Fundamentals of a RF Design
White Paper

Abstract:

This paper discusses the RF design fundamentals of an RF communication system, including the transmission medium, wave propagation, free space path loss, the transmit and receive portion, link design and key components with the intent to provide practical knowledge on the process for designing an RF system. In addition to the RF communication system and RF fundamentals, an overview of the test equipment and what to consider during the design, development, and verification process is provided.

White Paper
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1 A Simplified Communication System

Looking at the basic blocks of a typical communications system (Figure 1), at a minimum the system will include an information source, information processing, a transmitter, a transmission medium, a receiver, information processing again, and an information destination.

The information processing is the process of taking the source information and putting it into a format that can be transmitted over whichever medium is required. In a wireless or RF system, we are typically communicating through free space or air, as opposed to through a wire or a fiber network.

In early applications, it was more common to have a one-way path for the RF signals in RF design. Radio and television are good examples of the one way path as large antennas transmitted signals one way to the radios and televisions. Today data is the major part of the communicated information where there is a two-way path for the RF signals. Mobile smart phones are a great example of a device, which can both transmit and receive data.

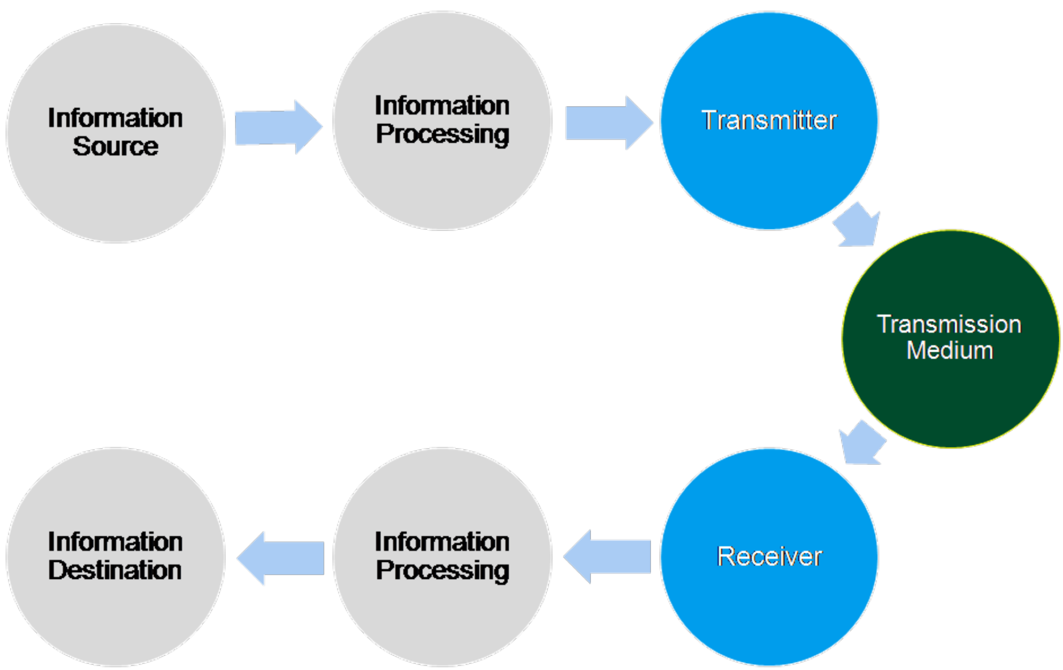


Figure 1: Simplified Communications System Block Diagram.

2 RF Fundamentals

In the early days of wireless communications, most signals were sine waves. A sine wave can be represented with a frequency, an amplitude, and a phase.

$V = A\sin(\omega t + \varphi)$

Where A = amplitude
$\omega = 2\pi f$, where f is the frequency
φ = phase

Figure 2 shows two signals in the time domain. In terms of our communications, the intent is to send information from a source to a destination by modifying these sine waves. It is more common to have more complex digital signals today.

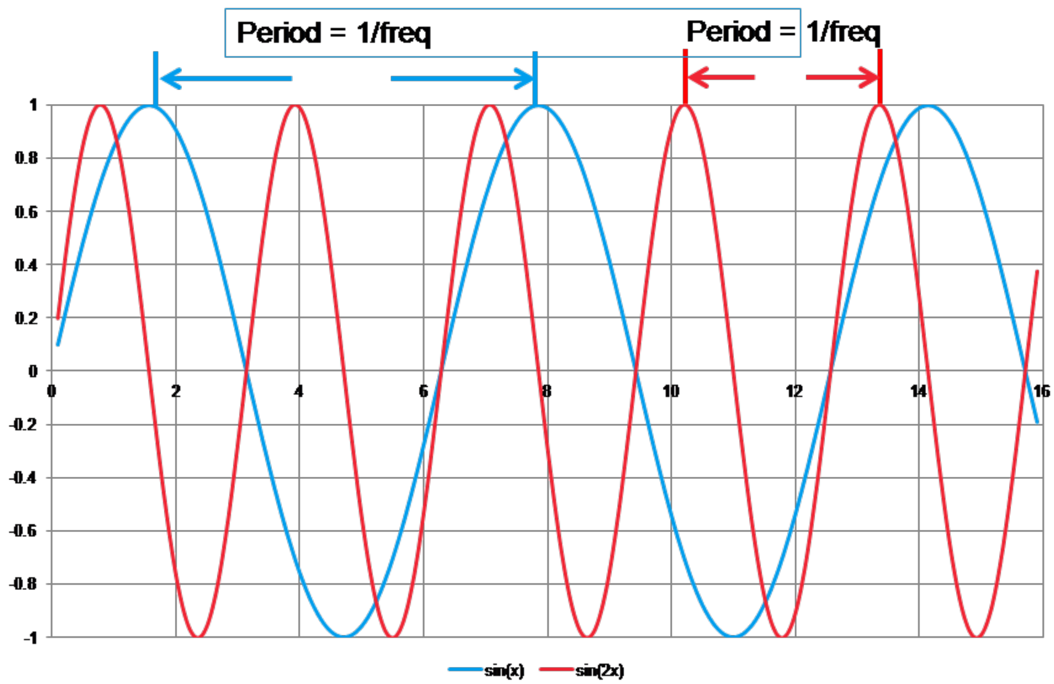


Figure 2: Basic sine waves carry information by varying their frequency, amplitude, and/or phase.

Typically, in terms of RF and microwave signals, we tend to look more in the frequency domain than in the time domain. Figure 3 shows a basic signal on a spectrum analyzer display. With the transmitted signals becoming more complex, modulated signals or signals with more information put on them, spectrum analyzer displays are better for understanding the multiple frequencies and modulation techniques.

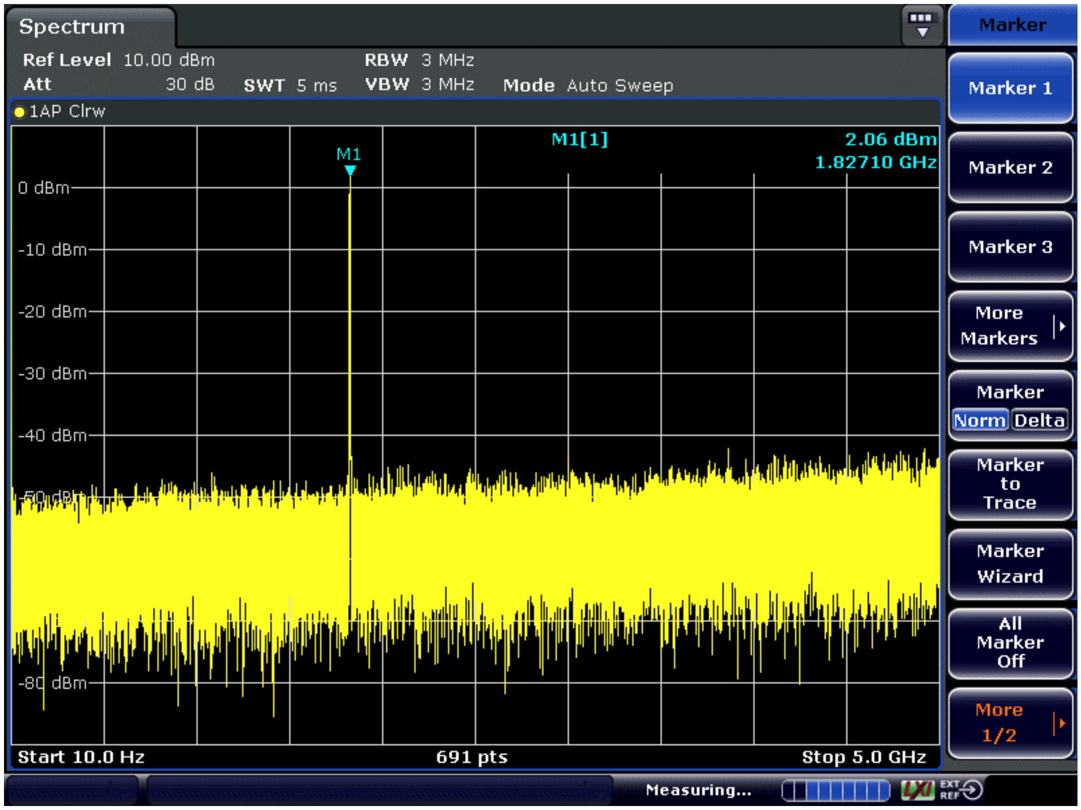


Figure 3: Spectrum analyzers are excellent tools for evaluating transmitted RF and microwave signals.

2.1 Spectrum Allocation

The Federal Communications Commission (FCC) defines and allocates the frequency spectrum in the United States. Similar government bodies around the world do the same for their countries and regions. Figure 4 shows the spectrum allocation chart for the US.

The local governing body, such as the FCC, decides who gets to transmit over each frequency, and at what power levels and how much bandwidth they get to do it with. When designing a wireless system, all radiating devices must adhere to their portion of the frequency allocation table. Many aspects of the spectrum frequency allocations have been defined for a long time. Other areas, such as the old analog TV bands are becoming available as countries are moving to new digital TV bands. It is important to note that the spectrum allocation varies across countries. For instance, emergency responder equipment from one country may not work in another country. Commercial wireless solutions like Bluetooth and Wi-Fi must be carefully coordinated among countries and manufacturers to ensure devices work in different regions.

Figure 4: The United States Frequency Allocations. Each country or region defines and allocates the frequency spectrum for use by various groups and applications.

3 Modulation

A basic definition of modulation is any detectable change in a signal's characteristics that can be used to carry information. The carrier wave is a waveform that is modulated for conveying the information, and typically is at a much higher frequency than the input signal. The purpose of the carrier is to transmit the information through space as an electromagnetic wave.

Figure 5 shows the basic characteristics of a sine wave in the time domain. The two example signals repeat their pattern based on the inverse of the frequency or period, which we call Omega (ω). The amplitude has a maximum peak amplitude of one or minus one. By varying the phase (φ) the signal can be shifted left or right.

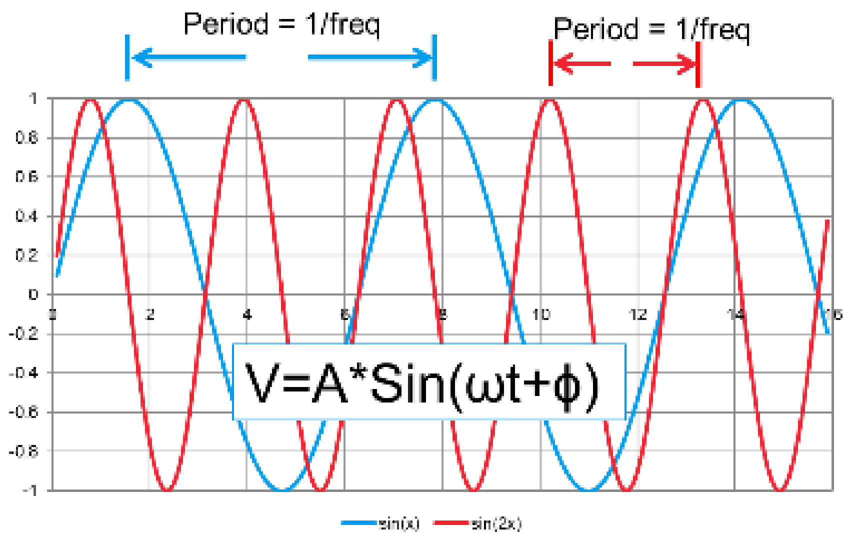


Figure 5: Simple analog signals in the time domain.

Modulation is achieved by changing the amplitude, the frequency, the phase or some combination of these three. The basic types of analog modulation include amplitude modulation, frequency modulation, and phase modulation (Figure 6). The Amplitude Modulation (AM) example shows a very fast varying sine wave and on top of which you can see an additional change in amplitude. This slower changing amplitude variation contains the information that is being sent over the carrier wave, which will be detected at the other end of the radio link.

Frequency Modulation (FM) is typically used in applications that require better fidelity as they have less problems with noise. Common applications include the car radio and satellite communication. In the example shown, the sine wave varies in frequency while maintaining a fixed amplitude.

Phase Modulation (PM) is more commonly used in data transmissions. The example in Figure 6 shows discreet changes in the signal as the phase changes. Common applications include cellular communications as well as wireless LAN (WLAN).

Today, modern digital communication signals use complex combinations of these techniques for both improved signal quality and increased data throughput.

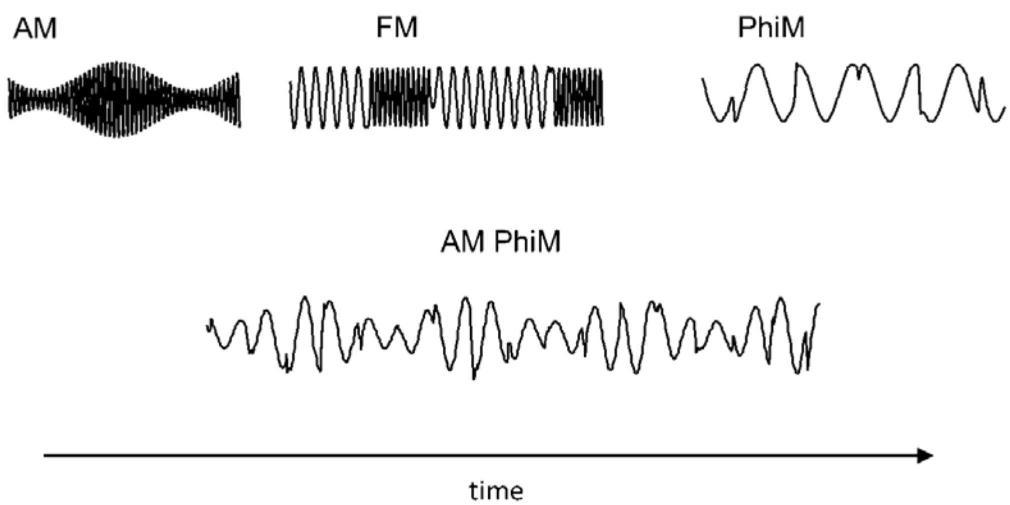


Figure 6: Basic types of analog modulation.

3.1 Wavelength Matters

Frequency is a critical parameter in RF design. Early applications were focused on audio frequencies, now referred to as analog systems most of the time. While there are still plenty of audio devices in use, there has been a broad increase of RF applications such as mobile phones, Bluetooth devices, and Wi-Fi. Today, many commercial applications also use microwave and even millimeter wave frequencies.

Table 1 highlights the fact that as the frequency increases, the wavelength decreases. The effects of wavelength on a design can have implications on both design complexity and the cost of the product. Let us first look at how to determine the wavelength:

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

where λ = wavelength
v = phase velocity, which in free space is 3x108 m/s
f = frequency

Application	Frequency	Wavelength (metric)	Wavelength (English)
AM Radio	1000 kHz	300 m	968 ft
FM Radio	100 MHz	3 m	9.7 ft
Wi-Fi, 802.11	2.4 GHz / 5 GHz	125 mm / 60 mm	5.9 in / 2.4 in
Automotive Radar	77 GHz	4 mm	0.15 in

Table 1: Examples of wireless applications and their wavelengths.

How does wavelength affect the RF design? When you consider the size of a device relative to wavelength, the physical geometry may become an important consideration. From the signals in Figure 5 we see that the sine wave starts at zero, increases to a maximum, decreases to zero, decreases to a minimum, and then increases to zero across a single wavelength. From Table 1, we can see that at audio frequencies this happens across a distance of meters to hundreds of meters. The phase effects of moving through a typical analog device are therefore minimal. However, as you move into RF frequencies or higher, the effect of these phase variations become a design consideration. Certain circuit design techniques take advantage of $\lambda/4$ and $\lambda/2$ effects to optimize or cancel signals, which is one way to minimize the effects reflections and interference.

3.2 Reflections and Interference

As the sine wave propagates down a transmission line or a cable, what happens when it hits a discontinuity or some change in impedance? This typically occurs at a connector or a solder point, or even changes in the widths of a transmission line. Figure 7 shows a signal that is propagating down a transmission line and hitting a discontinuity represented by a green box. While some percentage of that signal will pass through the green box, some of the signal will be reflected back through the transmission line.

This reflected signal will add in and out of phase depending on the phase of the signals. The red sine wave that is reflecting back could be completely out of phase with the incoming signal and could actually cancel out the signal. These effects need to be analyzed and mitigated when designing your transmission lines and circuit boards at higher frequencies.

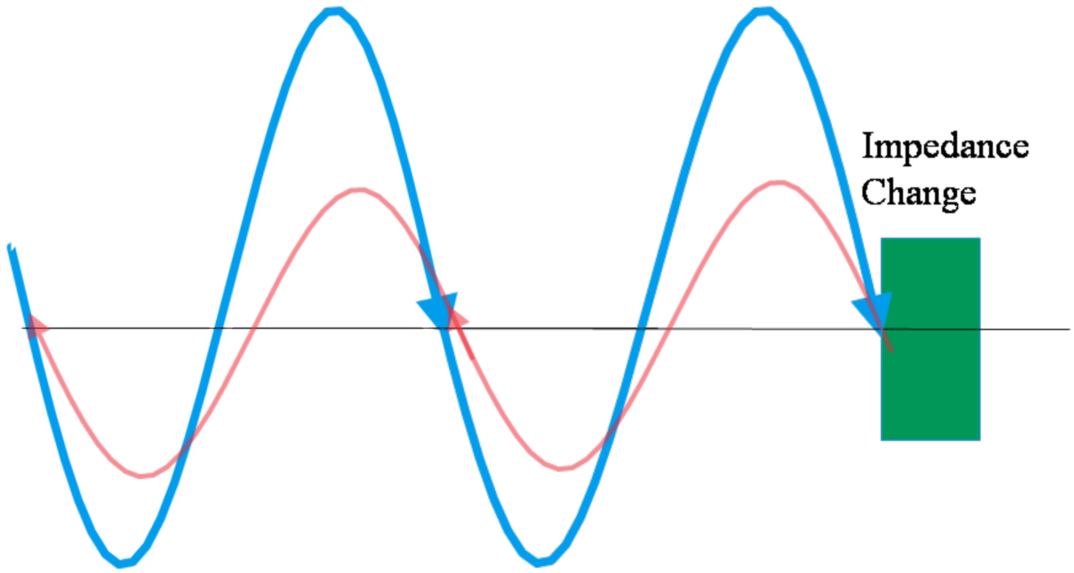


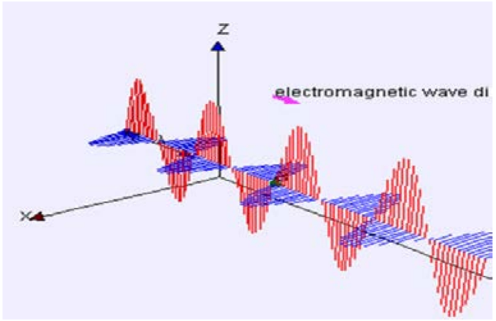
Figure 7: Discontinuities in transmission lines often cause reflections, which create new signals that may interfere with and distort the desired signals.

4 Wave Propagation

A simple way to perceive wave propagation is remembering the effect of a pebble being dropped into a pond (Figure 8a). Concentric rings of waves propagate out from where the pebble enters the pond. Dropping a pebble at a constant rate would generate continuous waves propagating through the pond. In this case, the propagation is considered a mechanical wave, because it is not propagating through free space or a vacuum, as we are moving molecules around in the water. Another great example of a mechanical wave is a sound wave. When you speak or sing, the vibrations of the air is causing the noise.

In the case of electromagnetic waves, we are varying the electrical and magnetic fields as it propagates through space (Figure 8b). The electric and the magnetic fields are varying over time as they propagate, in a very similar manner to how the wave propagated through the water.

(8a) Mechanical waves.



(8b) Electromagnetic waves.

Figure 8: Wave Propagation

Frequency and wavelength are important attributes to distinguish electromagnetic waves (Figure 9). Lower frequency signals, such as AM radio, are in the kilohertz (kHz) frequency range – that is thousands of cycles per second. FM radio is in megahertz (MHz), which is millions of cycles per second. If we consider how big a wavelength is at these frequencies, they are in the order of magnitude of the size of a building or humans. As frequencies increase, the wavelengths get smaller. At microwave frequencies, a wavelength is in the order of a honey bee or a pinhead. From infrared all the way to x-ray frequencies, the wavelengths continue to get smaller. This gives an indication of what size an antenna or radiating element needs to be in order to generate a given wavelength.

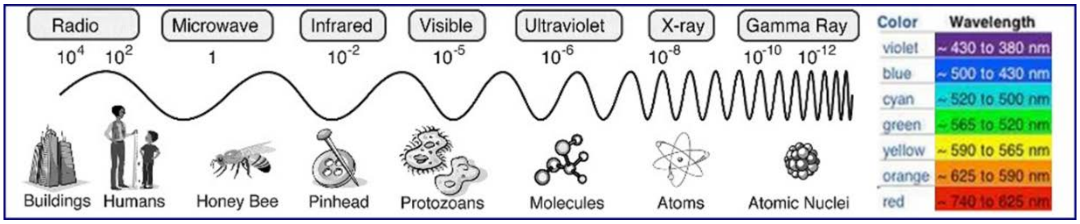


Figure 9: Frequency and wavelength across the electromagnetic spectrum.

5 Free Space Path Loss (FSPL)

Microwave theory often discusses isotropic antennas, which propagate equally in all directions. A signal transmitted by an isotropic radiator into free space will propagate outwards in the form of a sphere ($A = 4\pi d^2$). As the sphere expands, the intensity of the signal over the surface area of the sphere decreases as per the inverse square law (Figure 10).

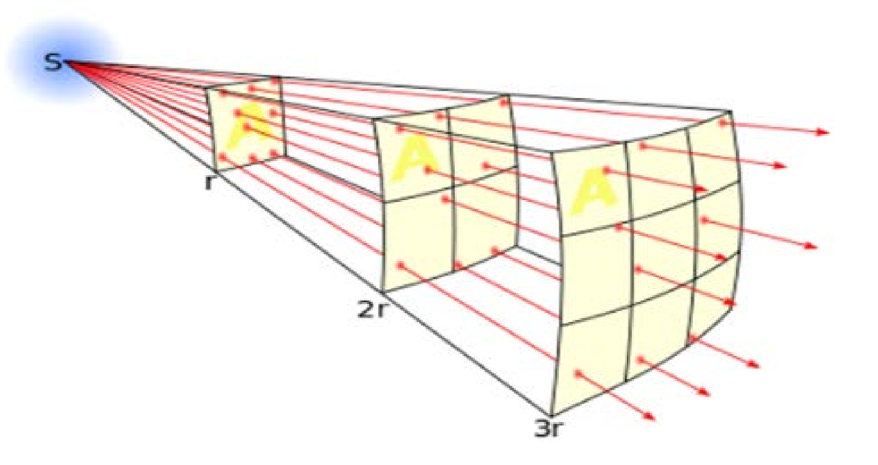


Figure 10: Free Space Path Loss (FSPL) increases over distance.

The Free Space Path Loss (FSPL) calculates loss of signal strength (attenuation) as a function of distance and frequency. It assumes an unobstructed path and co-polarized antennas. Thus, FSPL increases with increasing distance.

$$S = P_{tx} \frac{1}{4\pi d^2}$$

Where:

S = power density
Ptx = total radiated power
d = distance from antenna (radius of sphere)

Free space path loss is a calculation, not a measurement. Free space path loss (attenuation, A) is computed between isotropic antennas using the following equation.

$$A = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

The equation can also be re-written in decibel form as.

$$A = 32.4 + 20\log d + 20\log f$$

Where:

f = frequency in MHz

d = distance in meters.

These formulas can be found in ITU-R P.525-2 “Calculation of Free Space Loss”. Note that free space path loss calculations are only applicable in the far field.

Since FSPL increases with frequency, a common misconception is that free space attenuation is frequency-dependent. Although physical objects often exhibit frequency-dependent attenuation, FSPL is a free space calculation (i.e. no objects). FSPL is frequency-dependent because the effective aperture (Ae) of the receiving isotropic antenna changes with frequency. As frequency increases, effective aperture decreases. Therefore, path loss increases with increasing frequency.

$$A_e = \frac{\lambda^2}{4\pi}$$

In many cases, the Earth’s atmosphere can be considered “free space.” However, at some frequencies path loss can be influenced by both water and oxygen molecules in the atmosphere. At specific frequencies, the molecules of water and oxygen in the air resonant, which causes increased attenuation of the transmitted signals. This loss is frequency dependent, with significant attenuation peaks at certain frequencies (Figure 11). Note that in Figure 11, the first water vapor peak is at 22 GHz and the first oxygen peak is at 63 GHz. In many applications, these frequency ranges are carefully avoided. However, some applications, choose to operate at these frequencies to minimize interference or increase security.

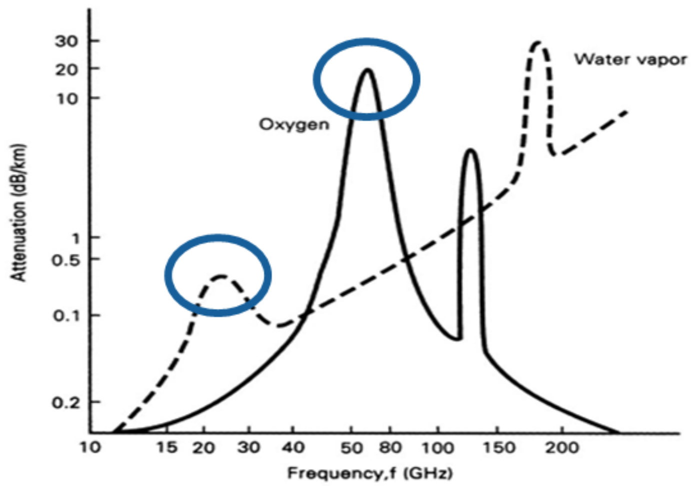


Figure 11: "Free Space" and the Earth's atmosphere.

5.1 Determining Power Using dBs

Typically signal levels for RF and microwave applications are discussed at the power level and not as voltages and currents. The power in watts is often converted into logarithms or decibels (dB).

Back in the early days calculators and spreadsheets did not exist. In order to manipulate signal levels quickly they started using dBs because you can simply add things. Rather than multiplying a ratio of 108 times 106 and factoring losses of 104, the logarithmic components can simply be added. If you know the losses of your components or gain from an amplifier, one can simply add them up to get an estimated signal level.

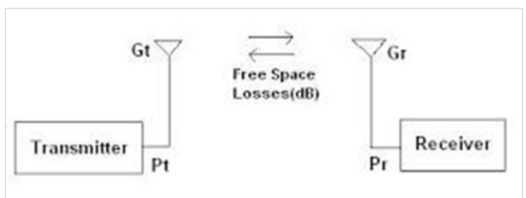
dB	power ratio	amplitude ratio
100	10 000 000 000	100 000
90	1 000 000 000	31 620
80	100 000 000	10 000
70	10 000 000	3 162
60	1 000 000	1 000
50	100 000	316.2
40	10 000	100
30	1 000	31.62
20	100	10
10	10	3.162
3	1.995	1.413
1	1.259	1.122
0	1	1
-10	0.1	0.316 2
-20	0.01	0.1
-30	0.001	0.031 62
-40	0.000 1	0.01
-50	0.000 01	0.003 162
-60	0.000 001	0.001
-70	0.000 000 1	0.000 316 2
-80	0.000 000 01	0.000 1
-90	0.000 000 001	0.000 031 62
-100	0.000 000 000 1	0.000 01

Table 2: Power levels are easier to determine using dBs.

6 System Design Blocks

Taking a look at the key system blocks in a modern RF communication design let's start with the transmitter, which is our information source. Next is the antenna, which is physically designed relative to the wavelength of the signal so that a standing wave on that antenna will allow propagation through space. The receiver side also has an antenna and amplifies the signal to a usable level and then the information is processed.

How far away are the transmitter and receiver antennas? How much antenna gain is needed? How sensitive does the receiver need to be? What are the government restrictions, if any, on the frequency, bandwidth, and power level? There are many considerations, which will influence the ultimate design needs of the communication system. Table 3 highlights several key considerations that will influence your RF design.



Link budget?
- **How big a signal do I need to transmit?**
- **How good a receiver or LNA do I need?**
- **What kind of antenna do I need?**

Where from to?

What does environment look like?
- **Weather**
- **Obstacles**
- **Direct Line of Sight**
- **Spectrum**

- **What am I sending**
  - **Real-time**
  - **How fast**
  - **How much data**
  - **Am I moving, stationary, how fast**
- **Physical limitations**
  - **Size**
  - **Weight**
  - **Power**

Table 3: Potential RF Design Considerations.

6.1 Transmitters

Figure 12 shows a high-level view of the key components that make up the transmit side of a communication system. First the multiplexer is used to route the desired information into the transmit path. To condition the signal for transmission we add signal processing. Next, the signal is modulated into whatever modulation scheme the application requires. This may have been Amplitude Modulation (AM) or Frequency Modulation (FM), but today there are a wide range of digital modulation schemes with many based on Orthogonal Frequency-Division Multiplexing (OFDM) techniques.

Up to this point the signal is typically at a very low or baseband frequency. A frequency converter is used to mix the transmitted signal up to the frequency that has been allocated for the particular application. The signal level is then increased to the appropriate power level using an amplifier. Next, the signal is passed through a filter to make sure a clean signal is transmitted and that the signal stays within the allocated frequency band. Finally, the signal is radiated through the air via an antenna.

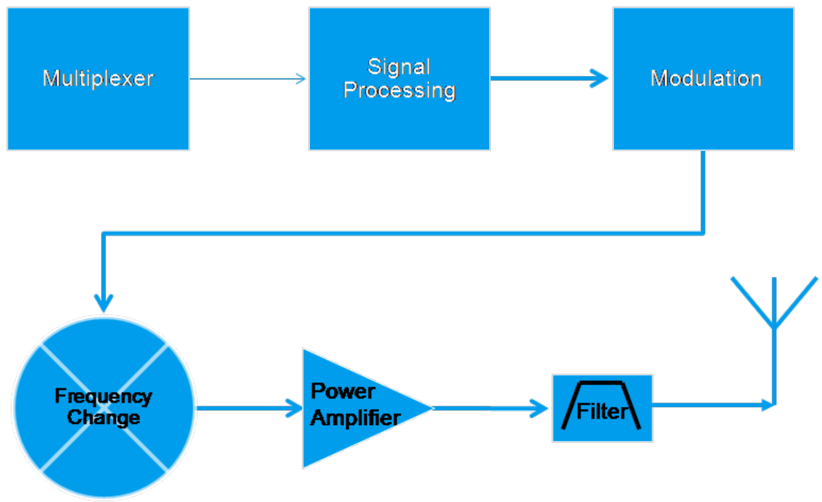


Figure 12: Simplified transmitter block diagram.

7 Receiver Overview

A receiver has similar components to a transmitter, but in the opposite order (Figure 13). The signal is received by the antenna, then runs through a filter to eliminate, or greatly reduce, signals outside the frequency band of interest. Incoming signals often have a low power level so a Low Noise Amplifier (LNA) is used to raise the desired signal above the noise floor. After this, the signal is then down converted to a lower frequency or baseband frequency where it is demodulated, processed and directed to the appropriate signal path for the received information.

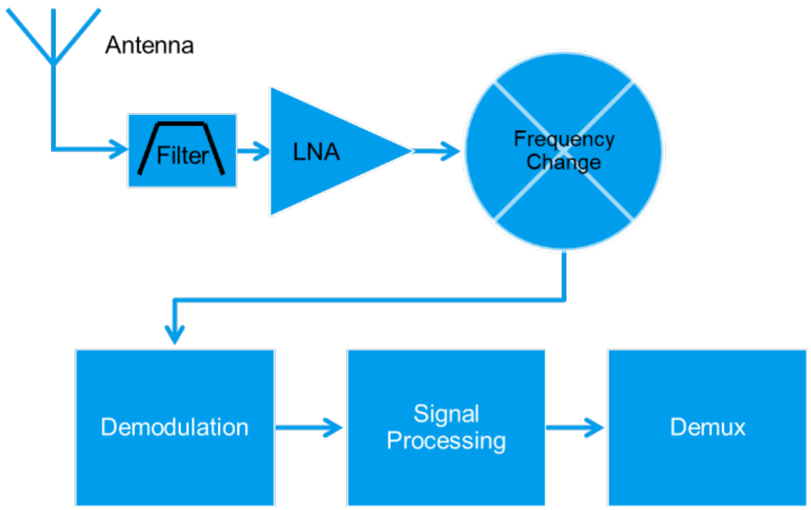


Figure 13: Simplified receiver block diagram.

Figure 14 shows what the receiver's frequency spectrum looks like. Mixing the RF signal and the LO signal, generates the IF or audio signal as shown. Image signals are also generated, which are copies of the RF and IF signals. The effects of these undesired signals are removed by using a filter around the desired signal frequencies.

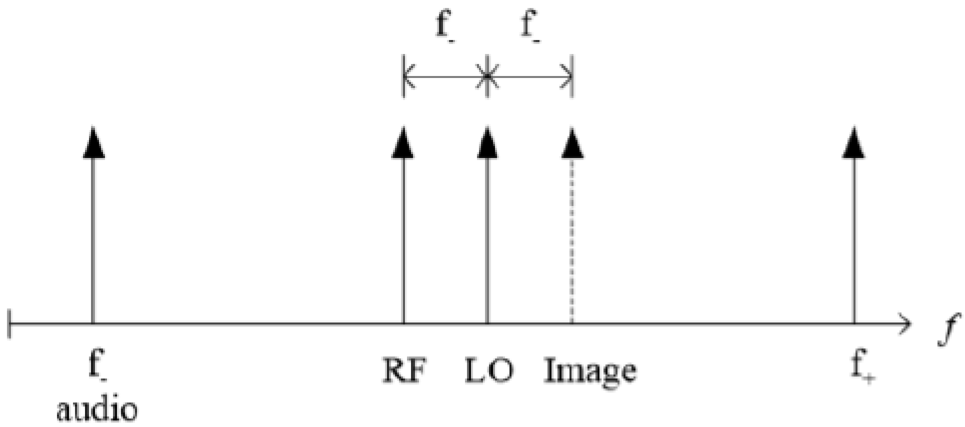


Figure 14: Simplified receiver spectrum.

In the real world, most receivers have a lot more complexity. Figure 15 shows a typical block diagram of a superheterodyne receiver. In this configuration, the first stage tunes the RF frequencies with RF components as described above (filters, amplifiers, mixers, LO). This stage provides some initial selectivity, suppresses the image frequency and prevents strong out-of-passband signals from saturating the initial amplifier. A local oscillator provides the mixing frequency; it is usually a variable frequency oscillator, which is used to tune the receiver to different frequencies. The first stage outputs the incoming RF signal to a higher or lower, fixed, intermediate frequency (IF). This second stage provides the IF band-pass filter for the narrowband filtering for the radio. The mixer outputs the audio or other modulation from the IF radio frequency, which can then be extracted for amplification by the audio amplifier.

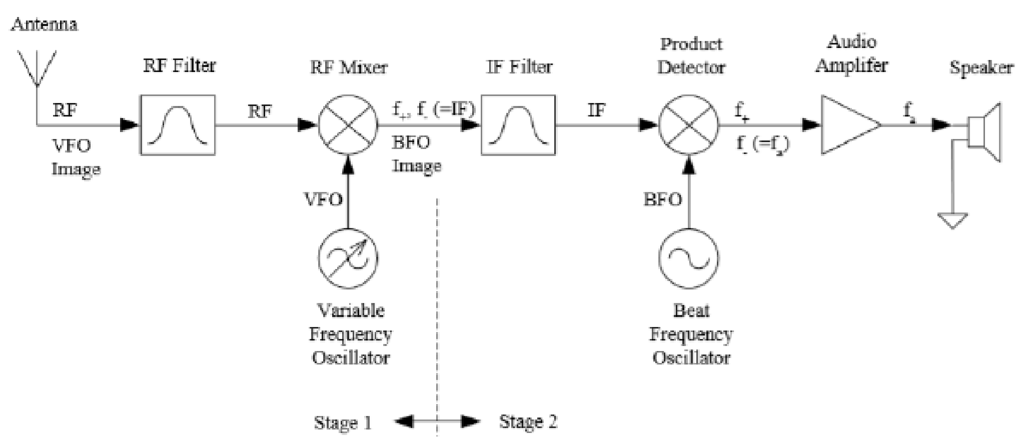


Figure 15: Superheterodyne receiver.

Figure 16 shows what the Superheterodyne receiver's frequency spectrum looks like. By breaking up the receiver functions into two stages it focuses the design at both the RF and IF bands, which allows for optimizing performance.

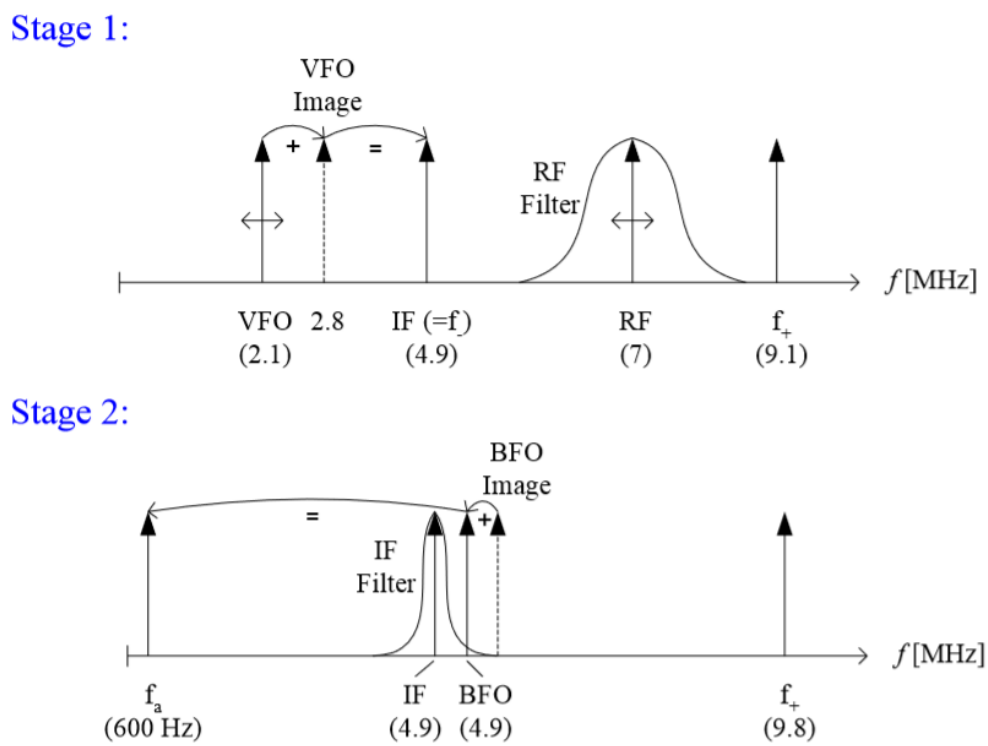


Figure 16: Superheterodyne receiver spectrum.

8 Antennas

An antenna is a device for converting an electrical power into a radio wave, which then propagates through free space (Figure 17). This is the mechanism to deliver the generated signal through free space captured on the other end by another antenna. The receiving antenna converts that electromagnetic wave back into a small voltage, which can then be amplified and decoded to get the transmitted information.

Figure 17: Antennas convert electrical power into radio waves and vice versa.

How do antennas generate the electromagnetic waves? If you remember, opens and shorts in circuits create reflections. By designing the geometry or the size of a circuit, we can generate a standing wave at a specific frequency (or range of frequencies). The length of conductor is typically a half a wavelength and it generates an electromagnetic field due to this resonance. Therefore, antenna sizes are dependent on frequency (or wavelength) and is the reason why low frequency antennas are very large.

Figure 18 shows an example of a standing wave on a half wave dipole being driven at its resonant frequency. The waves are shown graphically by bars of color (red for voltage (V) and blue for current (I)) whose width is proportional to the amplitude of the quantity at that point on the antenna.

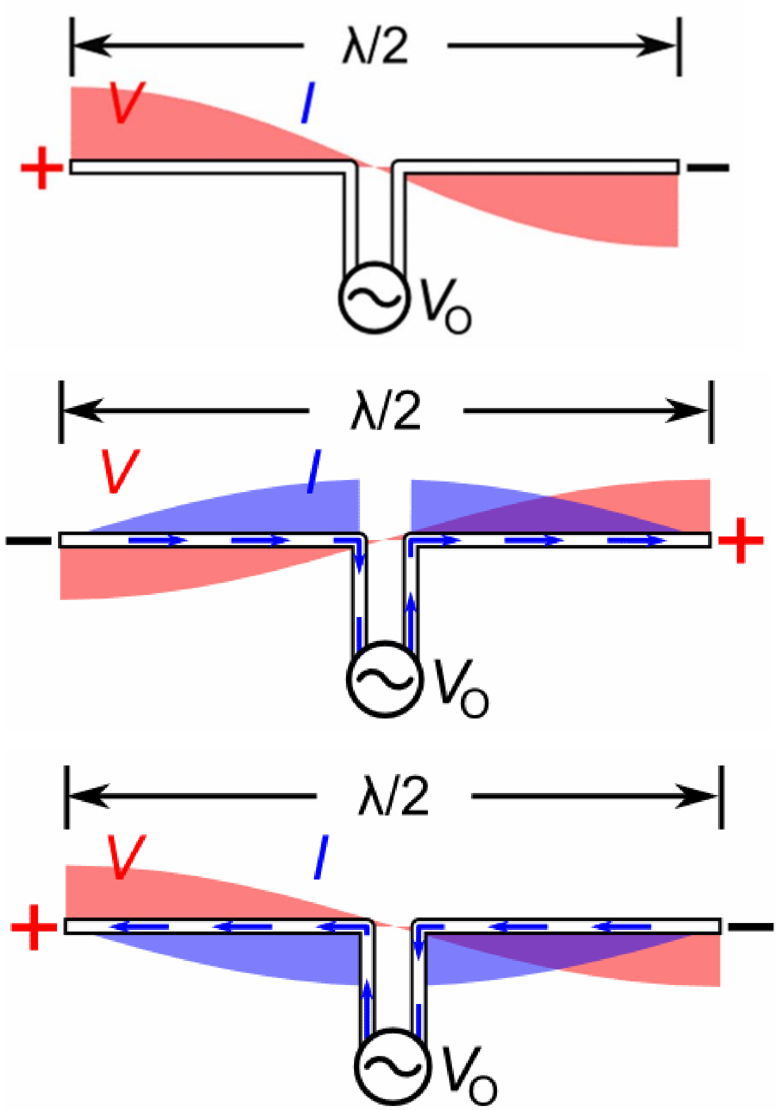


Figure 18: Propagation occurs when a half wave dipole is driven at its resonant frequency to create standing waves.

Again, microwave theory assumes that an isotropic antenna propagates equally in all directions. In reality, we often want an antenna to radiate the majority of its signal in a given direction. Gain or directivity are antenna specifications that tell how much an antenna transmits in a given direction relative to an isotropic antenna. Beam width is another specification that defines an angle range in which one can expect the antenna signal to meet the gain specification. Beam width is specified as the angle on either side of the signal peak that is reduced 3 dB from the peak.

As we discussed (and shown in Figure 8b), radio wave signals have both an electric and magnetic field component. For antennas, this translates into them having two polarizations, which are referred to as vertical and horizontal polarization. Each pattern can be measured by rotating the antenna under test by 90 degrees. It is typical for antennas to have different beam patterns depending on its orientation or polarization (Figure 19).

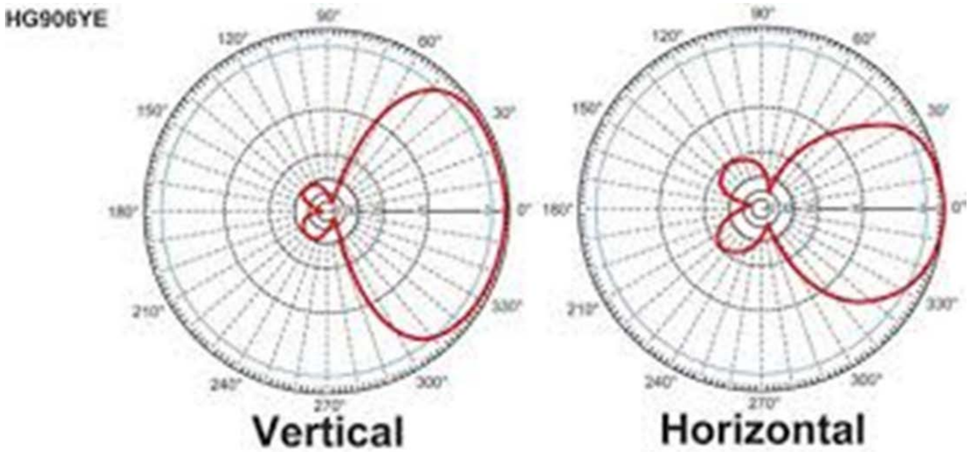


Figure 19: Antennas patterns measured in both polarizations.

Note the smaller little circles you see in the back of the antenna patterns, these are called side lobes. Unfortunately, just like in any engineering problem, real world antennas radiate some energy in undesired directions. Antenna design engineers often spend time trying to minimize the impact of these side lobes.

9 Designing a Link

Taking what we have discussed let's put this into a system to design a link. Remember, the objective is to send a signal from one place to another through the air. While most systems today have the ability to both transmit and receive, for simplicity sake let us assume a one-way path (Figure 20). On the transmitter side, we create the signal and radiate that signal from the transmit antenna over to a receive antenna and its receiver.

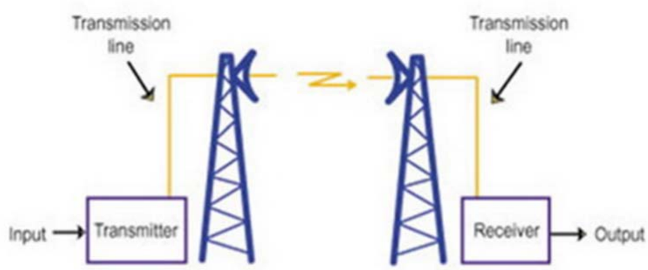


Figure 20: Designing a link.

When designing a link, there are many aspects to consider like what is the frequency and how about power levels and frequency bandwidth? While much if this information is defined in the regulation standards for a given technology there has to be an allowance for design considerations related to the requirements of the link being established. Is it point-to-point or one-point-to-many? What is the terrain like? What distance? Table 4 highlights some of the many factors that need to be considered when setting up a system. Given these parameters, we can put together a link budget to determine what is possible.

What is the frequency of operation?
How big of a signal is needed for transmit?
Point to point or to multipoint
Over what distance is required to transmit (Range)
What kind of antenna is needed?
How much margin is needed in the link budget?
Can the system lose signal for brief periods of time?
Where does the power come from and how much is available?
What else is required by the standards and governing bodies?

Table 4: Link Design Considerations.

The FSPL equations assume isotropic radiators with unity antenna gains at both ends. In practice, the gain of the transmit (Gtx) and receive (Grx) antennas are often added to the FSPL equation. Antenna gains (Gtx and Grx) are relative to an isotropic radiator (dBi).

$$A = 32.4 + 20\log d + 20\log f - G_{tx} - G_{rx}$$

Let us consider an example calculation using a GPS application. A GPS satellite at 20200m transmits its L1 signal (1575 MHz) at 50 watts using an antenna with 13 dBi gain. What is the received signal strength on Earth using an antenna with 3 dBi gain?

A = 32.4 + 20 log (d) + 20 log (f) - Gtx – Grx

A = 32.4 + 86.1 + 63.9 – 13 – 3

A = 184.4 – 16

A = 168.4 dB

Since 50 watts = 47 dBm, the received signal level should be approximately -121.4 dBm (= 47 – 168.4). Note that FSPL is usually a very good approximation for satellite systems.

On the internet there are several link budget calculator tools and other design resources (example in Figure 21). This offers an idealized link budget using transmit frequency, transmit power, transmit antenna gain, receive antenna gain, and distance. It calculates path loss and receive power. While there may be many more considerations, this provides a top-level view of what is required for a successful link.

Transmit Frequency(GHz):	1.575	INPUT
Transmit Power(dBm):	47	INPUT
Transmit Antenna(Gain in dBi)	13	INPUT
Receive Antenna(Gain in dBi)	3	INPUT
Distance between two antennas(meters)	20200	INPUT
Path Loss(dB)	-182.49	OUTPUT
Received power(dBm)	-119.49	OUTPUT
Receiver sensitivity(dBm for QPSK1/2)	-125	INPUT
Link Margin(dB)	5.5	OUTPUT

Figure 21: RF link budget calculator

Today, in many cases, one does not have just a transmitter or a receiver. Many devices are two-way such as your mobile phone, laptop or tablet. Each of these devices may contain transmitters, receivers and a series of antenna. These devices create a new set of challenges in designs that try to minimize signals bleeding into different sections.

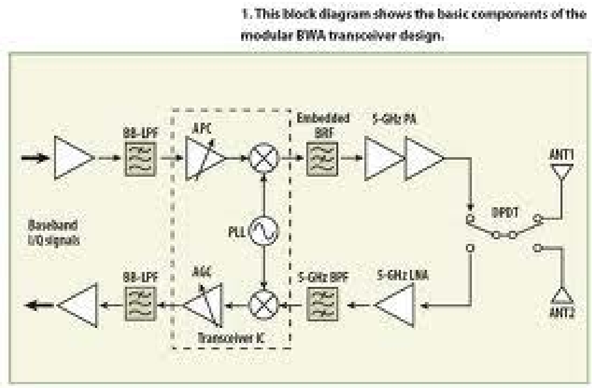


Figure 22: This block diagram shows the basic components of a modular (broadband wireless access) transceiver design.

10 Components

Looking at a few of the key components that we discussed at the system level, the design and the specifications of these components must be clearly understood to ensure that the system meets the need for the specific application.

10.1 Filters

As we discussed earlier, filters play an important role in both transmitter and receiver design. On the transmit side it is critical that the radiated signals adhere to the FCC guidelines for a particular application. On the receive side it is important that all extraneous signals that are picked up by the receive antennas are filtered out to achieve optimum signal quality of the desired signal.

There are many different types of filters including low pass, high pass and band bass. The low/high pass designs filter out all frequencies above/below the designed frequency. A band pass filter restricts frequencies to a particular frequency band (Figure 23).

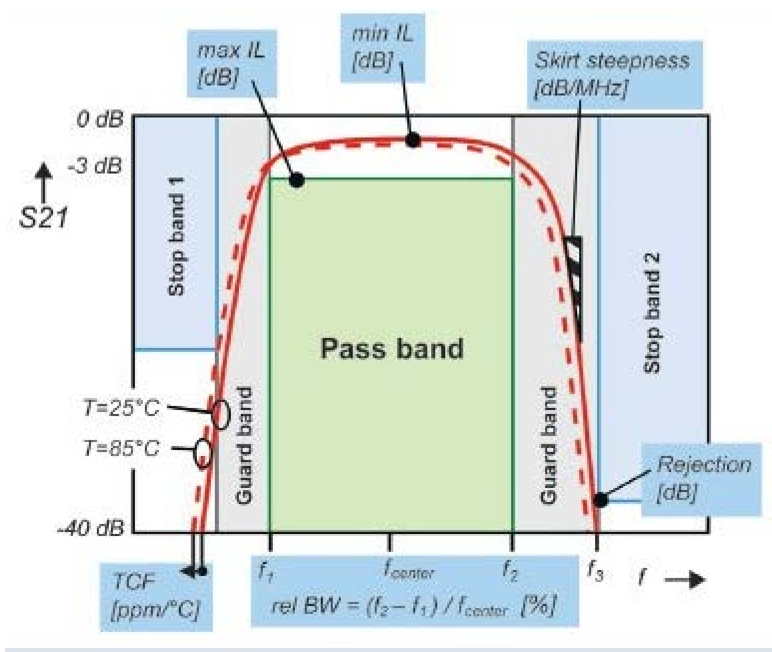


Figure 23: Illustration of a band pass RF filter performance characteristics.

The In-band or pass band performance minimizes the degradation of the desired frequencies. The bandwidth is defined by either (or both) the 3 dB and/or 1 dB drop in signal level on either side of the center frequency. The amount of lost power or insertion loss across the desired frequency range is another critical parameter. Finally, how much variation or ripple is caused to the magnitude of the signal and the same for the phase response across the pass band?

For out-of-band performance the critical parameter is with regards to how much the filtered signal is reduced. There may be different levels of performance based on distance from the filter's center frequency.

10.2 Amplifiers

Amplifiers are often located in both transmitter and receiver designs, however they have very different roles and performance requirements.

On the transmitter side, the desired signal has been created and is very well defined. Power amplifiers (PAs) are used to increase the signal level to the required power range to allow the radiated signal to be received at the other end, as well as meet the FCC requirements. The PA may be used in either the linear or nonlinear region. In the linear region, an increase in input signal yields a defined increase in the output signal, this is referred to as gain. However, at some point the input signal becomes large enough that the output starts to increase, but at a different rate. This is commonly referred to as the non-linear region. The rate of roll off in the gain vs. power measurement is known as the 1dB compression point.

Amplifiers operating in their non-linear region often have their harmonic and spurious signals specified. Amplifiers designed to operate a specific center frequency, Fc, will also radiate at multiples of the center frequency - 2Fc , 3Fc and so on. In addition, spurious signals may be generated from the transmitter components such as the power supply and amplified by the PA. Amplifier designs try to minimize these effects and the filters that were previously discussed are also key in minimizing these effects.

The Adjacent Channel Power Ratio (ACPR) is typically specified to ensure that the radiated signal stays within its given channel and does not spill into the adjacent channel. The entire allocated spectrum for a technology, such as Wi-Fi is divided up into channels to increase traffic capacity. It is important that signals stay within their specified channel and do not leak signals into other channels.

Dynamic range is usually specified to let system designers know what the minimum and maximum level signal are that can be transmitted.

On the receiver side the antenna is bringing in both the desired signals and unknown signals, over-the-air. These signals tend to be at lower power levels and may need to be boosted to separate from the noise floor. These amplifiers are often Low Noise Amplifiers (LNAs).

In wireless transmissions there is something that is referred to as thermal noise or kTB, where k is Boltzmann's constant, T is the absolute temperature of the load (for example a resistor), and B is the measurement bandwidth. The standard number we use for that is -174 dBm per hertz, which is the noise floor relative to a one hertz bandwidth. The goal of the LNA is to raise the signal above this noise level so that it can accurately be used. One of the key specifications of an LNA is its noise figure. The noise factor is the ratio of actual output noise to that which would remain if the device itself did not introduce noise, or the ratio of input SNR to output SNR. The noise figure is the noise factor expressed in decibels (dB)

As one would expect, amplifier performance is a key contributor to the overall performance of both the transmitter and receiver. While amplifiers offer the key benefit of raising signals out of the noise for easier detection, they can also add noise and spurious signals. Figure 24 shows the key characteristics that need to be considered, on both the input and output side, when integrating amplifiers into your design.

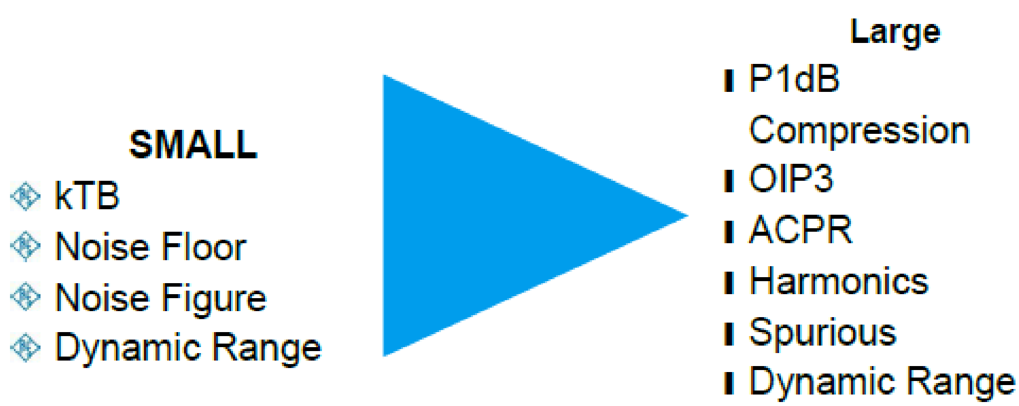


Figure 24: Key amplifier characteristics.

10.3 Mixers

Mixers are the components involved in the frequency up or down conversion in the transmitter/receiver design. On the transmit side the created signal or baseband signal is fed into one arm of the mixer. On the other arm is a local oscillator (LO) that is designed to mix the baseband signal to the appropriate frequency to be radiated via the third arm to the antenna. On the receiver side it is the same except for the reverse direction. The LO is used to mix the RF signal down to baseband.

The mixer produces not only the product of the baseband and LO frequencies, but also the difference of the two frequencies. As the mixer is a non-linear device, it also creates the harmonics of both the product and difference signals. Based on the design of the mixer, certain levels of both the input signal and the LO signal may “bleed through” the mixer and be part of the output signal as well (Figure 25).

While mixers play a critical role of moving signals to the proper frequency range, they can also be contributors for noise into the desired signal. Filtering plays a key role for reducing the effects created by unwanted mixer products.

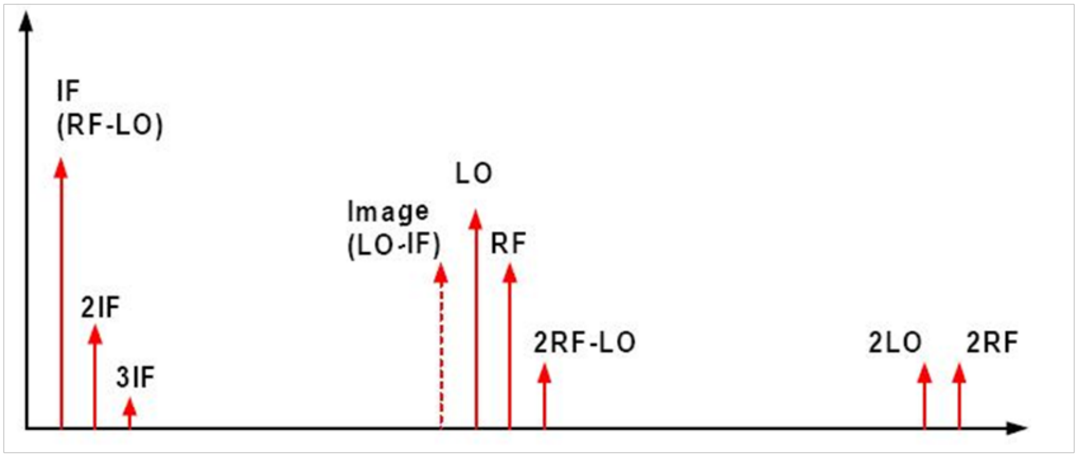


Figure 25: Mixer spectral output.

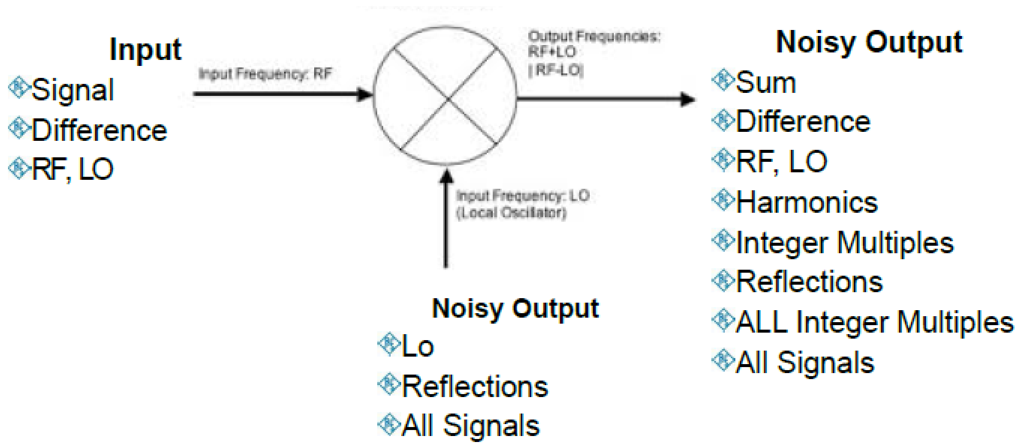


Figure 26: Key mixer characteristics that need to be considered when integrating mixers into your design.

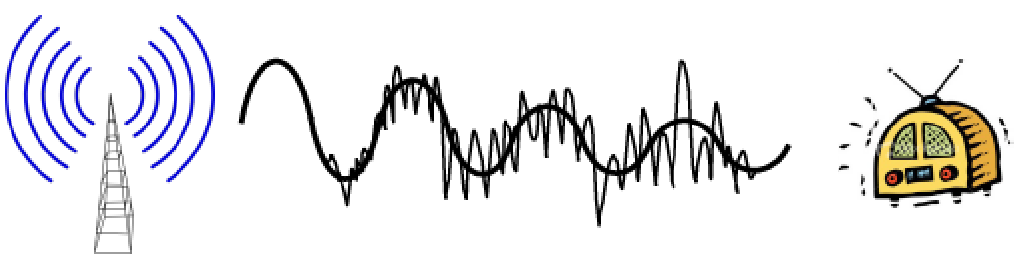
11 Key Design Parameters

11.1 Noise

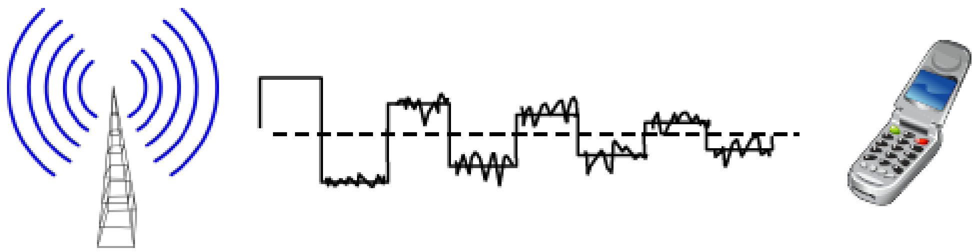
Often, noise is a key problem when trying to receive signals. When tuning between radio stations, that hissing noise is noise from your environment. There are multiple factors that contribute to this noise.

Thermal noise is a critical parameter within many RF circuits. This electrical or RF noise is generated because of thermal agitation of the charge carriers which are typically electrons within an electrical conductor. This thermal noise occurs regardless of the applied voltage because the charge carriers vibrate because of the temperature. This vibration is dependent upon the temperature - the higher the temperature, the higher the agitation and hence the thermal noise level. Thermal noise is always present in electronic circuits to a lesser or greater degree. Thermal noise, like other forms of noise are random in nature. It is not possible to predict the waveform and therefore it is not possible to reduce the effects by cancellation or other similar techniques.

Then there is noise from many other common sources: mobile phones, garage door openers, WiFi, etc. In receiver design all possible noise sources must be considered. As the desired signal gets closer to the noise level, the harder it is to detect. As an analog signal is attenuated in the presence of noise, it becomes increasingly difficult to detect the signal accurately (Figure 27a). Digital receivers have coding and redundancy built into the signal, so often bit errors don't occur at the receiver and the signal can be detected with no loss of information. However, as the digital signal approaches the noise floor, you'll have a steeper break-off where blocks of data are lost or there's no sound at all (Figure 27b).



(27a): Analog signals may develop hissing noise sound when low power signals approach the noise floor.



(27b): Digital signal will sound better, but may experience lost signal or no signals as they approach the noise floor.

Figure 27: How noise affects signals.

So how is the level of thermal noise determined? If we are below 100 GHz and above -150 °C (Rayleigh-Jeans approximation), input noise power from a matched resistor is:

$$N_{in} = Ktb$$

Where:

k is Boltzmann's constant = 1.38 x10-23 J / °K

T is the temperature in degrees kelvin (room temp ~ 19.8 °C = 293 °K) and To is defined as “standard temperature” and is equal to 290 °K = 16.8 °C

B is the noise bandwidth of the system

At standard temperature (290 °K) , kToB= -174 dBm/Hz

At 85 °C, kTB= -173.1 dBm/ Hz

At 19.8 °C, kTB= -173.9 dBm/ Hz

At -30 °C, kTB= -174.7 dBm/ HzkTBNin

To determine “B”, the noise bandwidth of the system, first determine the system bandwidth which is usually defined by a standard or specification. Convert that bandwidth into dB and then add that to -174 dBm/Hz (Nin at standard temperature) to determine the noise floor. For example:

If the channel bandwidth is	1 MHz =1x106 Hz
Convert that to db	10*log(1x106) = 60 dB
Add that to Nin	-174 dBm/Hz + 60dB Hz = -114 dBm

In this example, a receiver with a 1 MHz channel bandwidth will have a theoretical noise floor of -114dBm. Of course, there are still a variety of other noise factors that could further limit the noise floor – environment, components, or other receiver design issues.

How is the noise of a component determined or measured? Noise figure and noise factor are defined as the ratio of the SNR at the input to the SNR at the output of the device under test (Figure 28). It is a quantitative measure of a device's impact on signal to noise ratio. Noise Factor defines linear values and Noise Figure defines LOG scale values (in dB).

$$\text{(Linear) Noise Factor} = \frac{SNR_{in}}{SNR_{out}} = \frac{\left(\frac{S_{in}}{N_{in}}\right)}{\left(\frac{S_{out}}{N_{out}}\right)}$$

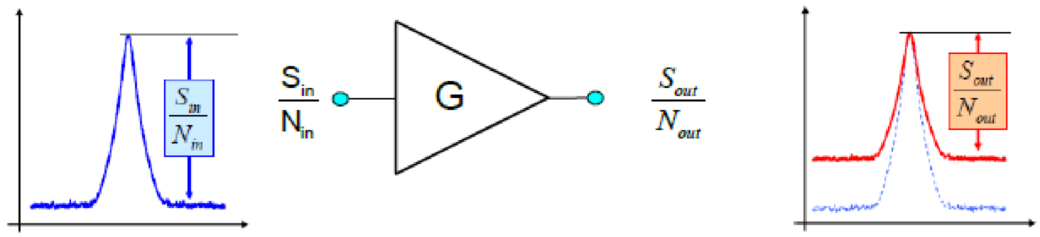


Figure 28: Noise measurement.

Note for a perfect device it would have a Noise Factor of 1

$$\text{Noise Factor } F = \frac{S_{in}/N_{in}}{S_{out}/N_{out}} = \frac{S_{in}/N_{in}}{S_{in}/N_{in}} = 1 \text{ (Linear value)}$$

Or a Noise Figure of 0

$$\begin{aligned}\text{Noise Figure } F_{dB} &= 10LOG(F) \\ &= 10LOG(1) \\ &= 0\,dB\end{aligned}$$

However, a real device adds some quantity of noise, which we denote here as Na. This makes our equation become

$$\frac{S_{out}}{N_{out}} = \frac{S_{in} \cdot G}{N_{in} \cdot G + N_a}$$

For Noise Factor, this becomes

$$\text{Noise Factor } F = \frac{\left(\dfrac{S_{in}}{N_{in}}\right)}{\left(\dfrac{S_{in}G}{N_{in}G + N_a}\right)} = \frac{S_{in}}{N_{in}} \frac{N_{in}G + N_a}{S_{in}G} = \frac{N_{in}G + N_a}{N_{in}G}$$

Remembering that Nin= kToB , this simplifies to

$$\text{Noise Factor } F = \frac{N_a + kT_oBG}{kT_oBG}$$

This is the IEEE standard definition of Noise Factor.

When measuring noise figure, it is common to use a calibrated Noise Source. The Noise Source provides the “known” input signal from which the Na of the device-under-test can be determined. A practical setup uses a spectrum analyzer to measure noise power (Figure 29). The spectrum analyzer is normally calibrated prior to making the noise figure measurement with the noise source (Step 1). Then the device-under-test is connected and measured (Step 2). From these two measurements, the device’s noise figure is determined using the Friis equation (Step 3).

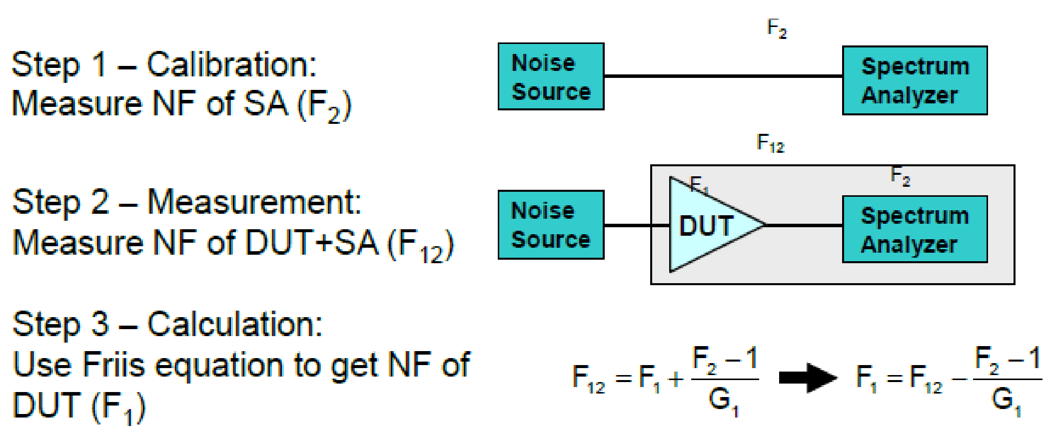


Figure 29: Measuring noise figure.

11.2 Spurious Response

In radio reception, a spurious response is a response in the receiver intermediate frequency (IF) stage produced by an undesired emission in which the fundamental frequency (or harmonics above the fundamental frequency) of the undesired emission mixes with the fundamental or harmonic of the receiver local oscillator.

Mixers are a key component in receivers that may generate unwanted signals, which need to be filtered out. Figure 30 shows the frequency domain of the expected mixer products.

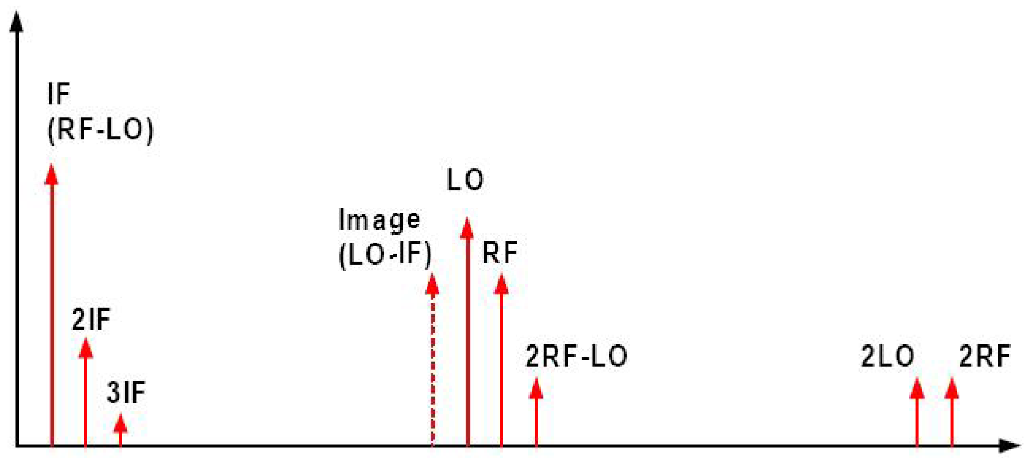


Figure 30: Mixer spectral output.

There are additional output frequencies caused by mixing with higher order harmonic terms. For example, mixing products to consider with the third harmonic of the LO:

fif = 3*flo – f3 or f3 = 3*flo – fif

fif = 3*flo + f3 or f3 = 3*flo + fif

Example for mixing products with the fifth harmonic of the LO.

fif = 5*flo – f5 or f5 = 5*flo – fif

fif = 5*flo + f5 or f5 = 5*flo + fif

Mixing products with the higher order harmonic of the LO also exist.

By looking in the frequency domain, it is easy to see any of these signals and their power level. During the receiver design process, filters need to be defined to reduce the effects of these unwanted signals.

11.3 Third Order Intercept (TOI)

Third order intercept (TOI) and Intermodulation Distortion (IM3) are two closely related specifications that are used to enumerate the linearity of an RF system. Both specifications are insightful regarding the level of third order distortion products relative to the power of the instrument. The third order intercept point relates nonlinear products caused by the third-order nonlinear term to the first order linearly amplified signal.

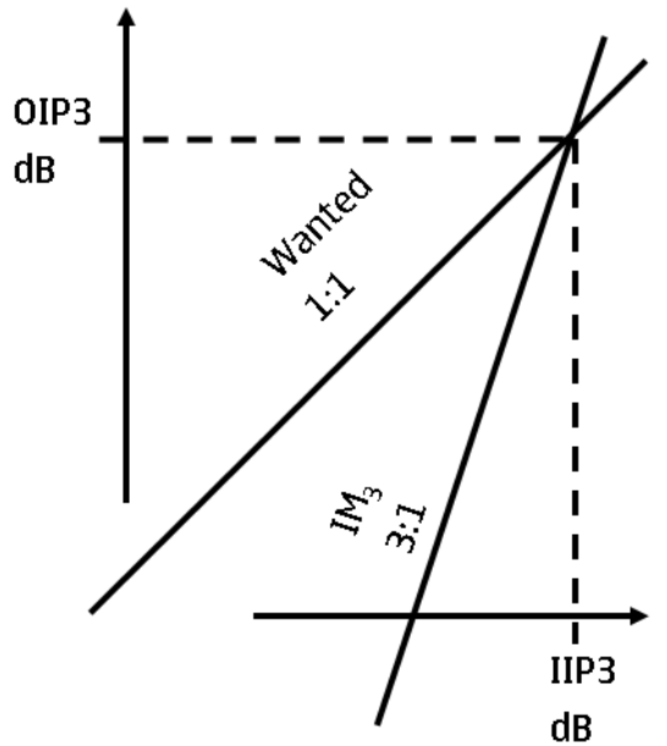


Figure 31: Third Order Intercept (TOI) definition.

TOI is a measure of the two-tone IM distortion of a device. With two input tones at f1 and f2, distortion (non-linearity) in the DUT, will create tones at 2f1-f2 and 2f2-f1 (third order products).

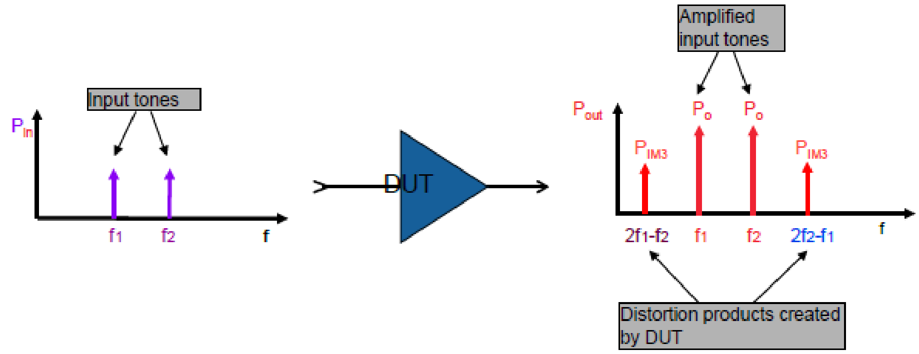


Figure 32: Third Order Intercept Measurement (TOI).

It is interesting to note that for every 1dB increase in the fundamental output level, the third order distortion products will increase 3dB. The extrapolated level at which the distortion tones “intercept” the level of the signal tones is called the Third Order Intercept Point (TOI or IP3).

11.4 Dynamic Range

The dynamic range of a receiver is where pieces come together. Dynamic range determines what incoming signal power levels can be accurately processed. If a low-level signal is coming into the receiver, then the noise figure of the receiver’s front end may become a determining factor. If a very large signal is hitting the receiver, then perhaps the intermodulation terms or even harmonics may become critical. When designing a system, one must consider the required dynamic range, i.e. from what is the very smallest signal needed to be measured, all the way to the biggest signal.

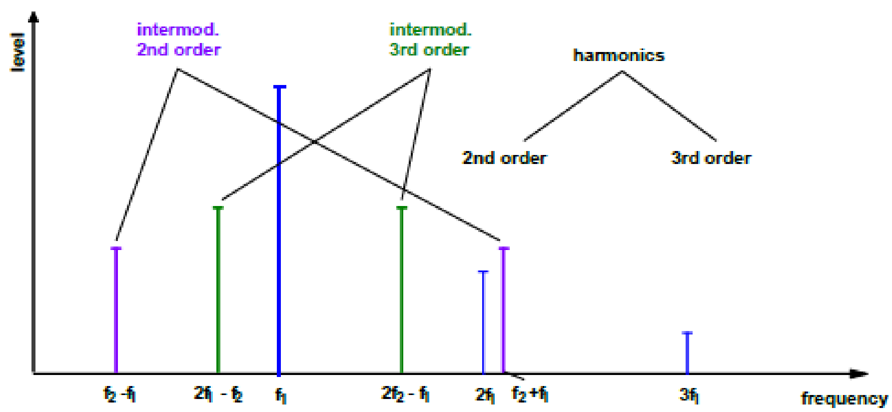


Figure 33: Dynamic range is impacted by intermodulation and harmonics.

12 Cascade Analysis

Cascade analysis is a simple yet powerful tool for analyzing system performance. Cascade analysis treats each part of the receiver as a separate entity – amplifiers, mixers, etc. (Figure 34). Knowing the key specs for each of the components, allows for an overall value for the receiver to be determined. You can analyze small-signal gain and noise figure nearly exactly, and come pretty close to modeling large-signal performance, such as predicting the one-dB compression point.

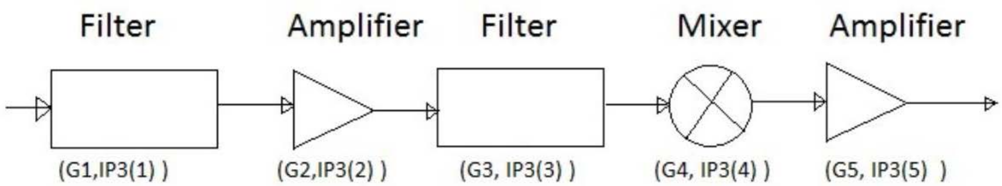


Figure 34: Cascade analysis on key receiver components.

Consider this simple example of determining the cascaded noise figure of two amplifiers in a circuit (Figure 35). The first amplifier has a gain of 20 dB and a noise figure of 2 dB. The second amplifier also has a gain of 20 dB, but a noise figure of 11 dB. By using the formulas discussed in the noise figure section, we can then determine that the effective noise figure of this two-amplifier configuration.

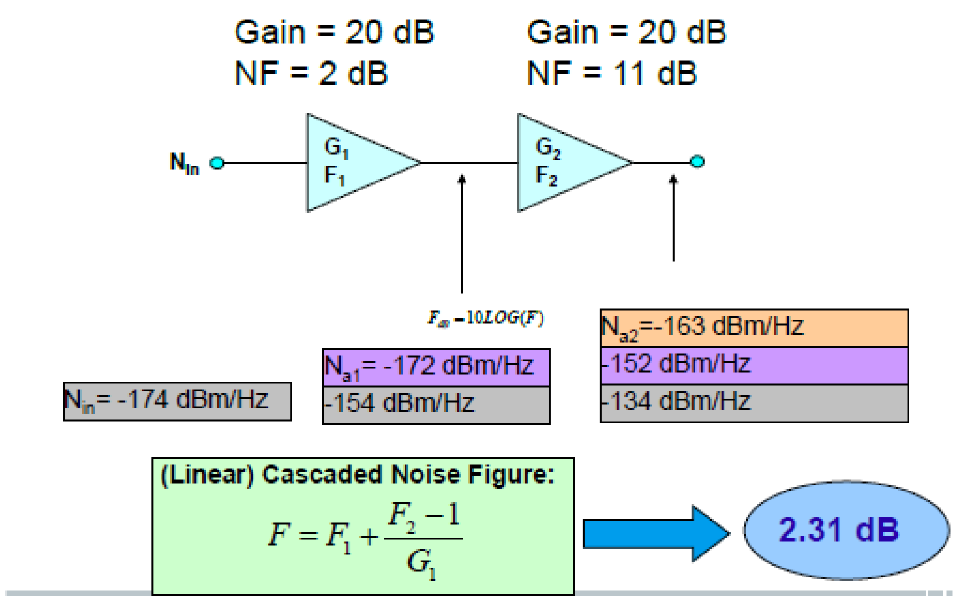


Figure 35: Determining noise figure for cascading amplifiers.

Table 5 highlights how this can be done for a series of components.

Device Parameters {@ Output}								
Component Designation	Gain (dB)	NF (dB)	IP2 (dBm)	IP3 (dBm)	P[sat] (dBm)	NBW (MHz)	Return Loss (dB) Input	Output
Amplifier	20.00	1.00	30.00	30.00	20.00	100.00	50.00	15.00
Filter	-3.00	3.00	250.00	250.00	250.00	100.00	50.00	15.00
Mixer	-7.00	7.00	25.00	25.00	15.00	100.00	50.00	50.00
Amplifier	20.00	2.00	30.00	30.00	20.00	100.00	50.00	50.00

Cumulative Output Parameters										
Gain (dB)	NF (dB)	IP2 (dBm)	IP3 (dBm)	P[sat] (dBm)	P[n] (dBm/BW)	SNR (dB)	DR (dB)	SFDR (dB)	IMD3 Power (dBm)	(DdB)
20	1	30	30	20	-72.85	92.85	92.85	68.57	0	20
17	1.03	27	27	17	-75.82	92.82	92.82	68.55	-3	20
10	1.3	16.12	18.81	10	-82.55	92.55	92.55	67.57	-7.61	17.61
30	1.48	26.51	29.46	20	-62.37	92.37	82.37	61.22	31.07	-1.07

Table 5: Cascade Analysis.

13 Test and Verification Instrumentation

Throughout the design process, it is important to evaluate the performance of your components and systems. Rohde & Schwarz offers test equipment that will verify your designs from prototypes through manufacturing and even field operations. This test equipment can be used to verify not only the total performance of the system, but can also be used to replace parts of the system, which may not be available at test time. This section provides a brief review of the most common types of test equipment for performing this verification.

13.1 Spectrum Analyzers

The testing of a transmitting device or subsystem generally requires a receiver of some sort. Spectrum analyzers have been designed specifically for this purpose and are one of the most common pieces of test equipment that will be found in an RF lab. A spectrum analyzer is a basic measurement device that is required if looking at complex signals or where multiple signals are being used. The basic measurement is frequency versus power.

Modern versions have many new capabilities for measuring including:

- Noise Figure
- Group Delay
- Phase Noise
- Basic Modulation Analysis
- Complex Modulation Analysis for:
  - Mobile Wireless
  - Wireless LAN
  - Bluetooth
  - Satellite Communications

- Radar Applications

13.2 Signal Generators

Signal generators are used to represent the transmitter by creating the required signals with the proper modulation formats. They are used as a basic measurement device when required to generate simple and complex input signals. There are two main types: analog and vector. The analog signal generator is used to create basic sine waves at different power levels and frequencies. They typically have basic modulation capabilities such as AM, FM, phase and pulse. Vector signal generators are used to create the more complex digitally modulated signals that are quite common these days.

Modern versions have many new capabilities for generating complex signals including:

- AM, FM, PM
- Arbitrary signals generated mathematically
- Frequency hopping signals
- Complex Modulation Signals including:
  - Mobile Wireless
  - Wireless LAN
  - Bluetooth
  - Satellite Communications
  - RADAR

13.3 Vector Network Analyzers

Vector network analyzers (VNAs) are used primarily for verifying component level performance. The VNA is a more complex measurement device used to stimulate and measure amplitude and phase response of high frequency devices. Basic use is to stimulate a device such as an amplifier with a sine wave and measure the amplitude and phase response. Network analyzers typically measure the Scattering parameters or S-parameters as signal power and energy considerations are more easily quantified than currents and voltages.

Modern versions have many new capabilities for measuring more complex parameters or devices such as:

- Differential and true differential Non-linear characteristics
- Impedance matching
- Mixers or converters
- Multiport devices up to 48 ports

13.4 RF Power Meters / Sensors

A power meter, is one of the most fundamental measuring tool and simply measures the power level coming out of a device. There are typically two types:

- Diode Based – high dynamic range
- Thermistor Based – more accurate but lower dynamic range

Power meters do not provide information as to the frequency content. Newer power meters typically include sensor with PC software based measurement unit. They can be used in for example, in conjunction with a signal generator to get the basic frequency response of devices. Many modern versions also have the ability to measure pulsed or bursted signals.

14 Conclusion

Today there are many wireless technology devices that utilize RF design ranging from mobile phones to satellite TV, to wireless Internet connections and bluetooth devices. A good understanding of RF design fundamentals is necessary to know how wireless technologies work and what to consider during the design, development and verification process. Designing an RF system is a complex process that requires a detailed understanding of different fundamentals of different areas.

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