Achieving Optimum Radio Range

Richard Wallace

ABSTRACT

This application report addresses the parameters that affect the radio range. For identical radio settings, the range is highly dependent on the surroundings and environment. The link budget and the positioning of the antennas and their distance to the ground surface are major contributors to long range. A general specific range can never be specified or guaranteed for any type of radio communication unless the environment is well defined. Predicting a range is difficult and the excel sheet calculation [1] helps to calculate a realistic range that can be achieved for a known environment.

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1   Introduction

When designing a system based upon a radio link, the maximum range between the transmitter and receiver is one of the most important parameters that will dominate the system configuration and installation. Most radio systems optimize the range since this avoids the use of repeater units or amplifiers. Maximum range should always be targeted and if the range distance is too great, then the output power can always be reduced and current consumption reduced.

Sending a radio signal through concrete re-enforced brick walls in an urban RF noisy environment a few 100 meters can be as just challenging as achieving a long range line-of-sight (LOS) distance with several km of distance

Choosing the optimum frequency for your system is not always a clear choice with ISM bands ranging from 169 MHz band to 2.4 GHz band. Antenna performance and location, output power regulations, unwanted RF jammers, operating frequency, radio configuration and material between the Tx and Rx units all determine the maximum radio range distance; all these parameters and the effects they have on the total range are covered in this application report.

Examples of realistic range expectations are shown and are based on a 2-ray Friis model, which can also take into account typical construction building materials. This application report also illustrates the range tests that have been performed with various user scenarios: high rise building apartment test, dense urban environment test and long range tests at high altitudes.

2   Theory

2.1   Propagation

There are basically three propagation modes for radio signals: ground waves that follow the earth's circumference but are at just a few MHz; sky waves reflecting from the atmosphere and earth but are in the approximate range of 3 MHz to 30 MHz, and LOS propagation.

The most common ISM bands for radio communication are at 169 MHz, 315 MHz, 433 MHz, 490 MHz, 780 MHz, 868 MHz, 915 MHz and 2.4 GHz. Propagation for all of these bands are with LOS. The maximum LOS distance is dependent on the earth's curvature (earth's radius = 6365 km) and the height of the transmitter antenna (H1) and height of the receiver antenna (H2).

$$LOS_{MAX} = \frac{\left(\sqrt{2*H1*6365000} + \sqrt{2*H2*6365000}\right)}{1000} = X \; kilometers \tag{1}$$

Table 1. Line-of-Sight With the Receiver at Ground Level

Height of Antenna H1 (m), H2 = 0 m	LOSmax (km)
10000	356.8
1000	112.8
100	35.7
10	11.3
1	3.6
0	0.0

Therefore, to test a radio link with a receiver placed at ground level that has a link budget capable of communicating greater than 112 km, then the transmitter must be positioned at a greater height than 1000 m.

2.2 Link Budget

The radio link budget is roughly the delta in dB between the amount of output power from the transmitter in dBm and the radio's sensitivity limit in –dBm; so with a transmitting output power of +10 dBm and a receiver sensitivity limit of -110 dBm the link budget is roughly 120 dB.

$$Link\ Budget \approx TX\ output\ power\ (dBm) - RX\ sensitivity\ (-dBm)$$

(2)

The actual link budget takes into account the transmitter and receiver antenna gain as shown in Equation 3:

$$Link\ Budget = TX\ output\ power\ (dBm) + TX\ antenna\ gain\ (dBi) - RX\ sensitivity\ (-dBm) + RX\ antenna\ gain\ (dBi)$$

(3)

$$Link\ Budget = P_T + G_T + P_R + G_R$$

(4)

- P_R: Power available from receiving antenna
- P_T: Power supplied to the transmitting antenna
- G_R: Gain in receiving antenna
- G_T: Gain in transmitting antenna

For an ideal dipole antenna, the antenna gain (dBi) is 2.1 dB; so using the previous example, link budget would be 124.2 dB.

In digital radio systems sensitivity is often defined as the input signal level where the error rate exceeds 1%. The error rate can be calculated based upon packet error rate (PER) or bit error rate (BER).

2.3 Path Loss

Communication is achieved through the transmission of signal energy from one location to another. The received signal energy must be sufficient to distinguish the wanted signal from the always present noise. This relationship is described as the required signal-to-noise ratio (S/N). The necessary S/N ratio for a radio link is sometimes specified in receiver data sheets. More commonly, the sensitivity is specified at an absolute level in - dBm.

2.4   Friis-Equation

This section addresses the theory used to determine the range for radio systems in open and free space environments. Range in radio communication is generally described by Friis (see Equation 5).

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi)^2 d^2}$$

(5)

- P_R: Power available from receiving antenna
- P_T: Power supplied to the transmitting antenna
- G_R: Gain in receiving antenna
- G_T: Gain in transmitting antenna
- d: Distance
- c: Speed of light in vacuum 299.972458·106 [m/s]
- λ: Wavelength; where λ = c / f
- f: Frequency

Equation 5 describes the signal level at the receiver (P_R) in relation to the transmitter output power (P_T), distance (d), frequency (λ) and antenna gain (G_T and G_R).

An example using the Friis standard equation is shown in Equation 6:

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi)^2 d^n} = 1mW \cdot \frac{1 \cdot 1 \cdot \left(\frac{3 \cdot 10^8}{2445 \cdot 10^6} \right)^2}{(4\pi)^2 \cdot 100^2} = 9.532 \cdot 10^{-12} = -80.2 [dBm]$$

(6)

- P_R: Power available from receiving antenna
- P_T: 1 mW (0 dBm)
- G_R: 1 dB
- G_T: 1 dB
- d: Set distance of 100 m
- c: Speed of light in vacuum 299.972458·106 [m/s]
- λ: Wavelength

Therefore, in free space the path loss to the receiver is 80.2 dB at 100 m distance when operating at 2445 MHz.

The difference between the received signal power (P_R) and the sensitivity of the receiver is referred to as the link margin or guard band. For a realistic link budget and range expectation, additional losses must be taken into account than the losses predicted by Friis.

Using the Friis equation (Equation 6), the theoretical range is the distance at which the link is operating at a signal level equal to the receiver sensitivity level.

2.5   2-Ray Ground Reflection Model

In a typical radio link transmission waves are reflected and obstructed by all objects illuminated by the transmitter antenna. Calculating range in this environment is a complex task. Many environments include some mobile objects which add to the complexity of the problem. Most range measurements are performed in large open spaces without any obstructions, moving objects, or interfering radio sources. This is primarily done to achieve consistent measurements. Equation 6 requires LOS to be valid. Hand-held equipment generally operates close to the ground. This implies that ground influence has to be considered for a more realistic range calculation.

Figure 1 illustrates the situation with an infinite, perfectly flat ground plane and no other objects obstructing the signal. The total received energy can then be modeled as the vector sum of the direct transmitted wave and one ground reflected wave.
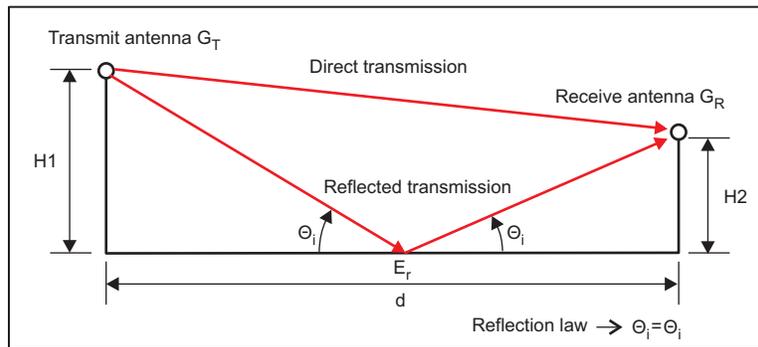

Figure 1. Transmission With Ground

The two waves are added constructively or destructively depending on their phase difference at the receiver. The magnitude and phase of the direct transmitted wave varies with distance traveled. The magnitude of the reflected wave depends on total traveled distance and the reflection coefficient (Γ) relating the wave before and after reflection.

2.5.1   Reflection Coefficient

Whenever an incident radio signal hits a junction between different dielectric media, a portion of the energy is reflected, while the remaining energy is passed through the junction. The portion reflected depends upon signal polarization, incident angle and the different dielectrics (ε_r, μ_r and σ). Assuming that both substances have equal permeability $\mu_r = 1$ and that one dielectric is free space, Equation 7 and Equation 8 are the Fresnel reflection coefficients for the vertical and horizontal polarized signals.

$$\Gamma_V = \frac{(\varepsilon_r - j60\sigma\lambda)\sin\theta_i - \sqrt{\varepsilon_r - j60\sigma\lambda - \cos^2(\theta_i)}}{(\varepsilon_r - j60\sigma\lambda)\sin\theta_i + \sqrt{\varepsilon_r - j60\sigma\lambda - \cos^2(\theta_i)}}$$

(7)

$$\Gamma_h = \frac{\sin\theta_i - \sqrt{\varepsilon_r - j60\sigma\lambda - \cos^2(\theta_i)}}{\sin\theta_i + \sqrt{\varepsilon_r - j60\sigma\lambda - \cos^2(\theta_i)}}$$

(8)

Equation 7 and Equation 8 require some electrical data for the ground surface in the test environment. For typical ground conditions, ε_r =18 (soil) is normally used. For water, ε_r of 88 is typically used and ε_r of 2.5 for sand.

In systems where H1 and H2 are low compared to the distance (d), Equation 7 and Equation 8 can be simplified to $\Gamma_v = \Gamma_h = -1$, (for example, for systems with a low incident angle, all of the energy is reflected). The phase change of the reflected wave is significant to the transmission budget as illustrated in Figure 2 and Figure 3.

Figure 2 and Figure 3 show the influence of polarization and ground in open field measurements. The values are calculated using the Excel sheet that is based upon the calculations shown in Appendix A. The figures also indicate that horizontal polarization (H) is more susceptible to multi-path fading than the vertical polarized signal (V).

For the majority of applications, there are strong cross-polarized components (mixture of vertical polarization and horizontal polarization), making it difficult to separate between the polarizations. The actual signal level is often between the vertical and horizontal levels calculated above.
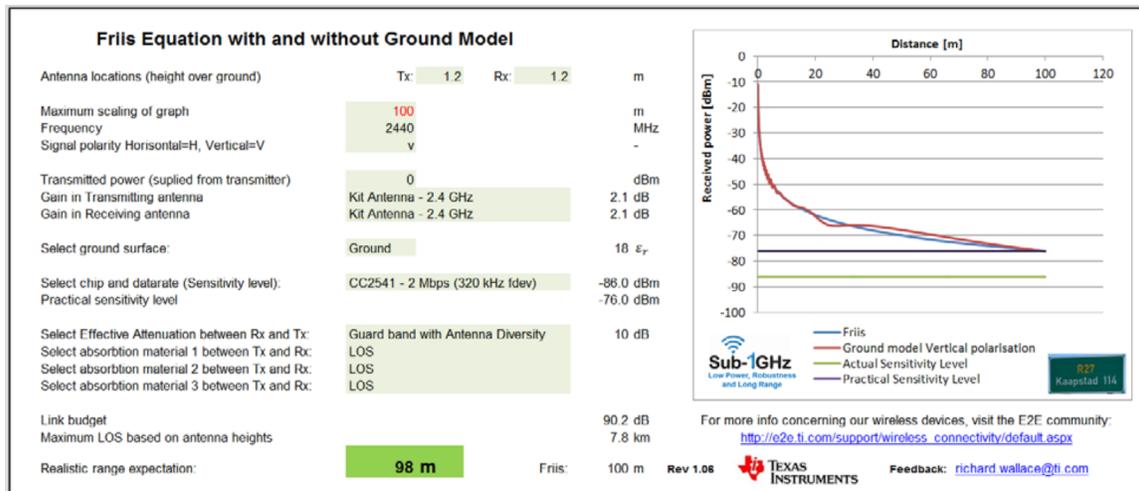
Figure 2. Range Estimation With Vertical Polarization

Figure 2 shows the estimated values for a 2440 MHz vertically polarized signal and Figure 3 shows the horizontally polarized signal. The range estimations for free space and the 2 Mbps sensitivity level (-86 dBm) of CC2541 is included in Figure 2 and Figure 3. When measuring the effective open field range for the CC2541 at this data rate, the PER test is typically started and the RSSI level recorded; then the distance is increased between the two radio units. Figure 3 indicates that communication could be poor at about 22 m but clearly the range potential is far greater with an expected total distance of should be around 100 m.
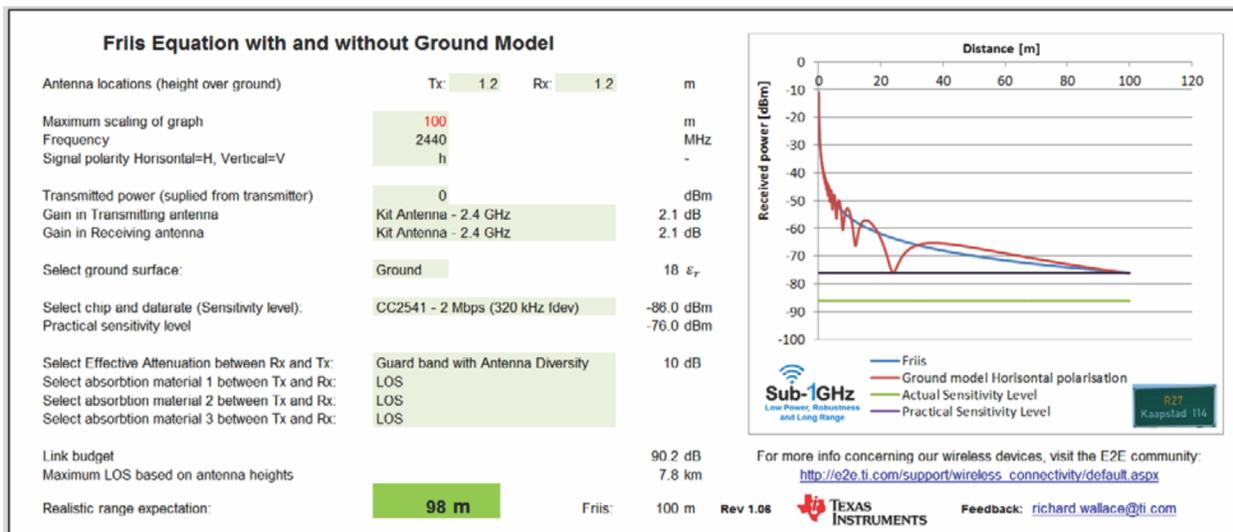

Figure 3. Range Estimation With Horizontal Polarization

The location of a blind spot varies with frequency, ground surface and antenna elevation. It is important to be aware of this during range testing to identify any blind spots or if the maximum range is reached.

2.5.2   Immunity to Unwanted RF Signals (Blocking/Selectivity)

It should be verified that the test area used is free from other RF sources on the same frequency band or close by frequencies (±10 MHz). This could be done using a spectrum analyzer (max hold) to look for RF sources prior to performing the test. This check could preferably be repeated at regular intervals during the test. Selecting a test area with low probability of interference is generally recommended.

In the event of unwanted RF signals, then the range may be affected depending on the level of the unwanted RF signals and how close these are to the radio's operating frequency. It is becoming more difficult to find clean RF test areas since the number of wireless devices is increasing. Predictions from external sources expect in the year 2020, approximately 24 billion – 50 billion wireless devices. So, the probability of finding a test area that is not affected by other RF signals is becoming very rare. Designing a radio link with respect to unwanted RF signals is becoming more critical due to the huge growth of wireless devices.

The ability to operate in a hostile RF environment should always be considered so that the system performance will not be degraded when unwanted RF signals appear. Radio systems with poor selectivity and blocking will become more apparent in the future in a hostile RF environment.

Selectivity and blocking is the radio's ability to handle RF interference. Selectivity is the ability to handle interference from unwanted RF signals operating in the same frequency band. Blocking is the ability to handle unwanted RF signals that are operating at a different frequency several MHz away, see Figure 4.
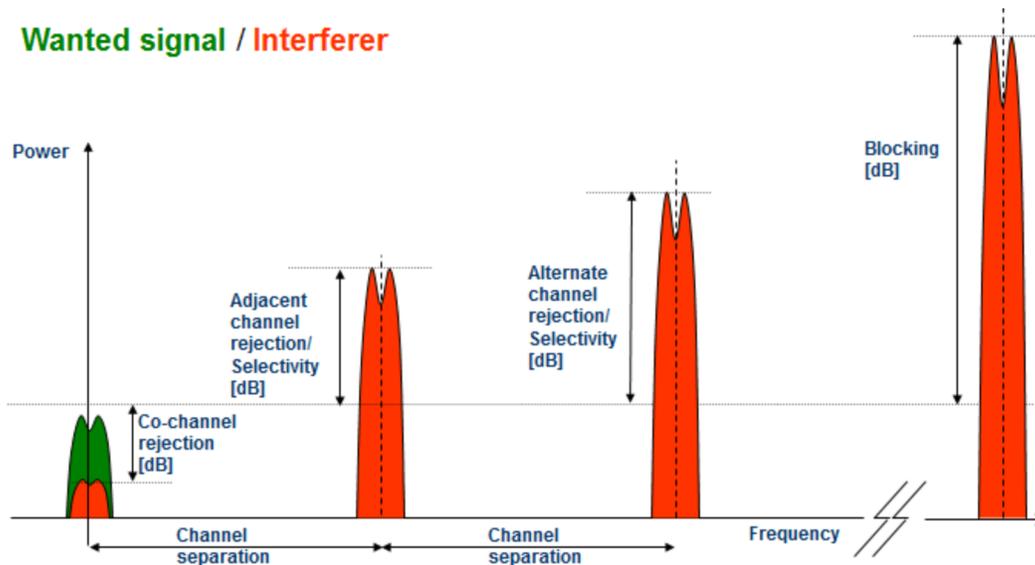

Figure 4. Selectivity and Blocking

When selectivity or blocking is mentioned in dB figures it is not always apparent what this actually means in terms of range. Examining two radio solutions with the same sensitivity level but with different selectivity and blocking requirements demonstrates the importance of a robust RF link.

Parameter	Radio 'A'	Radio 'B'
Sensitivity	-123 dBm	-123 dBm
Selectivity	54 dB	42 dB
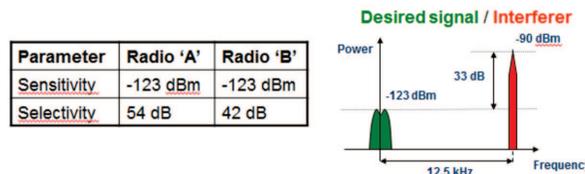
Figure 5. Weak RF Interferer Level of − 90 dBm

The power received from the interferer is -90 dBm, as shown in Figure 5. The sensitivity level is −123 dBm for both Radio "A" and Radio "B". The delta between the interferer level and the desired signal level is 33 dB and this is lower than the selectivity limit of both Radio "A" (54 dB) and Radio "B" (42 dB). The sensitivity limit of -123 dBm will not be affected by the interferer so the "actual sensitivity limit" will be the sensitivity level specified in the data sheet. Therefore, both radios will not see any degradation in performance during this weak interferer.
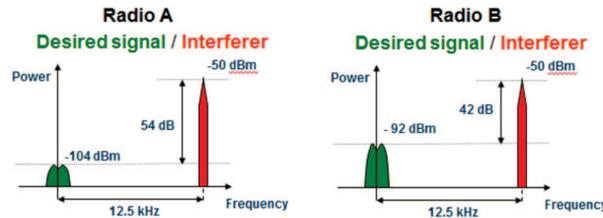

Figure 6. Strong RF Interferer Level of – 50 dBm

The power received from the strong interferer is now -50 dBm, as shown in Figure 6. The "actual sensitivity limit" of the radio is now dependent on the ability to block the strong interferer; Radio "A" will be limited to -104 dBm and Radio "B" limited to -92 dBm due to the selectivity specification, so the sensitivity level will never be reached.

If the range of Radio "A" and Radio "B" was previously 2600 m with a weak or no RF interference, then a strong interferer of -50 dBm could reduce the range of Radio "A" to 620 m and Radio "B" to 250 m. If the system application was designed to have distance of 500 m, then the Radio "B" solution would fail during a strong interference of -50 dBm.

It is important to understand the levels of the unwanted RF signals in the environment to specify a certain range. Strong selectivity and blocking specifications become more important when the number of unwanted RF interferers increase in the future.

3   Range Model in Excel

To ease the range estimation calculation, an excel sheet has been compiled that allows the various parameters entered to determine a range value; this can be downloaded from the E2E community [1].
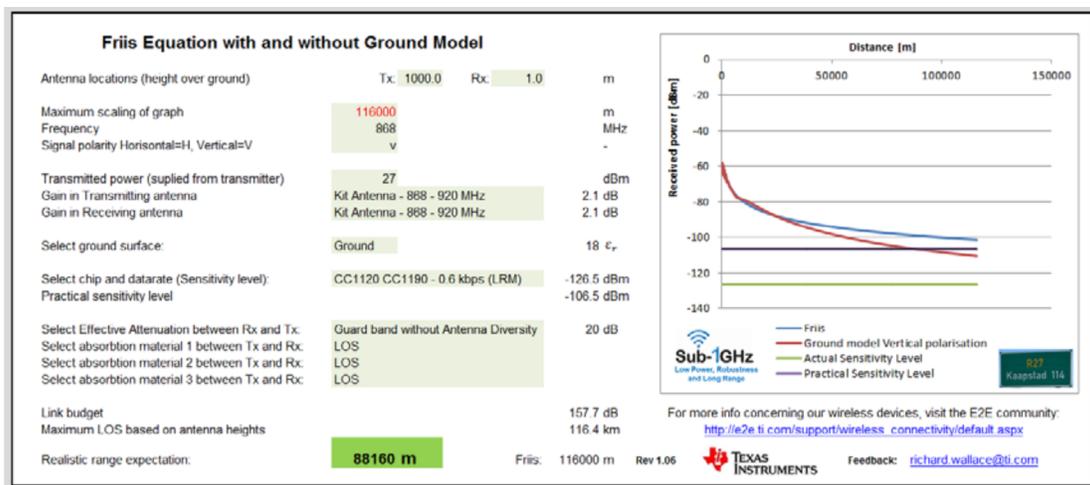

Figure 7. Screen Print of the Excel Sheet for Range Expectation

The fields that are shown in grey are the input fields. The heights of the Tx antenna (H1) and Rx antenna (H2) are entered at the top; for hand-held devices, this is typically in the region of 1.2 m. Note that there is a large difference between the Friis equation for free space and the expected range when ground model is included. This difference is reduced when the height of the antennas from the ground surface are increased (H1 = H2 >> 1 m). The realistic range expectation is based upon the ground model variant.

The scaling of the graph is just for the figure scale shown on the right hand side and this is shown in red if the scale is less than the calculated range for Friis and the ground model (2-ray). The frequency field is the operating frequency of the radio. For the signal polarity, "V" for vertical polarization and "H" for horizontal polarization can be entered. The conducted transmitted output power should then be entered and this is normally between -20 dBm to +30 dBm pending the radio solution. The gain for the Tx antenna (G_T) and Rx antenna (G_R) must be entered; for a perfect matched dipole, this is 2.1 dB, if this is unknown keep this value between 0 dB and 2.1 dB. There is a list of antennas which can be chosen with a recommended value for the gain; the gain in the list varies from -6 dB to +2.1 dB. The surface (ε_r) shown in Figure 7 can be set between ground (ε_r = 18), water (ε_r = 88) and sand (ε_r = 2.5); if this is unknown then keep this at a typical value of 18.

For the sensitivity level of the radio, a list is available of the various radios and the data rate settings. The data rate setting is important since this determines the actual sensitivity level of the radio for a particular date rate. A larger data rate will always have a lower sensitivity level.

Table 2 shows a list of radios with data rates supported in the excel version 1.07 release. If a specific radio and data rate cannot be found, choose a setting that gives the same sensitivity level that can be found in the device-specific data sheet.

Table 2. Sensitivity Levels for Various Devices and Data Rates

Sub-1 GHz Devices	Sensitivity Level (dBm)	2.4 GHz Devices	Sensitivity Level (dBm)
CC11L - 0.6 kbps	-116	CC2520 - 250 kbps	-98
CC11L - 1.2 kbps	-112	CC2530 - 250 kbps	-97
CC11L - 38.2 kbps	-104	CC2538 - 250 kbps	-97
CC11L - 250 kbps	-95	CC2540 - 1 Mbps (HG)	-93
CC11L - 500 kbps (MSK)	-90	CC2540 - 1 Mbps (Std)	-87
CC11L - 500 kbps (4-FSK)	-96	CC2541 - 250 kbps (160 kHz fdev)	-98
CC110x - 0.6 kbps	-116	CC2541 - 500 kbps (MSK)	-99
CC110x - 1.2 kbps	-112	CC2541 - 1 Mbps (160 kHz fdev)	-91
CC110x - 38.2 kbps	-104	CC2541 - 1 Mbps (250 kHz fdev)	-94
CC110x - 250 kbps	-95	CC2541 - 2 Mbps (320 kHz fdev)	-86
CC110x - 500 kbps (MSK)	-90	CC2541 - 2 Mbps (500 kHz fdev)	-90
CC110x - 500 kbps (4-FSK)	-96	CC2543 - 250 kbps (160 kHz fdev)	-98
CC111x - 1.2 kbps	-110	CC2543 - 500 kbps (MSK)	-98
CC111x - 38.2 kbps	-102	CC2543 - 1 Mbps (160 kHz fdev)	-91
CC111x - 250 kbps	-94	CC2543 - 1 Mbps (250 kHz fdev)	-94
CC111x - 500 kbps (MSK)	-86	CC2543 - 2 Mbps (320 kHz fdev)	-86
CC1125 CC1190 - 0.6 kbps (LRM)	-129	CC2543 - 2 Mbps (500 kHz fdev)	-90
CC1120 CC1190 - 0.6 kbps (LRM)	-126.5	CC2544 - 250 kbps (160 kHz fdev)	-95
CC112x - 0.3 kbps (CG - 4 kHz fdev)	-127	CC2544 - 500 kbps (MSK)	-96
CC112x - 1.2 kbps (4 kHz fdev)	-123	CC2544 - 1 Mbps (160 kHz fdev)	-87
CC112x - 1.2 kbps (10 kHz fdev)	-120	CC2544 - 1 Mbps (250 kHz fdev)	-91
CC112x - 1.2 kbps (20 kHz fdev)	-117	CC2544 - 2 Mbps (320 kHz fdev)	-84
CC112x - 4.8 kbps (OOK)	-114	CC2544 - 2 Mbps (500 kHz fdev)	-88
CC112x - 38.4 kbps (20 kHz fdev)	-110	CC2545 - 250 kbps (160 kHz fdev)	-98
CC112x - 50 kbps (25 kHz fdev)	-110	CC2545 - 500 kbps (MSK)	-98
CC112x - 200 kbps (83 kHz fdev)	-103	CC2545 - 1 Mbps (160 kHz fdev)	-91
CC120x - 1.2 kbps (4 kHz fdev)	-122	CC2545 - 1 Mbps (250 kHz fdev)	-94
CC120x - 4.8 kbps (OOK)	-113	CC2545 - 2 Mbps (320 kHz fdev)	-86
CC120x - 32.768 kbps (50 kHz fdev)	-108	CC2545 - 2 Mbps (500 kHz fdev)	-90
CC120x - 38.4 kbps (20 kHz fdev)	-110	CC2500 - 2.4 kbps	-104
CC120x - 50 kbps (25 kHz fdev)	-109	CC2500 - 10 kbps	-99
CC120x - 100 kbps (50 kHz fdev)	-107	CC2500 - 250 kbps	-89

Table 2. Sensitivity Levels for Various Devices and Data Rates (continued)

Sub-1 GHz Devices	Sensitivity Level (dBm)	2.4 GHz Devices	Sensitivity Level (dBm)
CC120x - 500 kbps (MSK)	-97	CC2500 - 500 kbps	-83
CC120x - 1000 kbps (4-GFSK)	-97	CC251x - 2.4 kbps	-103
CC13xx - 2.4 kbps	-121	CC251x - 10 kbps	-98
CC13xx - 4.8 kbps	-118	CC251x - 250 kbps	-90
CC13xx - 38.4 kbps	-112	CC251x - 500 kbps	-82
CC13xx - 50 kbps	-111	CC26xx - 250 kbps	-99
CC13xx - 100 kbps	-107	CC26xx - 1 Mbps	-97
CC13xx - 1 Mbps	-97		
CC13xx - 4 Mbps	-84		

The input field selection for "Select Effective Attenuation between Rx and Tx" contains a number of options that take into account the size of the guard band (link margin); and several input fields to select various construction materials normally used for indoor range prediction. The level of the guard band depends on the level of margin that is required. Theoretically, this can be 0 dB and the radio link will still work. However, a certain guard band should be taken and this is normally in the range of 10 dB to 20 dB. For a system that requires a strong and reliable "fail safe" RF link then the margin could be increased furthermore. Similarly, for a system that can accept re-transmissions and temporary link losses then this can be reduced. With multi-path propagation effects, the signal level can vary up to 15 dB so having a guard band >15 dB will take this into account. When not using antenna diversity, the recommended guard band is 20 dB and with antenna diversity this can be reduced to 10 dB guard band. For further information regarding the benefits with antenna diversity, see [4].

When calculating the outdoor LOS can be selected for the three input field options as shown in Figure 7. For improved indoor range estimation, various construction materials can be chosen for the three input field options. The choice of material is shown in Table 3.

Table 3. Typical Attenuation for Various Construction Materials

Construction Material	Attenuation (dB) 500 MHz	Attenuation (dB) 1 GHz	Attenuation (dB) 2.4 GHz
Line-Of-Sight	0	0	0
7" brick	3.5	5.5	7.5
8" concrete	21	25	32
1/2" drywall	0.1	0.3	0.6
1/2" glass	1.2	2.2	3.4
4" reinforced concrete	23	27	31
3" lumber	1.5	3	4.7

Table 3 shows that the material penetration is highly frequency dependent and the advantages of operating at a lower frequency is clearly seen in the link budget and range expectation. A rule-of-thumb is every 6 dB increase in a link budget doubles the range distance. To send a signal through an 8" concrete wall at 1 GHz will have approximately twice the range compared to a similar system operating at 2.4 GHz.

When all the parameters with the height of the antennas, frequency, polarization, output power, antenna gain, ground surface, sensitivity level, guard band, and material between Rx and Tx; then a more realistic range can be calculated compared to the standard Friis formula.

3.1 Excel Examples

Indoor and LOS for 868 MHz vs 2.4 GHz comparison.

The radio performance is very similar in Figure 8 and Figure 9; the only difference is the operating frequency. As can be seen, the range expectation is increased from a distance of 233 m at 2440 MHz to 292 m at 868 MHz for similar radio performance.
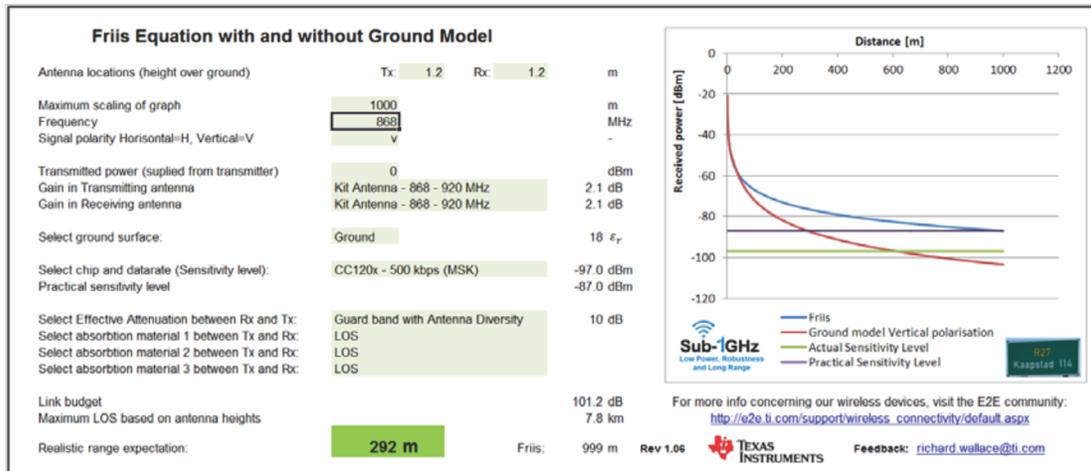

**Figure 8. Outdoor LOS, 500 kbps With CC1200 at 868 MHz; Expected Range 292 m**
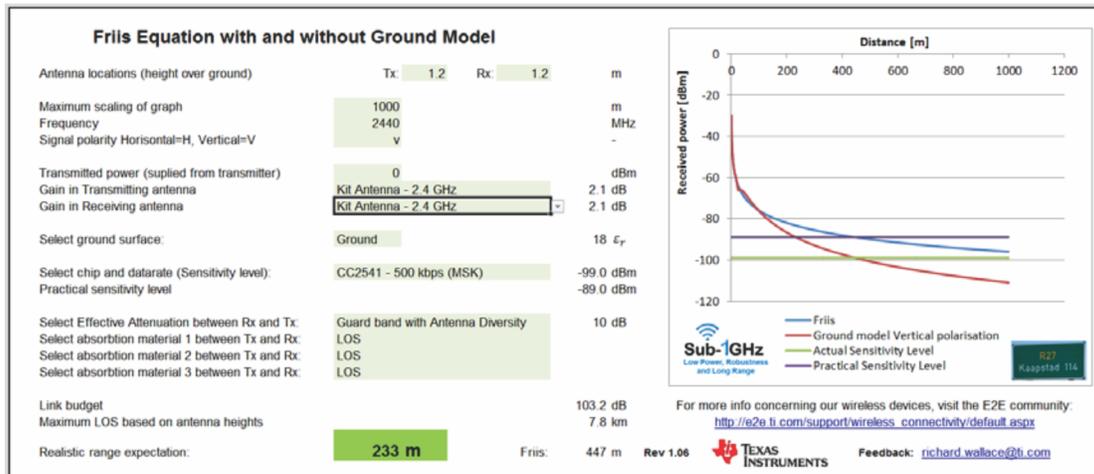
Figure 9. Outdoor LOS, 500 kbps With CC2541 at 2440 MHz; Expected Range 233 m

The radio performance is very similar in Figure 10 and Figure 11; the only difference is the operating frequency and the lower attenuation of the construction material at 1 GHz compared to 2 GHz. As can be seen, the range expectation is increased from a distance of 5 m at 2440 MHz to 31 m at 868 MHz for similar radio performance.
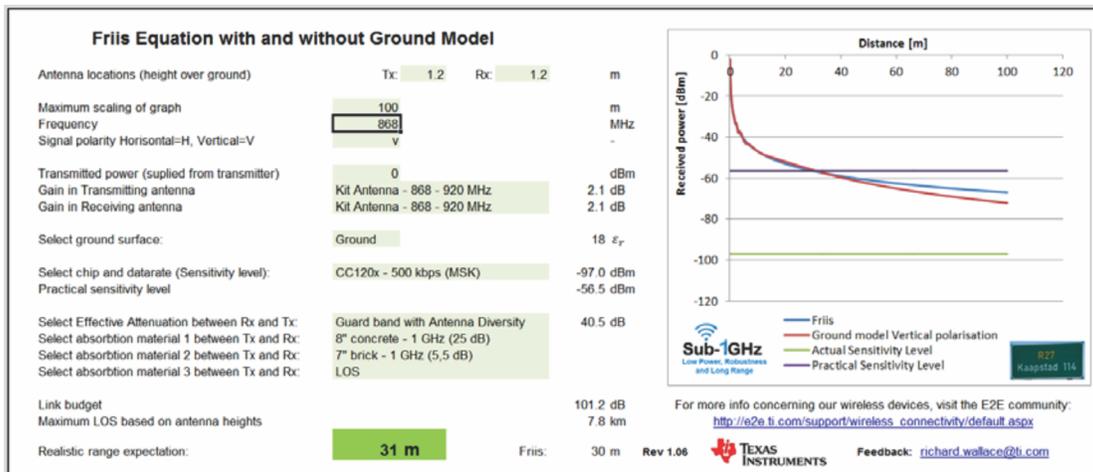
Figure 10. Indoor, 500 kbps With CC1200 at 868 MHz; Expected Range 31 m
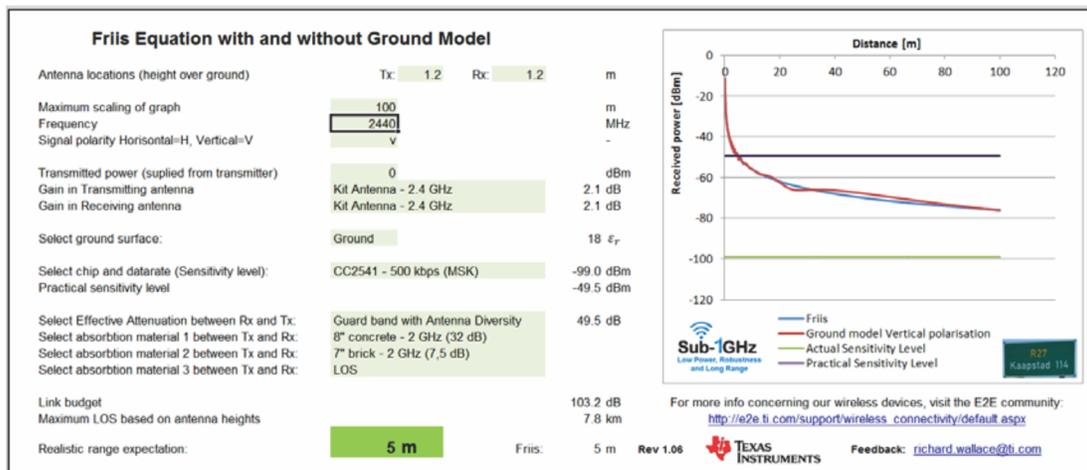
Figure 11. Indoor, 500 kbps With CC2541 at 2440 MHz; Expected Range 5 m

3.1.1   LOS 868 MHz Data Rates Comparison

The data rate for CC1200 was set to 500 kbps at 868 MHz and the expected range is 292 m. By decreasing the data rate the sensitivity limit is improved due to less noise is entering the receiver and a longer range can be achieved. Table 4 illustrates the expected distance when changing just the data rate from the previous example; all other settings are the same as in Figure 8.

Table 4. Increased Range Distance by Reducing the Data Rate of CC1200 at 868 MHz

CC1200 Data Rate	Estimated Range [m] (0 dBm, H1 = H2 = 1.2 m)
CC120x - 1.2 kbps (4 kHz fdev)	1902
CC120x - 4.8 kbps (OOK)	962
CC120x - 38.4 kbps (20 kHz fdev)	768
CC120x - 50 kbps (25 kHz fdev)	712
CC120x - 100 kbps (50 kHz fdev)	613
CC120x - 500 kbps (MSK)	292 (see Figure 8)

Table 5. Estimated Range Distance of CC1200 at 868 MHz

CC1200 Data Rate	Range [m] (0 dBm, H1 = H2 = 1.2 m)	Range [m] (14 dBm, H1 = H2 = 1.2 m)	Range [m] (27 dBm, H1 = H2 = 1.2 m)
CC120x - 1.2 kbps (4 kHz fdev)	1902	5535	14978 (7817) [1]
CC120x - 4.8 kbps (OOK)	962	2784	7515
CC120x - 38.4 kbps (20 kHz fdev)	768	2214	5978
CC120x - 50 kbps (25 kHz fdev)	712	2051	5535
CC120x - 100 kbps (50 kHz fdev)	613	1764	4748
CC120x - 500 kbps (MSK)	292 (see Figure 8)	828	2213

[1]   14978 meter cannot be achieved since the LOS is limited by the earth's curvature so the maximum distance would be 7817 meter when both antennas are placed at 1.2 m above the earth surface.

4   Radio Configuration for Long Range

To achieve a long range, the output power can be increased to the maximum limit specified by the regulations and the data rate reduced as much as possible for the application. Apart from these two parameters, there are additional parameters that can be utilized to achieve long range such as Feedback to PLL functionality, which effectively reduces the bandwidth furthermore.

4.1   *CC112x / CC12xx Feedback to PLL Function*

Feedback to PLL (FB2PLL) extends the Rx filter BW (RX_BW) without increasing the noise bandwidth. Setting FREQOFF_CFG.FOC_LIMIT = 0 the programmed Rx filter BW is extended by ±RX_BW/4. As an example, if Rx filter BW is programmed to 50 kHz and FREQOFF_CFG.FOC_LIMIT = 0, the noise bandwidth is still 50 kHz (the bandwidth that sets the noise floor), but the effective Rx filter BW is 75 kHz.

Setting FREQOFF_CFG.FOC_LIMIT = 1 the programmed Rx filter BW is extended by ±RX_BW/8. As an example, if the Rx filter BW is programmed to 50 kHz and FREQOFF_CFG.FOC_LIMIT = 1, the noise bandwidth is still 50 kHz (the bandwidth that sets the noise floor), but the effective Rx filter BW is 62.5 kHz.

The measurements in Table 6 show that for the same effective Rx filter BW, enabling FB2PLL improves sensitivity and close-in selectivity. The measurement results are the average of five CC1200 devices.

Table 6. 1.2 kbps, ±3 kHz, 2-GFSK. OBW (99%) = 6.9 kHz

BW [kHz]	14.37	10.96	9.69
FREQOFF_CFG.FOC_LIMIT	FB2PLL not enabled	1	0
Effective BW [kHz]	14.37	13.7	14.54
Sensitivity (1% BER) [dBm]	-121.4	-121.9	-122.1
Interferer offset [kHz]	Selectivity [dB]	Selectivity [dB]	Selectivity [dB]
-37.5	54.8	56.2	55.6
-25	55.4	55.6	55.8
-12.5	53.8	55.2	55.2
12.5	54.6	55.0	55.2
25	55.2	56.0	56.0
37.5	55.2	56.0	56.0

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Table 7. 4.8 kbps, ±2.4 kHz, 2-GFSK. OBW (99%) = 8 kHz

Programmed RX_BW [kHz]	12.63	9.69
FREQOFF_CFG.FOC_LIMIT	FB2PLL not enabled	0
Effective BW [kHz]	12.63	12.11
Sensitivity (1% BER) [dBm]	-118.8	-119.5
Interferer offset [kHz]	Selectivity [dB]	Selectivity [dB]
-37.5	52.6	53.4
-25	52.6	54.0
-12.5	52.0	53.0
12.5	51.6	53.0
25	52.6	53.8
37.5	52.4	53.4

5 Range Tests

The excel sheet [1], is a good tool to predict a realistic range for a specific application environment and radio setting. To confirm the calculations the range tests have to be performed as well. Since the range is highly dependent on the surroundings, three different range tests that have been performed and will be covered in this application report.

5.1 Long Range Tests at High Altitudes

As shown in Table 1 and the excel sheet [1], the LOS is dependent on the height of the antennas. To achieve an extremely long range, the antenna height must be increased. A good location to test long range is in Cape Town, South Africa. With the Tx positioned on the Table Mountain at a height of 1000 m, a long range can be achieved.

Test Setup:

- CC1120 CC1190 at 868 MHz, LRM, 27 dBm and standard kit antennas
- Modulation Format: GFSK
- Rx Filter Bandwidth:12.5 kHz for frequency compensation and 7.8 kHz for packet reception
- Location: Table Mountain, Cape Town, South Africa
- Antenna Positioning: H1 = 1000 m, H2 = 1 m for 78 - 98 km tests and 91 m for 114 km test
- Frequency: 868 MHz
- CC1120 CC1190 evaluation module includes a 32 MHz TCXO
- LNA = 0x03, extended data filter on
- Link Budget = 27 + 2.1 + 2.1 − (-126.5) = 158 dB
- Three tests performed at distances: 71 km, 98 km and 114 km

Table 8. LRM 868 MHz Sensitivity Levels

Device	Symbol Rate [ksps]	Frequency Deviation [kHz]	Programmed RX_BW [kHz]	FB2PLL [yes/no]	Sensitivity [dBm]
CC1120	0.6	1.5	7.8	yes	-124.0
CC1120 CC1190	0.6	1.5	7.8	yes	-126.5
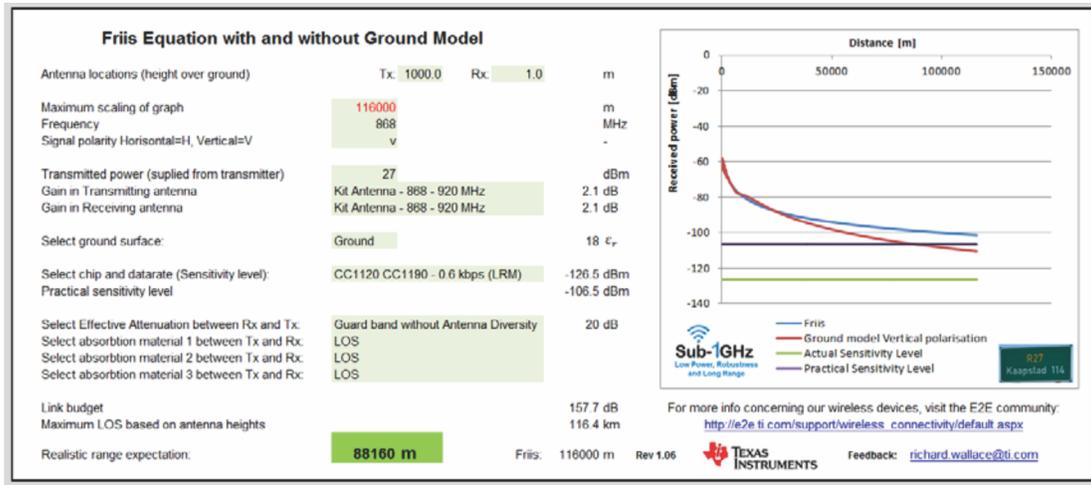
Figure 12. Excel Range Expectation for Test Distances 71 km and 98 km; H2

NOTE: LOS is limited to 116.4 km with H1 = 1000 m, H2 = 1 m for the 78 - 98 km tests.
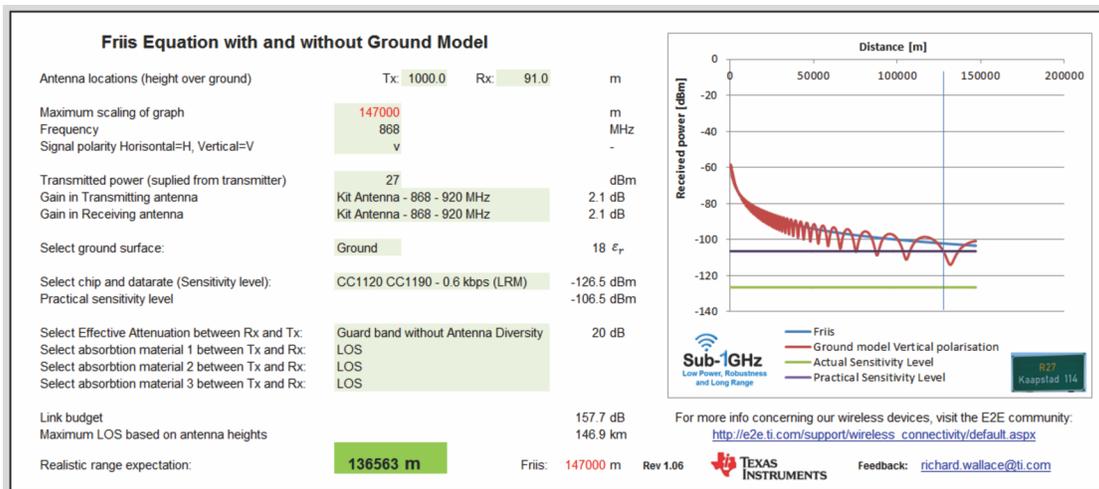
Figure 13. Excel Range Expectation for Test Distances 114 km; H2 = 92 m

NOTE: LOS is limited to 146.9 km with H1 = 1000 m, H2 = 91 m for the 114 km test.

5.1.1 Results

Figure 14. Road Sign Showing the Same Distance Covered with the Range Test

Over 600 data packets were sent with just 2 packets lost at 71 km; 1000 data packets were sent with just 2 packets lost at 98 km; and 1000 data packets were sent with no lost data packets at 114 km. Impressive range distances achieved. These results illustrate that the environment has a huge factor when targeting long distance. For the exact same radio setting but with an antenna height of 1 m instead for the Tx and Rx units, the calculated expected distance would be reduced from 136.6 km to 9.2 km.

5.2 High Rise Building Range Test

Test Setup:

- HW: CC1120EM 420-470 MHz modified with 32 MHz TCXO and TrxEB
- Modulation Format: GFSK
- Rx Filter Bandwidth:12.5 kHz for frequency compensation and 7.8 kHz for packet reception
- Frequency: 470 MHz
- Antenna: Tuned to 470-510 MHz operation
- SW: PER SW running on TrxEB MSP430
- Output power: 14 dBm
- 99% OBW: 4 kHz
- Data payload: 30 bytes (excluding preamble, sync word, CRC)
- Tx unit placed at floor 26 in the stairway
- LNA = 0x03, Extended Data filter on
- Link Budget = 14 + 2.1 + 2.1 − 125 = 143 dB

Table 9. LRM 433-510 MHz Sensitivity Levels

Device	Symbol Rate [ksps]	Frequency Deviation [kHz]	Programmed RX_BW [kHz]	FB2PLL [yes/no]	Sensitivity [dBm]
CC1120	0.6	1.5	7.8	yes	-125.0

5.2.1 Results
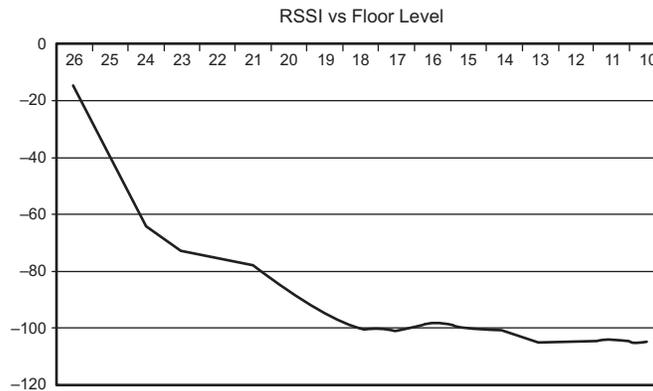
Figure 15. RSSI Level at Different Floors Through the High Rise Building
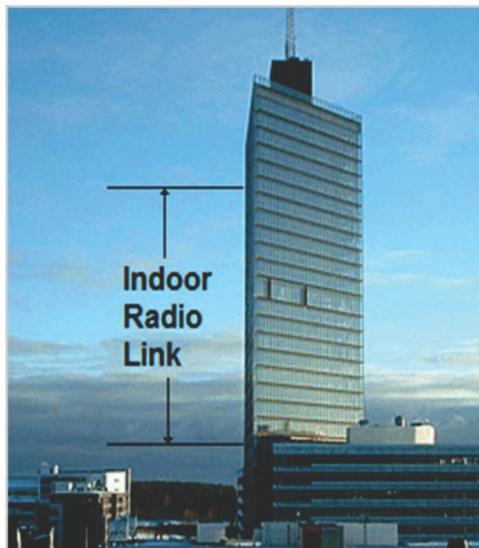
Figure 16. Radio Link Through the High Rise Building

Data transmission could be received 12 to 16 floors below the Tx unit.

> **NOTE:** The maximum number of floors that the radio signal can pass through is highly dependent on the construction material of the building. For the various levels of attenuation for different types of construction material, see Table 3.

8" concrete at 500 MHz has an attenuation of 21 dB so with a link budget of 143 dB, a result would be expected around 6 floors if the RF signal was solely traveling through the concrete floors. Since the Tx unit was placed in the stairway, the attenuation between each floor would be a mixture of free space and concrete attenuation. To ease the calculation assume 10 dB per floor (average of 21 and 1 dB). This correlates to the measured results that the signal was recorded at 12 to 16 floors lower in the building.

For example, link budget = 143/10 approximately 14 floors expected.

The radio link could easily be established outside the high rise building, as shown in Figure 17. The signal strength was -78 dBm and this still leaves an additional 40 dB for the link budget.
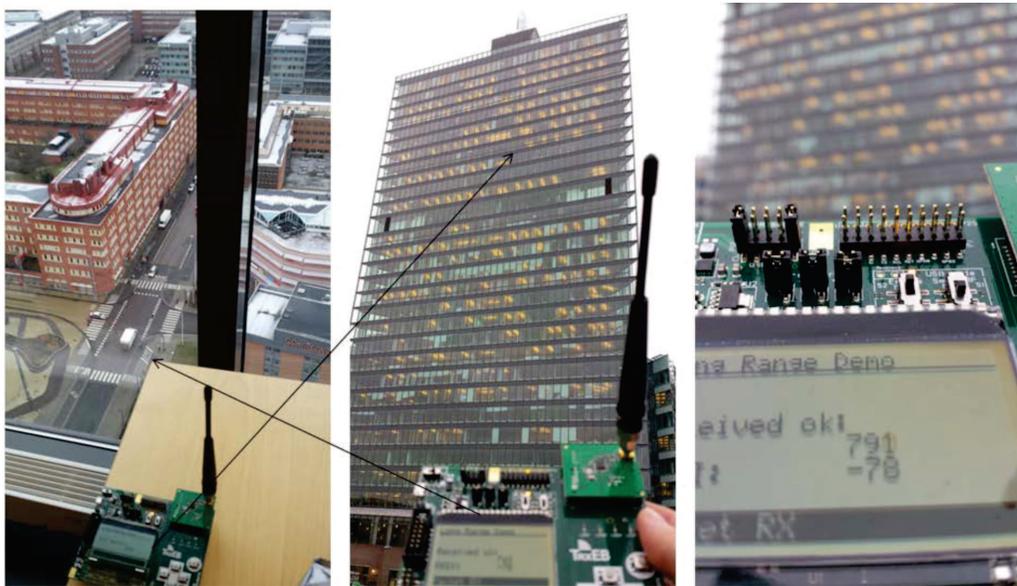
Figure 17. Testing Outside the Building

5.3 Dense Urban Environment Range Test

Test Setup

- CC1120EM with TCXO. Using long range demo SW with 600 bps,±1.5 kHz deviation, 7.8 kHz Rx filter BW. Frequency offset compensation done on each packet.
- Antenna heights above ground level: 1.2m
- Output power: 14 dBm
- Frequency: 868 MHz and 433 MHz
- Location: Oslo, Norway

5.3.1   Results

The range distance measured at 433 MHz was 2 km (see Figure 18) and at 868 MHz the range was 1.3 km (see Figure 19). The range was greater at the lower frequency due to the attenuation difference of the construction materials typically used in an urban environment.
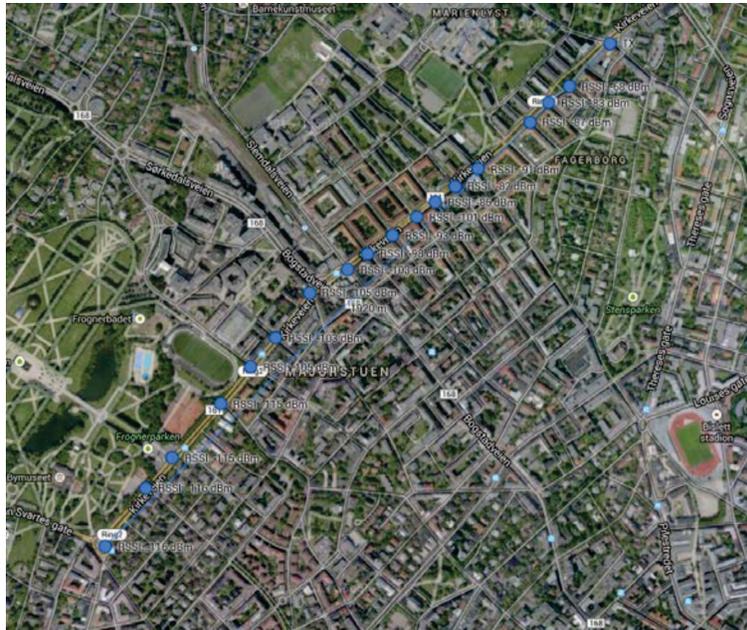
Figure 18. CC1120, 470 MHz - 2 km Range
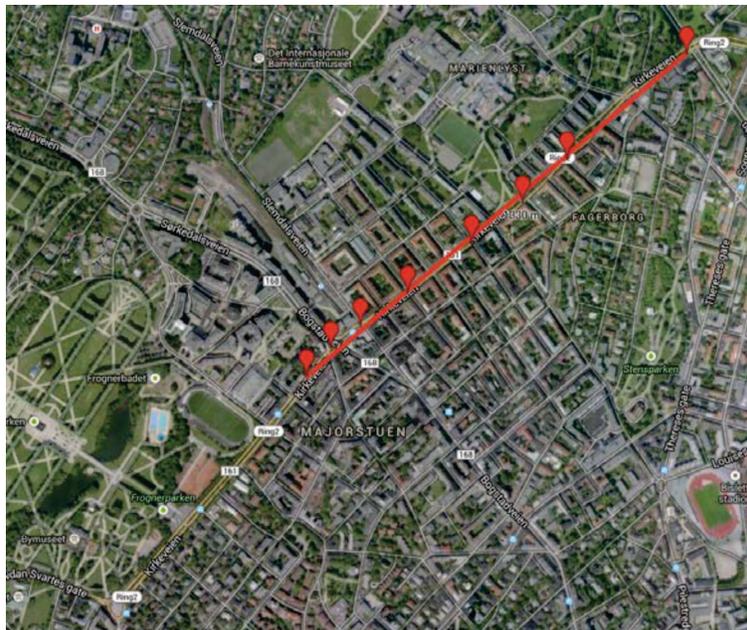
Figure 19. CC1120, 868 MHz - 1.3 km Range

6   Summary

The excel sheet calculation [1] uses both the Friis formula and a 2-ray model to the ground surface to calculate a realistic range estimation. The 2-ray model is preferred since this takes into account the ground surface effects, which will always reduce the practical range. In the calculation model, there are various construction materials that can be included in the range estimation for a more accurate estimate for indoor range.

Several examples of field tests have been documented in this application report that demonstrate the importance of antenna height and line-of-sight limitations; advantage of operating at a lower frequency to achieve greater range for both line-of-sight scenarios and indoor applications.

7   References

1. Excel Sheet for Range Calculation
2. *CC-Antenna-DK Documentation and Antenna Measurements Summary* (SWRA328)
3. *CC-Antenna-DK Reference Design* (http://www.ti.com/lit/zip/swrr070)
4. *Antenna Selection Quick Guide* (SWRA351)
5. *Antenna Diversity* (SWRA469)

Friis Equation With Ground Reflection

A.1 Friis Equation With Ground Reflection

```
% This function calculate the loss of a radio link with ground presence
% h1:   Transmitting antenna elevation above ground.
% h2:   Receiving antenna elevation above ground.
% d:    Distance between the two antennas (projected onto ground plane)
% er:   Relative permittivity of ground.
% pol: Polarization of signal 'H'=horizontal, 'V'=vertical
% freq: Signal frequency in Hz
% Transmitting and receiving antenna assumed ideal isotropic G=0dB
% **********************************************************************

function retvar=friis_equation_with_ground_presence(h1,h2,d,freq,er,pol)

c=299.972458e6;                  % Speed of light in vaccum [m/s]
Gr=1;                            % Antenna Gain receiving antenna.
Gt=1;                             % Antenna Gain transmitting antenna.
Pt=1e-3;                          % Energy to the transmitting antenna [Watt]

lambda=c/freq;      % m

phi=atan((h1+h2)./d);                   % phi incident angle to ground.
direct_wave=sqrt(abs(h1-h2)^2+d.^2);   % Distance, traveled direct wave
refl_wave=sqrt(d.^2+(h1+h2)^2);        % Distance, traveled reflected wave

if (pol=='H')                            % horizontal polarization reflection coefficient
 gamma=(sin(phi)-sqrt(er-cos(phi).^2))./(sin(phi)+sqrt(er-cos(phi).^2));
else
 if (pol=='V')% vertical polarization reflection coefficient
  gamma=(er.*sin(phi)-sqrt(er-cos(phi).^2))./(er.*sin(phi)+sqrt(er-cos(phi).^2));
 else
  error([pol,' is not an valid polarization']);
 end %if
end %if

length_diff=refl_wave-direct_wave;
cos_phase_diff=cos(length_diff.*2*pi/lambda).*sign(gamma);

Direct_energy=Pt*Gt*Gr*lambda^2./((4*pi*direct_wave).^2);
reflected_energy=Pt*Gt*Gr*lambda^2./((4*pi*refl_wave).^2).*abs(gamma);
Total_received_energy=Direct_energy+cos_phase_diff.*reflected_energy;
Total_received_energy_dBm=10*log10(Total_received_energy*1e3);
retvar=Total_received_energy_dBm;
%end function
```

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (March 2015) to A Revision **Page**