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AN027: RIIoT™ Range – Basics and Measurement Results

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Background

The core function of any wireless communications system is to transfer data from point A to point B. The longer the communications range is, the more robust and efficient the system becomes. Therefore, range is one of the most important parameters to consider when evaluating wireless RF networks.

However, understanding range, with its, terminology, concepts, and different influencing factors, is not a straight-forward task. This document aims to deliver a basic understanding of RF range and its various key parameters. To do so, this document consists of three parts. In the first chapter, the reader is introduced to different terms and concepts often encountered when dealing with RF networks. Chapter two describes the main factors which influence the RF range of wireless networks and how a developer can tweak certain parameters to his own advantage and achieve more range. Lastly, RIIoT's range is revealed, where measurement results under different radio conditions are shown with the application of some of the concepts learnt in chapter two.

1.0 Understanding RF communications range

1.1 Importance of understanding range calculations

A basic understanding of RF waves and their characteristics can play an important role in many parts of the process of planning an RF network. In specific, an understanding of the basics of RF range and how it is influenced by numerous factors can help cut costs, save time and effort, and most importantly, it could help planning the network in the most efficient way.

One of the most common questions often asked by developers in the network planning phase is, "How long will my range be?". The answer appears to be simple – The RF modules' manufacturer should state the range that his modules provide. However, in many cases, the actual range in real-life conditions differs from the range advertised. In addition, the developer might need to tweak a couple of parameters to achieve a certain goal, thus, it is also very beneficial for him to understand the different mathematical models and formulas used in range calculations, in addition to the various environmental factors which affect RF range and some tips and tricks to mitigate their effects.

1.2 Basics to understand range

Before diving into details, it is important to first establish some of the common terminology and concepts used when speaking about RF range and its calculations.

Range: Refers to the maximum distance at which the transmitter and receiver could be placed while still maintaining adequate service level.

dBm: This unit is often encountered in power calculations. It is used to quantify power in reference to 1 mW. For example, 0 dBm would translate to 1 mW. Taking this a reference, any increase in the mW side also translates to an increase in the dBm side. However, this increase in the dBm side is logarithmic. Which means, at 10mW it is also 10 dBm, but 100 mw is 20 dBm and 1000 mW is 30 dBm. Every multiplication by 10 in mW is just an addition of 10 in dBm. Below is a table with some of the commonly used values.

Power (mW)	Power (dBm)
0.001 mW	-30 dBm
0.01 mW	-20 dBm
0.1 mW	-10 dBm
1 mW	0 dBm
1.99 mW	3 dBm
3.98 mW	6 dBm
10 mW	10 dBm
100 mW	20 dBm
1000 mW	30 dBm

Table 1.mW to dBm Conversion table

RSSI: In the RF domain, received signals are measured in terms of the received signal strength indicator (RSSI). It is a power measurement in dBm which makes calculations easier as all units are in dBm.

Noise: Noise refers to all the other signals power available in the spectrum. Noise has many types and causes. It can be thermal noise from hardware components in everything, from your own RF module, to surrounding electrical appliances. Noise could also be caused by nearby transmissions.

1.2.1 The Link Budget

One of the pillars to understanding range calculations in RF systems is the Link Budget. Simply, a Link Budget is an account of all gains and losses in a communications link, in addition to the margin of losses a link can accommodate and still maintain an adequate quality of service.

Logically, the formula for the link budget would be expressing the amount of received power as the sum of the transmitted power and any gains along the way, minus any losses.

$$P_R = P_T + G_{Tx} - L_P + G_{Rx} \tag{1}$$

Where
P_R = Received Power (dBm)
P_T = Transmitted Power (dBm)
G_{Tx}= Gain at the transmitter (dBi)
L_P= Path Loss (dB)
G_{Rx}= Gain at the receiver (dBi)

1.2.2 Link margin and receiver sensitivity

Using equation (1), we might be able to correctly calculate the amount of received power, however, how can we make sure that whatever power received by the receiver will be enough for it understand the signal (decode it)? Thus, an important parameter to define is the receiver sensitivity. Receiver sensitivity basically refers to the lowest signal power at which the receiver can still receive a signal and produce an adequate power level.

Therefore, we can say that the link margin, which is the margin of losses the link can afford to lose, is defined as the difference between the received power and the receiver sensitivity. For example, if the link margin is 20 dB, it would mean that the difference between the received power and the receiver sensitivity is 20 dB, thus, if something happens on the communication link and it loses 19 dB, the receiver would still be able to differentiate between the signal and background noise.

$$L_M = P_R - S_R \qquad\qquad (2)$$
$$L_M = P_T + G_{Tx} - L_P + G_R - S_R \qquad\qquad (3)$$

Where
S_R = Receiver Sensitivity (dBm)
L_M = Link Margin

According to equation (2), the sent packets will be correctly received when the L_M is greater than zero, otherwise, decoding errors will occur.

1.3 Path Loss

Path loss refers to the attenuation in signal strength as it propagates through its designated medium. A wireless signal may experience different types of losses during its transmission from the transmitter to the receiver. Path loss is caused by one or several of the following phenomena.

1.3.1 Free-Space loss

Free-space loss is the most basic form of losses a wireless signal can encounter. It assumes a direct line-of-sight (LoS) path between the transmitter and the receiver, without any obstacles in between. In this case, the loss or degradation in signal strength is merely a result of the ever-expanding radiation pattern of the transmit antenna, which means the radiated power keeps spreading to a larger transmit area every moment, thus its energy decreases.

$$\text{PathLoss}_{dB} = 32.44 + 20 \times \log(d) + 20 \times \log(f) \qquad\qquad (3)$$

Where
d = Distance between transmitter and receiver (Km)
f = Frequency (MHz)

Equation (3) depicts the relation between link budget calculations and range estimation. It depends on your starting point. If you already know your transmission distance and all you need is an estimate of the losses your link will incur, then equation (3) is the correct formula to use. Whereas, if you are trying to estimate your system's RF range, the correct formula to use would be equation (4) below.

$$\text{Distance}_{km} = 10^{PathLoss - 32.44 - 20\log(f)/20} \qquad\qquad (4)$$

However, it is important to note that this type of path loss, since it is the least amount of loss a signal can experience, is only achieved in line-of-sight conditions. Please refer to chapter 2 to learn more about Fresnel zones and how to achieve true line-of-sight in your link.

1.3.2 Multipath propagation

In nearly any signal transmission scenario, the signal reaching the receiver is never the result of only the copy of the signal which has travelled directly from the transmitter to the receiver. Otherwise, the net signal received at the receiver is the sum of all copies of the original signal including the one that travelled straight towards the receiver, and also, the many copies which travelled elsewhere, reflected, then reached the receiver. This phenomenon is known as Multipath Propagation.

Reflection generally occurs due to the presence of obstacles in the path of the signal. Such reflective obstacles can include mountains, buildings, and even water surfaces. Reflection could also be caused by non-obvious reasons such as earth's surface or even its atmosphere. The issue with reflected signals is that they often experience changes in some of their physical parameters. This can cause instability when they are all added together at the receiver as they can add up constructively or destructively.

2.0 Factors influencing RF range

More often than not, developers are surprised by the fact that an RF module they purchased is not operating with the range specifications advertised by its manufacturer. An easy conclusion to draw from this situation is that manufacturers advertise unreal range numbers to create more marketing hype for their products. However, that is not the case. The issue usually lies in the testing circumstances which usually differ in tests done by the manufacturer than when the same tests are done by end-customers. In this section, we explore some of the main factors affecting communications' range of RF modules and some tips and tricks to achieve the ranges specified by the manufacturer.

2.1   Antennas

The most important components in a wireless link are the transmit and receive antennas. They emit the signal power into space with an attempt to retrieve it correctly at the receiver side. Therefore, the antenna's settings and positioning are of crucial importance as very slight changes might yield great benefit to the wireless link.

2.1.1   Antenna height and Fresnel zone clearance

As explained in the previous section, the presence of obstacles in the path of an RF signal hugely impacts the quality of service achieved. Thus, usually it is recommended to position transmitters and receivers in a manner where there is a direct line-of-sight path between them. However, this is not always possible as some obstacles are impossible to avoid. A possible solution for this is to position the transmitters and receivers in a high position, above any obstacles. This way ensures a clearer signal path for transmission.

In addition to avoiding obstacles, another important concept in RF propagation, named the "Fresnel Zone" also calls for high positioning of the antennas. The Fresnel zone is basically an area, in the shape of an American football, which shows how the signal is radiated from the transmitter to receiver. In other words, just because when standing next to the transmitter you are able to see the receiver, does not necessarily mean the link is a line-of-sight link. Instead, to have true line-of-sight in your link, Fresnel zone formulas dictate that a 60% clearance in the zone is essential.
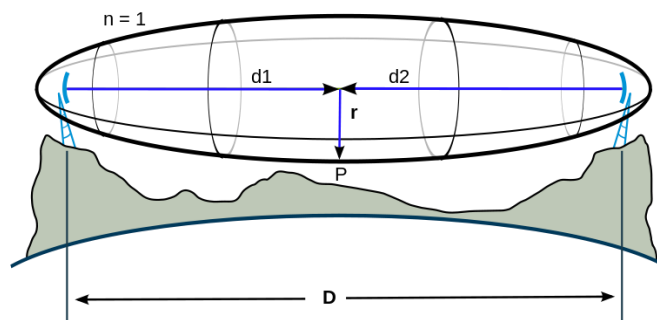

Figure 1. Fresnel Zone.

 Figure [2] below shows an illustrative example of how a Fresnel zone is disrupted by common obstacles such as earth's curvature, passing traffic, or fixed obstacles such as a tree.
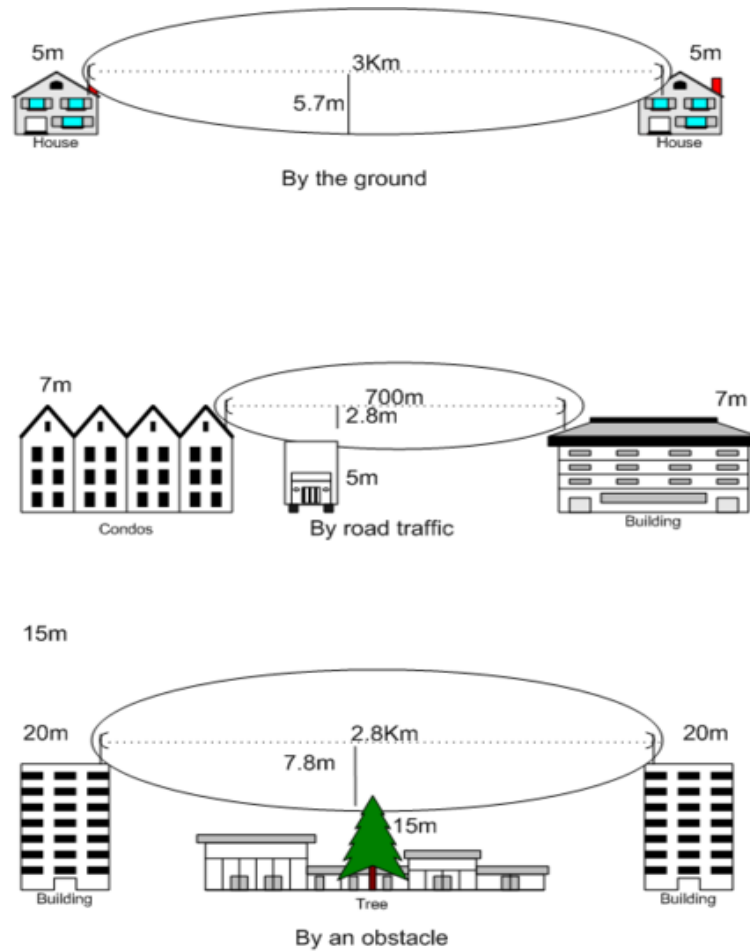
Figure 2. Different obstacles disrupting a Fresnel zone, License: https://creativecommons.org/licenses/by/4.0/

No changes to original picture

For example, as table [2] shows, consider you are planning a 300m link operating in the 900 MHz band. Fresnel zone calculations show that you would need an open spaced area with a diameter of 5m between the transmitter and receiver to achieve true line-of-sight.

Range Distance	Recommended Fresnel zone diameter for 900 MHz	Recommended Fresnel zone diameter for 2.4 GHz
300 m	5 m	3.4 m
1.6 km	10 m	6.4 m
8 km	21 m	13 m
16 km	29 m	18 m

Table 2. Recommended Fresnel zone diameters to be free for different operational bands

However, not only trees, cars, and buildings can obstruct a signal. Surprisingly, earth's curvature could also form an obstacle to a wireless link, in long distances of course. For example, a 32 km link operating in the 900MHz spectrum would need antennas 46m high to avoid the 15m obstacle caused by earth's curvature. While, for a link operating in the 2.4GHz spectrum with a length of 50 km, a 60% clearance means that an area of 23 meters at the midpoint of the link must be clear.

2.1.2   Antenna Position

As discussed in previous sections, antenna placement is crucial to link quality. This means that for best performance, antennas must be placed as high as possible, facing the coverage area intended. However, sometimes certain applications dictate very poor positioning of antennas. For example, a certain use case might dictate that the antenna has to be placed in a basement underground, or in a cabinet. In such cases, a good solution would be to connect the module to an antenna via a relatively long RF cable, which gives the user some margin to place the antenna in a better position, RF-wise.

2.1.3   Antenna Type

Depending on the application, a developer might be faced with the task of choosing the appropriate antenna for his network. In this section, we discuss some of the important parameters to be considered when choosing an antenna for your application, such as, antenna efficiency, size, and gain.

An antenna's efficiency is a measure of how much of the power entering the antenna is being radiated out towards the receiver. Logically, antenna efficiency is measured in percentage and the higher the number is, the better the antenna's performance will be.

On the other hand, an antenna's directivity is a measure of how directed the beam is, when compared to a theoretical antenna transmitting equally in all directions. For example, if an antenna doubles the amount of power transmitted in a certain direction, compared to a theoretical antenna which transmits equally in all directions, then this antenna is said to have a directivity of 3 dBi.
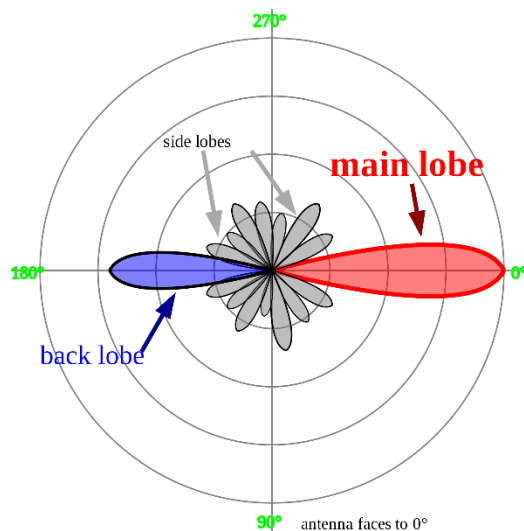

Figure 3. Illustration of an antenna's directivity

Often, the choice is between an internal antenna (PCB/chip) or an external antenna mounted by connector (typical SMA/RP-SMA). The product designer would normally want to use an internal (hidden) antenna due to design considerations. However, this will have a negative impact on range as the internal antenna will not radiate freely. Moreover, enclosure and components close to it will decrease its performance. If the requirement of internal antenna is absolute, it is important to consider the antenna design early in the design process and plan enough room for an antenna.

Another important factor in choosing the appropriate antenna is the antenna size. The main difference in performance is, the bigger the antenna, the more power it radiates and the more weak-signals it will pick-up. While this might sound perfect, there are a few challenges to it. However, output power can only be increased to a certain extent due to regulations (more information about that in the next chapter). On the receiver side, a larger antenna will also pick-up more noise. On the other hand, a smaller antenna would pick-up less noise, but still it would not pick-up the intended signal if its weaker than a certain limit. The conclusion is that a larger antenna on the receiver side will often show little effect on the overall range in practice.

Therefore, a rule of thumb here would be that you have to first decide what your limiting factor is, is it high noise which affects your signal, or is it a very long RF link with little noise. If high noise is your limiting factor, then sticking to a smaller antenna will be the right way to go as it will limit the amount of noise received. If noise is not a big issue in your environment, and you need more RF range, then using the bigger antennas might help radiate more power, under the condition that total radiated power is still under regulations limits.

Figure 4. Different antenna sizes

2.2   Transmitted power

Logically, the more power transmitted, the higher the margin for losses in the link will be. In addition, the higher the power of the main signal, the bigger the ratio between it and the noise power, thus, the easier it will be for the receiver to differentiate between them. However, different regulatory bodies, such as the FCC for the United States and ETSI for Europe, have strict transmission power limits for RF modules operating in unlicensed frequency bands. This sets a limit on the maximum transmission power to be used in the system.

Moreover, one of the key requirements to nearly all IoT networks is low power consumption. For numerous IoT network scenarios, RF modules will be deployed remotely, which might make frequent battery replacements a non-feasible solution. Thus, modules need to operate under minimal power consumption modes, which directly translates to using the least amount of transmission power possible.

Finally, another scenario where raising the transmission power is not a very good idea is when the same system uses more than just one transmitter and receiver. As the system's multiple radios raise their output power, they will start interfering with each other which would ultimately decrease system performance.

2.3   Data Rate

Data rate refers to the speed at which data bits are carried by the communications link from the transmitter to the receiver. Data rate is usually expressed as number of bits per second. Often, RF modules give the developer the freedom to choose between a number of available data rates.

The way data rate affects range is that it directly influences the receiver's sensitivity. Higher data rates decrease the sensitivity of the receiver, increasing the lowest level at which a receiver can detect a signal. In this manner, higher data rates decrease the RF range of a communications system.

In addition, higher data rates mean data will be sent through shorter packets. This makes the solution use less power and give longer battery lifetime. So, the extension of range by reducing data rate is a trade-off between power consumption and battery lifetime. However, due to the nature of noise waveforms, shorter packets are more prone to noise than longer packets. This idea is more understood through the figure below.
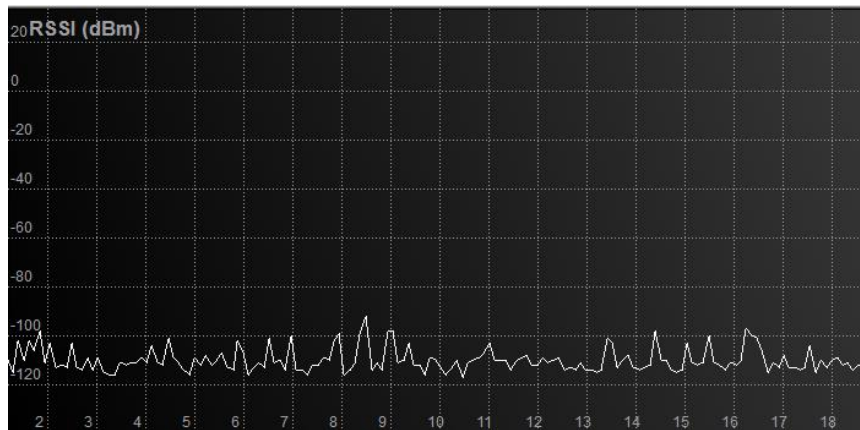

Figure 5. Noise at Radiocrafts' office for 5 kbps mode.

Figure [5] shows the nature of noise signals. The vertical y-axis represents the noise signal strength in dBm (the closer to 0 the stronger it is) and the horizontal x-axis represents time, in seconds. Signal peaks, such as those seen at the 7th and 8th second, are moments in time when the noise level is highest. Now consider a short packet, as shown in figure [6], as the case is with high data rates, when a short packet is being transmitted at the same time there is a noise signal peak, then the whole packet will be lost. On the other hand, lower-data-rate long-packets will be more spread in time, thus, even if it hits a noise peak, the remaining part of the packet might still be recoverable. This directly translates to error probabilities in the radio link which directly translates to RF range.
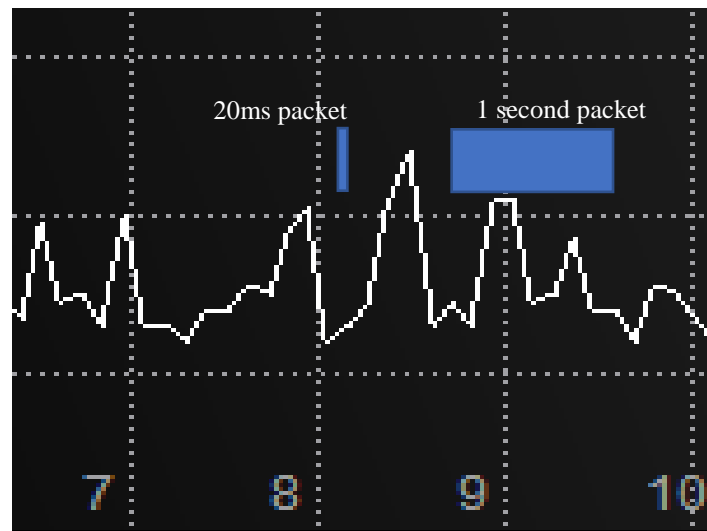
Figure 6. Illustration of the difference between long and short data packets.

2.4   Frequency band in use

The frequency band used by the system refers to the frequency or set of frequencies used by the system for its transmissions. The frequency spectrum, in general, is owned by a given country's government, and regulated in some aspects by the government and in some aspects by international regulation bodies. However, it has been agreed that certain frequency bands will be available for unlicensed use, under certain operation conditions. Amongst the most famous of these bands are the bands around, 433 MHz, 868 MHz, 915 MHz, 2.4 GHz, and 5.8GHz.

The relationship between the frequency and the RF range is inversely proportional, meaning, lower frequencies tend to offer wider range. This is mainly due to two reasons. Firstly, lower frequencies require bigger antennas to operate, and bigger antennas tend to collect more power at reception than smaller ones. In fact, under similar radio conditions, radio waves at 900 MHz travel twice as long as radio waves at 2.4 GHz. Secondly, lower frequencies, which have longer wavelengths, tend to penetrate obstacles much more efficiently than high frequencies with shorter wavelengths.

3.0 Test Results

As explained earlier, the communications' range, despite being predictable using mathematical formulas and channel models, is affected by various factors which might result in different estimates than those predicted by formulas. Thus, actual range tests under real radio conditions had to be conducted to ensure the best demonstration of RIIoT's range capabilities. The main objective of the tests was to demonstrate how a RIIoT™ radio link would operate under various radio links, such as in urban and indoor conditions. (To learn more about the RIIoT™ system, please check out https://radiocrafts.com/products/rf-network-solutions/).

3.1 LoS performance

To get an estimate of the free-space-loss for RIIoT™, we decided to place the antennas on two mountain tops to have the least number of obstacles and ensure LoS communications. As shown in figure [7], the LoS distance between the two points is around 7640m.

These two locations were chosen for a number of reasons. Firstly, they are at an adequate distance apart, which would yield a good estimate regarding RIIoT's LoS range. Secondly, being in locations with considerable height above sea-level, makes them less prone to radio noise usually found in the city. Thus, it would provide a rough estimate on how radio noise affects RF range and would also create an interesting point of comparison when comparing its results to range tests conducted at sea-level in the city. Lastly, finding a LoS path with a length of several kilometers is not an easy task in urban environments, thus, mountain tops were the right choice.
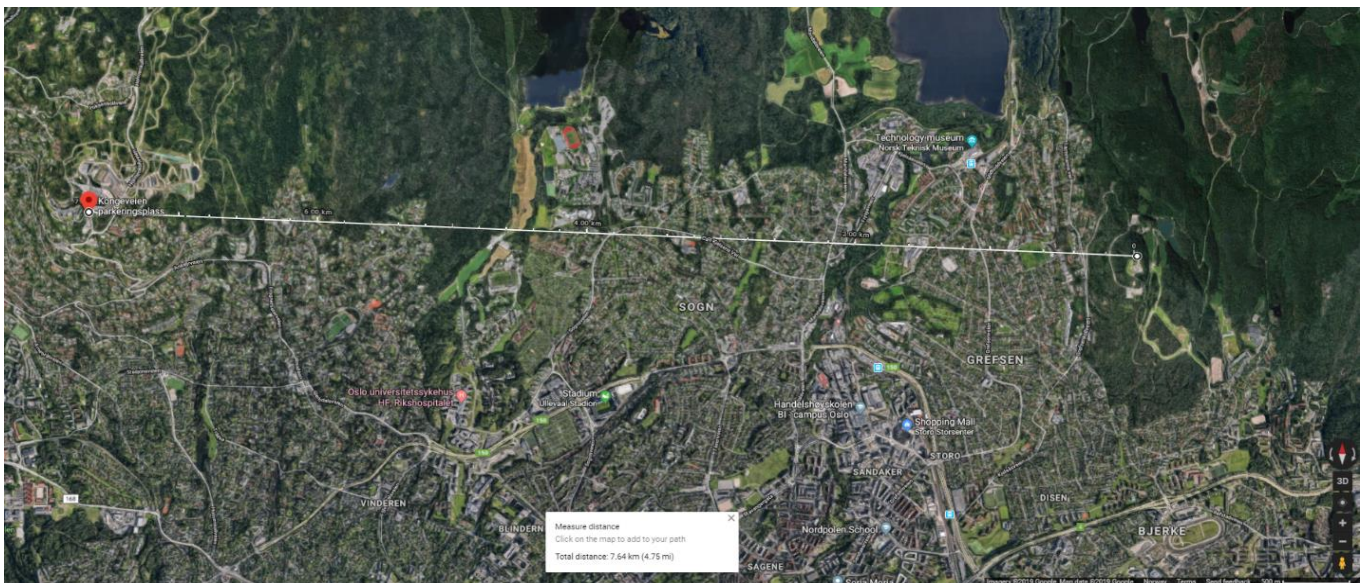

Figure 7. Distance between the two mountain tops/

The mountain to the right of figure [7], where the RIIoT™ sensor node was located, has a height of around 360m. While the mountain to the left, where the RIIoT™ gateway module was located, was around 160m above sea-level.
Backed-up by the theoretical range estimates, a distance of around 7.5 kms is well under RIIoT's coverage area in the 5kbps mode. Where the received signal strength indicator (RSSI) showed packets being received at around -99 dBm in average.
Even though an RSSI of -99 dBm predicts that even longer ranges can be accommodated, the background radio noise suggests otherwise. Figure [7] shows the noise levels picked-up by RIIoT's gateway module using the standard antenna included in the RIIoT™ kit.
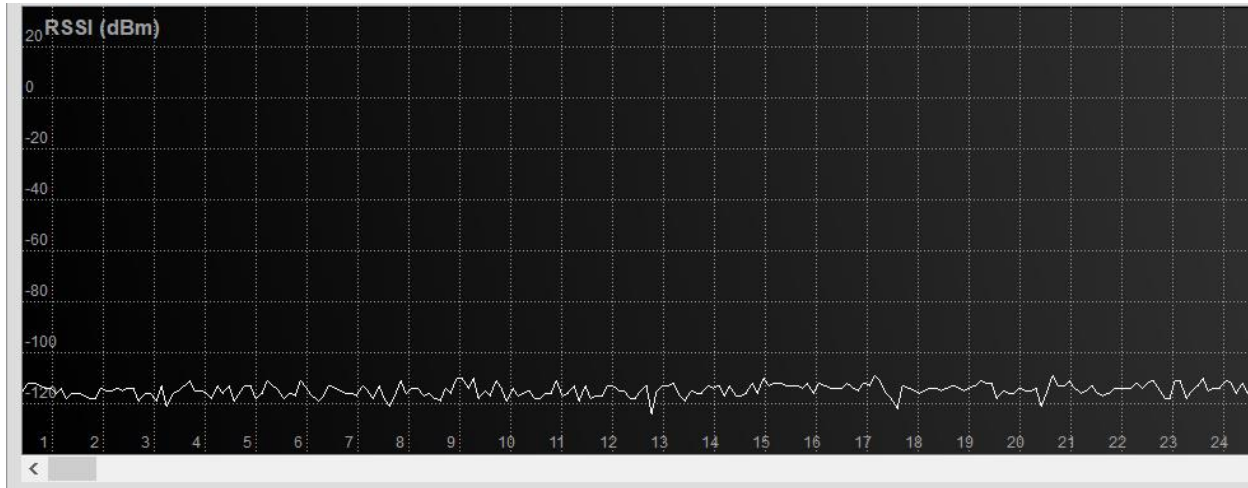
Figure 8. Noise floor for 5 kbps transmissions picked up by standard RIIoT™ antenna at mountain tops.

As shown in figure [8], the noise floor is around -116 dBm, which would theoretically mean that successful reception of data packets is possible till RSSI values of around -115 dBm. However, this is not the case. One of the most important parameters in wireless communications receivers is its operating signal-to-noise ratio (SNR). SNR basically refers to the minimum ratio between noise and the main signal at which the receiver can operate. For RIIoT™ radios, the minimum SNR is around 10 dB. Which means successful packet reception ends at around -105 to -106 dBm, thus decreasing the effective range nearly by half. According to (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.835.2366&rep=rep1&type=pdf) noise levels of around -115 to -120 are typical of urban environments, especially in well-developed cities such as Oslo.

3.2   Performance in an urban environment

A very important part of evaluating the range capabilities of an RF module is to test its performance in an urban environment. Urban environments are considered very challenging in terms of RF propagation for various reasons, such as the abundant presence of obstacles, which guarantees the absence of long range LoS, the RF noise created by other transmitters, either cellular, military, TV broadcast or similar modules, and lastly the movement of vehicles which makes the radio link more prone to fading and multipath propagation effects. As shown in figure [9], RIIoT's range was tested at multiple points throughout the area surrounding Radiocraft's office in Oslo city.
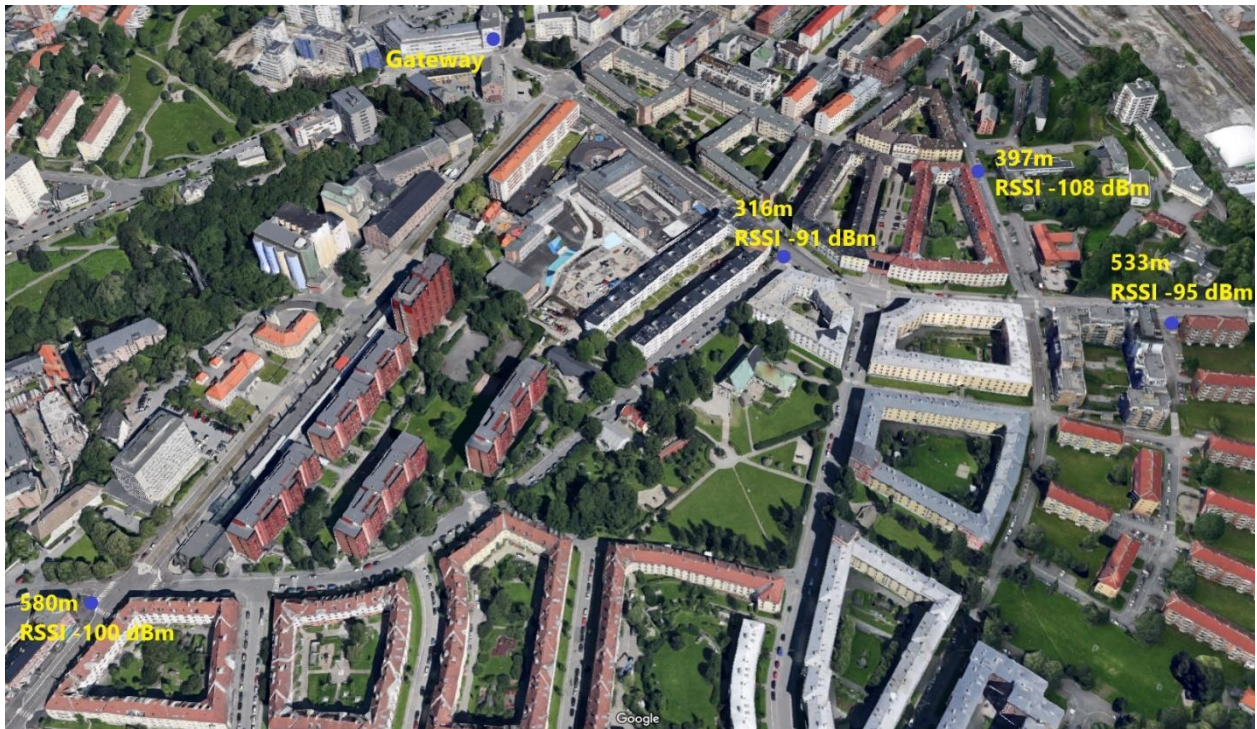
Figure 9. Coverage map around Radiocraft's office in Oslo city for 5 kbps mode.

In this test scenario, the GPR module was placed inside Radiocraft's headquarters office and the sensor node was placed at various points in the city at different distances and radio conditions, as depicted in Figure [9].

A very good illustrative example of how LoS affects radio link is the point at the bottom left corner of Figure [9]. Measurements show an average RSSI of -100 dBm, much lower than the result in the previous test, although the distance is significantly lower than that achieved over the mountain tops. This huge increase in path loss is due to the fact that in this link, there is no LoS. The signal has to endure effects caused by the various obstacles in the link which greatly impacted the communications range achieved.

On the other hand, the point at 316m with RSSI of -91 dBm is a very good illustration that visual LoS is not enough to have true LoS in a radio link. Figure [10] below shows the view from the transmitter's position, the point we are referencing is in the middle of the street in the picture below.

Figure 10. View from the transmitter's side.

The receiver at this measurement was in the street shown above, which means there was visual LoS in the radio link, and from the mountain's measurements we can assume that any visual LoS would yield a range of over 7.5 km. However, this is not the case as the RSSI was -91 dBm, which means it would not be long before signal is lost. The reason for that is, as discussed earlier, visual LoS does not necessarily mean radio LoS. The presence of passing by cars and people create multipath propagation effects, which degrade signal quality. Moreover, since the receiver is on ground-level, there is no Fresnel zone clearance in the link. Lastly, the fact that this measurement is in a city means that there would be higher background noise levels, which is proven by the below figure.
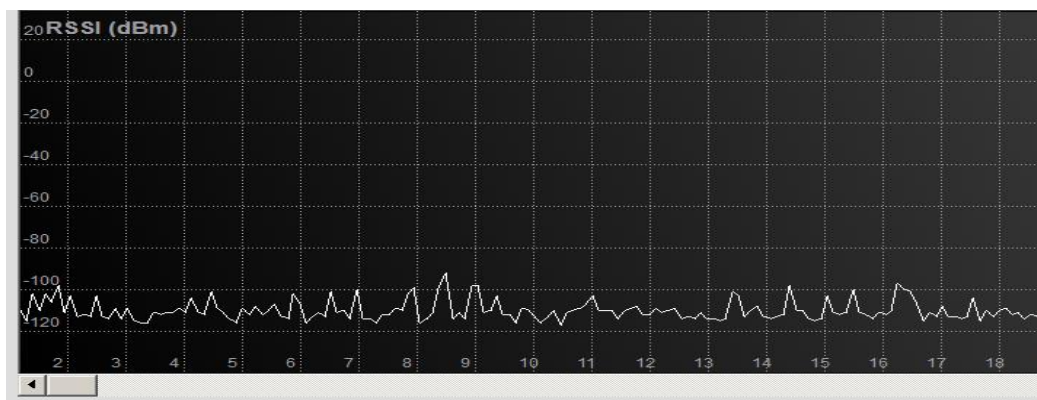

Figure 11. Noise level at Radiocraft's office area in Oslo city, for 5 kbps mode.

3.3 Indoor test results

To test how RIIoT™ radios would perform in an environment with dense obstacles, we also performed range and RSSI measurements inside the 6-floor building where Radiocraft's headquarters is located. The test scenario was to test coverage from an office in the 3rd floor down the basement, and also up to the 5th floor. Usually, concrete and steel walls cause the most attenuation to radio signals. However, in indoor environments, a number of propagation characteristics can be used to our advantage such as, the «corridor effect» where radio signals reflect between the walls and ceilings of corridors and thus travel longer distances, and «inter-floor propagation» where radio signals penetrate floors resulting in a stronger signal underneath the transmitter than that measured further on the same floor.

Tests revealed that RIIoT™ successfully covered the whole building, with the weakest signal being -82 dBm in the basement (floor 0).

Document Revision History

Document Revision	Changes
1.0	First release

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