APPLICATION NOTE

Range Calculation for 300MHz to 1000MHz Communication Systems

RANGE CALCULATION

Description

For restricted-power UHF* communication systems, as defined in FCC Rules and Regulations Title 47 Part 15 Subpart C “intentional radiators*”, communication range capability is a topic which generates much interest. Although determined by several factors, communication range is quantified by a surprisingly simple equation developed in 1946 by H.T. Friis of Denmark. This paper begins by introducing the Friis Transmission Equation and examining the terms comprising it. Then, real-world-environment factors which influence RF communication range and how they affect a “Link Budget*” are investigated. Following that, some methods for optimizing RF-link range are given. Range-calculation spreadsheets, including the special case of RKE, are presented. Finally, information concerning FCC rules governing “intentional radiators”, FCC-established radiation limits, and similar reference material is provided. Section 7. “Appendix” on page 13 includes definitions (words are marked with an asterisk *) and formulas.

Note: “For additional information, two excel spreadsheets, RKE Range Calculation (MF).xls and Generic Range Calculation.xls, have been attached to this PDF. To open the attachments, in the Attachments panel, select the attachment, and then click Open or choose Open Attachment from the Options menu. For additional information on attachments, please refer to Adobe Acrobat Help menu“

1. The Friis Transmission Equation

For anyone using a radio to communicate across some distance, whatever the type of communication, range capability is inevitably a primary concern. Whether it is a cell-phone user concerned about dropped calls, kids playing with their walkie-talkies, a HAM radio operator with VHF/UHF equipment providing emergency communications during a natural disaster, or a driver opening a garage door from their car in the pouring rain, an expectation for reliable communication always exists.

On what does the quality, robustness, and range of any RF communication link primarily depend? Simple… the physics of electromagnetic wave behavior.

The equation defined by H.T. Friis which describes this wave behavior in “free space*”, called the Friis Transmission Equation, is:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi}\right)^2 \times \left(\frac{1}{d}\right)^n \qquad \text{Equation 1}$$

where

P_R = power received (watts)
P_T = power transmitted (watts)
G_T = gain of transmit antenna (scalar)
G_R = gain of receive antenna (scalar)
λ = wavelength (metric or English)
d = distance separating transmitter and receiver (metric or English)
n = exponent for environmental conditions (n = 2 defines “free space”)

Essentially, this equation states that the strength of the electromagnetic radio wave received at some location is a function of: (a) the strength of the original transmitted signal, (b) the performance of the antennas at the transmitter and receiver, (c) the wavelength corresponding to the frequency of operation, and (d) the distance separating the transmitter and receiver.

In technical literature, this equation is sometimes expressed in other forms. It might be solved for a different variable; or, re-arranged into a “Path Loss” equation; or, written with additional terms, to give more detail; or, simply re-written in “dB” (decibel)* units, a logarithmic measure. Section 7. “Appendix” on page 13 gives some examples of these. In yet another form, the Friis Equation is used for a common communication system performance analysis called a “Link Budget”. Link Budgets are explored in Section 3. “Link Budgets” on page 8.

It is worth emphasizing that equation 1 considers only the electromagnetic characteristics of the RF field, and nothing more. “Smart” data transmission and received-signal processing techniques can compensate for marginal field strength levels in order to achieve an otherwise less-than-reliable communication link. A few are introduced in Section 2. “RF in a Real-world Environment” on page 4 but, again, those are not part of this equation.

1.1 Explanation of the Equation’s Terms

Before defining the equation’s individual components, consider the following relationships that provide insight into how received power is affected in an RF link.

First, notice that received power (P_R) increases as the square of the wavelength (λ). Therefore, it decreases with the square of the frequency (f, which is $1/\lambda$). This is reasonable to believe when one remembers that, because antennas are larger for lower frequencies, they are able to capture more of the radiated field. Second, the received power decreases as the “nth” power of the distance. As a receiver is further and further separated from the transmitter, the weaker the received signal becomes. It is both interesting and important that it decreases with the square (when n = 2) of this distance for free-space conditions. [Reference 1]

Now, a discussion of the equation’s components:

P_R (power received) - the strength of the RF wave arriving at the receiver. Because P_R is a separate term from the antenna gain (G_R), in the purest sense it represents only the energy incident onto the antenna – not what is measured at the input to the receiver’s front-end. In equation 1 the received power is a variable, dependent on (or, a function of) the other terms in the equation. If, however, P_R has a required value, the equation can be solved for one of the other terms in order to see what it must be in order to meet the P_R requirement. When approached this way, the value of P_R usually numerically represents the receiver’s sensitivity level plus some additional margin. Later, when exploring “Link Budgets” in Section 3. “Link Budgets” on page 8, how these two things are related – received power and receiver sensitivity -- is discussed. For some of the better-performing low-cost consumer, industrial, and automotive receivers in the 315MHz to 915MHz market, sensitivity figures (which equate to minimum received-power levels) are around –115dBm.

Higher received-power levels are represented by decibel numbers which are less negative. On the other hand, greater receiver sensitivities (i.e., better capability to hear weak signals) correspond to numbers which are more negative. More sensitive receivers can work to increase communication range.

P_T (power transmitted) - the RF power present at the output of the transmitter. Just like the P_R term, P_T does not include antenna gain. It is only a measure of the power delivered by the transmitter's final amplifier stage. Output for transmitters in the 315MHz to 915MHz frequency range is nominally up to 15dBm.

G_T, G_R (gain of transmit and receive antennas) - the antenna performance relative to a standard "reference antenna*". The gain of an antenna describes how much greater the radiated energy is in some direction and at some distance from this antenna, compared to what it would be at that same direction and distance from an isotropic antenna*. The antenna gain does not increase the actual power coming from the transmitter. Rather it is a measure of the concentration of a portion of the total available radiated power into a given direction. [Reference 1]

Antennas used with hand-held low-power transmitters have gains as low as –10dB to –15dB, which is typical for small-form-factor antennas. For non-hand-held devices, antennas that are at least 1/4-wavelength long have gains up to 5dBi or 6dBi.

λ (wavelength) - the distance a wave travels in one frequency cycle. The relationship between frequency and wavelength is:

$$\lambda = \frac{c}{f} \qquad \text{Equation 2}$$

where "c" is the speed of light (300,000,000 meters/second) and "f" is the frequency in Hertz. Because λ appears in the numerator of the Friis Equation (equation 1), longer wavelengths (from lower frequencies) usually result in increased communication range. The relationship, longer wavelengths from lower frequencies, is easily remembered by thinking about the two "L" mnemonic: Lower means Longer.

d (distance) - the distance separating transmitter and receiver. As the distance between the transmitter and the receiver is increased, the received signal strength decreases. A possible exception to this is the occurrence of a phenomenon called "multi-path". Although it is beyond the scope of this Application Note to discuss "multi-path" in great detail, some information appears in Section 2. "RF in a Real-world Environment" on page 4.

n - the exponential factor for environmental conditions. As stated earlier, Friis's original equation used n = 2 to define free space conditions. Other than in a specially-designed antenna test chamber, a free-space environment is difficult, if not impossible, to realize. Experimental data for various real-world situations is used in order to estimate practical values for "n". Because of the significant impact "n" has on the calculated range, influences which affect "n" are discussed later in detail in the next section, including "multi-path*" propagation and wave travel through materials other than air.

2. RF in a Real-world Environment

Modeling or predicting radio wave behavior in a real-world environment is an exercise always characterized by uncertainty. Using Friis's Equation with free-space conditions is a good "first approximation" but it can be, as we see in this section, quite inaccurate. The effects of "multi-path" wave propagation, separation distance, low transmitter output, poor receive sensitivity, and inefficient antennas all contribute to reduced communication range. Let's look at these influences with a level of detail appropriate for each.

2.1 Multi-path Wave Propagation

First, consider the phenomenon of wave travel known as "multi-path". When a wave leaves the antenna, it travels in all directions. "Multi-path" describes the situation in which the wave is modified by its propagation through the environment, before arriving at the receiver. These waves incident on the receiver's antenna are categorized into four types:

1. direct waves - waves which travel on a line-of-sight path
2. reflected waves - waves which bounce off smooth surfaces that are much greater than one wavelength in size for the specific operating frequency
3. diffracted waves - waves which are bent around sharp corners
4. scattered waves - waves which bounce off objects or features on a rough surface that are much smaller than a wavelength in size

Waves which are diffracted, reflected, or scattered experience changes in magnitude and phase, additional to what naturally occurs to a direct wave. These variations in magnitude and phase are caused by (1) absorption of some of the wave's energy by the reflecting surface, (2) the phase change caused by a reflection, and (3) the differences in length of the paths traveled by the various waves. These multi-path waves arrive from many angles and directions, causing them to sum with various magnitudes and phases at the receiver. As a result, the composite wave at the receiver can be either greater than or less than what would be produced by the direct wave alone. This means that some waves add to the direct signal and some subtract from it. The worst case could be total cancellation, yielding no detectable signal at all! It should be clear now how it can be quite difficult to predict a transmitted wave's behavior because of the multiple paths it takes before arriving at the receiver. [Reference 2}

2.2 Loss as a Function of Distance (the "n" Exponent)

Next, let us consider how the separation distance between the transmitter and the receiver affects the signal strength at the receiver. Since radio waves behave much like sound waves, we can draw a parallel here. As one is distanced further and further from a sound's source, the sound one hears is weaker. The same is true for radio waves. In the Friis Equation, the factor which affects the strength of a radio wave received at some distance from the transmitter is:

$$\left(\frac{1}{d}\right)^n \qquad \text{Equation 3}$$

where "d" is the separation distance between the transmitter and receiver. Friis determined that n = 2 accurately characterizes wave behavior in an environment absent of anything which alters the wave's travel. In equation 1, this was defined as the free-space environment. When n = 2, this means that the strength of the received radio wave is proportional to the square of the distance separating the transmit source and the receiver. To make sense of this, here are some easy-to-remember guidelines which help make quick range estimates using the free-space case.

Doubling the distance separating the transmitter and receiver reduces the received signal strength by:

- 1/4th as a fractional scalar, or
- to 25% of the original value, as a percentage, or
- 6dB as a decibel value.

On a larger scale, increasing the separation distance by a factor of 10 reduces the received signal strength by:

- 1/100 as a fractional scalar, or
- to 1% of the original value, as a percentage, or
- 20dB as a decibel value.

In reality, we do not live in an ideal free-space environment. RF waves are altered (bent, diffracted, reflected, attenuated, absorbed, etc.) as they propagate. Because of this, Friis's free-space equation gives, at best, an approximation. Assuming a free-space environment as a baseline does, provides a couple of advantages when comparing multiple scenarios: (1) the environment is always consistent for a mathematical analysis, and (2) the resulting calculations are still an acceptable approximation. For critical, detailed, and more accurate evaluation, it is important, however, to have a better model of the intended application environment. This leads to "n" values which are other than "2". Now let us consider some empirically-determined values for "n" for several types of environments.

The reason why the impact of the value of "n" on range is significant is because it is an exponent and not simply a multiplier. Several sources have published values for "n" which were determined by field measurements. Table 2-1 and Table 2-2 give some of these values. Notice that they are rarely < 2, making the impact of separation distance even more significant in real-world situations. Nonetheless, with them the Friis Equation more realistically predicts wave behavior for real environments.

Table 2-1. Values for "n" (Reference A)

Environment	"n" Value
Free space	2
Grocery store	1.8
Retail store	2.2
Office (hard walls)	3
Office (soft walls)	2.6
Remote keyless entry	4

[Chart source: reference 1]

Table 2-2. Values for "n" (Reference B)

Environment	"n" Value
Open field - TX and RX at 1.5m above ground	2.5
Open office or retail space	3
Dense office ("cubical farm")	4

[Chart source: reference 3]

2.3 Attenuation from Obstacles

In addition to the detrimental affects of multi-path travel and loss due to separation distance, RF waves are also attenuated when they pass through obstacles. As the following three tables show, this can be significant! These measured attenuation values are for common building materials. Low-power UHF radios are frequently used indoors, making this empirical information valuable for calculating realistic expected performance. Note that among these three tables, the values vary considerably in some instances. This variability simply reinforces the fact that calculations with the free space (n = 2) condition are only good approximations. They are not to replace field testing in the intended environment!

Table 2-3. Attenuation Values (Reference C)

Material/Environment	Attenuation
1 floor	13 dB
2 floors	19 dB
3 floors	24 dB
4 floors	27 dB
Concrete	13 dB to 20 dB
Window	2 dB

[Chart source: reference 1]

Table 2-4. Attenuation Values (Reference D)

Material	Attenuation
Interior wall	10dB to 15dB
Exterior wall (lower values with more windows)	0dB to 40dB
Floor	10dB to 30dB
Window (higher values for metal-tinted windows)	0dB to 30dB

[Chart source: reference 3]

Table 2-5. Attenuation Values (Reference E)

Material	Attenuation
0.25” glass	0.8dB
0.5” glass	2dB
32” lumber	2.8dB
3.5” brick	3.5dB
7” brick	5dB
10.5” brick	7dB
4” concrete	12dB
8” masonry block	12dB
7.5” brick-faced concrete	14dB
16” masonry block	17dB
8” concrete	23dB
3.5” reinforced concrete	27dB
24” masonry block	28dB
12” concrete	35dB

[Chart source: reference 4]

2.4 Antenna Losses

In the previous section which described each term in the Friis Equation, the performance of antennas typically associated with UHF communication systems was briefly mentioned. Let us investigate the reasons behind those statements, beginning with some simple theory about antennas.

Antennas are an integral part of an RF communication system. For a receiver, antennas convert the electromagnetic energy of a radio wave in space into a voltage/current that can be processed by the receiver. For the transmitter, the reverse occurs – an antenna converts the voltage/current signal generated by a transmitter into a radio wave that travels through space. In this way, antennas are a radio's link to the “outside world”. Without straying too far into a subject that well deserves a separate study, suffice it to say that the size of a properly designed antenna is related directly to the frequency on which it operates. Deviating very much from that, the performance of the antenna is noticeably affected (either positively or negatively).

Radios operating in the 300MHz to 1000MHz range with which we are most familiar are usually built on small PC boards and use data to control or communicate with another radio over a short distance. Two examples which come immediately to mind are RKE (remote keyless entry) keyfobs and GDO (garage door opener) remote-control units. Because of the size constraints, the antennas on these (and similar) hand-held devices are frequently 1/10 wavelength long or less. Antennas which are such a small fraction of the wavelength are very inefficient. The next paragraph explains why.

There exist industry-standard antennas against which other antennas are compared for assessment of performance. The two most common are the ¼-wavelength-long monopole and the half-wavelength-long dipole. Because of its radiation characteristics, the monopole is considered the best real-world equivalent of the theoretical “isotropic” antenna. The units of measurement for antenna radiation performance is dB (decibels) of gain, and the monopole is universally assigned a “reference” gain of 0dB. For comparison’s sake, note that the dipole has a gain of ~2.13dB over a monopole, indicating that it is a better-performing antenna. In some instances, a dipole is used instead of a monopole as the “reference” antenna. To indicate which antenna is used as the reference, the measured values are stated in “dBi” (decibels, relative to an isotropic antenna) for a quarter-wavelength monopole, or “dBd” (decibels, relative to a dipole) for a half-wavelength dipole.

In the section describing the various terms of the Friis Equation, we saw that the antennas on 300MHz to 1000MHz hand-held radios typically had “gains” of –10dB to –15dB. To put that into perspective, consider the following:

- a +3dB change is a 2x factor
- a –3B change is a 0.5x factor
- a +6dB change is a 4x factor
- a –6dB change is a 0.25x factor
- a –10dB change is a 0.1x factor
- a –15dB change is a 0.03x factor
- a –20dB change is a 0.01x factor

This means that the RF energy coming from an antenna with a “–3dBi gain” is 50% (i.e., half) as strong as it would be from an isotropic antenna. With a “–10dBi gain”, it is 10% (i.e., one-tenth) as strong. Likewise, with a “–20dBi gain”, it is only 1% (one one-hundredth!) as strong. It is clear that a seemingly small negative “dB” number actually indicates a significant decrease!

2.5 Summing These Losses

From here in Section 2. “RF in a Real-world Environment” on page 4, we see that an RF wave can experience significant degradation as it travels through a real-world environment, and that these influences must be accounted for during the design phase if a communication system has any chance of performing to realistic expectations.

So, when considering reduced receiver sensitivity, low antenna gains, distance between the transmitter and receiver, wave penetration through walls, and “n”, how do all these factors combine mathematically to affect the range of a transmitted signal?

The best answer is found in exploring the next topic, “Link Budgets”, where a modified form of the Friis Transmission Equation is discussed.

3. Link Budgets

The term “Link Budget” was introduced in Section 1. “The Friis Transmission Equation” on page 2. A Link Budget is simply an equation describing the performance of a communication link accounting for all gains and losses in the RF-path elements of the link. A typical Link Budget equation looks like this:

$$P_R = P_T + G_T + G_R - (L_P + L_T + L_R + L_M) \quad \text{Equation 4}$$

where

- P_R = received power (dBm)
- P_T = transmitter output power (dBm)
- G_T = transmit-antenna gain (dBi)
- L_T = transmit-chain losses (coax, connectors, matching...) (dB)
- L_P = path loss (dB)
- L_M = misc losses (fading margin, body loss, polarization mis-match...) (dB)
- G_R = receiver antenna gain (dB)
- L_R = receive-chain losses (coax, connectors, matching...) (dB)

The elements in this Link Budget equation are essentially those of the Friis equation, simply expressed with a bit more detail. Refer now to equation 9 in Section 7. “Appendix” on page 13. Equation 9, just like equation 4 above, is expressed in decibels (dB). When a “scalar” equation, such as equation 1, is converted to a logarithmic format such as these, multiplication and division is replaced by simple addition and subtraction.

Look again at equation 4, above. At first glance, the “L” terms (L_P, L_T, L_R, and L_M) might appear to be new. Actually, though, three of these occur in equation 1. The L_T and L_R terms are components of “P” and “G”, respectively, and L_P represents the two components of path loss (see also equation 10). Arguably, only L_M is a new term. It accounts for losses that one might unknowingly fail factor into the calculation. By studying closely this Link Budget equation, someone unfamiliar with the total make-up of an RF communication link can quickly learn which of the various factors are involved and how they interact to affect an RF communication system’s performance.

Link Budget analysis is essential for designing a robust RF link. In preliminary assessment of the potential performance capability of an RF communication link, the requirements on each of the equation's elements can be determined. This is easily done by first identifying the terms in the Budget equation which have “fixed” values in the real system, then substituting estimates for the remaining terms. Iterative substitutions of estimates will identify what constraints might exist on some of the other terms, or, at minimum, reveal realistic ranges for them. Later, the Budget equation can be used with actual field-measured data to verify the performance of the link against these calculated expectations.

When using the Link Budget equation to predict system performance, remember that the signal at the receiver P_R must be some minimum value, as determined by the receiver’s sensitivity specification. Below that particular P_R value, the signal would be somewhere between marginal and unintelligible. Let us take a closer look at that now.

In equation 4, the L_M term is a very important component. This term is the “fading margin”, and “margin” is the key word. Fading is essentially a time variation of the exponent “n” of equation 3, creating fluctuations in the signal levels at the receiver. These fluctuations, as we saw in Section 2. “RF in a Real-world Environment” on page 4, are caused by changes in the environment in which the communication system operates. In order to have a robust communication system, it is imperative that sufficient margin for these fades be factored into the Link Budget equation. Otherwise, as stated previously, during one such fade communication may be disrupted or totally lost because of a marginal or unintelligible signal.

A recommended minimum fading margin (L_M) is 15 dB. This value, when added to the receiver’s sensitivity specification, determines the minimum received signal level (P_R) that should be present at the receiver’s front-end. For example, a receiver with sensitivity of –107dBm should have a minimum signal level (P_R) present at its front-end of –107dBm + 15dB = –92dBm.

The system design engineer has control over most, or potentially all, of the elements of the Link Budget equation. Constraints come from many sources and they vary from application to application. Achieving maximum system performance from come of these link elements can be simple, easy, and inexpensive alternatives. With other elements, it can be challenging. It is important, therefore, to carefully identify those elements over which one has control and plan for link-performance optimization accordingly.

4. Methods to Improve Range

Hand-in-hand with the Link Budget topic is a discussion on optimizing range performance. The following guidelines are fundamental to a robust, reliable, range-maximized system, but are not meant to be an all-inclusive list.

4.1 Optimize RF-energy Transfer

According to the Maximum Power Transfer Theorem, the amount of RF power that reaches the antenna from the radio's output depends primarily on how well the impedances of the transmitter's output and the antenna are matched. Simple in theory but more difficult to achieve in practice, this theorem requires that in order to transfer the maximum amount of power from the source (the transmitter's output) to the load (the radiating antenna), these two impedances must be a complex-conjugate* pair. Incidentally, this impedance-matching requirement applies not only to the transmitter, but to the receiver as well. The objective there is to maximize delivery of the energy captured from the antenna to the receiver's input.

Impedance matching is achieved using passive L-C networks. Mathematically, determining component values for a matching network based on two impedances is straightforward. Once again, difficulties arise in the real world from several sources. First, the exact impedances of the source and the load may not be known. Second, even if given a Specification or Data Sheet, they are "guaranteed" to be different once mounted on a PC board! This is, of course, because of parasitic impedances present on the PC board. And, last but not least, there are impedances associated with the traces and component mounting pads between the source and the load which are difficult to quantize. These problems make impedance-matching an interactive exercise requiring both time and patience.

In addition to their impedance-matching function, these passive L-C networks also inherently behave as filters which are either low-pass, band-pass, or high-pass, depending on configuration. As filters, these networks can be used to suppress harmonics. This is a "two-for-one" added benefit since Governmental regulatory agencies, such as the FCC and ETSI, have requirements on harmonic signal levels for low-power UHF radios.

While iteratively adjusting component values during an impedance-matching exercise, realize that the filter characteristics are simultaneously being changed. The converse is also true, reinforcing the fact that these two characteristics of L-C networks are mutually interactive. It is not uncommon that small changes in component values can have significant effects on either the impedance-matching characteristics, the shape of the filter curve, or both! Expertise in impedance-matching or filter-shaping skills comes with much repetition, keen observation of trends, and experience with many different PC-board layouts.

4.2 Focus on the Antenna Situation

Much too often, insufficient attention is given to the antennas in a communication system. The all-too-common exclamation, "Oh, just hook it up to a wire... it'll radiate", can be a costly generalization. It is certainly true that "any ol' wire" will radiate RF energy. However, we learned earlier that the size of the antenna, relative to the intended operating frequency, is very important. Even if an antenna theoretically should perform well, it may not because it is deployed incorrectly. For example, relying on a manufacturer's performance claims without understanding the validity of those claims or heeding associated caveats and advisements, can result in disappointment. In light of the importance of a properly performing antenna to a range-maximized RF communication system, the following things are important to consider.

Size: As a general rule, larger antennas capture/radiate more RF energy. To improve RF-link performance, then, the largest antenna possible (properly designed for the frequency of operation) should be used.

Efficiency: Skirting a lot of theory, suffice it to say that the antenna characteristic known as "radiation resistance" needs to be appropriately large in order for an antenna to be effective. Drawing a simple parallel from DC circuit theory, Ohm's law states that the current through a resistance produces a voltage (V = IR). Likewise with antennas, output current from the transmitter passing through the "radiation resistance" of an antenna produces a voltage. This voltage is converted on the antenna to an electromagnetic wave which propagates through space. Antennas which are at least 1/4-wavelength for the operating frequency have "appropriately large" radiation resistances. PC-board-trace antennas, which are only fractions (< 10%) of a wavelength long, have a very, very low radiation resistance. Hence, these very small antennas produce very little voltage on the antenna. In turn, the wave radiated by the antenna has a very small amplitude. A similar situation occurs with a receiving antenna, on which a current is created from an arriving wave. With a low radiation resistance, only a small voltage results. A fair range of values "appropriately large" for an antenna's radiation resistance is 35Ω to 100Ω.

In Antenna Theory, the Reciprocity Theorem states, essentially, that an antenna works equally well as either a transmit antenna or a receive antenna. This presents an interesting option in an RF communication system for antenna deployments, in light of size and efficiency. Whenever one antenna in an RF link is constrained by size so that its performance is measurably diminished, the Reciprocity says that this can be compensated for by the other antenna in the link. Looking back at equation 1 or equation 4, this is readily apparent from the relationship between the G_T and G_R terms. This can be very helpful in an automotive remote keyless entry (RKE) system or a garage-door opener (GDO) installation, two very common examples where small, inefficient antennas are used.

Polarization: Also important is the orientation of the transmit and receive antennas relative to one-another. The electromagnetic waves which antennas radiate and receive have two components – an electric field and a magnetic field. These two fields travel through space at right angles (90°) to one another. The orientation of the electric field designates the "polarization" of the wave radiated by that antenna. Radio waves are polarized horizontally, vertically, or circularly. To maximize energy transfer from the transmitter to the receiver, the antenna polarizations need to match, regardless of which polarization is chosen.

Near-by Objects: As a final recommendation, antennas should be kept away from nearby metal or other electrically-conducting objects. Their presence distorts the radiation pattern from an antenna, more often that not yielding poorer-than-expected performance. If the metal object is between the transmitter and receiver, it can substantially reduce the transmitted RF reaching the receiver.

4.3 Choose Another Operating Frequency

Another alternative for improving range is to consider another operating frequency. Here are some trade-offs when making this decision.

Lower frequencies are characterized by less free-space path loss, making them favored in terms of propagation. This is clear from equation 1 and equation 4. These longer waves also penetrate walls and obstructions better. However, lower-frequency antennas are larger than those for higher frequencies and, therefore, require more physical space. Conversely, higher frequencies, because of their smaller wavelengths, are better for applications where the antenna space is restricted.

FCC Rules generally allow more transmitter power output as the operating frequency increases, but not all UHF frequency bands are available for low-power transmitter use. Likewise, regulations in other countries restrict output power and operation on certain frequencies.

Interference from another RF system is possible and, depending on the operating frequency, very likely. When assessing the impact of a potential interferer, consider not only the fundamental operating frequency but also its harmonics. For example, the 2nd harmonic of an FM broadcast station transmitting on 105MHz could be of sufficient magnitude to interfere with a low-power application operating at 315MHz.

4.4 Employ Signal Processing

While it is not related to the focus of this Application Note, the physics of wave behavior, significant improvements can be made in communication range with signal processing techniques. As an introduction to the topic, three such techniques are briefly discussed here. This is by no means a comprehensive list, but these three do represent some commonly-implemented schemes.

First, consider a method which broadens the bandwidth of the signal between its transmission and subsequent reception. In essence, the payload data-transmission rate is reduced, relative to the utilized signal bandwidth, yielding an improved noise and interference response. This technique is known as "Spread Spectrum" transmission. In addition to improved signal-to-noise ratio, spreading the signal across a frequency range makes it more difficult to intercept (by a clandestine receiver) and de-modulate.

Another approach for improving range is through "diversity" in the receiving system. Here, multiple antennas and/or receivers are spatially separated by a sufficient distance (typically ¼ wavelength), allowing them to receive the same signal, but with differing magnitude and phase. The transmitted information is then extracted using comparative signal analysis. This technique is very effective against multi-path fading.

Finally, another popular technique is acknowledgement of the transmission by the receiver. If the transmission is not acknowledged, it is re-sent some pre-determined number of times. Of course, this requires 2-way communication capability for each participant in the communication link and it slows the maximum effective data rate for the system. For transient interference, however, it is a good solution.

5. A Range-calculator Spread-sheet

This Application Note began in first paragraph of Section 1. “The Friis Transmission Equation” on page 2 by saying, “... range capability is inevitably a primary concern”. To that end, we have investigated, among other things, equations which help predict the communication range for an RF link. Figure 5-1, appearing below, shows a snap-shot of a Range Calculator spread-sheet which was developed to provide quick parametric analysis using the Friis Transmission Equation. The form of the Friis equation used in the spread-sheet is shown. In Section 7. “Appendix” on page 13 and on page 21 of this Application Note, equation 12 is that same equation solved for the range, or distance, “d”. The spread-sheet has six input parameters: transmitter output power, transmit-antenna gain, receiver sensitivity, receive-antenna gain, and frequency of operation. The output is the calculated estimate of the communication link range.

Figure 5-1. Range Calculator

RF Range Calculator

Frequency = 433.92 **MHz** $\lambda =$ 0.691 **m**

P_T (dBm)	G_T (dB)	L_P (dB)	G_R (dB)	P_R (dBm)	**Fade Margin (dB)**	Range (m)
8	-20	-88	-8	-108	30	43.7

INPUTS

P_T: effective radiated power of transmitter

P_R: sensitivity of receiver (or received power)

G_T: antenna gain of transmitter

G_R: antenna gain of receiver

Fade Margin: Allowance to accommodates for expected fading

CALCULATED

L_P: path loss

a_r: path loss + fade margin

Range: $r = \frac{\lambda}{4\pi 10^{\frac{a_r}{20}}}$

Note: 1. See attached Excel file “RF range calculator.xls”

6. FCC Regulations

Several times in this Application Note, the FCC Rules and Regulations have been mentioned. The portion which applies specifically to the low-power UHF transmitters we have discussed, called in the Regulations “intentional radiators”, is Subpart C, Sections 15.201 - 15.257. In particular, we are most interested in the regulations which apply to transmitters in the range 315MHz to 915MHz.

The FCC defines two types of applications in which these “intentional radiators” may operate. “Control” signals, one of those classifications, are signals which are very limited in duration and in total transmit time during an hour-long period. They cannot repeat transmissions at a regularly-occurring interval. “Periodic” signals, the other classification, are essentially all other signals which do not fit into the “control” signal category. These are allowed to repeat transmissions at a regularly-occurring interval. Additionally, they are less restricted on the duration of a single transmission and on the time interval of repetitive transmissions.

The product of two parameters in the Friis Equation (equation 1), transmitter output power (P_T) and transmitter antenna gain (G_T), yield a field-strength measure called the “Effective Radiated Power” (ERP)*. Intuitively, greater range is achieved with higher output power and increased antenna gain, but it is limited by the FCC for “intentional radiators” operating in the 315MHz to 915MHz spectrum.

As a point of reference, Table 6-1 shows the general radiation limits for these intentional radiators” as defined in the cited sections of the FCC Rules.

Table 6-1. FCC Radiation Limits at 3m for “Intentional Radiators”

	Frequency (MHz)	µV/m	dBm	FCC Regulation
“control” signals	315	6042	–19.60	15.231(b)
	433.92	10997	–14.40	15.231(b)
	868.3	12500	–13.30	15.231(b)
“periodic” signals	315	2417	–27.57	15.231(e)
	433.92	4399	–22.36	15.231(e)
	868.3	5000	–21.25	15.231(e)
Any signals	915	50000	–1.25	15.249(a)

The following formulas were used to determine the values in Table 6-1.

for “control” signals

up to 470MHz: $E\mu V/m = 41.6667 \times f_{MHz} - 7083.3333$
above 470MHz: $E\mu V/m = 12{,}500$ (fixed)

for “periodic” signals

up to 470MHz: $E\mu V/m = 16.6667 \times f_{MHz} - 2833.3333$
above 470MHz: $E\mu V/m = 5000$ (fixed)

for any signals

902MHz to 928MHz: $E\mu V/m = 50000$ (fixed)

Quite frequently, RF signal intensity is stated in “dBm” instead of EµV/m, which is “decibels referenced to a milliwatt”. A convenient conversion formula for EµV/m to dBm (when referenced to an “isotropic” antenna and when measured at 3m) is:

$$E_{dBm} = 20 \log(E\mu_{V/m}) - 95.23 \qquad \text{Equation 8}$$

[Reference 1]

If the desired reference is to a half-wave dipole (also a common antenna used in measurement labs), subtract 2.15dB from the E_{dBm} result.

As they apply to these “intentional radiators”, the complete FCC Rules are more complex than might appear from these general comments. For that reason, consulting the Rules for details is highly recommended. When FCC Compliance Testing is necessary, it is advisable to engage a consulting firm who is intimately familiar with the FCC Rules and their detailed, accurate interpretation.

7. Appendix

7.1 Definitions

Complex Conjugates - two complex numbers whose real parts are equal and whose imaginary parts are equal in magnitude but opposite in sign.

dB (Decibel) - a logarithmic measure of power

dBi - “decibels, referenced to an isotropic antenna”; a power measurement found in statements/quantifications of an antenna’s gain

dBm - “decibels, referenced to a milliwatt”; a commonly-used measurement for lower levels of RF power

Effective Radiated Power (ERP) - mathematically, the power into an antenna multiplied by the gain of the antenna; also, the power radiated by an antenna in a given direction, relative to the power (in that same direction) which would be radiated by a reference (isotropic or dipole) antenna

Fading Margin - the additional signal strength desired so that, when fading occurs, the signal of interest does not drop below the sensitivity threshold of the receiver; or, the difference between the received signal strength (RSS) and the RX sensitivity (typically at least 15dB is desired). Fade margin ensures reliable/sustained communication under varying operating conditions. The value entered into the Link Budget equation is positive and it decreases range.

Free Space - an environment in which there are absolutely no nearby objects (ground included) which would create absorption, diffraction, reflections, or any other characteristic-altering phenomenon to a radiated wave

Intentional Radiator - (an FCC definition) a device that purposefully generates and emits radio frequency energy by radiation or induction

Isotropic Antenna - one that radiates equally well in all directions

Link Budget - an equation describing the performance of a communication link. It accounts for all gains and losses in the transmit, receive, and RF-path elements of the link.

Reciprocity Theorem - a theorem which states that an antenna performs equally well in a receive or a transmit application.

Reference Antenna - an antenna used in measurement labs, etc. against which another antenna’s performance is gauged. The typical reference antennas are either ¼-wavelength monopoles or ½-wavelength dipoles.

UHF - “Ultra-High Frequency”; the frequency range of the electromagnetic spectrum covering 300MHz to 3000MHz

7.2 Formulas Related to the Basic Friis Transmission Equation

Friis equation in decibel form:

$$P_R(dB) = -20\log\left(\frac{4\pi}{\lambda}\right) - 10n\log(d) + G_T + G_R + P_T \qquad \text{Equation 9}$$

Path loss in scalar form (where $G_T = G_R = 1$):

$$L_{PATH} = \frac{P_R}{P_T} = \left[\frac{\lambda}{4\pi}\right]^2\left[\frac{1}{d}\right]^n \qquad \text{Equation 10}$$

Path loss in decibel form (where $G_T = G_R = 1$):

$$L_{PATH}(dB) = P_R - P_T = 20\log\left(\frac{\lambda}{4\pi}\right) + 10n\log\left(\frac{1}{d}\right) \qquad \text{Equation 11}$$

The generic Range Calculator spread-sheet equation solved for distance “d”:

$$d = \frac{\lambda}{4\pi 10^{\frac{a_r}{20}}} \qquad \text{Equation 12}$$

7.3 References

(1) Texas Instruments®, Application Report SWRA046A, “ISM-Band and Short Range Device Antennas”, March 2005.

(2) Spread Spectrum Scene, “Indoor Radio Propagation SSS Online and Pegasus Technologies” (http://www.sss-mag.com/indoor.html), December 1998.

(3) Motorola®, Application Note AN2611, “System Considerations for Short Range RF Devices2”, November 2003.

(4) MaxStream®, Application Note XST-AN005a-Indoor, “Indoor Path Loss”, September 2003.

(5) Maxim®, Application Note AN3945, “Path Loss in Remote Keyless Entry Systems”, November 2006.

8. Revision History

Please note that the following page numbers referred to in this section refer to the specific revision mentioned, not to this document.

Revision No.	History
9144C-RKE-07/15	• Put document in the latest template

Atmel Corporation 1600 Technology Drive, San Jose, CA 95110 USA **T:** (+1)(408) 441.0311 **F:** (+1)(408) 436.4200 | **www.atmel.com**