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Understanding Range for RF Devices

October 2012

White Paper

Understanding how environmental factors can affect range is one of the key aspects to deploying a radio frequency (RF) solution. This paper will provide a high-level overview of the factors that can affect RF range, including hardware selection, environmental factors, frequency ranges, and proper implementation.

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UNDERSTANDING RANGE FOR RF DEVICES

Understanding how environmental factors can affect range is one of the key aspects to deploying a radio frequency (RF) solution. Whether you are looking to connect across 10 meters in a crowded hall or 10 kilometers outdoors, the environment plays a significant role in the maximum range that can be achieved. This white paper explains how range numbers are calculated and discusses the factors that limit range.

Link Budget and Path Loss

For simplicity, RF characteristics are often measured in decibel-milliwatt, or dBm. A decibel is a logarithmic unit which is a ratio of the power of the system to some reference. A decibel value of 0 is equivalent to a ratio of 1. For every increase of 10 dB, the actual power increases by a factor of 10. Decibel-milliwatt is the output power in decibels referenced to one milliwatt (mW). Since dBm is based on a logarithmic scale, it is an absolute power measurement. For every increase of 3 dBm there is roughly twice the output power, and every increase of 10 dBm represents a tenfold increase in power. 10 dBm (10 mW) is 10 times more powerful than 0 dBm (1 mW) and 20 dBm (100 mW) is 10 times more powerful than 10 dBm. The power conversion between mW and dBm are given by the following formulas:

$$P_{(\text{dBm})} = 10 \cdot \log_{10}(\, P_{(\text{mW})}\,) \quad \text{and} \quad P_{(\text{mW})} = 10^{(P_{(\text{dBm})}\,/\,10)}$$

Table 1: mW to dBm Conversion (approximate)
(http://www.rapidtables.com/convert/power/mW_to_dBm.htm)

Power (mW)	Power (dBm)
0+ mW	-∞ dBm
0.01 mW	-20.0 dBm
0.1 mW	-10.0 dBm
1 mW	0.0 dBm
2 mW	3.0 dBm
3 mW	4.8 dBm
4 mW	6.0 dBm
5 mW	7.0 dBm
6 mW	7.8 dBm
7 mW	8.5 dBm
8 mW	9.0 dBm
9 mW	9.5 dBm
10 mW	10.0 dBm
100 mW	20.0 dBm
1 W (1000 mW)	30.0 dBm
10 W	40.0 dBm
10 MW (10000 KW)	100.0 dBm

Path loss is the term for the reduction in power density that occurs as a radio wave propagates over a distance. The primary factor in path loss is the decrease in signal strength over distance of the radio waves themselves. Radio waves follow an inverse square law for power density: the power density is proportional to the inverse square of the distance. Every time you double the distance, you receive only one-fourth the power. In decibels per milliwatt, this means that every 6 dBm increase in output power results in a doubling of the possible distance that is achievable.

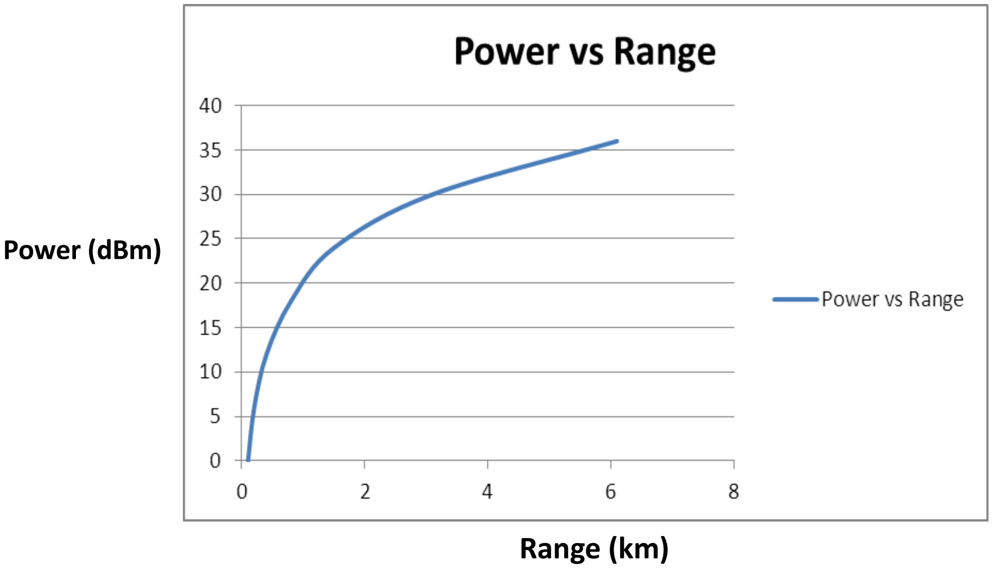

Figure 1: Range (km) vs. Output Power (dBm)

When both output power and receiver sensitivity are stated in dBm, you can use simple addition and subtraction to calculate the maximum path loss that a system can incur:

Maximum Path Loss = Transmit Power - Receiver Sensitivity

Because receiver sensitivity is less than 0 dBm (1 mW), it is typically stated as a negative number.

This can also be stated as a function of link budget, which is the accounting off all gains and losses of a system to measure the signal strength at the receiver.

Received Power = Transmit Power + Gains – Losses

In free space (an ideal condition), the inverse square law is the only factor affecting range. In the real world, range also can be degraded by other factors:

- Obstacles such as walls, trees, and hills can cause significant signal loss.
- Water in the air (humidity) can absorb RF energy.
- Metal objects can reflect radio waves and cause the waves to destructively (and sometimes constructively) interfere with themselves – this is called multipath.

There have been numerous studies that attempt to characterize and quantify the real-world signal loss that occurs. Radio propagation models can provide a good rule of thumb for both indoor and outdoor settings. This paper will not go into a detailed analysis of link budget equations; rather it will serve to provide a high-level overview of the factors that can affect RF range.

RF Range as a Function of Frequency

Radio waves at lower frequencies propagate further than radio waves at higher frequencies. For example, a 900 MHz radio will transmit more than twice as far in free space as a 2.4 GHz radio when both radios use the same modulation and output power. In addition, the longer wavelength of 900 MHz radios versus 2.4 GHz (333 mm vs. 125 mm) means that a 900 MHz signal will propagate through typical construction walls to a greater degree than a 2.4 GHz signal. Longer wavelengths also require greater area to transmit and receive resulting in increased antenna size and/or length at lower frequencies.

While lower frequencies provide better range for a given output power and receiver sensitivity, other considerations may require the use of higher frequencies, such as 2.4 GHz. These considerations are:

- The need for a smaller antenna
- The need for more bandwidth
- The need for a worldwide frequency band for use in multiple countries
- Line-of-sight considerations over long distances

Radio waves emanating from an antenna will spread out slightly, such that what would be considered line of sight for an RF system is more than just the visual line of sight.

Note: This concept is explained well in relation to Fresnel zones.

The amount of clearance required is higher for lower frequencies than it is for higher frequencies. As an example, at 8 km (5 miles) a 2.4 GHz radio needs 9.6 m (31 feet) to reach 60% clearance from the Fresnel zone, where a 900 MHz radio would need 15.2 m (50 feet). To achieve the best range possible, the 900 MHz antenna needs to be almost 60% higher.

Antenna and Cable Selection

Once you have chosen transceivers for the appropriate frequency and the best transmit power and receiver sensitivity, you need to match the transceivers to an appropriate antenna, possibly connecting the two through an RF cable. Antennas come in a variety of physical packages and radiation patterns; a detailed study of each antenna's datasheet will be necessary to identify the best antenna.

All antennas are passive devices. An ideal isotropic antenna (which is only theoretical) would radiate the signal out in all directions with no gain (0 dBm). In reality, antennas reduce the signal strength in some directions and increase the signal strength in others, providing gain. Omnidirectional antennas radiate out perpendicular to the direction of the antenna in donut (or flattened torus) pattern, as shown in Figure 2.

Figure 2: Toroid (http://en.wikipedia.org/wiki/File:Elem-doub-rad-pat-pers.jpg)

Examples of omnidirectional antennas include dipole and monopole antennas. A dipole antenna consists of two metal conductors in line with each other. Traditional “rabbit ears”, such as television antennas and small whip antennas, are common examples. Monopole antennas have a single conductive line and are mounted over a ground plane. The ground plane plays a critical role in the quality of the transmission. For lower frequencies a larger ground plane is necessary; in these cases, the earth is often used. Examples of monopole antennas include whip antennas and mast radiators, such as the ones sometimes used in AM broadcast towers.

By redirecting some of the energy of the signal, the antenna can provide gain to the overall signal strength; a dipole antenna could gain between 1 and 5 dBm. More directional antennas (such as Yagi antennas) can provide even greater gains, on the order of 6 dBm to 15 dBm, by providing a very narrow transmission beam. Yagi antennas consist of multiple elements used to focus the transmission beam and produce larger gain. Figure 3 shows a radiation pattern from a 900 MHz Yagi antenna with 13 dBi of gain.

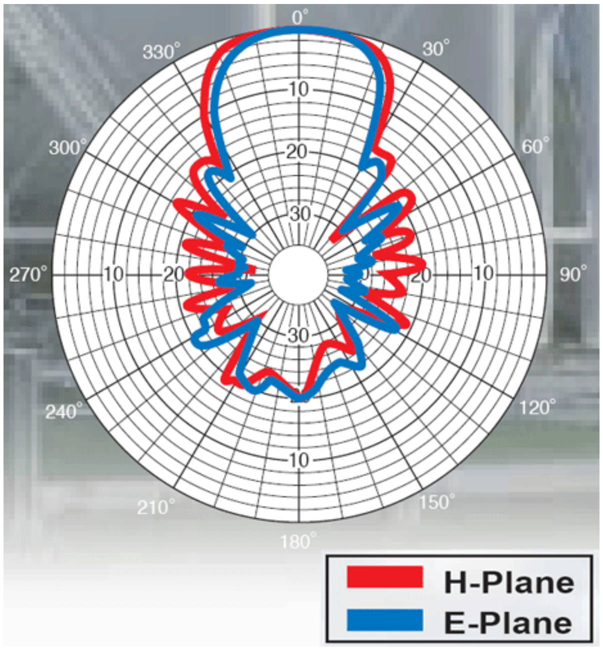

Figure 3: Laird Technologies PC9013N Radiation Pattern

Directional antennas not only provide better gain; they also help reduce the amount of interference received at the antenna by producing an overall signal loss from directions where the antenna does not point. If there is a known interferer in proximity, placing the antenna such that there is a loss from that direction can help alleviate interference. Due to the specific directional nature of the Yagi and other directional antennas, they are limited to applications where the antenna can be pointed at the destination, such as in point-to-point networks. Additionally, too much gain on an antenna can cause it to violate local regulatory restrictions for radiated output power. Refer to the user manual on the transceiver or with a local regulatory body for emissions rules.

Often, to place an antenna in the best location for transmission, a cable will be required to connect the transceiver to the antenna. Cables can be a huge loss for the signal strength and care should be taken to choose the right cable type and length. A poorly chosen cable can more than offset any gains which would be received by placing the antenna in an optimal location. In general, you get what you pay for with RF cables, so read the specifications carefully and choose the one which fits your application the best. Cables with less loss are often more expensive, but tend to be less flexible and may not work in a specific installation.

Table 2 lists common cable types and how much loss can be expected for a given distance. Note that cable loss increases as frequency increases. As you can see from the table, choosing a poor quality cable can account for some large losses. For a 30-meter run, a LMR-240 cable will cause an additional 6.1 dBm loss over a LMR-400 at 2.4GHz. This 6 dBm will halve the possible distance that the link can achieve.

Table 2: Attenuation of Various Transmission Lines in Amateur and ISM Bands in dB/100m. (dB/100 ft.)

Cable Type	450 MHz	915 MHz	2.4 GHz	5.8 GHz
RG-58	34.8 (10.6)	54.1 (16.5)	105.6 (32.2)	169.2 (51.6)
RG-8X	28.2 (8.6)	42.0 (12.8)	75.8 (23.1)	134.2 (40.9)
LMR-240	17.4 (5.3)	24.9 (7.6)	42.3 (12.9)	66.9 (20.4)
RG-213/214	17.1 (5.2)	26.2 (8.0)	49.9 (15.2)	93.8 (28.6)
9913	9.2 (2.8)	13.8 (4.2)	25.3 (7.7)	45.3 (13.8)
LMR-400	8.9 (2.7)	12.8 (3.9)	22.3 (6.8)	35.4 (10.8)
3/8" LDF	7.5 (2.3)	11.2 (3.4)	19.4 (5.9)	26.6 (8.1)
LMR-600	5.6 (1.7)	8.2 (2.5)	14.4 (4.4)	23.9 (7.3)

Source: *http://www.w4rp.com/ref/coax.html*

Antenna Height

After selecting your radio transceivers to account for the largest maximum path loss, and after selecting the appropriate antenna, you then need to do only one thing to get the maximum RF range from your equipment: put the antenna as high as possible. A higher antenna does two main things. First, it can help get you above any possible interferers like cars, people, trees, and buildings. Second, it can help get your true RF line-of-sight by getting you at least 60% clearance in the Fresnel zone.

Finally, don't forget about the curvature of the earth. At eight kilometres (5 miles) the Earth's height at midpoint is .95m, (3.12 ft), not accounting for hills and other terrain features. At 32 km (20 miles) the height at midpoint is 15.2 m (50 ft). For a 2.4 GHz transmission path to go 5 miles, you would need antennas at 9.6 m (31 ft). For 900 MHz at 32 km, you need antennas at least 46 m (152 ft.) to achieve a good signal of at least 60% of the Fresnel zone. In many practical settings, your transceivers may function with a lower antenna height, but the higher the better. There is also a trade-off between the antenna height and the amount of RF cable needed to span the transceiver to the antenna. It is possible a lower antenna height will work better because there is less loss in the cable.

When configuring the height of your antenna, make sure you check with local regulations about how high an antenna can be. Some local and federal agencies regulate the height of antennas, so be aware of the regulations in your area.

CONCLUSION

Once you have numbers, either stated or empirically derived, that you are comfortable with, you can utilize them in the Link Budget Equation:

Received Power = Transmit Power + Antenna Gains – Cable Losses – Free Space Loss – Losses due to obstructions

To ensure good transmissions in all conditions, check that the Received Power (calculated above) is significantly higher than the Receive Sensitivity of the radio. While there is no standard for what this difference should be, 10-12dBm or greater is the minimum that should be accepted.

RF propagation models are as much art as science and if you are looking to achieve the absolute maximum range possible, even small obstructions can significantly degrade the signal. The information in this paper should be used to give you an idea if the distances you are trying to achieve are possible, but only a real-world test will tell you for certain. If you are operating in a location prone to seasonal changes, you may want to make multiple tests throughout the year to see how foliage, snow, rain, and other factors affect the link. Real world tests are also needed to verify the manufacturer's numbers for Transmit Power and Receive Sensitivity. The stated numbers could be ideal numbers based on calculations or could have been measured in a lab with an ideal setup. Often times, the actual Transmit Power and Receive Sensitivity will be worse than what is stated.

To ensure the best range, place your antennas as high off the ground as possible, at least enough to be above 60% of the Fresnel zone. Where possible, you should also increase the number of retry attempts for transmitted packets. This will help with your overall reliability, but may not be an option on all radios and will negatively affect the possible throughput. Utilizing directional antennas can also increase the link reliability by negating some interference from other sources. Directional antennas tend to have higher gains, which will also help in the link budget, but make sure you are still within the scope of any government regulations for transmit power.

About Laird Technologies, Inc.

Laird Technologies designs and supplies customized, performance-critical products for wireless and other advanced electronics applications.

The company is a global market leader in the design and supply of electromagnetic interference (EMI) shielding, thermal management products, mechanical actuation systems, signal integrity components, and wireless antennae solutions, as well as radio frequency (RF) modules and systems.

Custom products are supplied to all sectors of the electronics industry including the handset, telecommunications, data transfer and information technology, automotive, aerospace, defense, consumer, medical, and industrial markets.

Laird Technologies, a unit of Laird PLC, employs over 14,000 employees in more than 40 facilities located in 14 countries.