Application Report

SWRA169B–January 2008–Revised June 2018

Range Measurements in an Open Field Environment

Design Note DN018

ABSTRACT

Range is one of the most important parameters of any radio system. Data rate, output power, receiver sensitivity, antennas, and the intended operation environment all influence the practical range of the radio link.

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Trademarks

1 Introduction

Range is one of the most important parameters of any radio system. Data rate, output power, receiver sensitivity, antennas, and the intended operation environment all influence the practical range of the radio link.

An open field is one of the simplest and most commonly used environments to do RF range tests. However here there are important effects to consider, and failing to address these often results in the test results being misinterpreted. This application report addresses non-ideal effects to consider when doing open field range measurements.

In this application report, the term "open field" means a large open area without any interfering radio sources (for example, a football field).

2 Abbreviations

EB: Evaluation board (SmartRF™04)

EM: Evaluation module

HW: Hardware (for example, the PCB or components)

LPW: Low-power wireless

PER: Packet error rate

SNR: Signal-to-noise ratio

TI: Texas Instruments

3 Path Loss and Propagation Theory

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 SNR for a radio link is sometimes specified in receiver data sheets. More commonly the sensitivity is specified. This is the absolute signal level (S). When sensitivity is used, one assumes that only thermal noise is present and that the device is operated at room temperature. This chapter addresses the theory used to determine the range for radio systems in open and free-space environments.

3.1 Friis Equation

Range in radio communication is generally described by Friis equation (see Equation 1). This equation describes the dependency between distance, frequency (wavelength), antenna gain, and power.

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

where

- 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
- λ = wavelength, where $\lambda = c/f$, c = speed of light, f = frequency
- d = Distance
- c = Speed of light in vacuum 299.972458×10^6 m/s (1)

3.1.1 Using the Friis Equation

Equation 2 shows an example of using the Friis equation. In free space, the path loss is 80.2 dB over a 100-m distance when operating at 2.445 MHz.

In more typical applications, higher attenuation is expected, because an open field is one of the simplest environments.

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

3.2 Link Budget

The Friis equation is often referred to as the link budget. The difference between the received signal power, PR, and the sensitivity of the receiver is referred to as the link margin. In a realistic link budget additional loss has to be added to the losses predicted by Friis equation. This application report addresses some of these losses in an open field environment. Range is the distance at which the link is operating with a signal level equal to the receiver sensitivity level. In digital radio systems sensitivity is often defined as the input signal level where PER exceeds 1%.

3.3 Ground Reflection (2-Ray) Model

In a typical radio link transmission waves are reflected and obstructed by all objects illuminated by the transmitter antenna. Calculating range in this realistic environment is a complex task requiring huge computing resources. Many environments include some mobile objects, adding 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 get consistent measurements. The Friis equation requires free space to be valid (see Section 3.1). Hand held equipment generally operates close to ground. This implies that ground influence has to be considered to do valid range calculations.

Figure 1 shows 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.

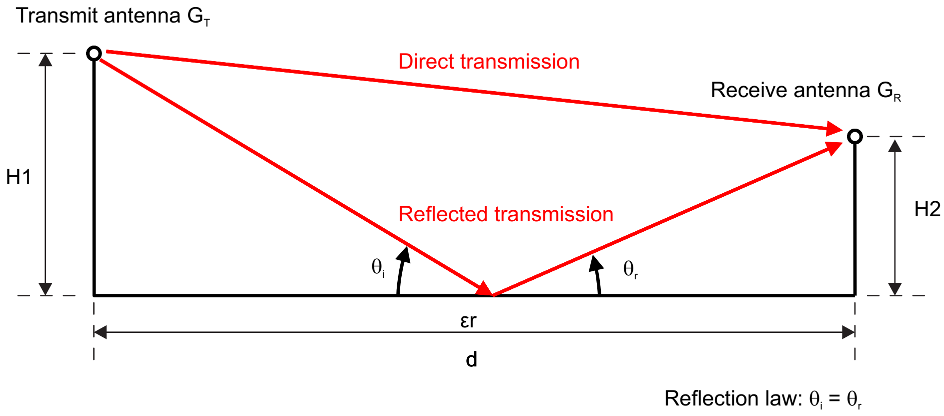


Figure 1. Transmission With Ground

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.

3.3.1 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 depend 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 3 and Equation 4 are the Fresnel reflection coefficients for the vertical and horizontal polarized signals, respectively. [1]

$$\Gamma_V = \frac{(\varepsilon_r - j60\sigma\lambda)\sin\theta_i - \sqrt{\varepsilon_r - j60\sigma\lambda - \cos^2(\theta_i)}}{(\varepsilon_r - j60\sigma\lambda)\sin\theta_i + \sqrt{\varepsilon_r - j60\sigma\lambda - \cos^2(\theta_i)}} \tag{3}$$

$$\Gamma_h = \frac{\sin\theta_i - \sqrt{\varepsilon_r - j60\sigma\lambda - \cos^2(\theta_i)}}{\sin\theta_i + \sqrt{\varepsilon_r - j60\sigma\lambda - \cos^2(\theta_i)}} \tag{4}$$

The equations require some electrical data for the soil in the test environment. Reference [1] includes a table that lists ε_r and σ for some typical soil conditions. $\varepsilon_r = 18$ and $\sigma = 0$ is used for all of the calculations in this application report.

For systems in which H1 and H2 are low compared to d, Equation 3 and Equation 4 can be simplified to $\Gamma_v = \Gamma_h = -1$. This simplification assumes that with low incident angle all of the energy is reflected. The phase change of the reflected wave is significant to the transmission budget (see Figure 2).

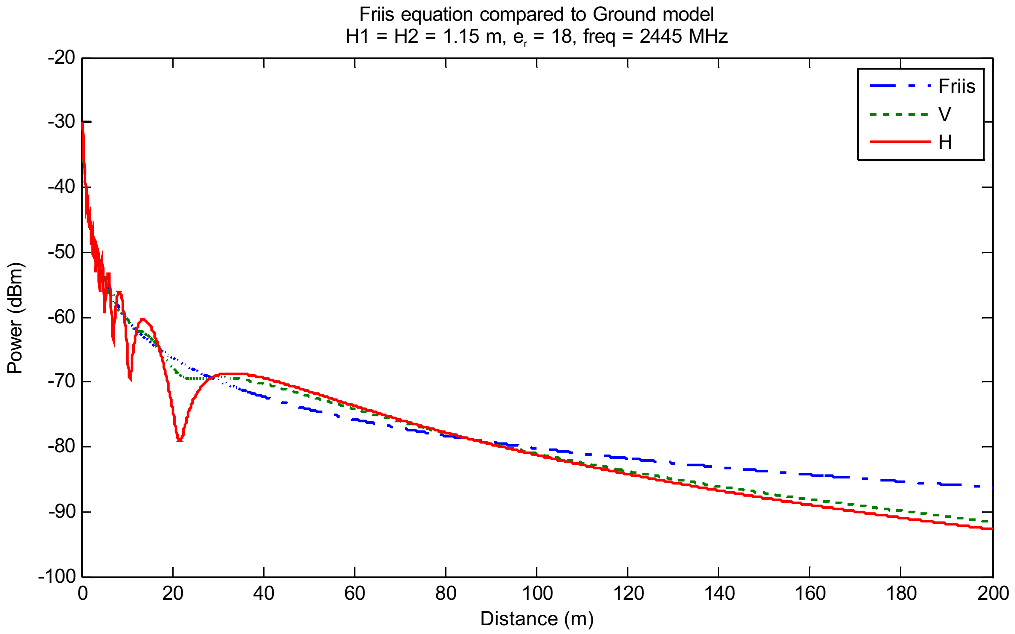


Figure 2. Difference in Transmission Loss Due to Polarization

Figure 2 shows the influence of polarization and ground in open field measurements. The values are calculated using the Matlab function in Section 4.2. The figure indicates a large difference between the Friis equation for free space and the expected performance when ground influence is included. Figure 2 also indicates that horizontal polarization (H) is more susceptible to multi-path fading than the vertical polarized signal (V). At long distances, the signal level including ground is considerably lower than predicted by the Friis equation. Finally, observe that vertically polarized signals have higher energy at long distance when compared to horizontally polarized signals.

NOTE: Many applications have strong cross-polarized components, making it difficult to separate between the polarizations. In this case, the actual signal level is often between the vertical and horizontal levels calculated as previously shown.

Figure 3 shows calculated values for a 2445-MHz horizontally polarized signal. The Friis equation for free space and the 500-kBaud sensitivity level is included in the figure for comparison. To measure the effective open field range for the CC2500 at this data rate, the typical process would be to start the EB PER test and then increase the distance between the two radio units.

The figure indicates that communication would be lost at approximately 35 m. Clearly the range potential is far greater. To identify this unused potential, the two units have to be separated by more than 39 m to regain communication. The location of this blind spot will vary with frequency, ground electrical characteristics and antenna elevation. It is however important to be aware of this during measurement to identify if the test has reached a local blind spot or the final range of the equipment. The difference between the level predicted by the Friis equation and the receiver sensitivity is often called the fade margin.

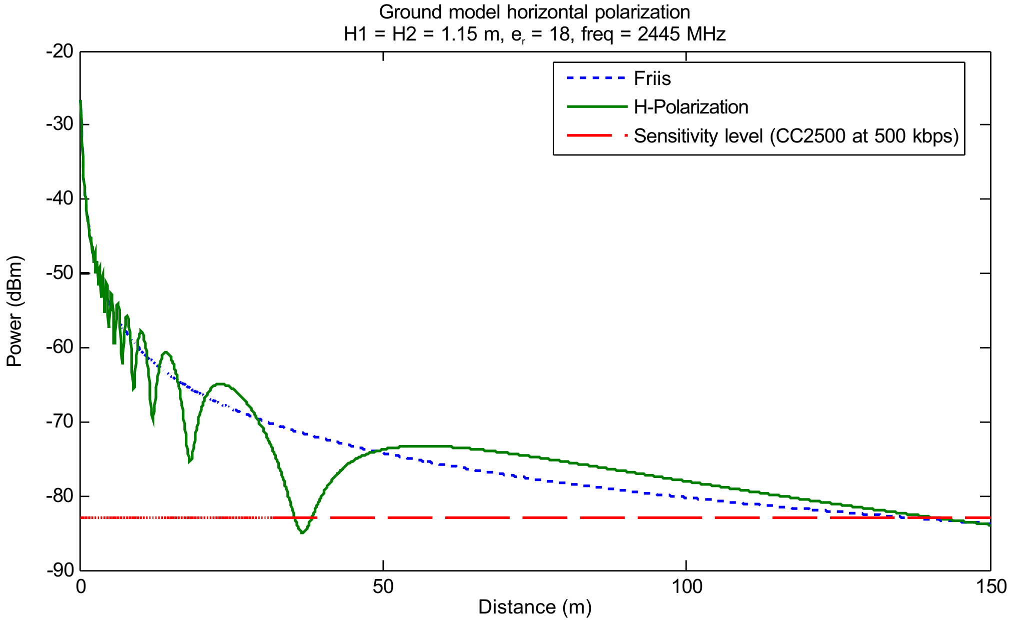


Figure 3. Multi-Path Fading

3.4 Noise

Noise is another important parameter when considering range. Noise can be categorized by its source. Thermal noise is noise generated by all objects due to its molecular thermal activities. Other radio traffic may be considered another form of noise. The noise from other electrical equipment is inherently difficult to describe in mathematical or statistical models. Equation 5 describes thermal noise.

$$v_n = \sqrt{\frac{4hfBR}{e^{\frac{hf}{kT}} - 1}} \approx \sqrt{4kTBR} \quad [V_{rms}] \tag{5}$$

Temperature, effective noise bandwidth, and impedance determine the total thermal noise. At room temperature (300K, 27°C) this equation is often approximated by –174 dBm + $10\log_{10}(B)$, describing the situation with a perfect load match.

3.4.1 Thermal Noise

The CC2500 with 500 kBaud and BW = 812.5 kHz (recommended values) gives a room temperature noise floor at −174 dBm + 59.1 dBm = −114.9 dBm. The sensitivity is specified to be −83 dBm resulting in an SNR of 31.9 dB. An SNR of 31.9 dB is more than the demodulator requires, clearly indicating the potential range extension using an external LNA. (CC2500 has a simulated typical noise figure of approximately 16 dB).

Thermal noise is not a problem during range measurements. It should however be verified that the area used is free from other noise sources on the same frequency band. This could be done using a spectrum-analyzer (maximum hold) to look for noise sources before performing the test. This check should preferably be repeated at regular intervals during the test. Selecting a test area with low probability of interference is generally recommended. A picture of the test area used in the model validation tests can be seen in Section 4.2.2.

4 Validation Tests

4.1 Friis Equation for Free Space

```
% friis_equation(Gt,Gr,f,n,d);
% This function is based on the theory in application report SWRA046
% This function calculates the propagation loss.
% path_loss_indoor =Gt·Gr·(C/(4·pi·f))^2·(1/d)^n
% Gt: Gain in transmitter antenna [dB]
% Gr: Gain in receiving antenna [dB]
% f: Carrier frequency [Hz]
% d: distance in meter [m]
% n: path loss exponent (Se table below)
%
%    Location                                          n       Standard Deviation
%    free space                                       2.0
%    Retail store                                     2.2        8.7
%    Grocery store                                    1.8        5.7
%    Office, hard partitions                          3.0        7.0
%    Office, soft partitions                          2.6        14.1
%    Metalworking factory, line of sight              1.6        5,8
%    Metalworking factory, obstructed line of sight   3.3        6.8

%    Constants:
%    c = 299.972458e6;        Speed of light in vacuum [m/s]

function out=friis_equation(Gt,Gr,f,n,d);
c = 299.972458e6;          % Speed of light in vacuum [m/s]

out = (Gt + Gr + 20*log10(c/(4*pi*f)) – n*10*log10(d));    % Loss in [dB]
```

4.2 Friis Equation With Ground Reflection

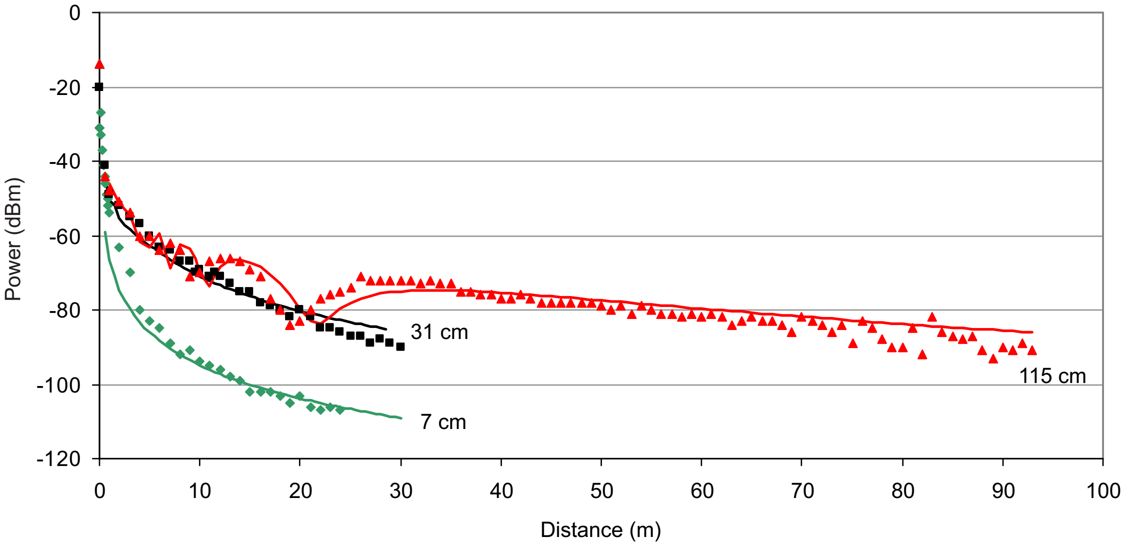
```
% friis_equation_with_ground_presence(h1,h2,d,freq,er,pol)
% This function calculate the loss of a radio link with ground presence
% h1:   Transmitting antenna elevation above ground.
% h2:   Receiving antenna elevation above ground.
% d:    Distance between the two antennas (projected onto ground 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
```

4.2.1 Validating the Ground Reflection Model

Figure 4 shows a comparison between the CC2500 operated in a SmartRF04EB and the Matlab ground reflection model. The measurements have been performed on a football field (se Figure 5). Dots are measurements and lines represent calculated values.

A fixed correction level has been added to the calculated values to get an overall better match to the measured values. This correction value represents the difference between the ideal isotropic antenna and the efficiency of the CC2500EMK Evaluation Module and the SmartRF Studio EB. The plotted values are the values measured.

The measured signal energy was higher for the horizontal polarized signal. This is explained by the directivity of a horizontally oriented quarter-wave antenna. When the same antenna is vertically oriented, the energy is radiated in all directions, reducing its effective gain in the direction of the receiver.



NOTE: Signal strengths with transmitter 7 cm, 31 cm, and 115 cm above ground.

Figure 4. Measured and Simulated Signal Strengths

4.2.2 Open Test Field

A rural environment significantly reduces the probability of 2.4-GHz interference. Figure 5 shows the test area where the Matlab ground model was validated.

The EB is mounted on a plastic pole to minimize the influence of the mount on the measurement results.

The iron light towers showed no significant influence on measurements; they where sufficiently far away to allow the direct and ground reflected signals to be the only significant contributors to the total received power.

The presence of a person had significant influence on the measurement. Measurements at each distance were made with nobody present.

Figure 5. Gravel Football Pitch in the Town of Finstadbru

5 Summary

This application report addresses the influence of the ground during range measurements.

It has been shown that multi-path fading can generate confusion during measurements if you are unaware of the phenomenon. Ground presence has also been shown to generate more rapid signal degradation than predicted by Friis equation for free space. Ground reduces the effective range.

Vertical polarization was shown to be less susceptible to ground reflection fading and range degradation than horizontal polarization. For hand held equipment polarization is generally not controllable and this observation has minor importance.

Finally it has been emphasized that other radio traffic influences range measurements and should be controlled or monitored throughout the measurements. For example, make sure that nearby Bluetooth transmitters are off during measurement. Coexistence with other equipment is generally not implemented in test software for range measurements.

6 References

1. *Radar Technology Encyclopedia*, David K. Barton, Sergey A. Leonov, 1997 Artech House Inc. Boston/London, ISBN 0-89006-893-3

Revision History

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

Changes from April 5, 2008 to June 21, 2018	**Page**
• Changes to document format and editorial updates throughout document	1

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