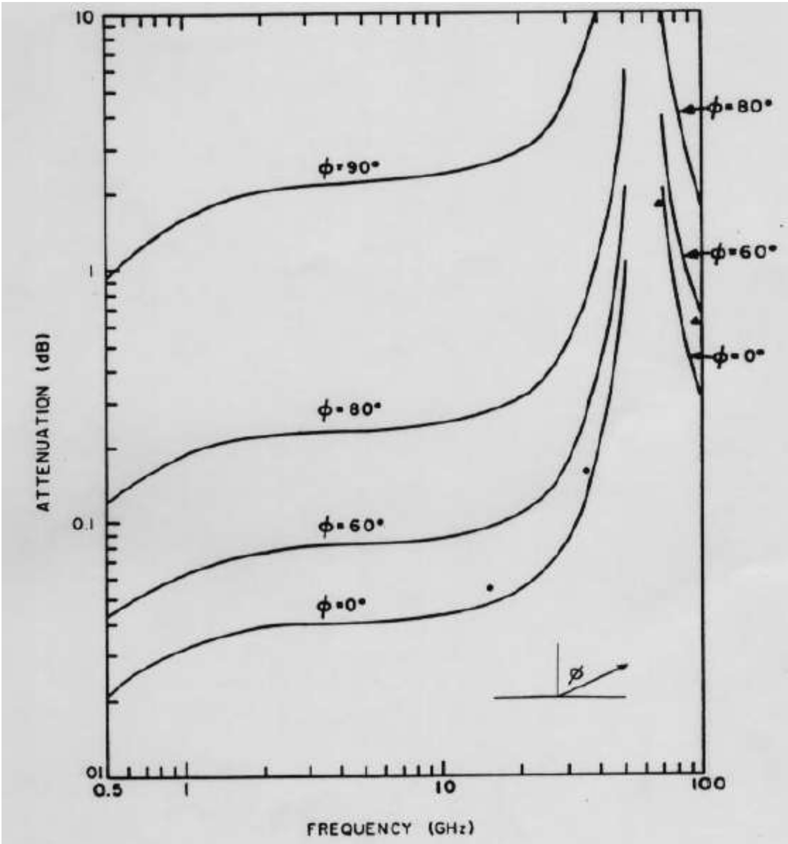


Fig 33
Oxygen Absorption

TYPICAL RADIO TRANSCEIVER

- Most radio transceiver systems will have somewhat similar architectures and share common features and problems. All will require some form of:
  - Antennas
  - RF Transmit Amplifiers and RF Receive Amplifiers
  - RF\Baseband Transmit Filters and RF\Baseband Receive Filters
  - Transmitter Modulation and Receiver Demodulation circuits and\or Digital Signal Processing (DSP)
  - Frequency synthesizers and clock generators (Often shared by both Receive and Transmit circuits)
  - DC Power Supplies

- The manner in which each piece is implemented may differ, depending upon:
  - Communications distance required.
  - Operating frequency allowed or required.
  - Type of information to be communicated (voice, data, video, etc).
  - Allowable degree of error (how good\reliable is the recovered data after transmission?)
  - etc.

- The next pages detail a typical Digital Data Transceiver, such as those used to pass data for (among others):
  - WLANs (Wireless Local Area Networks) in pcs.
  - Microwave radio Back Haul links.
  - Campus connectivity.
  - Military communications for high speed data and video.

- Many of the topics discussed for this particular Digital Data Radio would apply to almost any other radio system regardless of operating frequency, modulation type, power level, etc; commonly seen analog voice only radios are a prime example, such as those used by operators of:
  - Amateur Radio or Citizens Band Radio.
  - Public Safety Radio (Police, Fire, Ambulance, Homeland Security, etc.)
  - Transportation Radios (School bus, Taxi, Marine craft, etc.)
  - General military voice only communications' radios.

TYPICAL DIGITAL DATA RADIO TRANSCEIVER

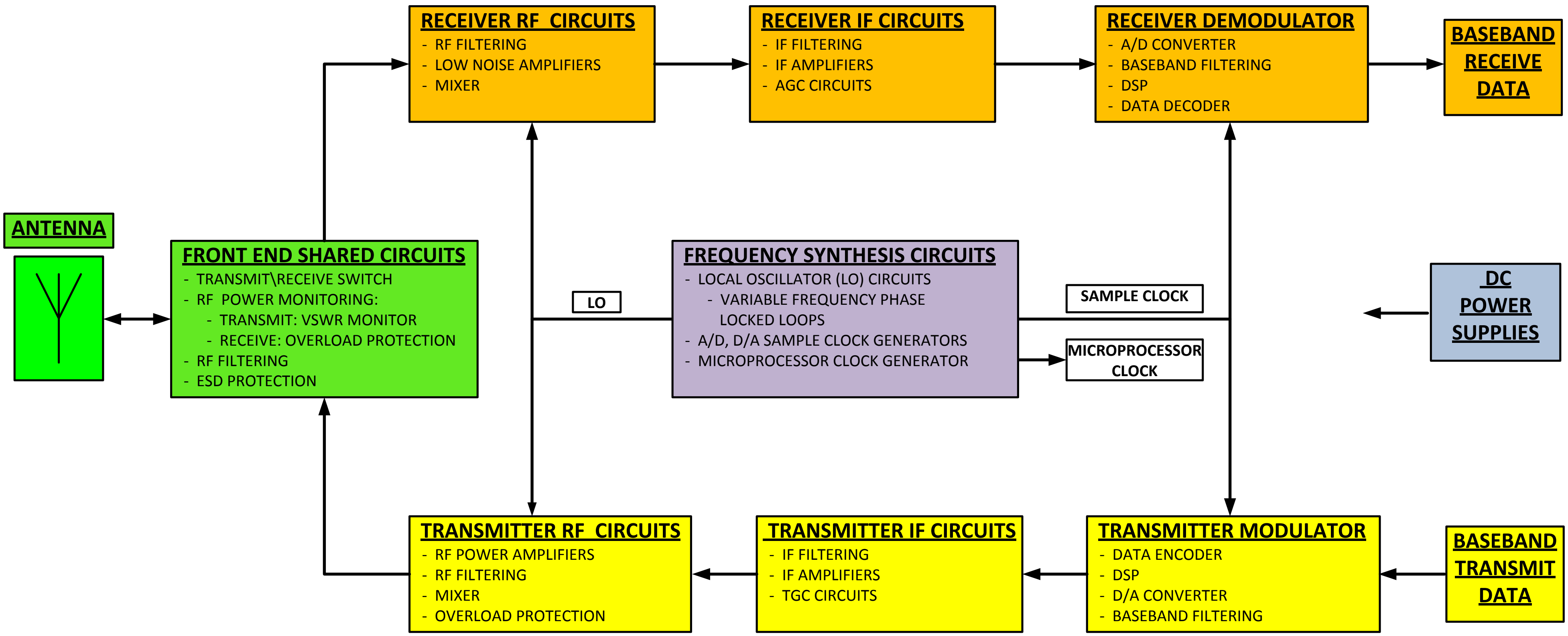


Fig 34
Typical Digital Data Transceiver

TRANSMITTER

- **<u>Transmission Impairments in the RF Power Chain</u>:**
  Transmission range is directly proportion to the amount of RF Power transmitted from the Antenna. Insufficient transmission range is often caused by poor Power Amplifier and/or Antenna design choices, which then could result in needing more powerful Transistor Power Amplifiers in order to develop enough RF power for the transmission range needed.
  This results in higher cost, more wasted heat which must be removed, more pwb space, larger DC Power Supplies, and larger enclosures.

  - **<u>Proper Power Amplifier Path Design</u>:**
    - Minimize losses between the Power Amplifier and the Antenna, such as: Output Harmonic Filter, T/R switch, VSWR Detector, Antenna cable/connectors, and controlling pwb trace and dielectric losses.
      Utilize proper Impedance Matching to the Antenna, in order to minimize reflected (wasted) power.

    - Provide sufficient Power Amplifier linearity for the waveform used. Poor linearity equates to a distorted transmit signal; it will displace the transmitted symbol locations from the ideal locations. At the fringes of reception, a receiver will have a harder time differentiating the symbol locations in the presence of noise, so the transmitter power would have to be increased to give the receiver " a fighting chance" to demodulate the signal properly.

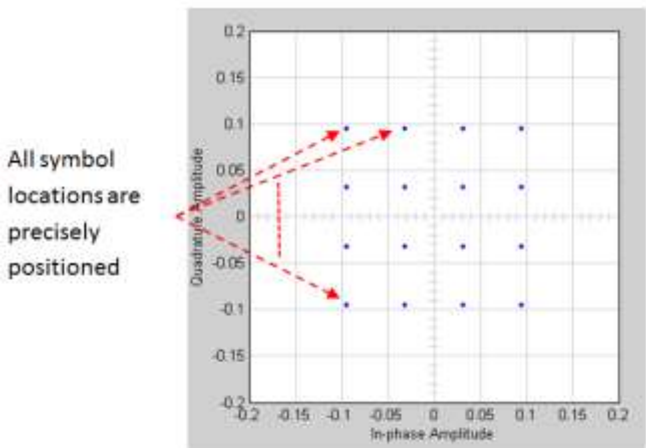


Fig 35
Clean, easy to demodulate 16 QAM signal

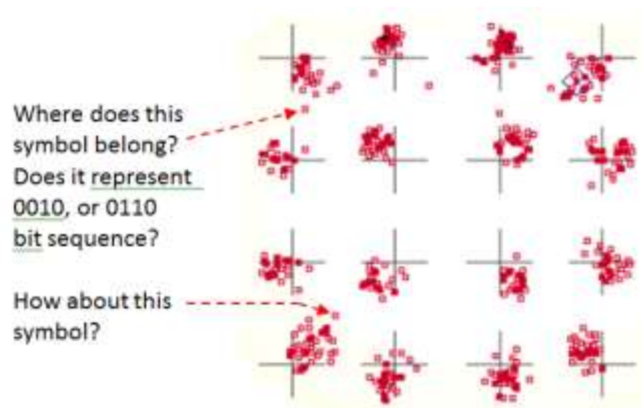


Fig 36
PA Distortion results in a difficult
to accurately demodulate 16 QAM signal

- Design for worse case, not nominal conditions. Devices must be robust enough to reliably produce full, non-distorted power under adverse conditions:
  - Challenging antenna loading conditions (ice, general wear\degradation, etc.)
  - Potentially damaging\weakening degradation due to high voltage spikes. (Static discharge, lightning strikes, etc.)

- **DC Power Supply Impairments:**
  - Design for proper voltage and current under worse case conditions:
    - When transmitters turn on to supply RF power, they typically will draw large slugs of current from the power supply, which can cause the power supply to sag, and reduce its voltage. This will cause less RF power to be transmitted and/or distortion.
    - Design must account for the worst case Antenna VSWR anticipated. Increasing VSWR requires more RF power to be developed, and consequently more DC power must be provided. Increasing VSWR can be caused by:
      - Different antennas being used, with different VSWR values.
      - Inevitable antenna\coax degradation over time due to wear, ice loading, etc.

- **Antenna Impairments:**
  - Maximize efficiency by proper choice of the antenna.
  - Choose proper gain/directivity characteristics for the application.
  - Antenna location, orientation and mounting must be optimized; the higher the better, and proximity to nearby structures must be taken into account and\or avoided.

- **Filters' Responses Issues:**
  - Certain critical filters, particularly in the IF and Baseband DSP Modulator, can distort the transmitted waveform. Group Delay Distortion causes some portions of the waveform to take longer to pass through the filter than other portions. Consequently, the signal at the filter output is distorted because not everything that went in, came out, in the correct time sequence.
    Always choose the proper filtering to match the transmitted waveform's requirements.
  - Band limiting filters in the RF, IF and Baseband paths prevent undesired signals from being transmitted and causing Receiver Demodulation difficulties. Typical sources are switchers, microprocessors, clock signals, dividers, etc.

- **<u>Frequency Synthesizer Issues</u>**:
  - <u>Poor Frequency Accuracy</u>:
    The Transmitter must be on the exact frequency that the Receiver is expecting it to be. This is primarily determined by the master Reference Oscillator, which is typically temperature compensated.

  - <u>Undesired Spurious Generation</u>:
    The Synthesizer must minimize spurious signals which corrupt the transmit signal and make receiver demodulation difficult.

  - <u>Phase Noise problems</u>:
    Poor design results in excessive Phase Noise, a "smearing" of the Transmit Local Oscillator signal that the Receiver interprets as noise, making accurate demodulation difficult and a corresponding high probability of error. (High BER)
    In the plot below, the pink trace is a clean signal, while the blue trace suffers from spurious and poor phase noise.

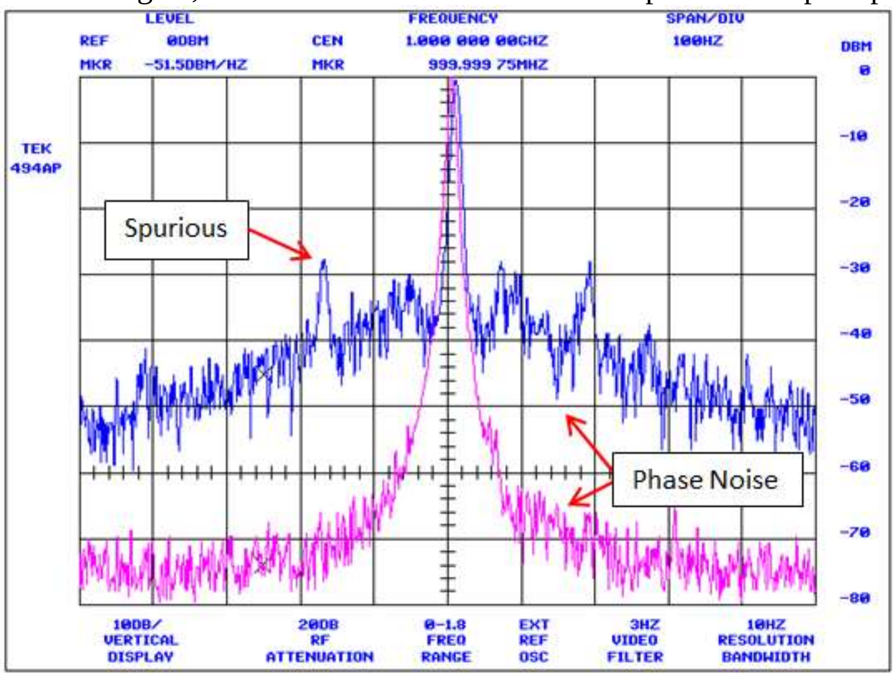


Fig 37
Frequency Synthesizer examples

RECEIVER

- **Insufficient Signal to Noise Ratio (SNR) causing poor Sensitivity and high Bit Error Rate:**
  In order to obtain a desired Receive range (sufficient Sensitivity), it is necessary to have a sufficiently high Signal to Noise ratio (SNR) presented to the demodulator such that the recovered data will have a low probability of error. (Low Bit Error Rate (BER))

  $\text{SNR} = \frac{Received\ Signal\ level}{Noise\ level}$ at the demodulator input. Typical solutions to insufficient SNR include:

  - **Use higher Transmit power.**
    Costly solution, as previously mentioned.

  - **Antenna possibilities.**
    - Could use higher gain and\or directive antennas. However, the system may be cost\space constrained, or may need omni directional coverage, which precludes directive antenna use.
    - Improve impedance matching (lower VSWR) to the Antenna, to minimize reflected (wasted) power (same as for Transmit).

  - **Lower the data rate.**
    This results in an easier demodulation task in a noisy environment, but may not be allowable since it lowers data throughput.

  - **Decrease the Receiver additive noise by lowering the Receiver cascaded Noise Figure.**
    - Reduce losses in passive circuits which generate noise, between the Antenna and the Digital Down Converter. These typically are the antenna cable/connectors, VSWR Detector, T/R switch, RF Filters, and PWB dielectric losses.
    - Use a quieter (lower Noise Figure) Low Noise Amplifier (LNA); any active circuit such as an amplifier will generate it's own noise, making fringe area reception difficult.
    - Use Amplifiers with sufficient gain (at the appropriate NF) in order to boost the RF signal and isolate stages from one another.

- Cascaded Noise Figure can be calculated from the formula below and Fig 38 as a guide:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 G_3 \cdots G_{n-1}},$$

where F_n is the noise factor for the *n*-th device and G_n is the power gain (linear, not in dB) of the *n*-th device. In a well designed receive chain, only the noise factor of the first amplifier should be significant.

NF = Noise Figure (dB) = 10 log F

F = numeric value of Noise Figure = $10^{\left(\frac{NF}{10}\right)}$

Ga = Gain (dB) = 10 log G

G = numeric value of Gain

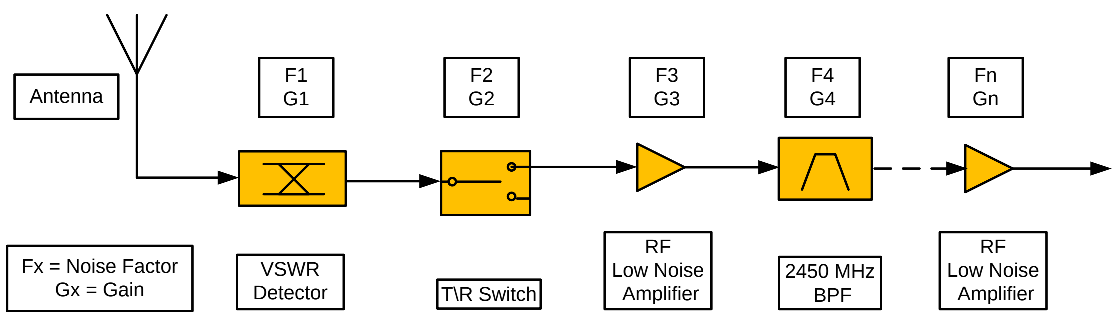


Fig 38 Cascaded Gain and Noise Figure Calculation

- **<u>Use a different type of modulation</u>.**

Each Modulation type has a different SNR requirement; choose one which allows a lower SNR.
Among other things, this may allow using narrower bandpass filters, which then cuts down on the amount of noise that the demodulator sees, thereby increasing Sensitivity.
However, there is a possible impact to hardware\software\cost, and the required data throughput and compatibility with other radios are at risk.

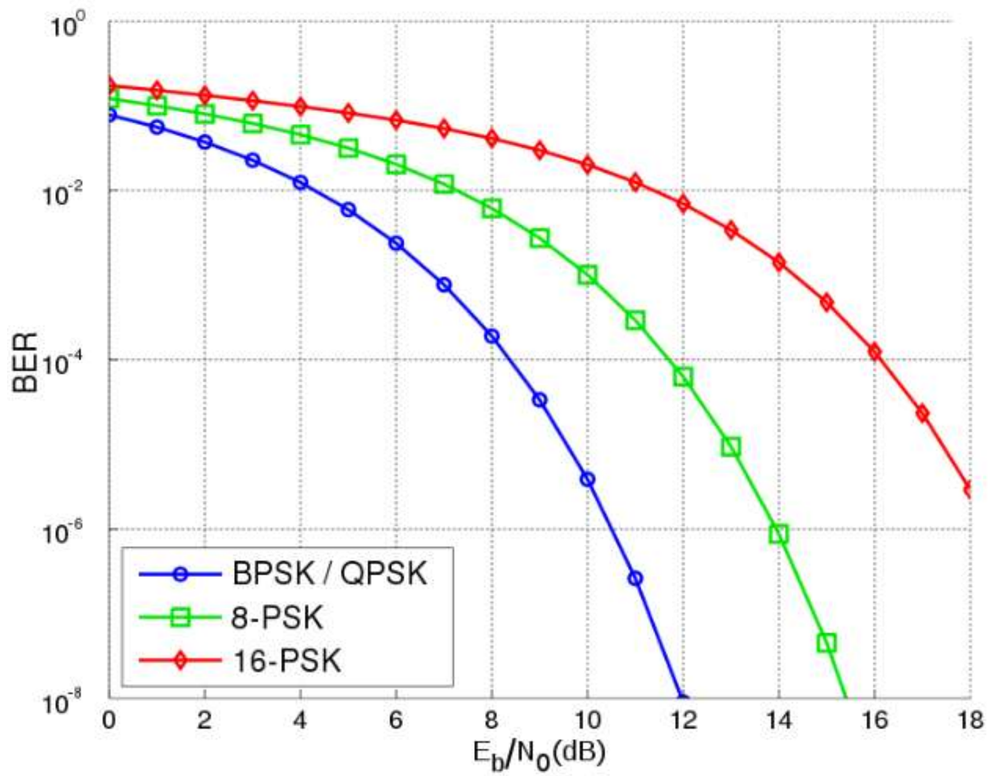


Fig 39
BER Curves Example

- **<u>Filters' Responses Issues</u>**:
  - **Interference Rejection Filters:**
    The Receiver is likely operating in a "hostile" environment; there are probably strong co-located signals that must be rejected, or these undesired signals can block out the ability to hear weak desired signals. Interference rejection filters are mandatory for all but the least critical applications.
    - In the figure below, the desired, low level signal is surrounded by several stronger signals. If these stronger signals are not eliminated, they can overload the various amplifiers and circuits in the signal chain leading up to the ADC, causing the desired signal to be covered up or distorted. The purpose of the RF and IF filters is to reject these undesired signals.

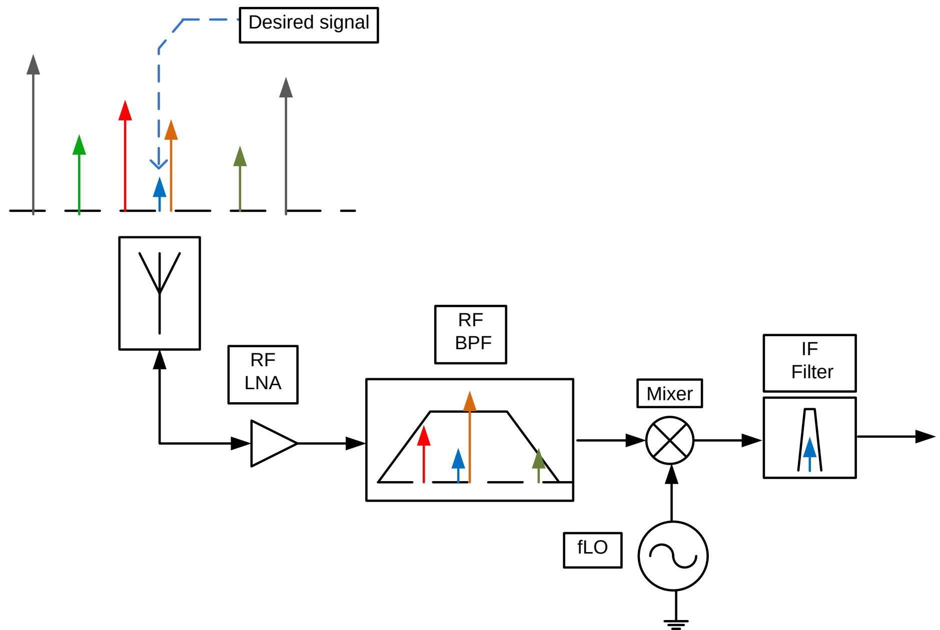


Fig 40
Interference Rejection Example

  - **Group Delay Distortion:**
    Same function and comments as for Transmit apply: Non-uniform time delay of signal components through a filter result in a distorted signal at the filter output. Always choose the proper filtering to match the received waveform's requirements

- **<u>Frequency Synthesizer Issues</u>:**

  - **Must generate "sufficiently accurate and spectrally pure" signals; same issues as for Transmit:**
    - Be on the exact frequency that the Transmitter is on.
    - Present a "clean enough" signal (wrt Phase Noise) for demodulation with a low probability of error.
    - Minimize spurious which corrupt the receive signal and make demodulation difficult.

  - **Prevent Reciprocal Mixing:**
    Excessive Phase Noise will allow the possibility of off channel signals to combine with the Phase Noise.
    In this sense, the Phase Noise acts as a sort of secondary "Local Oscillator" which can allow a strong adjacent channel signal to convert to an IF frequency, reach the demodulator, and mask any desired lower level signals.
    If the desired signal is weak, and the off channel signal is strong, the off channel signal will block the desired signal, resulting in a high probability of error. In the figure below:
    - The wanted RF signal (f1) is converted by the LO (fLO) to produce the IF frequency.
    - However, an unwanted RF signal (f2) can be converted by the phase noise (fn) to produce the same IF frequency.

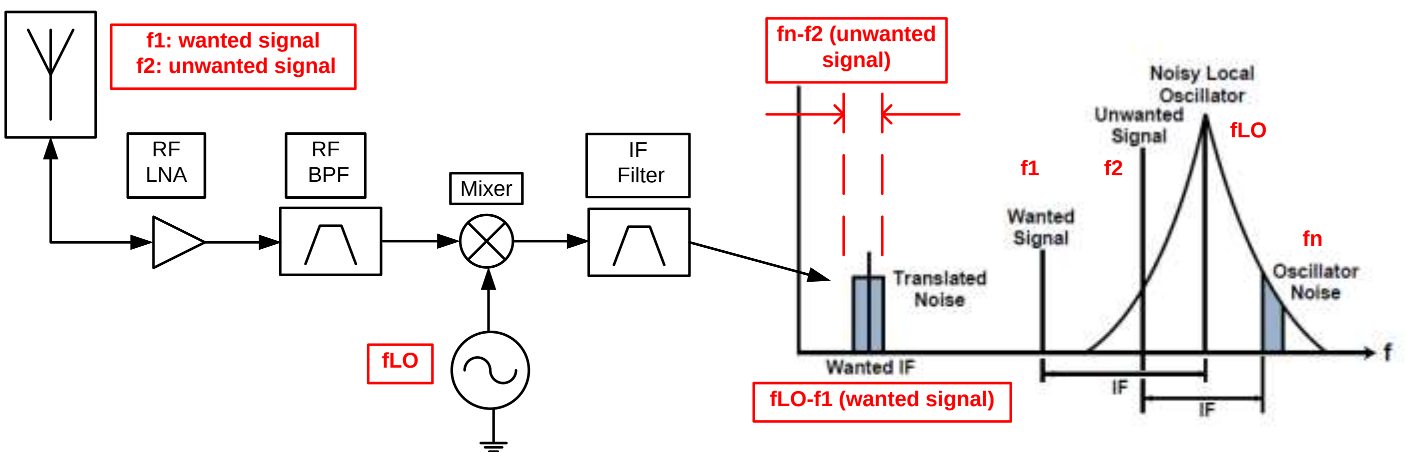


Fig 41
Adjacent Channel\Phase Noise Issue Example

- **Analog to Digital Converters (ADCs) Issues:**

  ADCs sample the analog signal at their input at a specific and precise periodic rate, and convert that signal into a digital word which is then processed by the Digital Signal Processor. Common problems are:
  - Sampling Resolution:
    - Must have sufficiently high resolution (# bits used) to differentiate low level RF signals from random noise.
  - Sample Clock Generator:
    - Must be extremely accurate, so that the analog signal is sampled at the proper instant and the resultant digital signal can be assembled in the correct time sequence.
    - Must be spectrally pure, to prevent any inadvertent signal conversions due to Clock Generator spurious (typically harmonics) from causing interference that block desired signals.

- **Unintentional Spurious Signal Generation Issues:**

  Same comments as in Transmitter section; spurious signals can cover up data and make demodulation difficult.
  Typical sources are switchers, microprocessors, clock signals, dividers, etc.

PROCESS GAIN ENHANCEMENTS

- **Process Gain:**
  Process gain can tend to recover a desired weak signal from the noise, effectively improving the Receiver Sensitivity.
  It must be implemented concurrently in both the transmitter and receiver.
  Two common types, simplistically described:

  - **Direct Sequence Spread Spectrum**:
    - Transmitter sends multiple coded copies of the data simultaneously, spread out in bandwidth.
      The Receiver, knowing the code, correlates the signals and constructively adds the copies together.
      The channel noise, however, is random and uncorrelated and therefore not additive.
      This operation results in a larger SNR at the demodulator.
      It requires large bandwidths which are not allowed on all frequency bands, and only Transmitters\Receivers with the same code can communicate.

  - **Error Correction**:
    - Transmitter includes information about the data, within the data message itself.
      The Receiver can use this extra information to reconstruct data bits lost in transmission due to marginal range.
      If the extra information about the data itself is corrupted, the Receiver can request the Transmitter to resend the message.
      There are data rate throughput penalties because:
      - The extra information sent occupies a portion of the transmission, decreasing the effective data rate of the desired data.
      - Resend\repeat of data takes time away from sending any new data.

COMMUNICATIONS RANGE ESTIMATIONS AND CALCULATIONS

- Range estimations are generally made using computer simulation programs. The programs can be purchased commercially, or can be created using any one of several varieties of math software, or even EXCEL.
  Commercial programs can easily run into tens of thousands of dollars for the highest accuracy programs, to under 100 dollars for programs which may be “good enough”.

  It’s difficult to account for all the impairments that can hinder communications range, and the results have to be taken with a grain of salt. Like anything else, the more the data, and the more accurate the data used in the simulation, the more accurate the result will be.
  The hardest data to obtain is generally that which consists of the propagation path (Multipath, Foliage losses, etc), and companies exist which measure, analyze and sell this sort of data. It’s very difficult to characterize this, and very expensive.
  Often, rough “rules of thumb” and prior experience are used to estimate some of the unknown characteristics.

- Presented below is an example 2.4 GHz range calculation, simulated in an EXCEL program that we use at Vanteon with respectable results. This particular example was for a wireless LAN within a building.

  - The goal is to assure the 100 ft range with a low (1x 10 -6) BER, with at least a 10 dB link (or “safety”) margin.

  - First step is to input the known or anticipated system parameters as shown in the chart, then run the program.

  - If the goals aren’t met, you can play “what if ?” games. What if:
    - The antenna had more gain?
    - The Low Noise Amplifier had a lower Noise Figure?
    - We used different Error Correction, with a higher Process Gain?
    - We place an antenna at a different height, on a different building or hill?

  - The final results show that at 100 feet:
    - The Receiver by itself can adequately hear a signal at -87.7 dBm with sufficient SNR to properly decode data, with a low probability of error (1 x 10-6 BER)
    - The Transmitter and Propagation path would place a signal of -73.4 dBm at the Receiver’s antenna.
      Hence, there is a (-75.4) – (-87.7) = 12.3 dB Link Margin (a safety factor) which is hopefully sufficient to cover anything left out of this analysis.

Specs\Calculation			
- Desired Sensitivity : -83 dBm			- TX Antenna Gain: 5 dBi
- Frequency: 2400-2483 MHz			- TX RF Cable, Connector, VSWR losses: -1.5 dB
- Modulation: 8FSK Eb/No = 16 dB			- RX Antenna Gain: 3 dBi
- Processing Gain (via FEC): 4.5 dB			- RX RF Cable, Connector, VSWR losses: -1.5 dB
- Transmit Power: 27 dBm			- Implementation Loss: 2 dB
- Receiver Noise Figure: 5 dB			- Multipath Loss: - 20 dB
- On Air Occupied BW (99%) : 3.8 MHz			- Fresnel Zone loss: - 5 dB
- Data Rate: 6 Mbps			- Absortive loss (partitions, chairs, etc) : -10 dB
- Communications Distance: 100 feet			- Folliage loss: 2 dB
- BER: Uncorrected, 10^-3. Corrected, 10^-4			- Link Margin: 10 dB reasonable
	Required Input		
Constants	**Value**	**Units**	**Comments**
Speed of Light	3.00E+08	m/s	
Noise Floor	-174	dBm/Hz	Theoretical kTB (1 Hz BW)
System Characteristics			
Data Rate	6.0	Mbps	
BER	0.001000		BER of 10^{-4} (FEC improves to acceptable level)
Signal (RF) Bandwidth	3.80	MHz	
Fmin (@ -10dB)	2.400E+09	Hz	
Fmax (@ -10dB)	2.483E+09	Hz	
Center Frequency (geometric)	2.441E+09	Hz	Entire 2.4 GHz band
Transmit Characteristics			
Transmit Power	27	dBm	
Transmit Antenna Gain	5	dBi	
RF Cable, Connector, VSWR losses	-1.50	dB	
TX EIRP	30.50	dBm	Antenna radiated power
Path Characteristics			
Max Range (Distance)	100.00	feet	
Max Range (Distance)	30.49	meter	
Free Space Path Loss at Distance	-69.88	dB	Using geometric center frequency
Multipath Destructive Interference	-20.00	dB	
Fresnel Zone multipath	-5.00	dB	
Absorptive loss	-10.00	dB	
Folliage Loss	-2.00	2B	
Total Path Loss	-106.88	dB	
Receiver Characteristics			
Receive Antenna Gain	3.0	dBi	
RF Cable, Connector, VSWR losses	-2.00	dB	
Signal Power at Receiver input	-75.4	dBm	Based on path characteristics
Average Noise Power	-108.2	dBm/Hz	kTB floor based on RF bandwidth
Receive Noise Figure	5.0	dB	per hardware design
Required Eb/No	16.0	dB	8FSK
Required SNR	18.0	dB	Calculated
Implementation Loss	2.0	dB	Assumption
Receive Process Gain	4.5	dB	FEC Processing Gain
Minimum Possible Receiver Sensitivity	-87.7	dBm	Calculated (-83 dBm min desired)
Results			
Link Margin	12.34	dB	Received Signal - RCVR Sensitivity (10 dB min desired)

Fig 42 Radio Range Calculator: 2400 MHz Digital Data Radio System

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Tony Manicone is a Principal RF Hardware Designer with 35 years of RF and Microwave design experience in Receiver, Transmitter, and Frequency Synthesis circuitry.
Currently at Vanteon since Feb 2011, he was been employed previously at:

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- Microwave Data Systems (a division of California Microwave at the time)
- ENI Power Systems (a division of Emerson Electric at the time)
- Clearwire Corporation

Tony holds:

- BSEE in Electrical Engineering from the Rochester Institute of Technology, and an MSEE from the University of Massachusetts at Amherst.
- 5 patents in radio design
- FCC 1^{st} Class Commercial Radio license and an Advanced Class Amateur Radio license.