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Spec No: 001-15215

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Replaced by: NONE

AN4008

Maximizing Range in WirelessUSB™ Systems

Author: Sai Prashanth Chinnapalli

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Range is one of the vital features in a Wireless system. AN4008 provides the necessary points to consider, to increase the range in a WirelessUSB system.

Introduction

Long range wireless performance can be an important factor for many applications. There are several system design elements that should be considered to ensure robust wireless operation at the desired range. Some techniques for maximizing range will compromise system cost or power consumption, so the performance trade-offs must be chosen appropriately for each target application.

This application note discusses the three main areas that can be addressed in order maximize overall wireless range in systems that use the Wireless USB™ Radio (the Wireless USB IC will hereafter be referred to as the "Radio").

- Maximize the achievable receive sensitivity of the Radio
- Maximize the achievable transmit power of the Radio
- Minimize the controllable path loss in the operating environment

Each of these areas are addressed in detail in the following sections of this application note.

Maximizing Receive Sensitivity

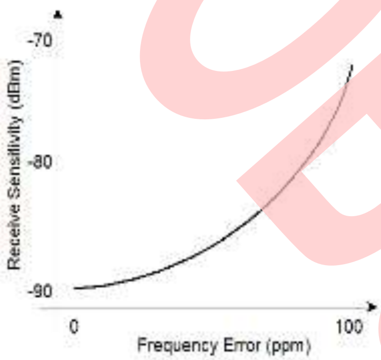
Receive sensitivity is defined as the minimum required RF power received to meet a certain performance metric. The level of performance is typically determined by the bit error rate (BER) of the received data. Many wireless systems use a BER metric of 10^{-3} when determining receive sensitivity. There are several factors that influence the receive sensitivity of a Wireless USB system.

Tuning Crystals

Ensure that the Radio has an accurate reference frequency is an important factor involved in maximizing the potential receive sensitivity in a system. The accuracy of the reference frequency is significant in wireless systems primarily because there are two or more remote devices attempting to inter-operate with each other in a relatively tight bandwidth. To ensure that all intended Wireless USB devices can inter-operate as desired, each device must be accurately tuned to a universally known reference frequency. The reference frequency chosen for Wireless USB is 13.000000 MHz. The Radio gets this reference frequency from a crystal oscillator circuit (the oscillator circuit is internal to the IC, while the crystal is an external component). The receiver is capable of dynamically adjusting to off-frequency signals to some extent, however, as the frequency of the transmitted signal moves further away from the desired carrier frequency, the receiver's narrow-band channel filter will begin to degrade the off-frequency signal. So it is important to ensure that all devices are tuned to a very accurate reference frequency. Tuning the crystal oscillator circuit involves adjusting the load capacitance applied to the crystal. The Wireless USB IC contains internal circuitry that is capable of tuning the frequency of the oscillator by varying the capacitive load. The load capacitance is adjusted by configuring register 0x24 of the Radio.

Frequency deviation (or error) from the desired reference frequency is typically measured in parts per million (ppm). For a 13-MHz reference frequency, a 1-ppm error translates into 13 Hz. Crystal manufacturers specify the accuracy of their crystals with a ppm rating under certain operating conditions. It is important to chose an appropriate crystal for use in a Wireless USB system. Figure 1 illustrates the approximate degradation in receive sensitivity that can occur in the Wireless USB receiver as the frequency error between a pair of devices increases.

Figure 1. Degradation in Receive Sensitivity



Note that the total frequency error is determined by the relative reference frequency used by each device. If the transmitting device is operating at 13.000130 MHz (+10 ppm from the desired reference frequency), and the receiving device is operating at 12.999870 MHz (–10 ppm from the desired reference frequency), the total frequency error between the two devices is 260 Hz (20 ppm).

Radio Supply Voltage

The Wireless USB Radio has a specified operating supply voltage range of 2.7 V–3.6 V. Both transmit power and receive sensitivity increase as the system voltage increases. Current consumption also increases as system voltage increases, so if the target application can tolerate a modest increase in current consumption, then utilizing the highest practical voltage within the specified operating range will improve both transmit and receive performance. Figure 2 and Figure 3 illustrate the approximate relation between Radio supply voltage and transmit strength and receive sensitivity.

Figure 2. Relation between Radio Supply voltage and Receive Sensitivity

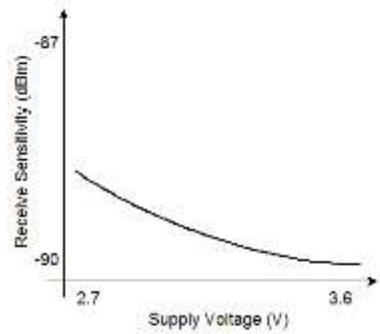
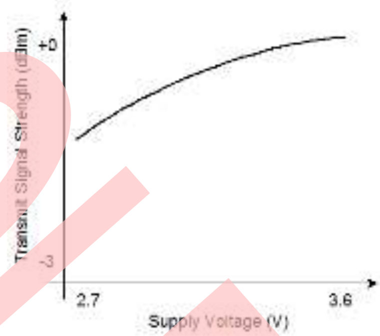


Figure 3. Relation between Radio Supply voltage and Transmit Strength



As illustrated in the graphs, transmit strength can be increased by up to 1 dBm, and receive sensitivity can be improved by up to 1 dBm for a total improvement of approximately 2 dBm (when comparing a 2.7 V system with a 3.6 V system). This total increase in transmit and receive performance will increase the operating range of the system.

Radio Supply Voltage Noise

High-frequency noise present in the RF supply voltage may inject noise into the highly sensitive receive path of the radio, which will degrade the overall sensitivity of the receiver to the desired signal. It is best to make every attempt to minimize the noise present on the Radio's VCC pins. It is a good idea to try to use a linear voltage regulator with low noise characteristics if possible. If a boost converter (switching regulator) is required to derive the desired system supply voltage, then a simple low-pass filter should be used to minimize high-frequency noise from the output of the converter. Other sources of electrical noise in the system should also be considered. Proper bypass capacitance should be added to prevent ringing due to signal transitions from other components in the system. Shielding should also be considered to isolate the Radio from other sources of electro-magnetic noise.

Bandpass Filters

Since sources of out-of-band interference may compromise the performance of the receiver, the addition of an external band-pass filter to the receive path can effectively increase the operational range of the system by significantly attenuating out-of-band signals. The addition of a band-pass filter to the receiver may also slightly attenuate the desired receive signal.

Antenna Considerations

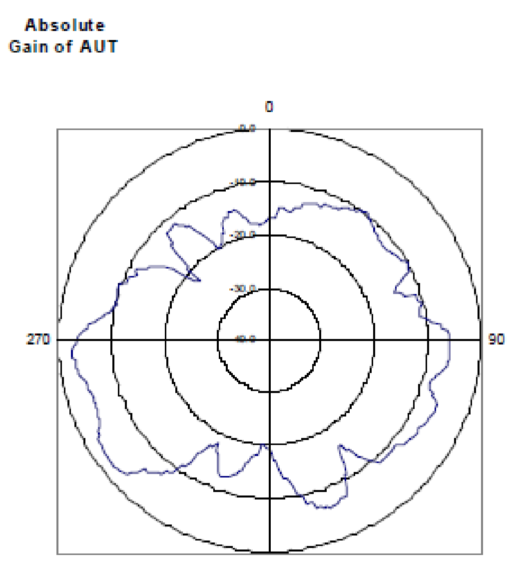
Antenna Type

Antenna design significantly affects wireless performance. The antenna should be designed to maximize the coupling of signals in the ISM frequency band (2.400 GHz–2.4835 GHz). Ideally, the antenna should have poor coupling for signals outside of this range, especially in frequency bands where common sources of radiated energy may exist (1.9-GHz PCS for example).

Antenna Orientation

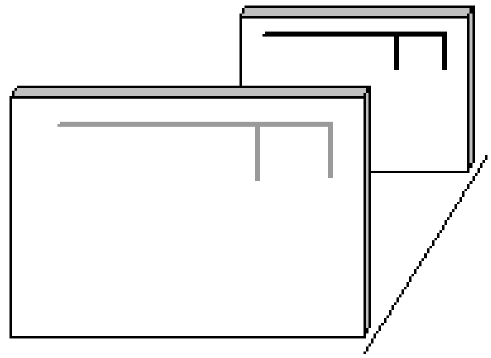
The orientation of the antennas may be very important, depending on the type of antenna used. Each antenna has a different radiation pattern. If the orientation of the antennas in the target application can be controlled (if both devices are typically stationary during use), then a directional antenna should be used to maximize the range and minimize interference. Even if a non-directional antenna is used, it is wise to determine characteristics of the antenna so that the the ideal orientation can be used to maximize range (most antennas have at least some directionality). A common printed circuit "F" antenna (the planar inverted F antenna, or PIFA) has a radiation pattern shown in Figure 4 for one particular test scenario.

Figure 4. PIFA Radiation Pattern



The diagram shows that certain orientations have a significantly higher radiation strength than others. To maximize antenna coupling between a pair of F antennas, they should be oriented as shown in Figure 5.

Figure 5. Orientation of F Antennas for maximum Antenna Coupling



Antenna Matching Network

Similarly, using a properly tuned impedance matching network also has a significant impact on wireless performance. The antenna matching network should also be designed to maximize the transmission of signals in the ISM band, while minimizing out of band signals. Special care can be taken to design significant filtering capability into the matching network to remove unwanted out of band signals which may improve long-range performance by reducing interference.

Circuit Board Design

The design of the circuit board that is used in the Wireless USB system plays a key role in determining the overall performance of the system. The board should be designed to minimize the introduction of noise into the Radio. The board should also be designed to provide the appropriate trace dimensions to achieve the desired RF impedance matching. Please refer to the Wireless USB LS Printed Circuit Board Layout Guidelines application note for more details on designing printed circuit boards for use in Wireless USB systems.

Protocol Techniques

Various firmware techniques can be used to achieve improved range performance. The system's receive sensitivity is determined by the point at which the receiver is only able to recover the desired data below a certain tolerable error threshold. Various error correction techniques can be used to effectively improve the system's receive sensitivity.

Coding Gain

Utilizing the 64 chips per bit (cpb) mode of the radio effectively increases the tolerable error threshold of the system, since several individual chips can be corrupt within a single bit while the receiver can still properly recover each data bit. 64cpb mode uses 64-chip pseudo noise (PN) codes to encode each data bit. The 64cpb mode provides the strongest coding gain out of the three spreading options supported by the radio. The receiver correlator uses a threshold value (the "high threshold") to determine if a sufficient number of chips match in a received signal to interpret the received sequence as a 1 bit. Conversely, the receiver correlator uses a second threshold value (the "low threshold") to determine if a sufficient number of chips in the received signal did not match the desired PN code to interpret the sequence as a 0 bit. Refer to registers 0x19 and 0x1A in the Wireless USB data sheet for more information regarding the configuration of these thresholds. Since the low and high thresholds are typically adjusted symmetrically, it is easier to use a single value when discussing the thresholds. For example, a threshold of 8 would translate into a low threshold of 8 (which means that 8 or fewer chips must match the desired PN code for a 0 bit to be detected) and a high threshold of 56 (which means that 56 or more chips must match the desired PN code for a 1 bit to be detected). The typical threshold used in 64cpb mode is 8. The default threshold provides a significant coding gain while minimizing the possibility of false correlations. The coding gain can be increased further by increasing the threshold to 12, for example. Increasing the correlation threshold increases the probability of occasional false correlations due to noise patterns matching a sufficient number of chips in the PN code. However, if sufficient error detection and correction schemes are utilized, then the correlation threshold can be safely increased beyond the default setting. Increasing the correlation threshold above 14 will begin to cause a significant number of false correlations from noise that may become difficult for the application to handle.

Minimizing Payload Size

Minimizing the amount of data that is sent over the air will also effectively extend the operable range of an application since longer packets have a higher probability of containing uncorrectable errors (due to noise or path loss) which would require retransmission of the entire packet. This is especially true in an environment that contains sources of interference.

Keep in mind that there is a small amount of overhead included in each packet (typically a header byte and a checksum byte), so sometimes combining data to form a single slightly longer packet instead of using multiple short packets is a wise trade-off to minimize the overall number of bytes transmitted through the air. The risk in sending a longer packet is that it is more exposed to possible sources of uncorrectable interference, which would require the entire packet to be resent.

Error Concealment

For some applications, it is not imperative that all of the data is received perfectly. Some examples of applications that can tolerate at least a modest amount of data errors (as long as some appropriate processing is performed on the erroneous data) include voice, music, images, and video. Utilizing the concept of error concealment will effectively increase the receive sensitivity of the system since the desired data rate can still be obtained at a longer distance before packet retries are required.

For example, in wireless voice application, the wireless performance may be virtually error free up to a range of 10 meters. Beyond 10 meters, several packets contain errors, so the packets have to be dropped since there probably isn't enough time or bandwidth to retransmit the voice packet. However, if the error concealment technique is used to derive an approximation of the samples from the erroneous packets using interpolation, then the application may continue to operate satisfactorily out to 15 meters (for example), effectively increasing the range by 50%.

Maximizing Transmit Power

Transmit power is the amount of RF energy intentionally radiated from the antenna of the transmitting device. Transmit power is typically measured in mW or dBm, where:

$$[\text{Power in dBm}] = 10 \times \text{Log}_{10}([\text{PowerOutput in mW}])$$

Therefore 0 dBm translates into 1 mW. Values expressed in dBm can then be thought of power gained or lost relative to 1 mW.

Several concepts discussed in the Receive Sensitivity section of this application note also apply to maximizing transmit power (antenna design, system supply voltage, and so on.) and therefore, these topics will not be discussed again in this section.

Internal Power Amplifier

The first step to maximizing the potential transmit power is to ensure that the internal power amplifier of the Radio is configured to output the maximum power (+0 dBm typical). Radio register 0x23 (REG_PA) is used to set the power output of the internal power amplifier. REG_PA can be programmed from 0–7, with 7 being the maximum output power. Because of the internal architecture of the Wireless USB radio, the transmit power level has no significant effect on the amount of current consumed by the IC. Therefore, the maximum setting of 7 is desirable for most applications without suffering a power consumption trade-off.

External Power Amplifier

Adding an external power amplifier (PA) is a relatively easy way to significantly increase the range of a Wireless USB system. An external PA can increase the transmit signal strength to approximately +20 dBm while still complying with most worldwide regulations governing the ISM frequency band. The main tradeoffs to consider for using an external power amplifier are the additional cost and the additional power consumption of the PA device.

An external power amplifier can be easily interfaced to the Wireless USB IC. The Radio provides an output signal (PACTL) that can be used to automatically activate the external power amplifier during transmit mode. The output enable and polarity of the automatic PACTL signal can be configured in register 0x20 of the Radio. When using an external PA, you must also use either a Transmit/Receive switch or two separate antennas. This is required to minimize the coupling effect between the transmit and receive paths of the Radio. Figure 6 and Figure 7 show the block-level architecture for both a dual-antenna solution as well as a single antenna solution with a T/R switch.

Figure 6. Block-level Architecture for Dual-antenna Solution

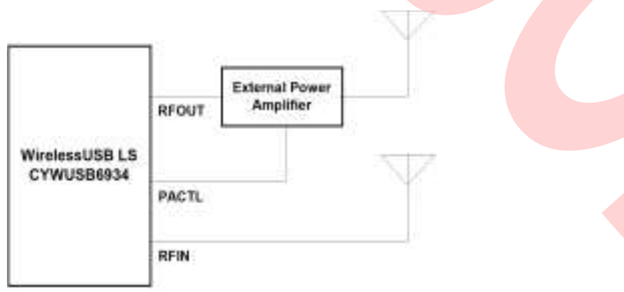
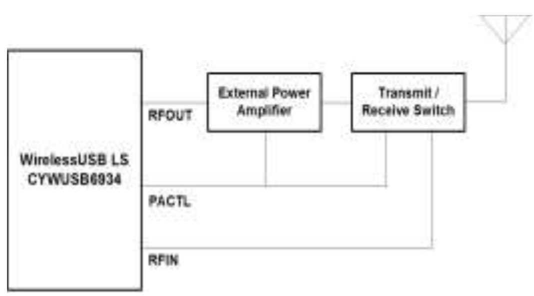


Figure 7. Block-level Architecture for Single Antenna Solution with a T/R Switch



Firmware driver modifications may be required to utilize an external power amplifier (to control the voltage ramp, etc.). Further protocol firmware modifications may be required if closed-loop transmit power control is desired. Closed-loop power control is achieved by having the receiving device measure the strength of the received signal so that it can report back to the transmitting device to indicate if the power level can be reduced to still achieve robust operation.

Ensure that the internal power amplifier of the Wireless USB radio is set to 7 (+0 dBm) when interfacing with an external PA because, it typically yields the most efficient performance from the external power amplifier. For more information on external power amplifier, see the datasheet.

It is highly recommended that a variable voltage drive be used to dynamically select the appropriate gain required from the external PA (for PAs that have this feature) to optimize current consumption in power sensitive devices. If the full gain is not required for robust operation at a certain range in a particular environment, it is wise to reduce the PA output power by several dB to conserve perhaps dozens of mA of current. For the SiGe PA2423L PA, configuring the PA for +15 dBm output power consumes only 40 mA of current, however +22 dBm requires over 100 mA.

Minimize Path Loss

Path loss is defined as the attenuation of a wireless signal as it travels from the transmitter to the receiver. In an ideal environment, only free space would separate the transmitter and receiver. Most typical applications will have to contend with factors that increase the path loss such as device enclosures, obstacles in the operating environment, and indirect line of sight.

Enclosure Considerations

Metal enclosures can obviously significantly affect wireless performance. If a metal enclosure is used, then the antenna should be exposed on the outside of the enclosure to achieve reasonable performance.

Antennas can be completely enclosed in plastic packaging, however the type of plastic and type of paint used may also degrade wireless performance. Some plastics are impregnated with carbon or metallic substances which may inadvertently provide some shielding for the RF energy attempting to pass through the enclosure. Consideration should also be made for the placement of an internal antenna. Be careful not to route any other cabling near the antenna and make sure that other metallic objects are kept as far away from the antenna as possible. The presence of these types of objects can either shield RF energy, or inadvertently alter the impedance of the antenna thereby degrading the achievable receive sensitivity.

The intended use of the devices should also be considered when designing the system. For example, if one of the devices is typically placed on a desk in a particular orientation, then the antenna should be located in the top-most portion of the enclosure. It would be unwise to place the antenna near the bottom of the enclosure because the unknown desktop material may significantly affect the performance of the antenna, or may shield some of the RF energy. Another example is a wireless mouse. Since the antenna is likely to be located inside the plastic mouse enclosure, the typical placement of the human hand on top of the mouse should be considered when determining the location and orientation of the internal antenna. The human hand can act as an RF shield and can also alter the impedance of the antenna at close proximity.

Environment

The general operating environment plays a significant role in determining the range of a wireless system. Proximity of other objects in the operating environment may contribute to degraded range. For many wireless applications, it is difficult to control the operating environment since the wireless devices are typically portable. Considerations should be taken for applications where any control of the environment is possible. For example, when installing wireless sensors in a building or warehouse, the sensors should ideally be placed in the line-of-sight of the central receiving device. If a line-of-sight installation is not possible, then care should be taken to minimize the obstacles that block the line-of-sight path between the transmitter and receiver.

Separate Transmit and Receive Antennas

Using a single-antenna design can reduce receive sensitivity due to coupling between the receive and transmit paths. To achieve maximum range, a separate transmit and receive antenna should be used. In a well designed single antenna system, the receive sensitivity would only be reduced by approximately 1 dBm due to coupling. Using an external power amplifier provides even more reason to use separate receive and transmit antennas so that the use of a costly transmit/receive switch can be avoided.

Antenna Diversity

Performance degradation from both multi-path issues and path loss due to obstacles or antenna orientation can be reduced by utilizing redundant receive antennas (and sometimes even redundant transmit antennas). The antennas need to be configured in different orientations and should be physically separated by at least a few centimeters. The idea is to create two or more possible paths for the signal to travel from the transmitter to the receiver. If one path is degraded due to antenna orientation, then it is likely that the second antenna will have a more favorable orientation. The same is true for multi-path issues where destructive interference degrades the receive signal at one antenna, but because of the physical separation, the second antenna is able to receive a suitable signal. Firmware driver modifications would be required to implement antenna diversity in a Wireless USB system. The firmware would have to determine which antenna to enable based on the quality and intensity of the received signal at each antenna.

Summary

There are many system design considerations that can affect the range performance of a Wireless USB system. The system designer must decide which trade-offs are appropriate to maximize the wireless range for the specific target application. Many of the recommendations in this application note apply to all wireless applications seeking robust performance, even those that don't require long range operation.

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**	1787932	CSAI	11/30/2007	OLD APP. NOTE: This note had no technical updates.
*A	3155460	CSAI	01/27/2011	Added Abstract. Updated to new template.
*B	3370177	CSAI	09/13/2011	No technical updates. Completing Sunset Review.
*C	4519964	CSAI	09/30/2014	Updated to new template. Completing Sunset Review.
*D	5892511	AESATMP9	09/22/2017	Updated logo and copyright.
*E	5930488	ANKC	10/16/2017	Obsoleting the spec

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