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Embedded Wireless Solutions

AN021: RF MODULES RANGE CALCULATIONS AND TEST

APPLICATION NOTE

We Make Embedded Wireless
Easy to Use

RF Modules Range Calculation and Test

By T.A.Lunder and P.M.Evjen

Keywords

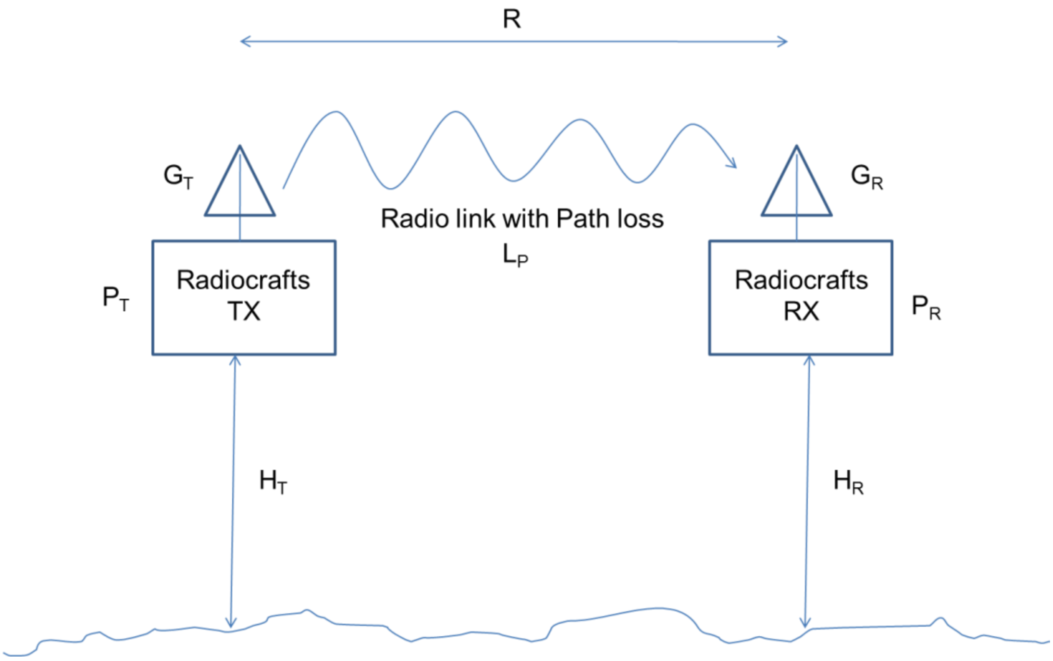
- Definition of Link Budget, Link Margin, Antenna gain, Path loss
- Models for indoor and outdoor range
- Range calculation
- Case studies of range testing

Introduction

Radiocrafts offers a series of RF Modules with integrated wireless communication protocols that are easy to use in a wide range of applications. When selecting the right radio technology, the achievable communication range is an important factor. This document review how to analyse radio range based on parameter provided in the data sheets for the different module families. Some measurement results from practical range testing are also shown.

Link Budget

The key parameters for a radio link analysis are the transmitter output power, the transmitter antenna gain, the receiver antenna gain and the receiver sensitivity. Also, of critical importance are details of the environment that is between the transmitter antenna and the receiver antenna, including the distance between them, any obstacles, the antenna height (above ground), and radio noise present. A simple illustration of a radio link is given below.



The link budget is the sum of all of the gains and losses in the radio system link. For a radio link system based on a radio module, the transmitter output power and the receiver sensitivity are known parameters from the data sheet, and a simple link budget equation will looks like this:

$P_R = P_T + G_T + L_P + G_R$

Where

P_R = Received Power (dBm)
P_T = Transmitted Power (dBm)
G_T = Transmitter antenna Gain (dB)
G_R = Receiver antenna Gain (dB)
L_P = Path Loss (dB)

Link Margin

The transmitted signal is spread out from the transmitter so that only a fraction of the power reaches to the receiver. This is represented by the Path Loss (LP) which models the loss of power due to distance and the antenna area. Because the antenna area (how large area the antenna can catch power from) depends on the frequency, the path loss is frequency dependent.
A common misunderstanding is that higher frequency signals are attenuated by "space" more than lower frequencies. This is not the case. The frequency dependency of the Path Loss is just a result of the fact that the electrical size (and the physical size) of the antenna scales with the wavelength. A low frequency antenna is larger and therefore has a larger antenna area which can catch more power from the transmitter.

As long as P_R is greater than the sensitivity of the RC module, the packet will normally be received correctly. The link margin, $L_{M,}$ informs about how much margin there is on the communication link before starting to get packet errors:

$L_M = P_R - S_R$
$L_M = P_T + G_T + L_P + G_R - S_R$

Where

P_R = Received Power (dBm)
S_R = RX Sensitivity (dBm)
$L_M>0$ = Link OK
$L_M<0$ = Link corrupted or errors in packet

Randomly variation of path loss due to fading and environmental RF noise must be taken into account, and will require you to always have at least few dB Link margin in your deployed destination to ensure reliably communication over time.

Antenna Gain

An antenna with gain 0dBi is called an isotropic antenna. In a transmitter it spreads power equally in all directions, and it receives power equally from all directions. An antenna with gain above 0dBi is directional, and the more the gain the more directional the antenna is. So antenna gain is really a measure of the antenna's ability to focus the transmitted energy in one direction, or as a receiver, to listen to one direction and exclude others. A theorem called reciprocity states that it doesn't matter if you use an antenna as a transmitter or receiver, the gain is always the same. This is an assumption that will be used in the rest of this document.
Here is a list of the antennas used in the Radiocrafts Development Kit, and their respective gain:

Frequency Band	Type	Antenna Gain
169 MHz	H169-SMA	-9 dBi*
433 MHz	ANT433QW-SMA	0 dBi
868 / 915 MHz	ANT868-915QW-SMA	0 dBi
2.4 GHz	ANT433QW-SMA	0 dBi

*Low gain due to small ground plane area compare to the wavelength at 169 MHz

A quarter wave antenna on an ideal infinite ground plane, have 5.15 dBi gain. However, on a small ground plane like the Development Board, the gain will be reduced to approximately 0 dBi.

Path Loss

Path loss (or path attenuation) is the reduction in power density of a radio signal as it propagates through space. Path loss is a major component in the analysis and design of the link budget of radio systems. The estimate of the path loss depends on the distance and environment between the transmitter and receiver. We use propagation models to estimate the path loss L_P.

Calculation of the path loss is usually called *prediction*. Exact prediction is possible only for simpler cases, such as the above-mentioned *free space* propagation or the *flat-earth model*. For practical cases the path loss is calculated using a variety of approximations. As an overview, three different models (Free space model, Over-Ground model and Simple indoor model) are presented in the following.

The ***Free space model*** assumes that there are no obstructions between the transmitter and receiver, or any significant reflecting objects (including the ground). The spacing between the transmitter and receiver is R and the Path Loss is then given by:

$$L_P = P_0 - 20*\log_{10} R$$

Where R is distance in meter between the transmitter and the receiver. P_0 is the Path Loss at 1 meter distance given by:

$$P_0 = 20 * \log(300/4*PI*frequency)$$

P_0 for a selection of frequencies are:

P_0 @ 169 MHz = -17.0 dB
P_0 @ 433 MHz = -25.2 dB
P_0 @ 868 MHz = -31.1 dB
P_0 @ 915 MHz = -31.6 dB
P_0 @ 2.4 GHz = -40.4 dB

In the ***Over-Ground Model***, the transmitter is at height H_T above flat ground and the receiver is at a height H_R. The distance between the transmitter and the receiver is R. P_0 is as defined for the free space model. The path loss is given by:

$$L_P = P_0 - 10*\log_{10} (H_T * H_R / R*R)$$

In the ***Simple Indoor model*** the type of environment is modelled by an index n. The spacing between the transmitter and the receiver is R. P_0 is as defined for the free space model. The path loss is then given by:

$L_P = P_0 - n*10*\log_{10} R$

Some reported values for n are:

n	Description
2	Free space
2.2	Retail store
1.8	Grocery store
3	Office, hard partitions
2.6	Office, soft partitions
3.3	Metalworking factory, obstructed line of sight
2.1 – 4.5	General non-LOS in office building
1.2 – 6.5	Different indoor environment over several floors

This Simple Indoor model can also be used when estimating range outdoor in urban environment.

Range Estimate

Absolute maximum range can be calculated by setting the link margin to 0 and first calculate the maximum path loss the radio link can have before packets are lost. This take place when:

$L_M = 0$
$L_M = P_R - S_R = P_T + G_T + L_P + G_R - S_R = 0$
$L_P = S_R - (P_T + G_T + G_G)$

The range, R, can now be calculated based on one of the path loss models described above; the Free space model, Over-Ground model or Simple indoor model.

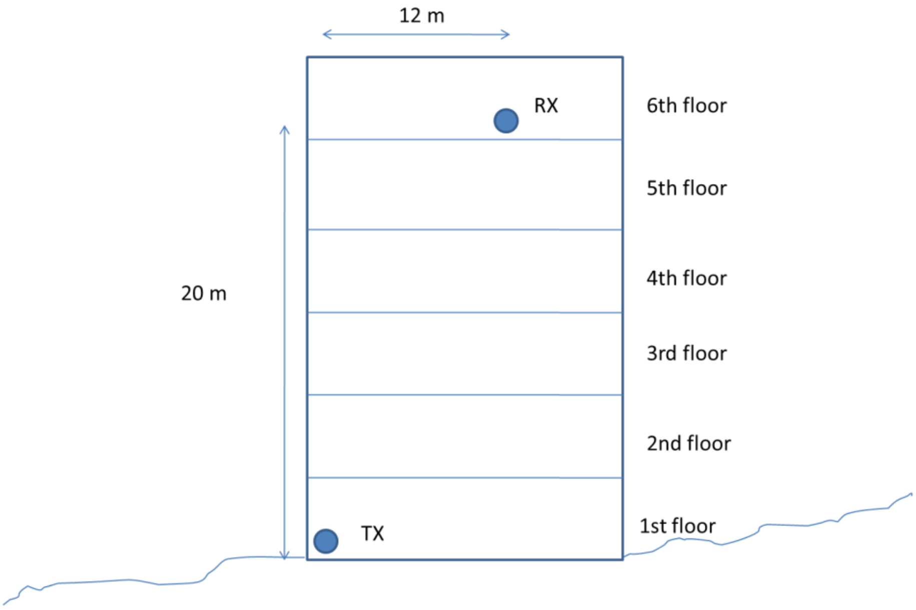
You will see that you will reach a certain range at a given frequency limited by the link budget. A rule of thumb for range estimation is that 6 dB increased of margin in the link budget will increase the range by a factor 2. The link margin is increased by configuring the Radiocrafts module for higher output power or better sensitivity. Better sensitivity is achieved by using lower data rate or selecting one of the narrowband modules. Another rule of thumb is that for a given link budget the range will be increased by a factor 2 if the frequency is reduced by a factor 2.

Case Study 1: 868 MHz Indoor environments

The RC1180-MBUS was tested inside the Radiocrafts headquarter building. The S mode configuration use the following parameters:

Frequency:	868.3 Mhz
Output power:	9 dBm
Sensitivity:	-106 dBm
Antenna gain:	0 dBi
R:	23 meters (6 floors)
N:	5

A modelling index of 5 was selected due to link going through several floors and that the transmitter was located close to an elevator made of steel. The figure illustrates the side view of the Radiocrafts building and shows the position of the transmitter in 1st floor, and the receiver at the 6th floor.



The simple indoor model gives the following path loss:

$P_L = P_0 - n*10*\log_{10} R$

$P_L = -31.1 \text{ dB} - 5*10*\log_{10} 23 = -31.1 \text{ dB} - 68.1 \text{ dB}$

$P_L = - 99.2 \text{ dB}$

The Received power from 1st floor to 6th floor will then be:

$P_R = P_T + G_T + L_P + G_R$

$P_R = 9 \text{ dBm} + 0 \text{ dBi} -99.2 \text{ dB} + 0 \text{ dBi}$

$P_R = - 90.2 \text{ dBm}$

Giving a Link Margin of:

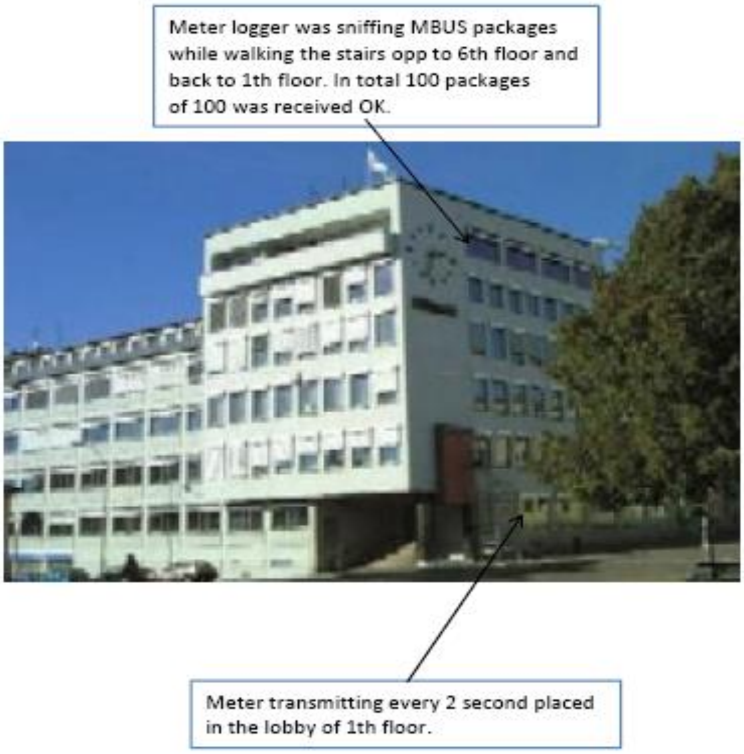
$L_M = P_R - S_R$

$L_M = P_T + G_T + L_P + G_R - S_R$

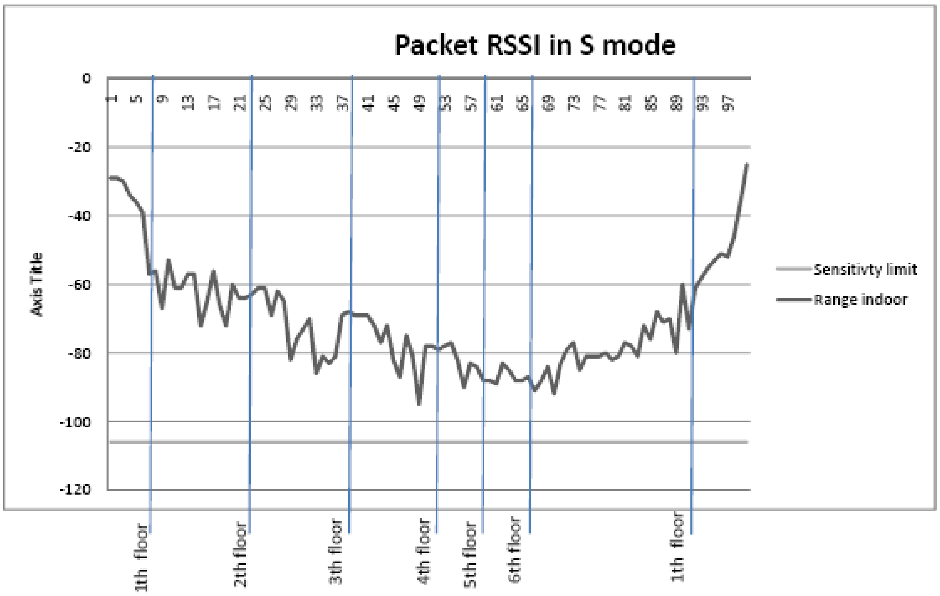
$L_M = 9 \text{ dBm} + 0 \text{ dBm} -99.2 \text{ dB} + 0 \text{ dBm} - (-106 \text{ dBm})$

$L_M = 15.8 \text{ dB}$

The theoretical value can be verified by a simple range test in the Radiocrafts building. The transmitter located in the lobby of 1st floor was constantly transmitting packets every 2 seconds. The receiver was logging all the received packets and recording the RSSI level for each packet. The receiver was carried while walking from the transmitter at the 1th floor, to the end position at 6th floor, and back again.



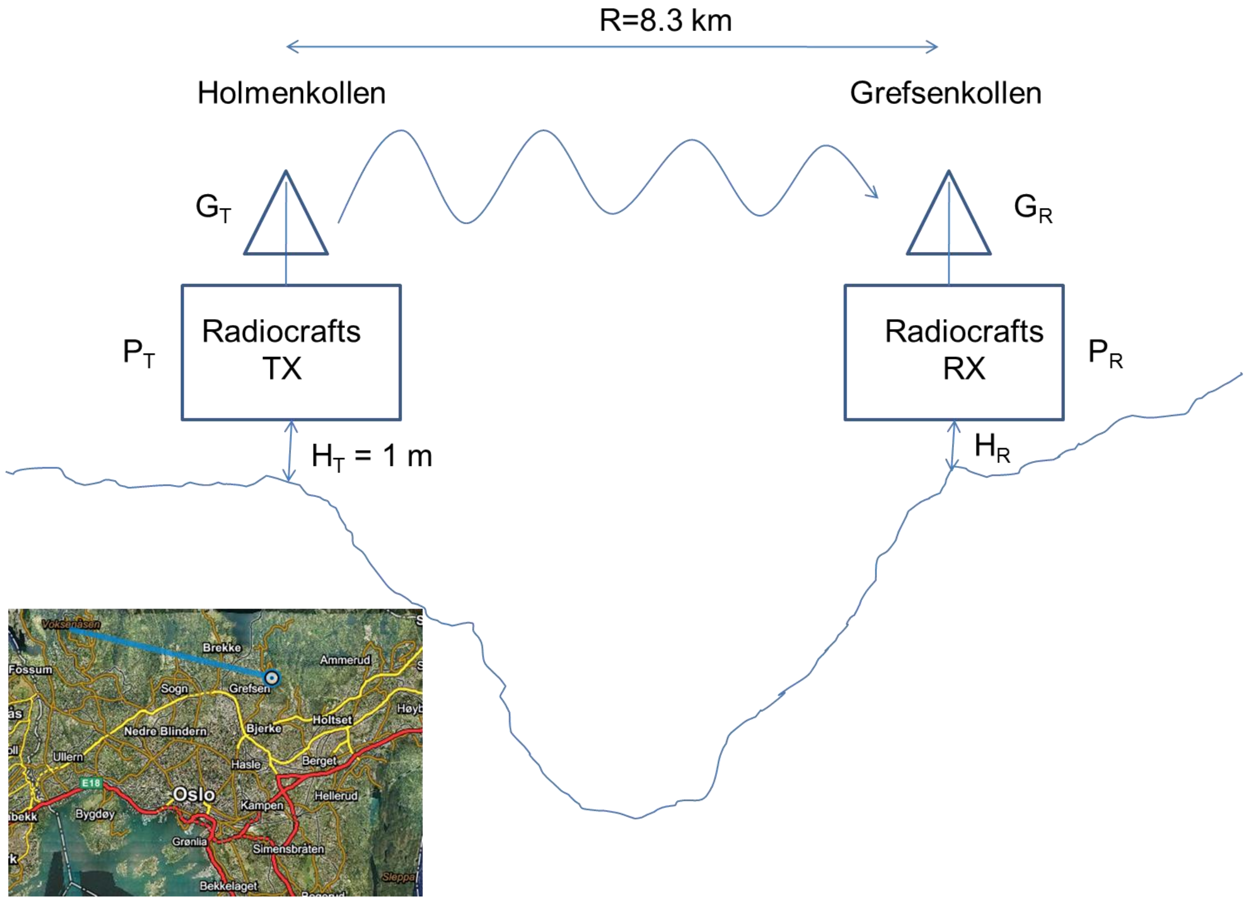
The plot below gives a graphical representation of the RSSI values detected from 1st floor up to 6th floor. At the end location at 6th floor the RSSI level is typical -90 dBm, in good match with the number previously calculated.



This range test was performed using the RC1180-MBUS module from Radiocrafts. The hardware platform was RC1180-MBUS-DK that uses the ANT868-915QW-SMA antenna.

Case study 2: 169 MHz antenna comparison in free line of sight

The RC1700HP-MBUS4 Development Boards including the Kit antenna was used to compare a wide selection of 169 MHz antennas. This illustrates the antenna Gain differences. A free Line-of-Sight (LoS) between Holmenkollen and Grefsenkollen in Oslo has a distance of 8.3 km. This line was used as a fixed location for the antenna comparison test.



The table below summarizes the RSSI level on the receiver for different RX antennas. The TX antenna used in all tests is antenna A.

RX antenna type	H169-SMA	Vtronix LD20	Vtronix LD74	Vtronix X12B	ANT F02-000	ANT F02-001	Pulse SPWB24150	2JD02 Dipole	Fractus FR01-B3
Antenna ID	A	B	C	D	E	F	G	H	I
RX Polarisation	V	V	V	V	V	V	V	V / H	V /H
RSSI	-88	-81	-75	-88	-84	-88	-90	-83/-92	-93/-96
RSSI noise (no signal)	-114	-102	-101	-114	-101	-114	-100	-99/-104	-126 / -122

The received signal strength (RSSI) differs between the RX antennas, and illustrates the antenna gain difference compared to antenna A.

The following parameters were used during the test:

Frequency:	169 Mhz
Output power:	+27 dBm
Data rate:	2.4 kbps
Sensitivity:	-119 dBm
Antenna gain TX:	-9 dBi

The free space model gives a path loss of:

$L_P = P_0 - 20*\log_{10} R$

$L_P = -17 \text{ dBm} - 20*\log_{10} (8300)$

$L_P = -95.4 \text{ dB}$

When using the antenna A also at the receiver side, the Link margin is:

$L_M = P_R - S_R$

$L_M = P_T + G_T + L_P + G_R - S_R$

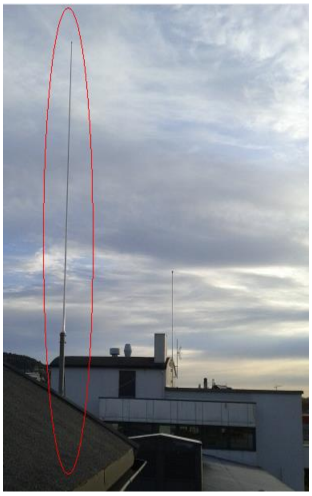
$L_M = +27 \text{ dBm} -9 \text{ dBm} -95.4 \text{ dB} - 9 \text{ dBm} - (-119 \text{ dBm})$

$L_M = 32.6 \text{ dB}$

This margin shows that RC1700HP will reach much longer than 8 km in free line of sight range since. In theory, 6 dB margin gives twice the range. With more than 30 dB margin, we would reach 32 times longer.

Case study 3: 169 MHz urban environment range test

Antenna C was selected to be mounted on the roof top of the Radiocrafts building based on the antenna comparison test in Case study 2. This antenna was connected to a RC1700HP Development Board that transmits packets continuously. Another Development Board using the Kit antenna (Antenna A) was used as a portable collector by walking around in the streets using a small laptop running the RC-Tools Packet sniffer to collect radio packets.



The following parameter was used during the test:

Frequency:	169 Mhz
Output power:	+27 dBm
Antenna gain TX:	4 dBi (antenna C)
Data rate:	2.4 kbps
Sensitivity:	-119 dBm
Antenna gain RX:	-9 dBi (antenna A)

Packets were received outside "Oslo City shopping Mall" at a distance of 3.5 km in urban environments. Some packets were lost and some packets were received at this location, meaning it was marginal coverage at this spot.

Let's use the simple indoor model and assume index 3.5 is suitable for this urban outdoor environment and find the path loss as:

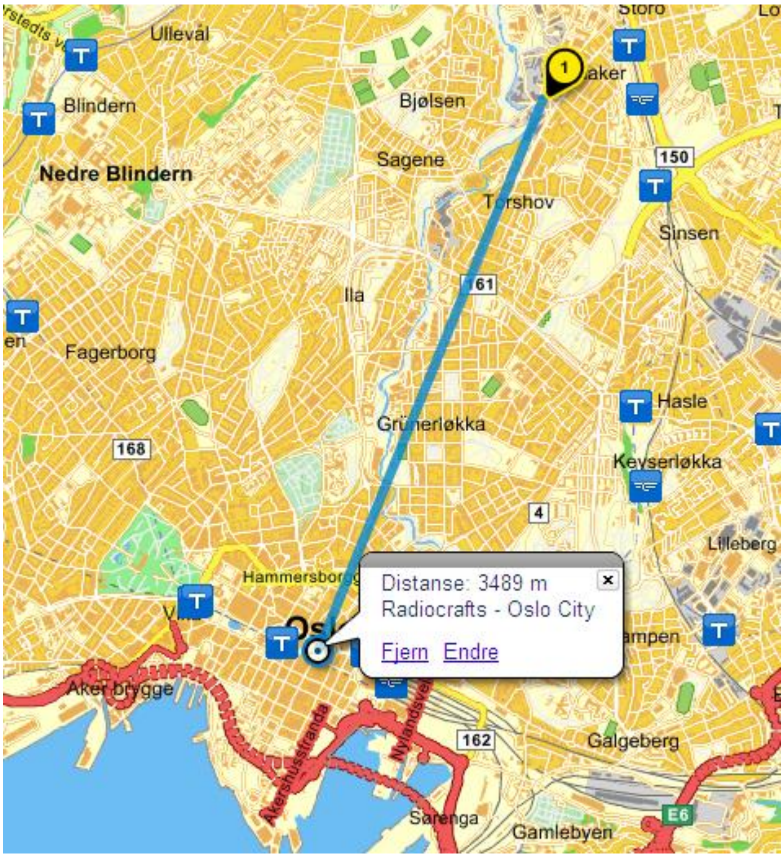
$$L_P = P_0 - n*10*\log_{10} R$$
$$L_P = -17 - 3.5*10*\log_{10} (3500)$$
$$L_P = -141 \text{ dB}$$

The link Margin will then give:

$$L_M = P_R - S_R$$
$$L_M = P_T + G_T + L_P + G_R - S_R$$
$$L_M = +27 \text{ dBm} + 4 \text{ dBm} -141\text{dB} - 9 \text{ dBm} - (-119 \text{ dBm})$$
$$L_M = 0 \text{ dB}$$

This show that index 3.5 could be the correct assumption for 169 MHz urban environments when placing an efficient antenna on top of a building. Additional measurements at other location are recommended to give a more accurate estimate of the urban path loss index.

The city map below shows the actual communication distance.



Summary

This Application Note was written as an attempt to explain in a simple way how to estimate achievable range for a Radiocrafts radio module. Case studies illustrate the relationship between theoretical calculations and the actual measured range. But keep in mind that the models are simplifications, and actual range results are subject to great variation from location to location and environment to environment.

Line-of-Sight tests, as well as tests in urban environment have shown that the Radiocrafts RC1700HP module operating at 169 MHz using high output power (27 dBm) and narrowband reception technology, give an extremely long range compared to many other solutions available.

Document Revision History

Document Revision	Changes
1.0	First release

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Please Visit Our Website!

www.radiocrafts.com

Email: sales@radiocrafts.com

Tel: +47 4000 5195