Optimizing the RF Link

One of the most frequent questions we get is "how far can your radios go?" This is not an easy question to answer, as there are many factors that go into this. This application note gives an overview of the major considerations and discusses methods to optimize the link performance. Our intention is to provide some useful insights which can help during the design of a RF link.

Our overall recommendation is to design a link with about 10-15 dB fade margin to account for changes in the environmental and operational conditions. Mobile nodes change the orientation that can affect the link margin. Use the highest gain antenna and keep maximum distance between the antennas possible within the physical constraints of the system. The objective is to operate the link with the highest SNR (RSSI) possible (Sweet spot for Smart Radio is around -60 dB to -70 dB RSSI). Higher RSSI level will allow the link to operate at the highest modulation, provide the best throughput, interference resistance and reliability.

Factors affecting the RF link

By laws of physics, the RF link range, can be expressed in simple terms as a function of -

RF Link Range = *f*(Tx power, Rx sensitivity, Antenna Gain, Path loss).

Unpacking this shows us that many factors affect the RF link range. Here we list the major factors affecting the RF link and we will briefly discuss each of them and provide some insights that can help achieve the long range links.

1. Operating frequency
2. RF power
3. Receive sensitivity and channel bandwidth
4. MIMO technology
5. Antenna selection
6. Fresnel zone clearance
7. Fade margin
8. Environmental noise
9. Mesh Relay
10. Very Short Range operation

Choosing the Operating Frequency

Operating frequency is one of the major factors in determining range. It requires careful trade-offs in the system design to achieve maximum range.

Low frequency signals have lower transmission losses and able to penetrate through the vegatation. They also have higher refractivity to go around the obstacles. All these characteristics allow for longer-distance communication. However, at lower frequencies, the Fresnel zones (discussed later) are larger and create obstruction for low height operations. The antenna size and weight are also larger at low frequencies.

On the other hand, higher frequency signals have higher transmission loss, reduced penetration and lower refractivity. However, the antennas are smaller size and less bulky. Which means that a higher-gain antenna can be used to partly compensate for the higher link loss. The Fresnel zone is smaller and thus allows for longer links at low height.

Hence, a careful balance is required to meet the system requirements. The Smart Radios are available in many frequency bands and in the same form factor. This allows a simple swap of the radio module and make it easier to meet various requirements the system will need to meet.

For drone operation, the Fresnel zone obstruction is not a consideration since the communication link is pointing up. However, the size and weight of the antennas play an important role. For these reasons, many UAV manufacturers utilize the unlicensed ISM band 900 MHz Smart Radio. Typically a small 3 dBi antenna is used on the flyer and a larger gain 6-9 dBi Omni antenna is used at the ground control station.

For ground robot use cases, because the links are at low height, the Fresnel zone plays a decisive role to determine the operating range. For robots that don’t require deep penetration, it is advantageous to use higher frequency to benefit from smaller Fresnel zones so the signal can travel further. For ground robots, usually the weight and size of the antenna are not as critical and hence higher gain antennas can be used on both the rover and the control station.

RF Power

Higher RF power makes the signals go farther. For license free bands, the regulatory requirement places the limit the amount of RF power. The Xtreme category of Smart Radios feature the maximum RF power (1W or 30 dBm) that is allowed by FCC. The Pro category of Smart Radios feature 27 dBm of RF power. Hence the range will be about 75% that of the Xtreme models.

Due to the physics of the material science and the nature of the OFDM signals, the power amplifiers provide higher power at lower data modulation rates. There is usually power backoff of 6-7 dBm to transmit at the highest modulation rate.

We recommend to use the highest gain antenna possible in the system, and lower the radio's Tx power to stay within regulatory EIRP limits. This will help run the wireless link at higher modulation rates. This has an added benefit of lower power consumption.

Receive Sensitivity and Channel Bandwidth

A wider channel bandwidth offers higher data throughput and lower Rx sensitivity (i.e. shorter range). Overall, wider channel bandwidth offers better immunity to intermittent sources of interference as the data is transmitted at higher modulation rates and require shorter airtime. In this case, the data packets with short duration have better probability of success in the presence of intermittent noise spikes. On the other hand, wider bandwidths provide fewer non-overlapping channels so the nodes may interfere with other nodes operating in the area. So in general, wider bandwidths are useful for high throughput, short range applications in low density environments.

Smaller channel bandwidth increases the SNR and hence, better Rx sensitivity. When the bandwidth is reduced from 20 MHz to 5 MHz, it provides 6 dB better Rx sensitivity. This translates into 2x longer range. However, the data throughput is reduced by 4x.

Smaller channels give ability to choose from more non-overlapping channels to avoid interfering with other nodes in the area. So smaller channel bandwidth is useful for low throughput, long range applications operating in high density environments.

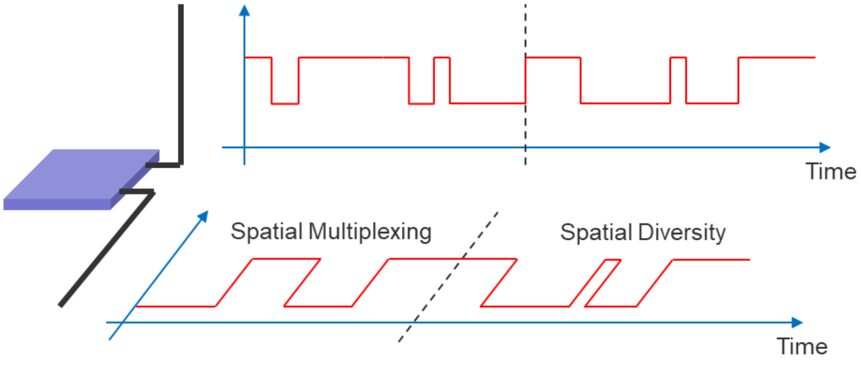
The Smart Radio channel bandwidth can be software configured between 3-40 MHz (10 and 20 MHz for Pro models). This helps accommodate a wide range of use cases and operating environments. The Smart Radio datasheet provides Rx sensitivity information for different channel bandwidths and radio modulation rates.

Overall, our recommendation is to operate the radio at the widest channel bandwidth as allowed by range and link budget requirements and density of other nodes in the environment.

MIMO Technology

Smart Radios employ the stat-of-the-art 2×2 MIMO technology (Multi-In and Multi-Out). The MIMO Is a game changer in the field of wireless communication. It turns the legacy RF on it's head. MIMO uses multi-path reflected signals and powerful DSP algorithms to help improve the speed and reliabilty. For best performance 2x2 MIMO requires two antennas for transmit and receive. Having two antennas allows the radio to use either spatial-multiplexing to improve the data rate or spatial-diversity to improve the reliability of the link.

In spatial-diversity, the same stream of data is sent redundantly over both antennas and combined at the receiver in an intelligent way to optimize the link quality and SNR. Depending on the application, it may be beneficial to mount one antenna horizontally and the other vertically to get the most diversity in the polarization, or to mount both antennas horizontally (for example) to get the most power if the polarization is known.



In spatial-multiplexing, two different streams of data are sent to the two antennas resulting in double the throughput. In order not to interfere with each other in a line-of-sight (LoS) link, the antennas should be oppositely polarized. In a non-LoS link, it is not necessary for the antennas to be oppositely polarized as the radios make use of multipath propagation to combine the data streams.

For mobile applications, where the orientation of nodes constantly changes, it is beneficial to mount the antennas in a cross-polarized orientation to get the most diversity in the polarization. Doodle Labs has developed special multi-polarized antennas to get the best performance from Smart Radio.

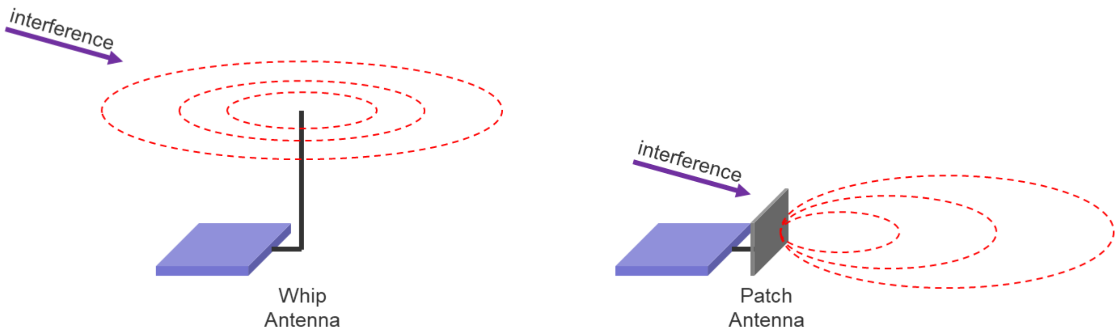
Doodle Labs recommends using two multi-polatized antennas. Smart Radios automatically switch between spatial-diversity to spatial-multiplexing modulations in order to optimize link quality.

Antenna Gain and Directivity

Antennas are the passive amplifiers of the RF signals. They amplify signals and increase the signal reception without adding any signal distortion. In general terms, the term “bigger the better” applies well to the antennas. There are many variables like gain, directivity, polarization, and position that go into the proper selection of antennas. Refer to our App Note – How to Choose an Antenna.

Antenna selection and placement is very important for link optimization. The diagram below shows radiation patterns of two types of antennas. Antennas concentrate power in different directions.

The first example is of an omni directional antenna. They spread the RF energy in all directions. They are useful for communicating with wireless nodes spread out in all directions. They are usually available in maximum 6 to 9 dBi gain.

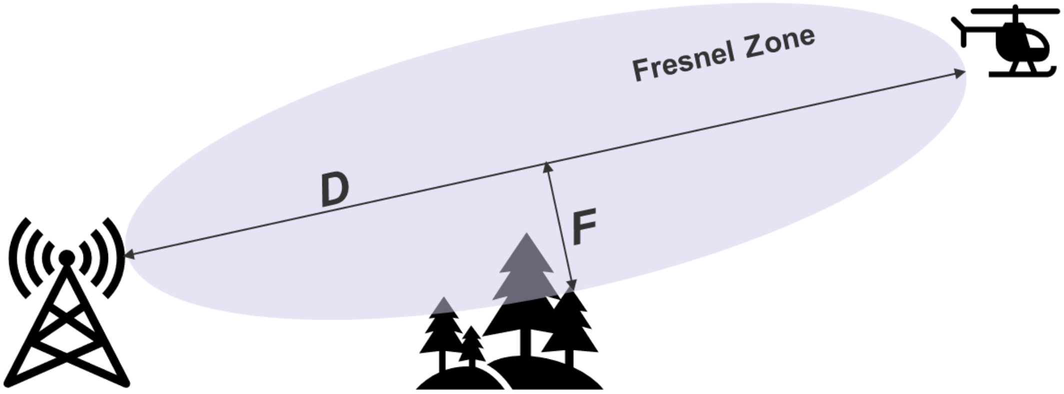


The second example is of a directional antenna in both the elevation and azimuth. By focusing the RF power in a smaller beam width, provides important benefits like higher gain to achieve longer range. They also help avoid interference originating outside of the link path. Looking at the diagram above, the directional antenna could get a significantly better link quality because it cannot “see” the interference coming from the back of the antenna.

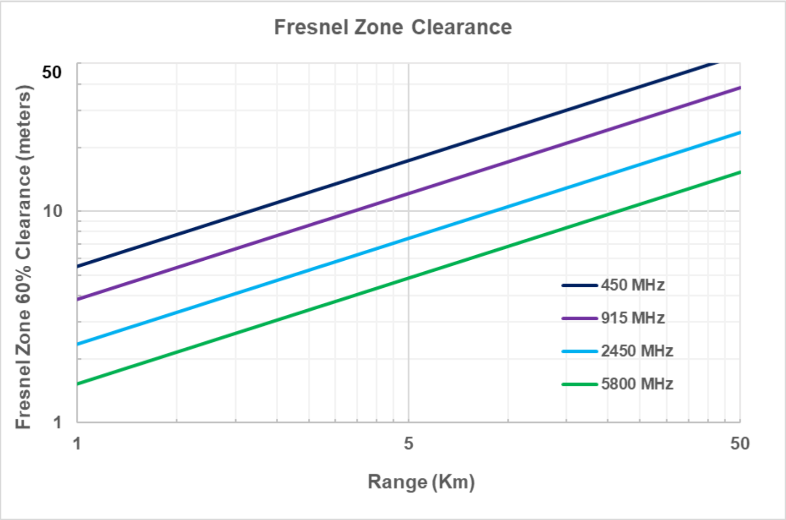
We recommend to use the highest gain antenna and place them as far apart that can be accommodated by the size and directivity requirements of the system.

Fresnel Zone

An important factor to consider when establishing a RF link is potential signal obstruction due to Fresnel zone. The Fresnel Zone is an elliptical zone within which the RF signals propagate. Therefore, any objects within the Fresnel zone can affect the signal propogation. In the diagram below, the trees are considered to be obstructing the Fresnel zone even though they do not obstruct the clear line of sight.



Due to dispersion, the Fresnel zone size increases as the signals travel further out. Mid-point of the link has the biggest Fresnel zone. Another important factor is the frequency. Lower frequency has larger Fresnel zone and vice versa. Generally speaking, more than 60% obstruction of the Fresnel zone will adversely affect the link distance. We've included a reference chart that gives an idea of the size of the 60% clerance required based on distance and frequency.



When designing the RF link for mobile nodes, it is important to consider the potential Fresnel zone obstruction at all locations.

Our recommendation is to install antennas as high as possible to overcome the Fresnel zone obstruction and increase the range.

Fade Margin

Fade margin is the difference between the strength of the received signal at the antenna port and the minimum receive sensitivity for signal strength for reliable operation. The higher the fade margin, the more reliable the link will be. Smart Radio receive sensitivities are listed on each model's datasheet. Maintaining a sufficient fade margin will create a buffer to account for natural degradation of the signal strength during operation. A fade margin of 10-15 dBm is a conservative value to target.

Our recommendation is to design a link with about 10-15 dB fade margin.

Environmental Noise

The throughput and range achievable in a communications system is limited by the received Signal-to-Noise Ratio (SNR). Smart Radio's PHY aware Mesh Rider OS uses high Q filters to limit the effects of out-of-band noise. The radios employ techniques like spectrum scanning and automatic channel selection. Doodle Labs has Smart Radios available in many different frequency bands. Additionally, Doodle Labs is developing multi-band Smart Radios that can switch to an entirely different band to avoid noise and intentional jamming.

Our recommendation is to select the Smart Radio model most suitable for the operating environment.

LTE Desensitization

The Smart Radio includes highly selective RX filtering which allows it to operate in close proximity to high power LTE Base Stations. That said, the EIRP of a LTE Base Station can exceed 1,000W (60 dBm) in some cases making coexistence a challenge. We recommend careful consideration of the LTE networks operating in the deployment area when designing your network.

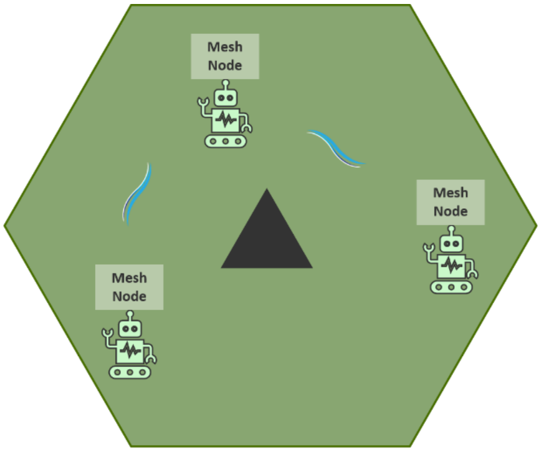
The typical desensitization level of a 2.4 GHz Smart Radio (RM-2450) due to an out-of-band OFDM blocker is -8 dBm. As an example, assume the following parameters

- Base Station EIRP = 60 dBm
- LTE Band = 1
- Downlink frequency = 2140 MHz
- Smart Radio antenna gain = 3 dBi

In this case, the Smart Radio and LTE Base Station can be as close as 40m.

Mesh Relay Nodes

It should be noted that the Mesh relay feature of the Smart Radio can help increase the range further, even for Non-Line of Sight (NLOS) conditions. Smart Radios support dual band mesh operation also to further extend this functionality.



Operating a Very Short Link

In contrast to the foregoing discussion to extend the link range, in some situations it is necessary to operate the Smart Radios at very short range (e.g. drone/robot operating near the control station before moving away). The Smart Radio includes transmit power control (TPC). When a node detects another node that is too close, messages are exchanged between the nodes so that they each reduce their transmit power to an optimal level. How close units can get to each other depends on the model as path loss is frequency dependent. For reference, RM-2450-2H-XS works well to within about half a meter.

As can be seen from this discussion, there are many system design and use-case related factors that go into optimizing the link distance. We provide indicative range charts in each Smart Radio model's datasheet. For more detailed link design, use of Link Budget Calculator is required. Here is a link to one of the many free online calculators.

Conclusion

Our overall recommendation is to design the RF link with about 10-15 dB fade margin to account for changes in the environmental and operational conditions. Mobile nodes change the orientation that can affect the link margin. Use the highest gain antenna possible within the physical constraints of the system. The objective is to operate the link with the highest SNR (RSSI) possible (Sweet spot for Smart Radio is around -60 dB RSSI). Higher RSSI level will allow the link to operate at the highest modulation, provide the best throughput, interference resistance and reliability.

References

[1] EverythingRF Freespace Path Loss Calculator, https://www.everythingrf.com/rf-calculators/free-space-path-loss-calculator, Feb 2021