Demystifying RF for IoT Deployments

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The Internet of Things (IoT) Ecosystem comprises a wide variety of RF-enabled sensors, gateways, and infrastructure. But even though wireless solutions are ubiquitous, the technology is viewed by many people as magic. This high-level overview of RF fundamentals will demystify some of the key concepts.

With the Internet of Things (IoT) and the emergence of the Industrial Internet of Things (IIoT), a surge of innovation is occurring across the industry that connects an ecosystem of sensors, devices and equipment to a network that promises to improve asset utilization, enhance process efficiency and boost productivity. With the estimated number of connected "things" expected to reach over 25 billion by 2020, this provides an opportunity to change the way business is done. [1]

The IoT Ecosystem, as depicted in **Figure 1**, consists of sensors, gateways, infrastructure, and of course, the flashy part of the IoT ecosystem, big data and analytics. A speaker at a recent IoT conference summed it up best with the statement: "Big data will be big!" The modelling of data supporting predictive analytics, whether it resides in the cloud or at the edge, gives organizations the ability to quickly diagnose and troubleshoot not only their sensor networks from a predictive maintenance perspective but also their operations, reducing excess use of energy and/or raw materials.

While the Ecosystem can be hardwired, typically, a hybrid approach is utilized. This includes wireless sensor networks (WSN) and much of the network infrastructure through high-speed, broadband links. Even though radio frequency (RF) technology is a part of our everyday lives and, in terms of IIoT, has been adopted for decades in some of the harshest conditions, wireless technology is still viewed by many as magic. [2] Arthur C. Clarke was a brilliant futurist and writer, but he

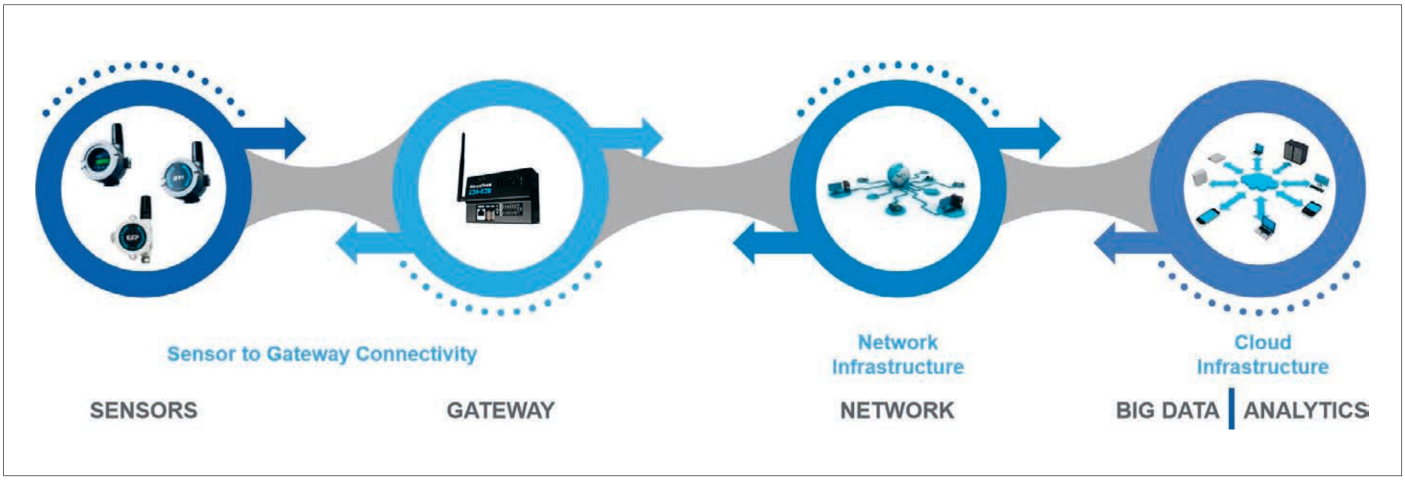

Figure 1: IoT Ecosystem

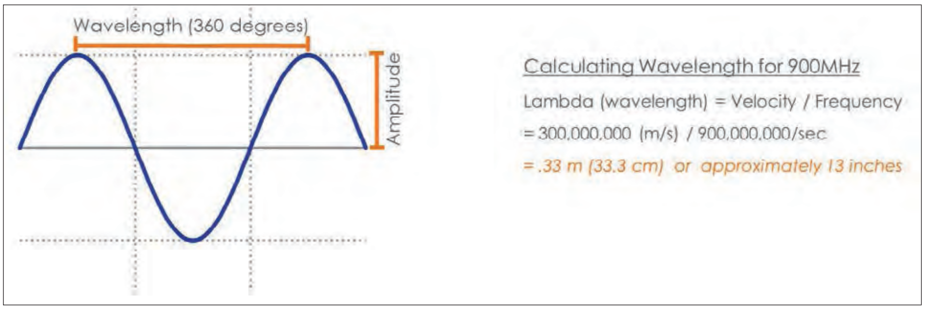

Figure 2: Wavelength and Amplitude

is best known for one of his laws being: "Any sufficiently advanced technology is indistinguishable from magic." [2] Certainly, wireless (or RF) communications falls within that law. The purpose of this paper is to help demystify the subject, as regardless of the RF technology used in IoT deployments, the same core principles apply.

Foundation

In the simplest of terms, wireless transmissions are RF signals which travel based on behaviours called propagation characteristics. RF radiates from an antenna on the transmitter end and is received by an antenna on the receiver end. The actual data being carried is modulated on one end, transmitted over the air, and demodulated on the other end. The RF signal's propagation characteristics are dictated by frequency, wavelength, and amplitude.

Depending on the technology and the part of the world the system is being deployed, regulatory bodies for that country will govern the frequencies that can be used. For instance, in the US, the Federal Communications Commission (FCC) allocated what is known as the Industrial, Scientific, and Medical (ISM) Band, which allows license free operation in the 900 MHz, 2.4 GHz, and 5.8 GHz bands.

However, other countries may use 900 MHz for their national cellular band or even over the air television. In addition, there are also licensed bands used below 900 MHz and above 5.8 GHz.

Regardless of the band selected, the same propagation characteristics mentioned earlier apply. Using 900 MHz as an example, which is one of the more common IoT bands, the typical operation is from 902–928 MHz. Hertz (Hz) simply means frequency or cycles per second, where the preceding "M" is a prefix meaning Mega, denoting a factor of 1 million. Therefore, at 900 MHz, the frequency is 900 million (900,000,000) cycles per second. Wi-Fi most commonly uses 2.4 GHz and 5.8 GHz, where the G is a prefix meaning Giga, denoting a factor of 1 billion. Therefore, the frequency is 2.4 billion (2,400,000,000) and 5.8 billion (5,800,000,000) cycles per second, respectively.

Wavelength, which is typically represented by the Greek symbol lambda λ, is the distance between the starting point of one cycle and the starting point of the next cycle. Wavelength is inversely proportional to the frequency described above. The higher the frequency, the shorter the wavelength. Conversely, the lower the frequency, the longer the wavelength. Knowing the frequency allows calculation of the wavelength by dividing the speed at which RF signals travel (the speed of light, rounded up to 300,000,000 meters per second) by its frequency as illustrated in **Figure 2**. At 900 MHz, the wavelength is 33.3 cm, or approximately 13 inches. Knowing wavelength is critically important to antenna design which will be covered later.

The last of the RF propagation characteristics is amplitude. Amplitude, as illustrated in Figure 2, is the height or peak of the wave and is a function of power. The higher the output power or amplitude, the higher the peak.

Almost all of the technologies being deployed in the IoT industry have fully adjustable output power. This is important because, as mentioned above with respect to Arthur C. Clarke's law, many believe that the higher the output power, the better. However, in some cases, higher output power just increases the overall noise floor and can create self-interference. Although, in other cases, higher output power is needed just to overcome ambient noise.

Regarding output power, RF power is measured by two units on two different scales. The first is a linear scale using milliwatts (mW). On the linear scale, the reference point is zero but does not reveal gain or loss in relation to the whole. The second, is a relative scale, measured in decibels (dB) where the reference point is the measurement itself. dB is nothing more than a ratio expressed on a logarithmic scale and gets very confusing because it is completely relative, with no reference but does reveal gain or loss in relation to the whole. Using dB for power measurement simplifies our calculations and is what allows us to add and subtract our gains and losses.

A couple of the most common examples of referenced dB values are dBm and dBi. dBm is absolute power measured relative to 1 mW, whereas dBi is antenna gain referenced to a hypothetical, perfect isotropic radiator. System gain and fade margin will be discussed later in this document which will provide some clarity into why dB is important. For now, perhaps the most important thing to remember in the world of RF is the rule of 3s and 10s. If you can remember five basic steps, you can perform any RF math calculation. The five basic steps are as follows:

0 dBm = 1 mW (starting point)
30 dBm = 1 W
Increase by 3 dBm, power in mW doubles

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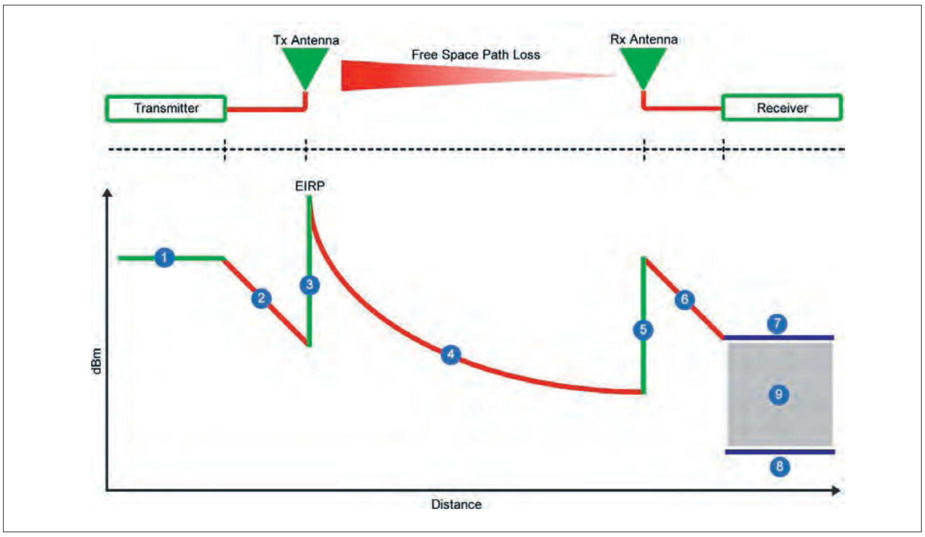

Figure 3: Link Budget. The numbers in this figure correspond with the steps listed in the "Practical Application" section of this article.

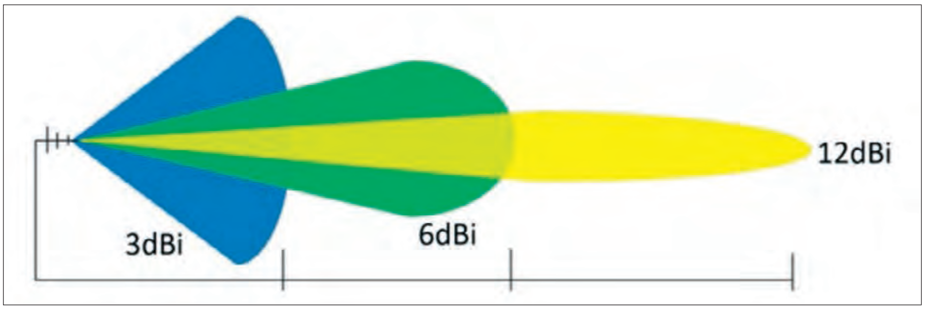

Figure 4: Antenna Gain

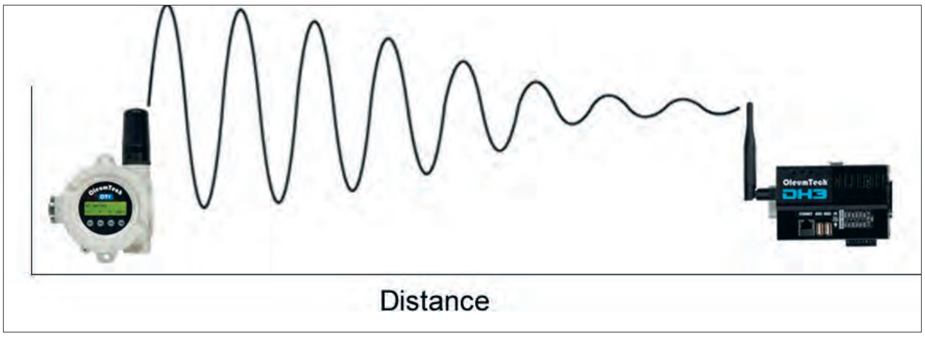

Figure 5: Attenuation

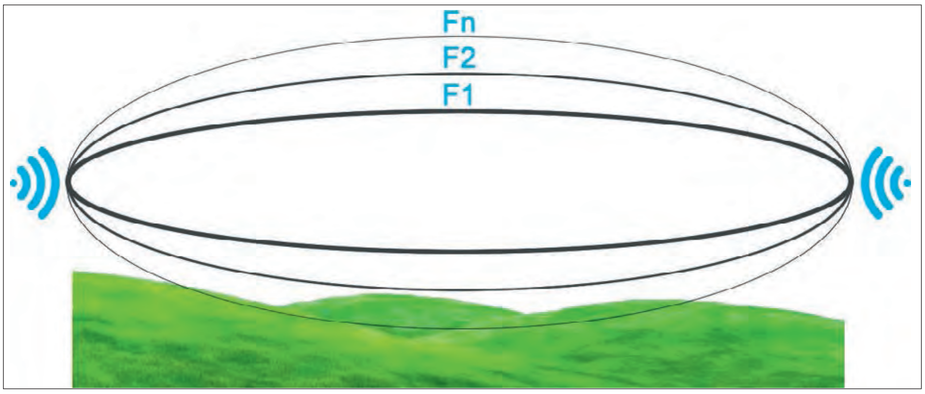

Figure 6: Fresnel Zone

Decrease by 3 dBm, power in mW is halved
Increase by 10 dBm, power in mW is multiplied by 10
Decrease by 10 dBm, power in mW is divided by 10

Sensitivity

When evaluating wireless technology, the sensitivity specification is just as important as the raw output power. In our everyday conversations, we know that it is just not about how loud someone can talk, but also how well we can hear and, more importantly, be able to understand what they are saying. Sensitivity provides this "hearing" specification. Receiver sensitivity is the lowest power level at which the receiver can detect an RF signal and, just like being able to understand a conversation, demodulate the data.

Usually, there is a bit error rate (BER) specification following the receiver sensitivity specification. It is typically expressed as 10 to a negative power and is, essentially, the ability to understand what the other device is transmitting. For example, a bit error rate of 10^{-4} means that the probability of a bit error will occur for every 10,000 bits transmitted. As with output power, the rule of 3s and 10s also applies here. When comparing a receiver sensitivity specification of –110 dBm to that of one with a –107 dBm, the first thought is that there is only a difference of 3 dB. However, the receiver with the –110 dBm specification can hear signals that are half as strong as the receiver with the –107 dBm specification. Because receive sensitivity indicates how faint a signal can be successfully received, the lower the power level, the better. This means that the larger the absolute value of the negative number, the better the receive sensitivity.

Practical Application

With some of the fundamentals behind us, let's make practical use of the information as well as introducing new terminology and concepts. Regardless of the wireless technology being implemented, link budgets are key in determining whether a system will work. Link budget [3] accounts for all of the gains and losses from the transmitter, through the medium (free space, cable, waveguide, fiber, etc.) to the receiver in a telecommunication system. It accounts for the attenuation of the transmitted signal due

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to propagation, as well as the antenna gains and miscellaneous losses. A simple link budget equation looks like this:

Received Power (dB) = Transmitted Power (dB) + Gains (dB) − Losses (dB)

The image in **Figure 3** helps to explain this concept and will certainly provide some insight as to why some wireless links work and others do not. Starting from the transmitter, we will walk through each step of the wireless link and discuss each item as numbered in Figure 3, providing a simplistic hypothetical example for each variable on a system operating at 900 MHz, completing the Link Budget calculation in step 9.

1. Transmitter Output Power

The transmitter output power will be based on the technology being deployed and the country it is being deployed in. With intrinsically safe, battery-powered wireless sensor networks, minimizing energy use is a primary goal to maximize battery life. As such, output power could be as low as 10 dBm (or 10 mW). However, for other systems such as licensed radio systems, output power can be significantly higher.

Hypothetical Example: 30 dBm (1 W)

2. Transmitter Loss

From the RF connector of the transmitter to the antenna, the system will experience losses from the coaxial cable as well as insertion loss [4] resulting from jumpers, adapters/connectors, lightning arrestors, etc. It is very important when remote mounting an antenna to consult the manufacturer's specifications for the coaxial cable being used. Misapplication of the improper cable can result in a loss that will prevent the system from working properly. As an example, LMR400 low loss cable will experience a loss of 3.9 dB/100 ft. at 900 MHz whereas using the same cable at 2.4 GHz will result in a loss of 6.8 dB/100 ft. [5]

Hypothetical Example: 4.3 dB of loss (3.9 dB from 100′ LMR400 and two connectors at 0.2 dB each)

3. Antenna Gain

Antennas are a complete subject in itself and perhaps one of the most complicated aspects of an RF system. There have been numerous books published on antenna theory and design that go into explicit detail. However, an antenna is an electromagnetic radiator converting electrical currents to radio waves at the transmitting end and back to electrical currents on the receiving end.

The most common types of antennas are omni-directional and directional antennas. Omni-directional antennas radiate its energy in a 360° pattern whereas a directional antenna will focus its energy in one direction. In point-to-multipoint systems, omni-directional antennas are typically used at the gateway (or access point) and repeater sites whereas the remote sites use directional antennas, especially in those applications where remote transmitters are located a significant distance from the gateway.

All antennas have a gain specification typically expressed in dBi, which, as mentioned previously, is referenced to a hypothetical isotropic antenna. In directional antennas, as shown in **Figure 4**, as gain increases, so does the directionality.

The energy radiated from the antenna, identified above in Figure 3 as EIRP, is the Effective Isotropic Radiated Power and accounts for all the gains and losses on that end of the system. In our hypothetical example thus far, the transmitter has an output power of 30 dBm, the losses in coax and connectors are 4.3 dB, and shown below, we will use an antenna with a gain of 3d Bi. Therefore, the EIRP is 28.7 dBm.

Hypothetical Example: 3 dBi of gain

4. Free Space Path Loss

Just like our voices attenuate over distance (the further you get from someone the harder it is to hear them), as illustrated in **Figure 5**, so does RF. Essentially, signal power is diminished by geometrically spreading of the waveform over distance.

Based on the principles of physics, the higher the frequency, the faster it attenuates. As a rule of thumb, when frequency is doubled, range is cut in half. There are a number of online calculators available to calculate the loss based on frequency and distance, but free space path loss (FSPL) can be calculated by the following formula:

$$FSPL = 36.56 + 20\text{Log}_{10}(\text{Frequency in MHz}) + 20\text{Log}_{10}(\text{Distance in miles})$$

It is important to note that energy radiated from an antenna is not a straight laser beam as some think. It radiates in a parabolic or ellipsoid shape which is the Fresnel Zone (**Figure 6**).

Almost all RF range specifications are followed with the disclaimer "with clear line of sight," which means taking into account the Fresnel Zone. Theoretically, there are an infinite number of Fresnel Zones, each having less impact on the link. Most Path Study or Propagation software default to 60% clearance in Fresnel Zone 1 (F1), which is most impacted by obstructions. The closer the obstruction to the radiating antenna, the more impact it has on the wireless link much like holding a notebook directly in front of your mouth versus at arm's length as you talk.

Hypothetical Example: 110 dB of Loss (5 miles at 900 MHz)

5. Receiver Antenna Gain

Same principles apply from number 3.
Hypothetical Example: 3 dBi of gain

6. Receiver Loss

Same principles apply from number 4.
Hypothetical Example: 4.3 dB of loss

7. Received Signal Strength

This is the received signal strength at the Receiver after all the gains and losses (Free Space Path loss of −110 dBm plus 27.4 dB of system gain).
Hypothetical Example: −82.6dBm (the expected received strength level)

8. Receiver Sensitivity

Receiver sensitivity, as covered earlier, is the threshold or lowest power level at which the receiver can detect an RF signal. Having a received signal strength (from number 7) equal to or less than the receiver is not desirable and will not produce a reliable link. Therefore, contingency or margin must be factored in and will be covered in number 9.
Hypothetical Example: −110 dBm (Receiver Sensitivity, specified from manufacturer)

9. Fade Margin

Finally, that contingency mentioned above is just how much margin (expressed in dB) there is between the received signal and the receiver sensitivity. This margin can help overcome the attenuation through obstacles, attenuation from rain and atmospheric conditions as well as challenges faced with terrain.
Like most RF parameters, there are differing opinions of recommended fade margins. However, designing systems with 20 dB of margin will leave you with a robust system and a high degree of reliability.
Based on the information supplied above, **Figure 7** provides a summary of the Hypothetical Example and our Fade Margin. It is extremely important to note that receiver sensitivity alone is not an indication of the weakest signal that can reliably decoded. In the real world, we have to deal with noise. This could be the result of heavily saturated areas of the frequency being used and the system may be limited by the noise floor rather than the Receiver Sensitivity. The image in **Figure 8** is a screen shot from a spectrum analyser used to measure the ambient noise floor.
This was an area where the actual performance did not meet the calculated performance. As shown, the ambient noise across the 900 MHz band was approximately −95 dBm. Therefore, if applied to our hypothetical example, the noise floor has a significant impact on our overall performance, and instead of having a very envious margin of 27.4 dB, it becomes 12.4 dB.
In extreme cases of a high noise floor, increasing the gain of the receiving antenna will not help. The only solution is to increase the EIRP (within legal limits) of the transmitter to overcome the noise. If presented with this challenge, spectral analysis in other bands may yield viable solutions in other bands.

Gain/Loss	Description
+ 30 dBm	TX Power of Wireless Transmitter
+ 3 dBi	Antenna Gain of Wireless Transmitter
- 4.3 dB	Cable/Connector Loss of Wireless Transmitter
+ 3 dBi	Antenna Gain of Receiver
- 4.3 dB	Cable/Connector Loss of Receiver
27.4 dB	Total System Gain
-110 dBm	Free Space Path Loss @ 5 miles
- 82.6 dBm	Expected Received Signal Level
- 110 dBm	Sensitivity of Receiver

27.4 dB of Margin ✓

Figure 7: Calculated Link Budget

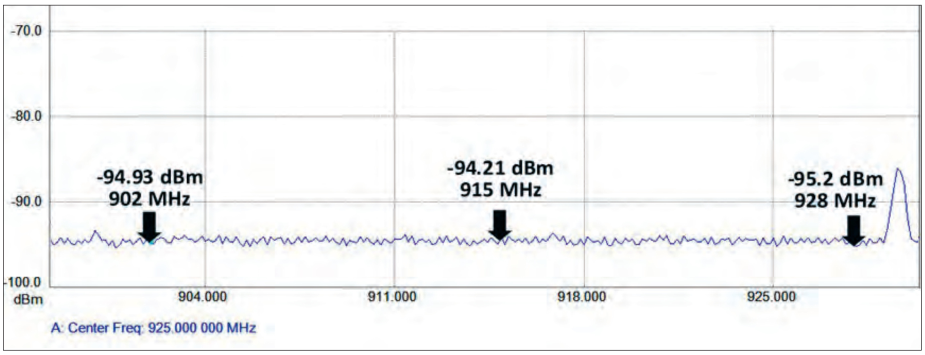

Figure 8: Noise Floor

Conclusion

The IoT harnesses the power of connected systems to predict, learn, and make real-time business decisions. However, to have connected systems, you must first have connected devices. While IoT may seem like a relatively new concept or buzzword, it is hardly new at all. For decades, companies have adopted technologies to monitor, analyse, and control their key assets. However, what is new is the accelerated growth of innovation across the entire IoT Ecosystem. With this accelerated growth of innovation, IoT brings with it an explosive increase in the demand for wireless technologies. From sensor to gateway data communications, through IoT infrastructure, understanding RF fundamentals will ensure proper application and implementation of wireless systems.

The Author

Brent McAdams is the Sr. Vice President of Global Strategic Initiatives for OleumTech Corporation and leads the company's OEM efforts as well as developing strategic partnerships to deliver a global IoT strategy, including edge-to-enterprise solutions. Mr. McAdams has appeared in a number of publications, including *Pipeline & Gas Journal*, *Control Engineering*, *ISA InTech Magazine*, and *Plant Engineering* as well as being a featured speaker at industry events around the world.

There are many IoT applications in the industrial and commercial markets and the successful design of wireless data links are paramount in producing reliable IoT links. At the end of the day, it is all about gains and losses. Hopefully, this high-level overview of the fundamentals takes a little of the black magic out of the subject. ⏮

Web Links

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[3] Link budget, October 21, 2016. In Wikipedia, The Free Encyclopedia. Retrieved 10:48, October 21, 2016, https://en.wikipedia.org/w/index.php?title=Link_budget&oldid=745477270.

[4] Insertion Loss, November 12, 2016. In Wikipedia, The Free Encyclopedia. Retrieved 14:35, November 12, 2016, https://en.wikipedia.org/w/index.php?title=Insertion_loss&oldid=749116874.

[5] LMR®-400 Flexible Low Loss Communications Coax. Times Microwave Systems, http://www.timesmicrowave.com/documents/resources/22-25.pdf.