Range Measurements in an Open Field Environment

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Keywords

- *Friis Equation*
- *Ground Model*
- *Range*
- *Sensitivity*
- *Transmission Budget*

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; failing to address these often results in the test results being misinterpreted. This design note addresses non-ideal effects to consider when doing open field range measurements.

In this note "open field" refers to a large open area without any interfering radio sources, i.e. a soccer field.

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2 Abbreviations

EB	Evaluation Board (SmartRF®04)
EM	Evaluation module
HW	Hard Ware (PCB, components …)
LPW	Low Power Wireless
PER	Packet Error Rate
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 S/N ratio for a radio link is sometimes specified in receiver datasheets. 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 (Equation 1).

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

Equation 1

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 λ = c/f, c = speed of light, and f = frequency
d: Distance
c: Speed of light in vacuum $299.972458 \cdot 10^6$ [m/s]

This equation describes the dependency between distance, frequency (wavelength), antenna gain and power.

Example 1.

Using Friis Equation

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

In free- space the path loss is 80.2 dB over a 100 m distance when operating at 2.445 MHz.

In more down to earth applications higher attenuation is expected; an open field is the simplest of these environments.

3.2 Link Budget

The Friis equation is often referred to as the link budget. The difference between the received signal power, P_R, 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 note 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 recourses. 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 (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 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.

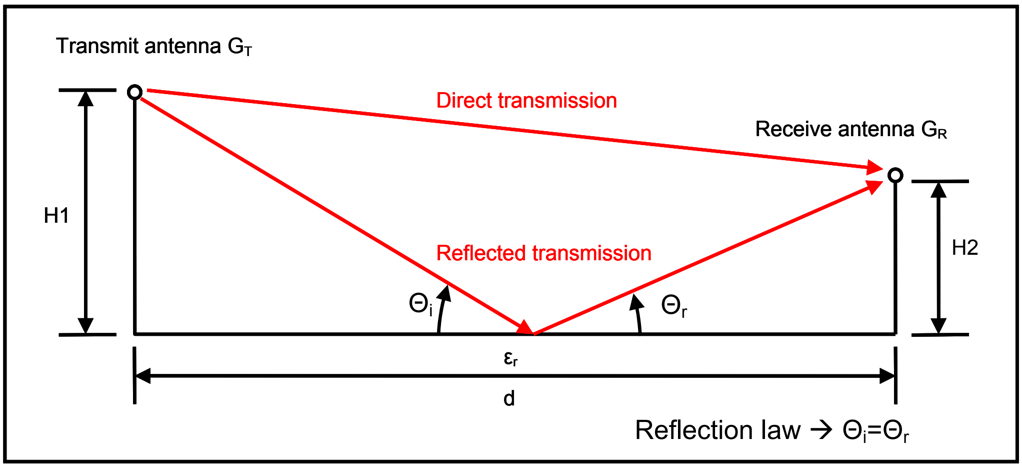

Figure 1. Transmission with Ground

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.

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 2 and Equation 3 are the Fresnel reflection coefficients for the vertical and horizontal polarized signals ([1], p 394)

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

Equation 2

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

Equation 3

The equations require some electrical data for the soil in the test environment. In [1], p 394, a table show ε_r and σ for some typical soil conditions. ε_r =18 and σ = 0 is used for all of the calculations reported here.

In systems where H1 and H2 is low compared to d, Equation 2 and Equation 3 can be simplified to $\Gamma_v = \Gamma_h = -1$. I.e. in systems with 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.

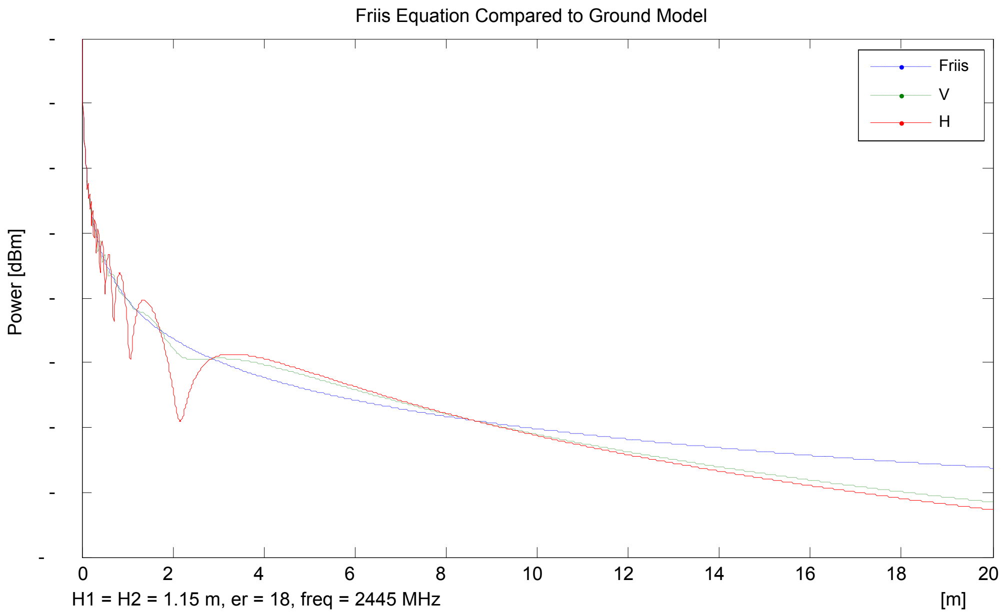

Figure 2. Difference in Transmission Loss due to Polarization

Figure 2 shows the influence of polarization and ground in open field measurements. The values are calculated using the Matlab function in section 6.2. The figure indicates a large difference between the Friis equation for free space and the expected performance when ground influence is included. The figure 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 considerable 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: In many applications there are strong cross polarized components, making it difficult to separate between the polarizations. The actual signal level is then often between the vertical and horizontal levels calculated above.

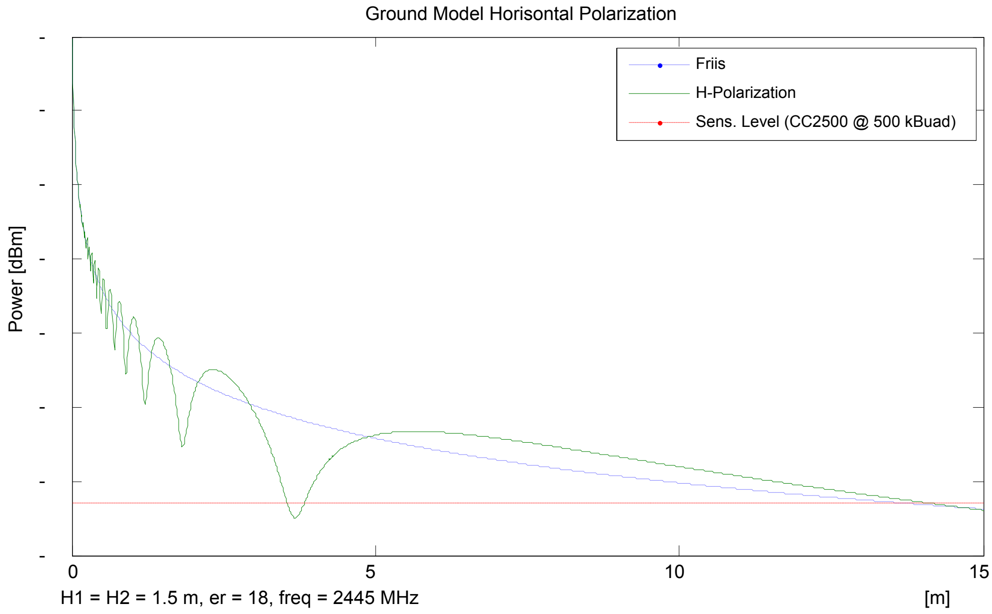

Figure 3. Multi-Path Fading

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. If someone wanted to measure the effective open field range for the CC2500 at this data rate, they typically would start the EB PER test and begin to increase the distance between the two radio units. The figure indicates that communication would be lost at about 35 m. Clearly the range potential is far greater. To identify this unused potential the two units have to be separated with 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 you have 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 denoted fade margin.

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 mathematic/statistical models. Equation 4 describes thermal noise.

$$v_n = \sqrt{\frac{4hfBR}{e^{\frac{hf}{kT}} - 1}} \approx \sqrt{4kTBR} \quad [Volt_{rms}]$$ **Equation 4**

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

Example 2.

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 S/N ratio of 31.9 dB. An S/N ratio 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 about 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 (max hold) to look for noise 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. A picture of the test area used in my model validation tests can be seen in 6.2.2

4 Summary

This design note addresses the influence of the ground during range measurements.

It has been showed 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. (Did you remember to turn off your mobile Bluetooth during measurement?) Coexistence with other equipment is generally not implemented in test software for range measurements.

5 References

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

6 Appendix A

6.1 Friis Equation for free space

```
% friis_equation(Gt,Gr,f,n,d);
% This function is based on the theory in Application report SWRA046A
% 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      std. 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]
```

6.2 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
```

6.2.1 Validating the Ground Reflection Model

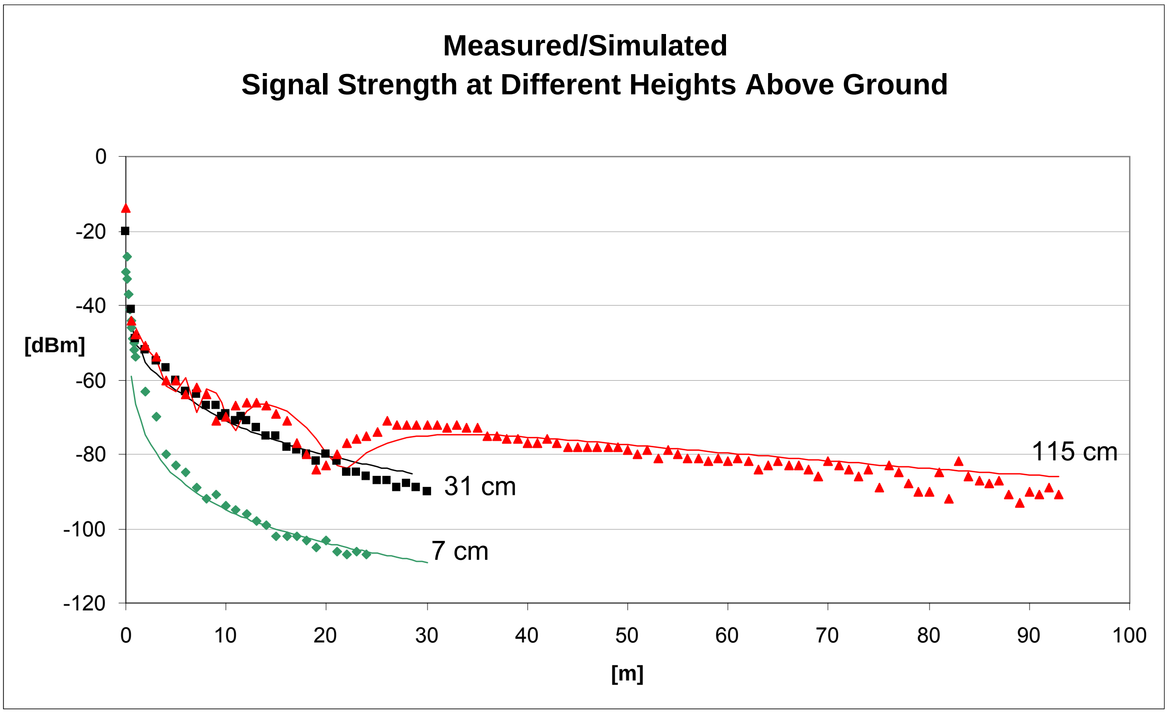

Figure 4. Signal Strengths at 7 cm, 31 cm, and 115 cm Elevation

Figure 4 shows a comparison between the CC2500 operated in a SmartRF®04EB and the Matlab ground reflection model. The measurements have been performed on a football/soccer field (picture below). 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 CC2500EM and 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 horizontal oriented quarter wave antenna. When the same antenna is vertically oriented the energy is radiated in all directions, hence reducing its effective gain in the direction of the receiver.

6.2.2 The Open Test Field

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

Note the EB mounted on a plastic pole to minimize its influence on the measurement results.

The iron light towers showed no real 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 body had significant influence on the measurement. The measurement at each distance point had to be done in my absence. This made the measurements extremely time consuming.

Figure 5. The Gravel Soccer Pitch in the Town of Finstadbru

7 General Information

7.1 Document History

Revision	Date	Description/Changes
SWRA169	2007.12.31	Initial release.

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