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ULTRA WIDE BAND (UWB) INTERFERENCE – ASSESSMENT AND MITIGATION STUDIES

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13. ABSTRACT ***(Maximum 200 Words)***

The objective of this study was to identify techniques for mitigation of Ultra Wide Band, UWB, ElectroMagnetic Interference, EMI, generated by (commercial) communication equipment upon the reliable operation of GPS systems.

14. SUBJECT TERMS GPS Electromagnetic Interference, GPS break-lock point, Unintentional GPS Jammers, GPS Jammer Suppression; UWB Spectral Elimination, Wideband Jammer Suppression, Normalized ESD Gausian Pulses, Spectral dithering, Hermite polynomial, BPSK, PAM, OOK, PPM pulse streams, EIRP limits.	**15. NUMBER OF PAGES** 85
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1. Executive Summary Introduction

This executive summary is written for the non-technical person who is trying to understand the ultra-wideband (UWB) phenomena of concern today and whether ultra-wideband transmitters pose a threat to conventional electromagnetic receivers. The document provides the reader with a basic understanding of how conventional systems, function, how ultra-wideband devices are different and why they are sought after for performing multiple functions. Suggestions are provided of how a manufacturer of conventional systems such as global positioning systems (GPS), cellular telephones, and pagers can assess their systems' performance when operating near ultra-wideband transmitters. There are many parameters and/or scenarios that can be constructed in which electromagnetic interference (EMI), hereafter referred to as interference, may occur. There are also many ways to mitigate interference caused by ultra-wideband transmitters. This report provides an overview of all these topics. Part II of this report provides more detailed information regarding ultra-wideband and its potential interference to conventional receivers.

Our study is not complete. That is, we cannot emphatically state there is a major problem with ultra-wideband and conventional receivers. Nor can we state there is not a problem. The answer depends upon the relative locations of a conventional receiver and transmitters, ultra-wideband modulation or coding methods, the transmitted power levels, antenna gains, the receiver algorithms, the receiver susceptibility levels, etc. Interference can exist in some scenarios, not in others, and in some cases the interference can be mitigated.

Section 2 provides a description of electromagnetic interference and how it can be avoided in conventional receivers. Section 3 describes how the military builds systems with electromagnetic compatibility (EMC) in mind. Section 4 provides a discussion of why there is concern with ultra-wideband and global positioning systems receivers operating in close proximity. Section 5 presents an argument of why there is no simple solution to this potential interference situation and presents our summary and conclusions. Section 6 presents an Introduction to Part II of our technical study. In Section 7 we present the basics behind UWB technology, including UWB mathematical models and some typical UWB signals. In Section 8 UWB interference and key parameters that define this interference are described. An overview of the related literature is also presented. Section 9 describes techniques for mitigating UWB interference. Analysis and simulation results for some techniques are shown. Appendix A provides a short description of the major documents referenced in this report.

2. What is Electromagnetic Interference (EMI)?

You are driving along a highway with your amplitude modulation (AM) radio on and, as you approach high electric power transmission lines, the radio signal is degraded by an increasingly loud static sound. This sound builds in volume as you approach the power lines and diminishes as you drive away. This is an example of interference. While the static noise increases you cannot intelligibly hear the radio signal. We say that performance is degraded.

You get on a commercial airliner and you are told not to use your cell phone while the aircraft doors are closed. The airline is concerned that the use of your cell phone may interfere with electromagnetic (EM) equipment on the aircraft such as its navigation system.

In both these cases the interference causes degradation in performance of one or more receivers. In the first case, when the radio signal is speech, the performance parameter may be measured by how many words are understood correctly i.e. an intelligibility factor. In the second situation performance may be measured by the accuracy in knowing where the aircraft is located (i.e. errors in latitude, longitude and elevation). If the interference is extreme, the navigation receiver may not be able to lock onto the system's radio beacon system causing the aircraft to fly off course. This is referred to as break lock or loss of signal.

To help reduce the possibility of interference the Federal Communications Commission (FCC) has developed rules for the assignment of frequencies and maximum power levels for licensed equipments. For example, television stations have to have a license to operate. Their carrier frequency is allocated based upon which channels are already assigned in the nearby areas. If there is a channel 3 in your local area, then the next carrier frequency assigned may be that of channel 5. The FCC most likely would not assign a channel 2 or channel 4 in your area because their carrier frequencies would be too close to that of channel 3. Taking into account that each cannel utilizes a frequency band centered on its carrier frequency, the frequency bands of channels 2, 3, and 4 could overlap causing interference between neighboring channels. Conventional communication systems are assigned a carrier frequency and a modulation type. Conventional modulation types are AM, frequency modulation (FM), and pulse code modulation (PCM). The frequency content of speech and music is too low to be transmitted efficiently. Modulation techniques are used to shift these frequencies about that of a high frequency carrier signal where they are readily radiated and received. For AM modulation the transmitter mixes the speech and/or music audio signals with the carrier signal, amplifies their combined signal level, filters out some of the frequencies outside the frequency band it is allowed to transmit and sends the signal to the antenna system which propagates the signal into the air. The carrier frequency is the frequency one selects to tune into a station. An AM carrier signal is a continuous sine wave, as shown in Figure 1, where its frequency is based on how many times it completes a cycle in one second. In the AM radio band transmitters operate between 550 KHz and 815 KHz, where a kilohertz (KHz) is one thousand cycles per second. When your radio is tuned to a 800 KHz station the transmitted frequency/content would look like that shown in Figure 2 when there is no speech or music. If information is being sent then the frequency content would look some what as shown in Figure 3 for a conventional AM signal. In many cases only one sideband is transmitted without the carrier frequency, as shown in Figure 4. For the speech or voice signal being considered in Figures 3 and 4, note that the bandwidth of each sideband is 15 KHz. All the information of the speech and/or voice is contained in the frequencies and their respective amplitudes within these sidebands. A time snap shot of what the modulation would look like is shown in Figure 5.

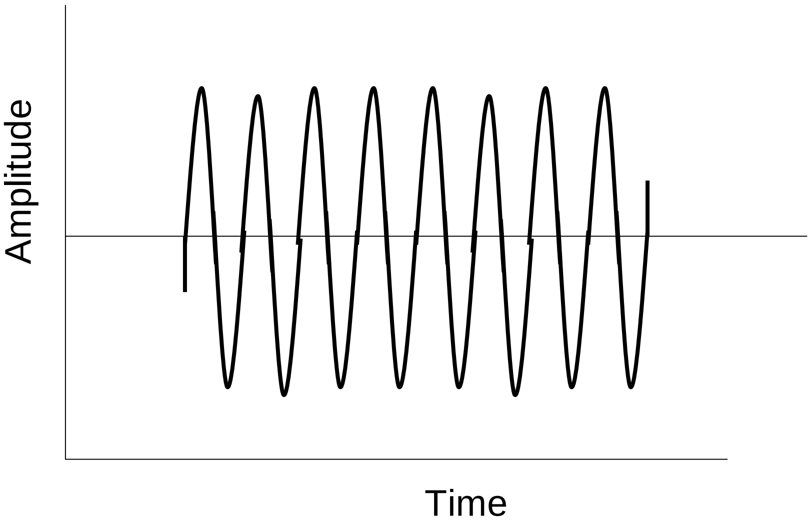


Figure 1 Example of Carrier Waveform (CW) Signal

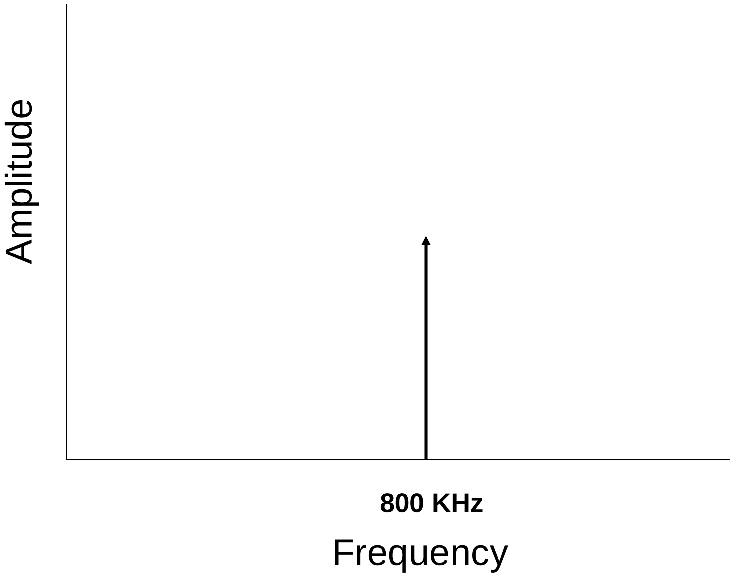


Figure 2 Frequency Content of a Carrier Signal

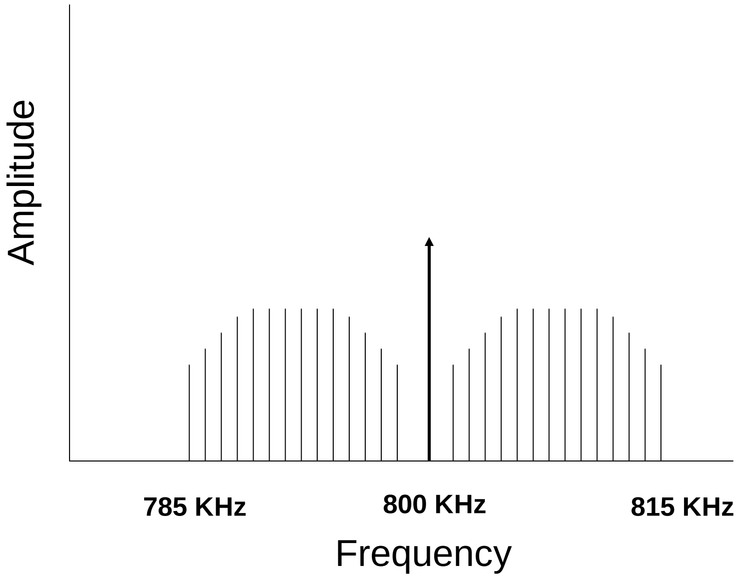


Figure 3 Frequency Content of a Conventional AM Signal

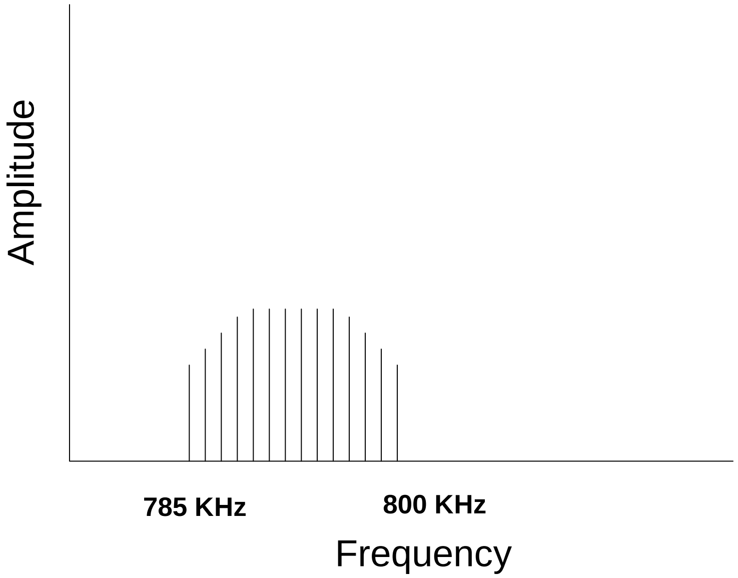


Figure 4 Frequency Content of a Single Side-Band AM Signal

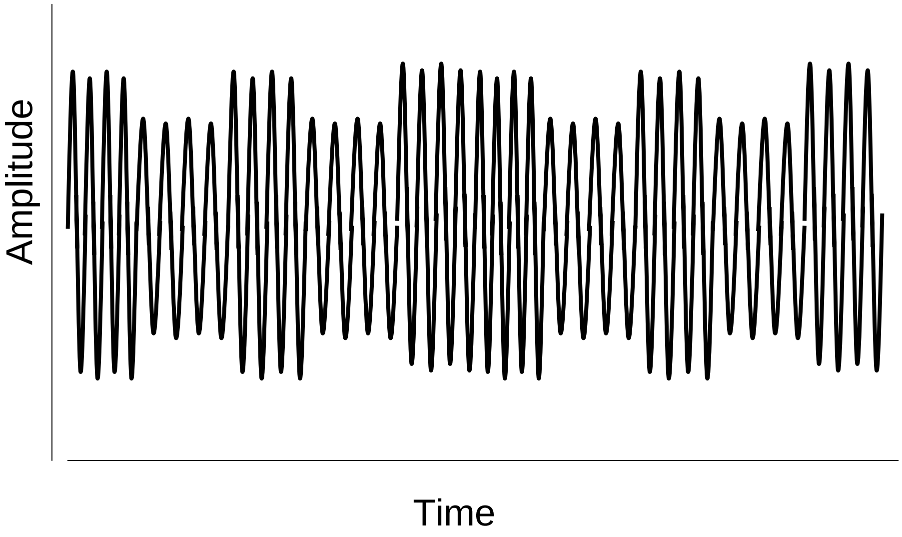


Figure 5 Example of AM Signal in the Time Domain

The FCC assigns channels to new radio stations by specifying the carrier frequency to be used and the maximum power to be transmitted. The same channel operating at 800 KHz can be assigned to multiple radio stations as long as their power and physical distances are such that people within the intended average radius of each station do not experience interference. The power of a signal decreases according to the square of the distance traveled. In Figure 6 we show two radio stations whose coverage areas are circles of radii R1 and R2, respectively. Given the power of the radio stations the circles represent those regions where there is sufficient power for receivers to have acceptable performance. The closer a receiver is to the station the stronger the signal. When a receiver is outside its circular coverage region, reception is unacceptable because the signal strength is below the ambient noise of the environment which is always present at the receiver input. This is how the FCC assigns frequencies to different radio stations without causing interference between them. This explains why you eventually lose your favorite radio station as you travel away from your home town.

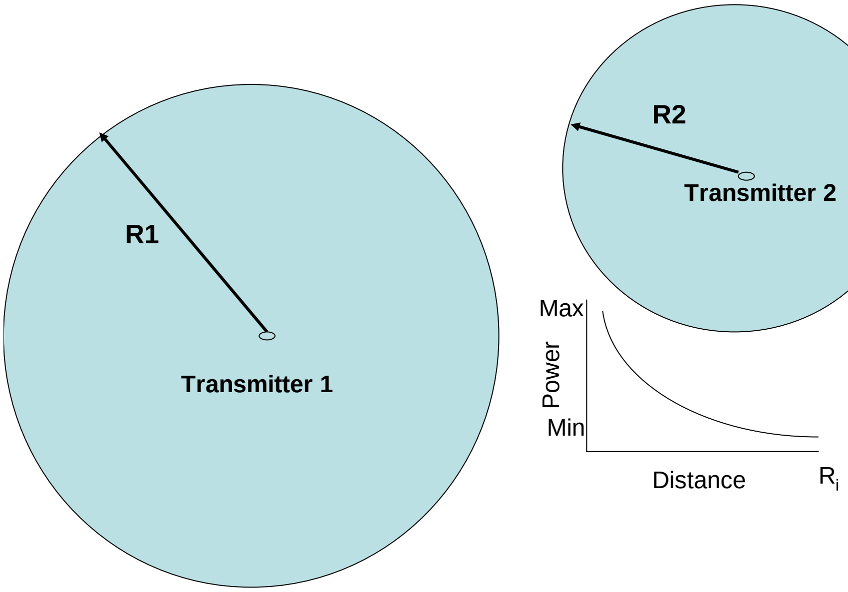


Figure 6 Locations and Coverage Areas of Two Radio Stations

The FCC allows radio/television stations to operate physically close to each other by controlling their assigned carrier frequencies and bandwidths of operation. They are also told that they must control the power levels of the signals being transmitted over a pre-specified frequency band. In Figure 7 we show the power levels, as a function of frequency that an AM radio station cannot exceed. The measure of power is decibels (dB) and the significance of subtracting 25, 35, 65, and 80 dB from the maximum output power (MOP) is given in Table 1. If frequency components are above these levels are radiated the stations can be fined. Therefore, by controlling the frequencies assigned and their emission levels, the FCC controls the potential of interference.

Note that the transmitted power at MOP – 80 dB is 100 million times smaller than the maximum output power of 100 Watts. As a result, if a radio/television station is to avoid being fined by the FCC, it must be very careful of the relatively small power levels emitted at frequencies which are 75 kHz above the carrier frequency. To put things in perspective, if one had 10 million dollars, and their worth was reduced by 80 dB they would then be worth 10 cents.

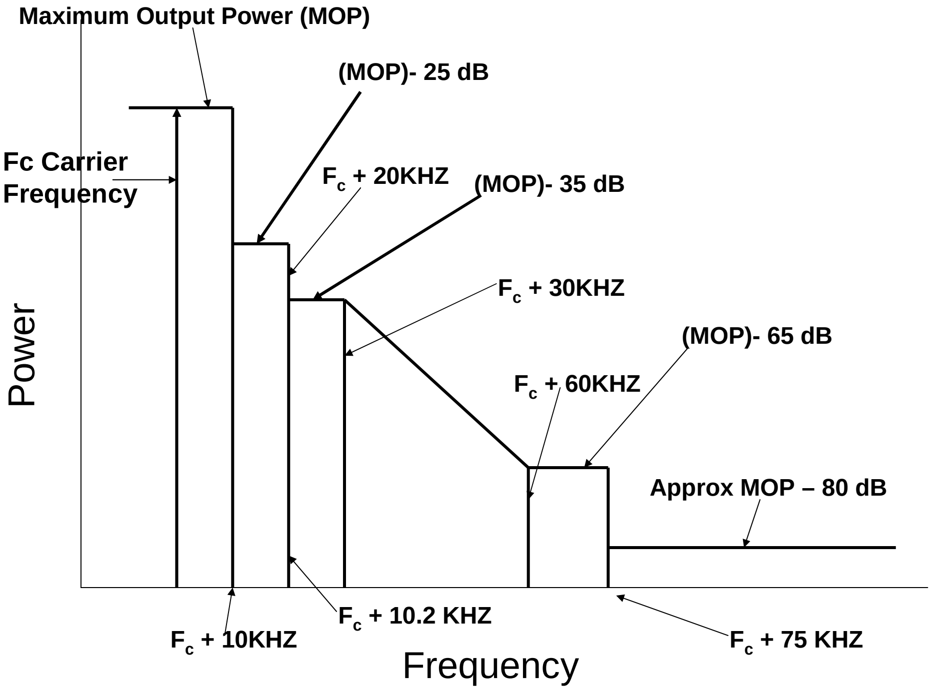


Figure 7 AM Signal Power Emission Limitations

Table 1 Power Levels in Figure 7 When MOP is Equal to 100 Watts

MOP	100 Watts
MOP – 25 dB	approximately 3/10 of a Watt
MOP – 35 dB	approximately 3/100 of a Watt
MOP – 65 dB	approximately 3/100,000 of a Watt
MOP – 80 dB	1/1,000,000 of a Watt

Frequency modulation (FM) is similar to AM. Rather than change the amplitude of the carrier signal, FM changes the carrier frequency by changing its frequency in accordance with the speech or music to be sent. Figure 8 shows a typical FM modulated signal transmitting between time T_0 and T_1. The FM radio band operates between 88 MHz and 108 MHz where a megahertz (MHz) is one million cycles per second. The frequency content of a typical FM signal extends over a frequency band whose bandwidth is approximately 200 KHz. Therefore, if a FM station's carrier frequency is 93.5 MHz then the transmitted signal will occupy the frequency band between 93.4 MHz to 93.6 MHz. FM is less susceptible to interference but requires channels with larger frequency bands.

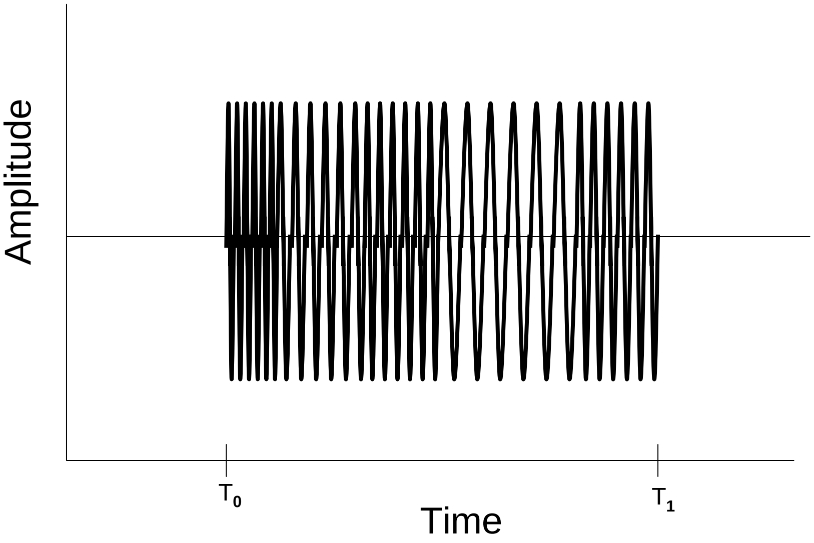


Figure 8 Example of an FM Signal in the Time Domain

These two modulation schemes both allow us to transmit and receive signals such as voice and music. However, radar signals and computers transmit digital signals or binary data. We know that we can take analog signals and code them digitally, transmit them or record them on our compact disks (CDs) and, when we receive or play them, we convert them to analog and listen to them on our computers. There exist numerous modulation schemes to represent digital data. One modulation scheme that allows us to transmit digital data is pulse amplitude modulation (PAM). Shown in Figure 9 is a typical PAM signal where there are only two discrete amplitudes. One can be designated as a 1 and the other as a 0 allowing us to transmit and receive digital data. Thus, in Figure 9 the digital data stream being transmitted is “1, 0, 1, 0, 0, 1”. Notice, however, that the pulses are sinusoidal pulses whose frequency is that of the carrier’s signal. The variation in amplitude conveys the information to be sent. Another form of pulse modulation is pulse width modulation (PWM) (see Figure 10). In this scheme the width of the sinusoidal pulse conveys the information being transmitted. A wider pulse may represent a 1 and a narrower pulse may represent a 0 where there is a fixed time interval period between the beginning of each pulse. The number of pulses per second is called the pulse repetition frequency (PRF). The larger the PRF the more is the information, or bits of data, that can be communicated between two or more equipments.

Increasing the rate of information transmission is one of the reasons driving the use of ultra-wideband technology. In your office you may have a local area network with wires connecting your computer to the file server where you save all your files. This network could have a transfer rate of up to 100 million pulses per second. The computing and communications industries would like to transmit and receive data at and beyond this rate without wires and ultra-wideband has the potential for meeting this goal.

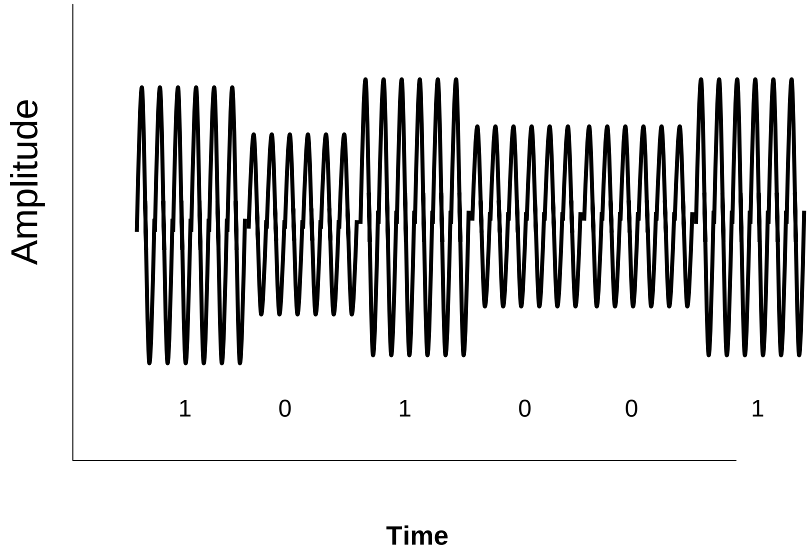


Figure 9 Example of a PAM Signal in the Time Domain

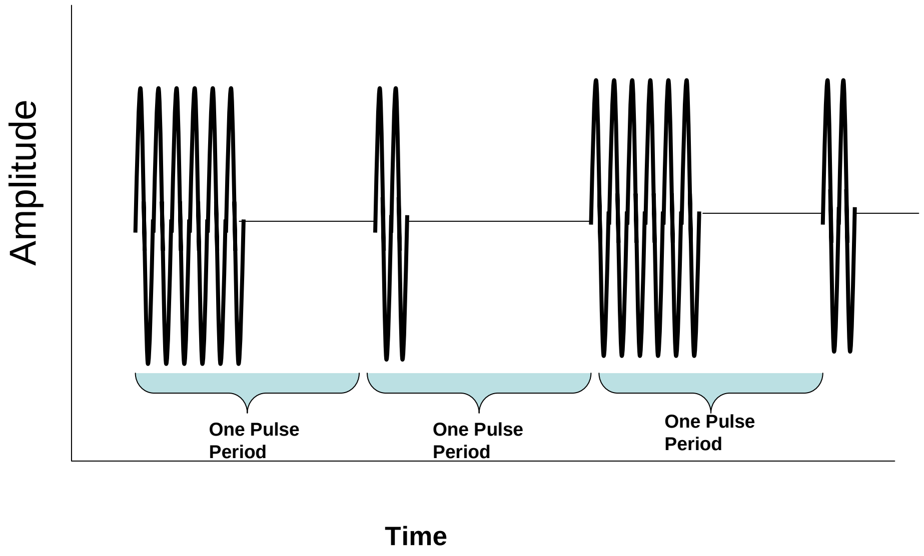


Figure 10 Example of a PWM Signal in the Time Domain

Interference in a pulse modulation scheme can cause a 0 that is transmitted to be received as a 1 and vice versa. Zeros and ones are referred to as binary digits or bits for short. A performance measure that is commonly used in digital systems for measuring degradation in performance due to interference is bit error rate. This measures the number of bits (0's and 1's) that are incorrectly received in a long data stream. In the absence of interference a bit error rate that corresponds to 1 error in 1 million pulses transmitted is not unusual. However, in the presence of sufficiently large interference the bit error rate may increase by several orders of magnitude such that more than 1 thousand errors occur per 1 million pulses transmitted.

Radar is another electronic system that can both cause and suffer from electromagnetic interference. Radar systems use pulse modulation techniques to detect and track targets and are mounted on the ground, ships, aircraft, and satellites. Amongst their many functions are mapping of the earth, prediction of storm fronts, and guidance of missiles to their targets. Radars send out a series of pulses and wait for them to reflect off of a target and/or the earth. Based upon the time that it takes the radar signal to return, the system can predict how far the target is from the radar. In addition, by measuring the change in the carrier frequency of the returning signal, known as the Doppler shift, a Doppler radar can determine the speed at which a target is moving toward or away from the radar. Performance measures commonly used to quantify radar operation are probability of detection, the number of lost targets, and probability of false alarms (or false targets). A tracking or surveillance radar attempts to increase its probability of detecting a target while minimizing the number of false alarms. To combat interference, a radar may reduce its sensitivity to false alarms. However, by doing this, it will also reduce its probability of detecting real targets. The radar community envisions the use of ultra-wideband signals to improve its capability for the location of underground objects, detection of moving objects inside buildings and collision avoidance between vehicles in motion such as automobiles.

Many things can be done to reduce the impact of interference. Some may or may not be feasible in all situations. The following list is based upon one transmitter interfering with one receiver. Later on the situation of multiple transmitters interfering with a single receiver is discussed. Interference can be reduced by implementing one or more of the following counter measures:

- Time share the spectrum (i.e. transmit only when the victim receiver is off)
- Increase the distance between the transmitter and the victim receiver
- Change either one or both of the equipments' carrier frequencies
- Change the shapes of one or both antenna patterns such that the transmitter and victim receiver's maximum antenna gain are not pointed at each other
- Reduce the transmitter's power
- Reduce the transmitter and/or the victim receiver frequency bandwidth
- Change the vertical orientation (i.e. polarization) of one or both of the antennas. (Antennas operating with the same vertical orientation have the maximum amount of power transfer. However, if antennas are of different orientation then the amount of power transfer is reduced.)
- Sample the interfering signal and cancel it before it enters the victim receiver
- Change the signal parameters (pulse waveform, modulation, etc.) to those for which the victim receiver is less susceptible.

3. Military Electromagnetic Compatibility (EMC) Standards

The Department of Defense (DOD), the Institute of Electrical and Electronic Engineers (IEEE), and the FCC are a few of the organizations concerned with building military and commercial systems that are electromagnetically compatible. The DOD, in particular, has a set of military standards used for the manufacturing of transmitters and receivers of electromagnetically energy and their subsequent integration into military systems such as air planes, ships, and/or space vehicles. It is worthwhile to briefly review how their systems are built because portions of what is done might help eliminate or predict interference caused by ultra-wideband transmitters in conventional receivers.

Military Standard 461E is a standard that sets the limits on how much unintended power can be radiated from a transmitter and how much out of band power a receiver must be able to withstand without having its performance degraded. The standard also describes the methodology by which the equipment manufacturer must make measurements so it can verify that the equipment has indeed met the standard. These standards are described for each possible signal input and output path of an equipment. Examples of such paths are the antenna port, or signal and control ports, the power connector, and openings in the equipment box itself. For this discussion only the antenna port is considered as an input/output port for electromagnetic power.

As shown in Figures 3 and 4 a transmitter needs only to transmit its frequency band of information (with or without the carrier frequency) in order to communicate. However, because of non ideal operation, other frequencies are usually emitted from a transmitter, and are defined as unintended emissions. Figure 11 shows the typical frequency content of an emission from an AM transmitter. One can see that the transmitter emits not only the desired frequency content but frequencies at multiple integers of the desired frequencies. These are referred to as harmonics. The military standard dictates the power levels below which these harmonics must fall. The military standard also describes the measurements to be made by the contractor in order to verify that equipments meet these limits. Note, however, that it is not satisfactory to show that a single equipment meets the limits. Instead it must be demonstrated that the manufacturing process is such that equipments, in general, meet the limits. Therefore, many manufactures randomly pick equipments at the assembly line output to verify compliance with the standard.

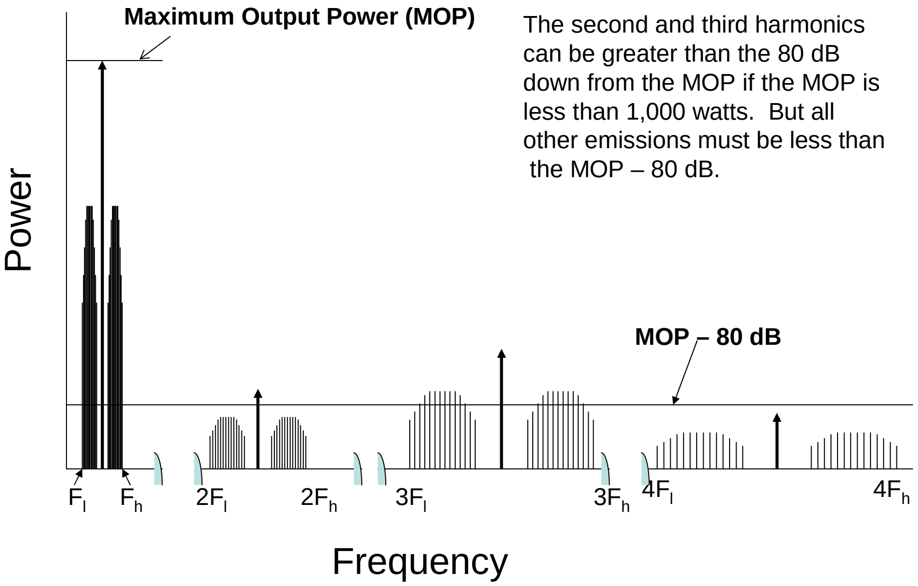


Figure 11 Typical Frequency Content of an Emission From an AM Transmitter

The receiver portions of electronic systems must also demonstrate they can withstand the electromagnetic environment in which they will have to operate. Receivers are tested to verify that they can receive electromagnetic power outside their desired frequency band without suffering performance degradation. A typical receiver susceptibility curve is shown in Figure 12. The receiver is most susceptible at its tuned frequency which is identical to the carrier frequency of the desired modulated signal. Power frequency assignments should eliminate the possibility that other transmitters within the coverage area of the receiver are intentionally transmitting signals at this same tuned frequency. The receiver, however, must provide enough attenuation to signals outside its tuned frequency band to reject signals that are transmitting at other tuned frequencies. The manufacturer must build its receivers to meet the required sensitivity levels and attenuation levels indicated by their susceptibility curves. Manufactures randomly check their receivers to verify compliance with the standard.

The receiver susceptibility curve shown in Figure 12 is for an Ultra High Frequency (UHF) (200 MHz to 400 MHz) receiver. The figure shows that the receiver is tuned to F_c and its sensitivity level is indicated on the Power axis. The sensitivity level is the minimum power level at the antenna port for which the desired signal produces an acceptable response in the receiver. The receiver susceptibility curve indicates, as a function of frequency, the maximum power level of an interfering signal that is simultaneously allowed to be present at the antenna port without degrading the performance of the receiver. Above this level serious interference is expected. Below this level the interference is expected to have negligible effect on receiver performance. Note that the receiver must be able to operate properly in the presence of signals up to one one-thousandth of a Watt outside the UHF frequency band. Communications receivers in this frequency range can have sensitivity levels smaller than one one-trillionth of a Watt.

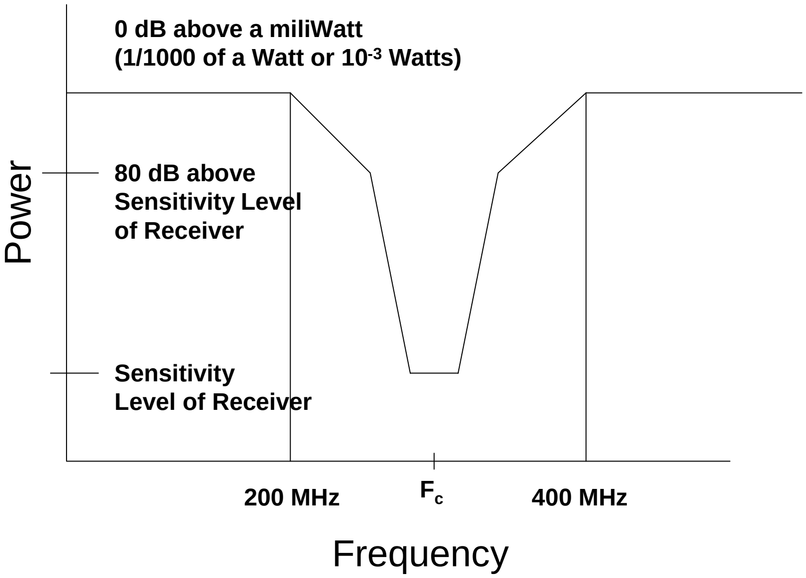


Figure 12 A Typical Receiver Susceptibility Curve

Military Standard 461E is based upon building an equipment irrespective of the system in which it must operate. Another standard, Military Standard 464, addresses the issue of electromagnetic compatibility between these equipments when integrated together within a platform such as a ship, aircraft, satellite, or communication's hut. The major way this is accomplished is through analysis and measurements on the actual system. If the system is yet to be built, then analysis and/or simulation models are used. The military has numerous sophisticated analysis tools at its disposal which, in many cases, require years of electromagnetic compatibility experience to use and assess along with measurements. Examples are tools based upon the method of moments and geometric theory of diffraction. For our analysis we propose a combination of simple measurements and analysis tools that can be solved using a simple calculator. They, along with proposed measurements, will allow for the assessment of whether an ultra-wideband signal will indeed cause a conventional receiver to suffer from electromagnetic interference.

The equipment measurements regarding unwanted electromagnetic coupling into a receiver consists of two different techniques. One technique involves injection of the desired and/or interfering signals directly into the antenna connector port while the other technique involves radiation of the total equipment by means of an antenna using the desired signal and/or interfering signals representative of the electromagnetic environment in which the equipment is expected to operate. Two different susceptibility curves are typically measured. The first is measured when the desired signal with carrier frequency Fc is not applied to the receiver which is tuned to Fc. Instead, an interfering signal having the same modulation as the desired signal is applied to the receiver. As indicated in Figure 13, the interfering signals are applied, one at a time, with carrier frequencies outside the desired frequency band which is centered at Fc. The power of the interfering signal is increased until a pre-specified minimum response is generated in the receiver. The power level at which this occurs is recorded. For example, Pi is the power level measured at Fi while Pj is the power level measured at Fj. This susceptibility curve is known as the receiver single signal response curve. Interfering signals with carrier frequencies outside the desired frequency band whose powers are less than those indicated in Figure 13 are not expected to cause noticeable interference.

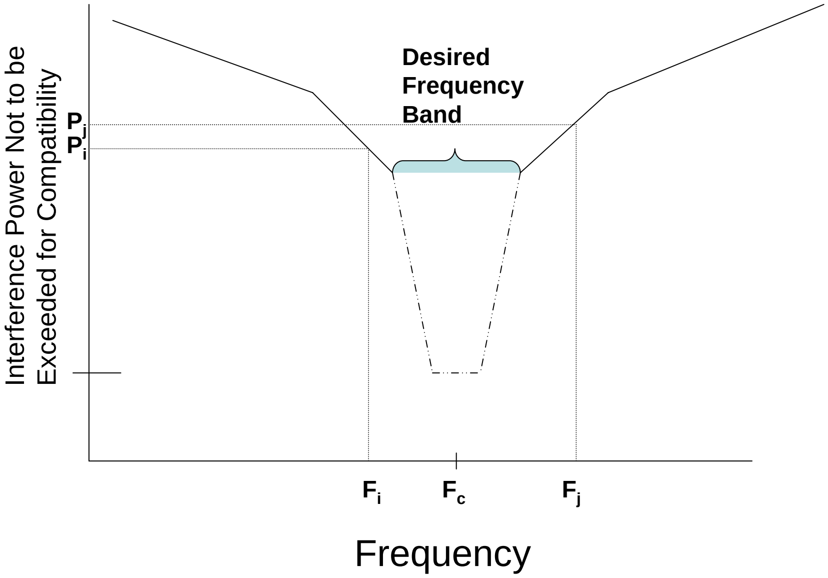


Figure 13 Receiver Single Signal Response Curve

The receiver two signal selectivity curve, shown in Figure 14, is the second of the measured curves. As the name implies, the measurement involves simultaneous application of a desired and interfering signal with the receiver tuned to Fc, the carrier frequency of the desired signal. The power level of the desired signal is adjusted such that a pre-specified receiver response is obtained. With a carrier frequency outside the receiver desired frequency band, the power level of the interfering signal is increased until a pre-specified amount of degradation in receiver performance is achieved. This power level and the interferer carrier frequency are recorded. In this way, the curve of Figure 14 gives the minimum interferer power level needed to cause unacceptable interference in the receiver (e.g. Pi at Fi and Pj at Fj).

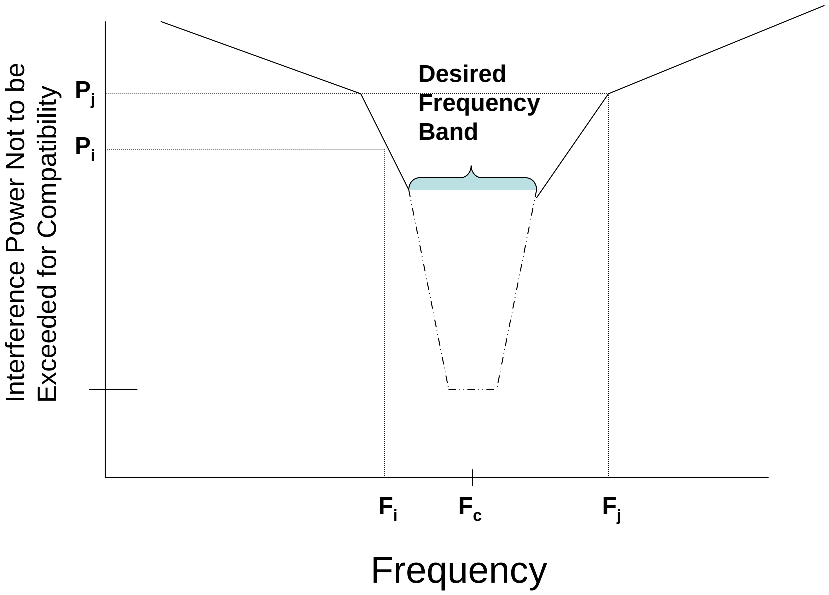


Figure 14 Receiver Two Signal Selectivity Curve

The degradation referred to is related to a performance measure that is predetermined before the measurements are performed. For instance, in the navigation example discussed previously, an unacceptable response may be said to occur when either the latitude, longitude, or elevation errors exceed 1%. The 1% error criterion may be based upon the manufacturer's stated performance guarantee provided the equipment is operating properly. If the receiver is a digital communication receiver, the performance measure may be a bit error rate (BER) of 1 error in a million binary digits. If this rate is exceeded, the equipment is considered to be operating in an unacceptable manner. This performance measure may either be guaranteed by the manufacturer or required by the military.

The susceptibility curves of Figures 13 and 14 are based upon measurements taken with the actual equipments. This is not possible when the equipments are still in the design stage or the measurements are too costly for the available budget. In such situations analytical tools are available to assess the possibility of electromagnetic interference. This is illustrated by the following example.

Consider the AM transmitter whose frequency content is displayed in Figure 11. Assume the carrier frequency is 100 mega Hertz so that the fourth harmonic is at 400 mega Hertz. Let a very sensitive receiver, whose sensitivity is one hundred-billionth of a Watt (i.e., 1/(100,000,000,000) Watt), be tuned to 400 mega Hertz and collocated at a distance on the order of 10 meters from the transmitter. This situation is depicted in Figure 15. Observe that a potential interference situation exists because the fourth harmonic of the transmitter falls at the tuned frequency of the receiver. The question that arises is, "What is the maximum output power (MOP) of the transmitter such that the transmitter does not interfere with the receiver?" This question can be answered by analysis.

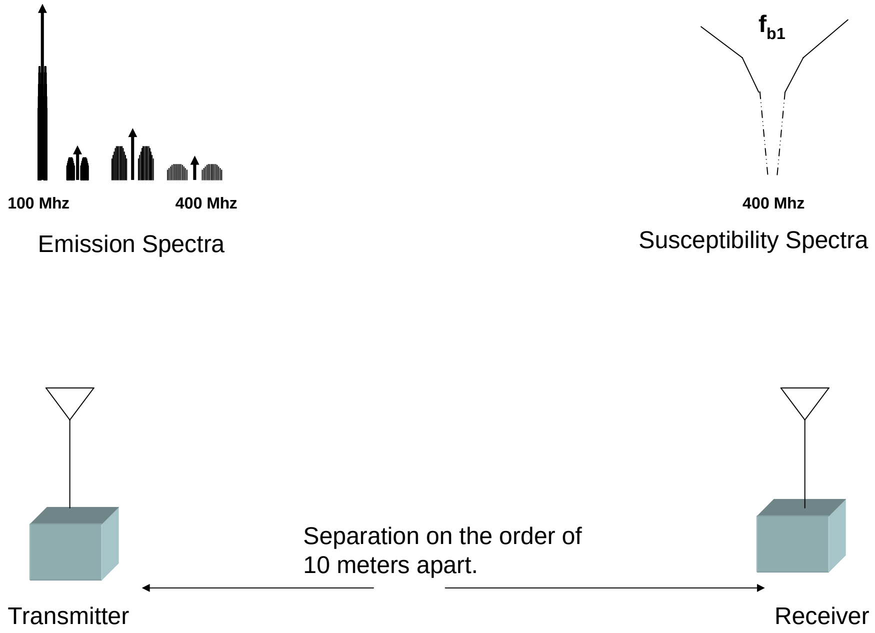


Figure 15 Collocated Equipments

Clearly, the power in the fourth harmonic at the receiver input must be less than the receiver's sensitivity level. The signal from the AM transmitter becomes attenuated as it travels from the transmitter to the receiver. The amount of attenuation is readily analyzed when the radiated power travels through free space. For situations where multiple objects are encountered as the radiated power propagates between the transmitter and the receiver antennas sophisticated electromagnetic codes can be used to determine the amount of attenuation. Assuming free space propagation, the fourth harmonic power at the transmitter antenna is in the order of 10,000 times stronger than that at the receiver antenna for the collocated equipments shown in Figure 15. Thus, taking the receiver sensitivity into account, the fourth harmonic power at the transmitter antenna must be less than one ten-millionth of a Watt (i.e. 1/(10,000,000 Watts)) if interference is to be avoided. As pointed out with respect to Figure 7, FCC and DoD standards require that power levels at the fourth harmonic be 100 million times smaller than the transmitter maximum operating power (MOP). For the collocated equipments of Figure 15, it is concluded that the transmitter maximum operating power must be less than 10 Watts if electromagnetic compatibility is to exist.

This example demonstrates that, though individual equipments can be built to meet FCC and Military Standard 461E, there may still be interference issues when they are collocated near each other. Various fixes are possible when interference is encountered. In the example just discussed the problem could be eliminated by assigning the carrier frequency such that harmonics do not fall within the tuning range of the receiver. Also, a maximum output power in excess of 10 Watts could be accommodated without changing the receiver's tuning frequency by applying a filter at the transmitter output that reduces the power level of the fourth harmonic. Other techniques, which will not be discussed here, can be applied to achieve electromagnetic compatibility.

Our presentation, thus far, has focused attention on signals that modulate a carrier. By changing the carrier frequency, the frequency content of the signal can be located in any frequency band of interest. We now focus our attention on one method for generating ultra-wideband signals that do not require the use of a carrier.

4. Ultra-wideband Signals and Their Impact on Global Positioning System (GPS) Receivers

Because of smaller and faster processing chips/computers and advances in digital signal processing, the engineering community has been able to build in recent years very sensitive receivers that can detect and process signals extremely low in power. For example, a GPS receiver can detect and process a signal whose power levels are approximately one hundred thousand times smaller than those that can be processed by the receiver considered in Figure 15. It achieves this capability through very sophisticated signal processing algorithms embedded in computer chips within the receiver. These algorithms enable the detection of signals that are lower in power than is the background noise. This capability is achieved due to the processing gain of the algorithms.

The extremely low sensitivity levels of GPS receivers are necessary because GPS transmitters are located on satellites which are at great distances from the GPS receivers on the ground. Because of the major costs associated with launching and maintaining a satellite in space, equipments on board must be as small as possible, made with light weight materials, and must use very little power. GPS receivers operate within the 1 to 2 GHz frequency band, where gigahertz (GHz) is one billion cycles per second. The higher the frequency, the greater is the attenuation of signal radiated in free space. Combined with the great distances involved, GPS receivers can function properly only if they can detect and process these extremely weak signals.

As the name implies, ultra-wideband signals have frequency content that extends over a very wide frequency band. As a result, a portion of this frequency content is likely to fall within the desired frequency band of a GPS receiver. Consequently, a potential interference situation exists. Some ultra-wide band signals consist of very short pulses that are transmitted without the benefit of a carrier. Neither was a carrier employed with the telegraph, the very first electrical communications system. Morse coded messages were sent using a pulse of duration equal to one time unit to represent a dot and a pulse three times as long to represent a dash.

Pulses can be modified in a variety of ways to transmit digital information consisting of 1's and 0's. In particular, their amplitudes, durations, or positions can be changed according to some pre-specified format consisting of two states. One state represents a "1". The other state represents a "0". Figure 16 illustrates one of the simplest of these schemes. Either a "1" or a "0" is transmitted each pulse period. A pulse of amplitude A (i.e., the pulse is ON) is used to represent a "1". A pulse of amplitude zero (i.e., the pulse is OFF) is used to represent a "0". This scheme is referred to as on-off keying (OOK). For the pulse sequence shown in Figure 16, the transmitted digital sequence is 1 0 1. Such pulse techniques are very effective for transmitting messages encoded in 1's and 0's that arise from voice, music, video, financial data, etc.

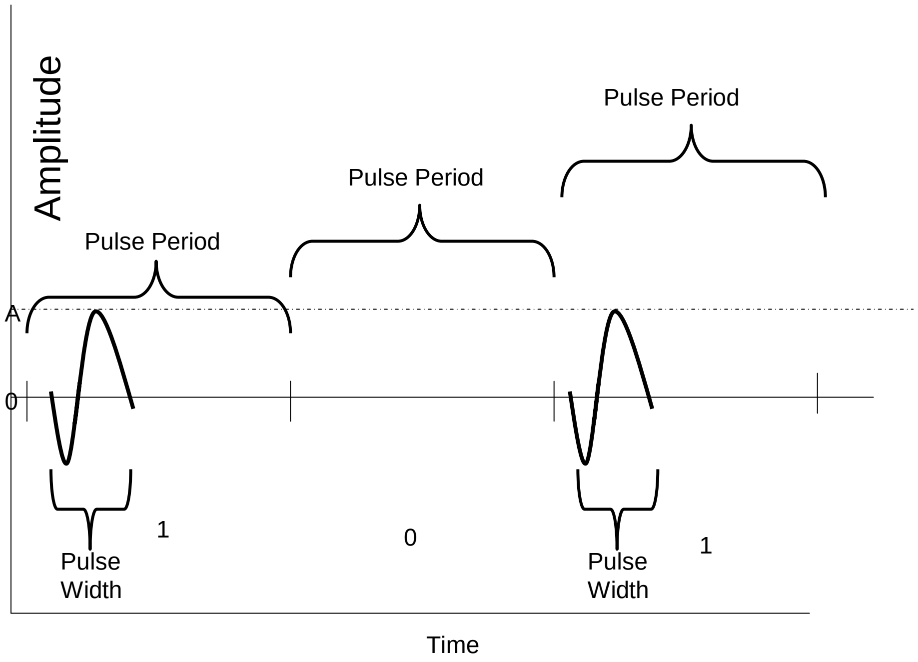


Figure 16 An Example of On-Off Keying

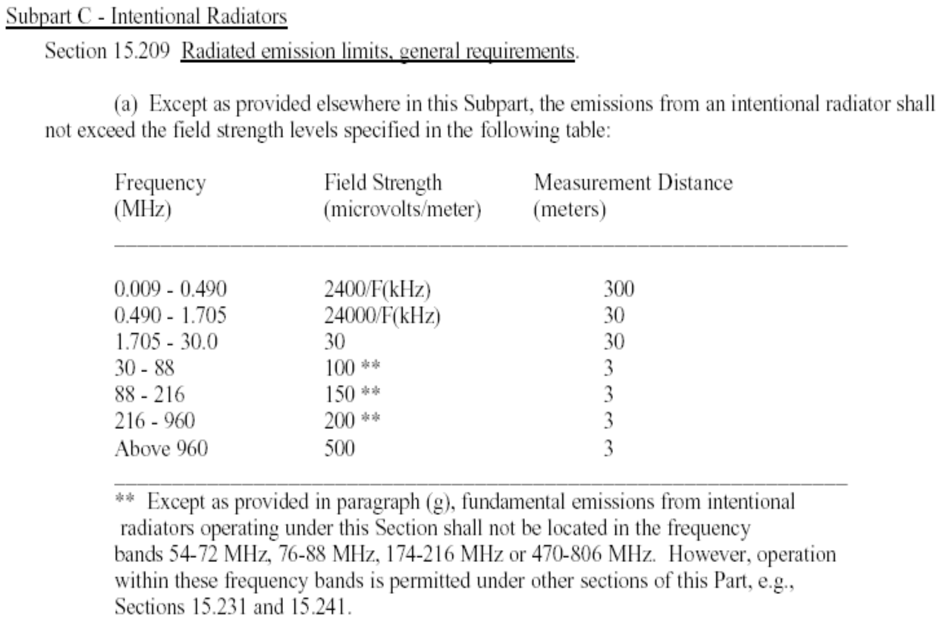
Currently, a local area network using cables can transmit 100 million bits per second. Recall from above that a bit, as shown in Figure 16, consists of a "1" or a "0". Whereas conventional pulses radiated by antennas have pulse widths on the order of a millisecond (one-thousandth of a second), ultra-wideband signals use pulses having widths on the order of a nanosecond (one-billionth of a second). Therefore, ultra-wideband technology offers the possibility of greatly increasing the speed at which information can be transmitted by wireless communication systems. In particular, by radiating ultra-wideband pulses, it is projected that the information rate of wireless systems should exceed the 100 million bits per second rate quoted above for cable systems.

However, the radiation of ultra-wideband pulses may pose an increased potential for electromagnetic interference. It can be shown that the frequency content of a pulse occupies a wider frequency band as its pulse width is decreased. By way of example, an ultra-wideband pulse whose width is one nanosecond occupies a frequency band that is one million times wider than a radar pulse whose width is one microsecond. Because of this, the frequency content of an ultra-wideband signal is much more likely to overlap the desired frequency bands of nearby receivers. Of particular concern is the potential interference of ultra-wideband signals with the very sensitive GPS receivers mentioned at the beginning of this section.

Advocates of ultra-wideband point out that they are willing to abide by the intentional radiation limits set by the FCC. These are shown in Table 2. Recall that GPS receivers operate within the

1 to 2 GHz band. From Table 2, the radiation limit in the GPS frequency bands is seen to be 500 microvolts/meter. At a distance of 3 meters this translates into a received power that is approximately one billion times larger than the sensitivity level of a GPS receiver. In recognition of this obvious problem the FCC subsequently adopted additional guidelines for five different classes of ultra-wideband devices. Figure 17 shows the limits for the class composed of indoor ultra-wideband systems. The limits are in terms of an antenna that radiates power equally in all directions. This is referred to as equivalent isotropically radiated power (EIRP).

Table 2 FCC International Limits



Subpart C - Intentional Radiators

Section 15.209 Radiated emission limits, general requirements.

(a) Except as provided elsewhere in this Subpart, the emissions from an intentional radiator shall not exceed the field strength levels specified in the following table:

Frequency (MHz)	Field Strength (microvolts/meter)	Measurement Distance (meters)
0.009 - 0.490	2400/F(kHz)	300
0.490 - 1.705	24000/F(kHz)	30
1.705 - 30.0	30	30
30 - 88	100 **	3
88 - 216	150 **	3
216 - 960	200 **	3
Above 960	500	3

** Except as provided in paragraph (g), fundamental emissions from intentional radiators operating under this Section shall not be located in the frequency bands 54-72 MHz, 76-88 MHz, 174-216 MHz or 470-806 MHz. However, operation within these frequency bands is permitted under other sections of this Part, e.g., Sections 15.231 and 15.241.

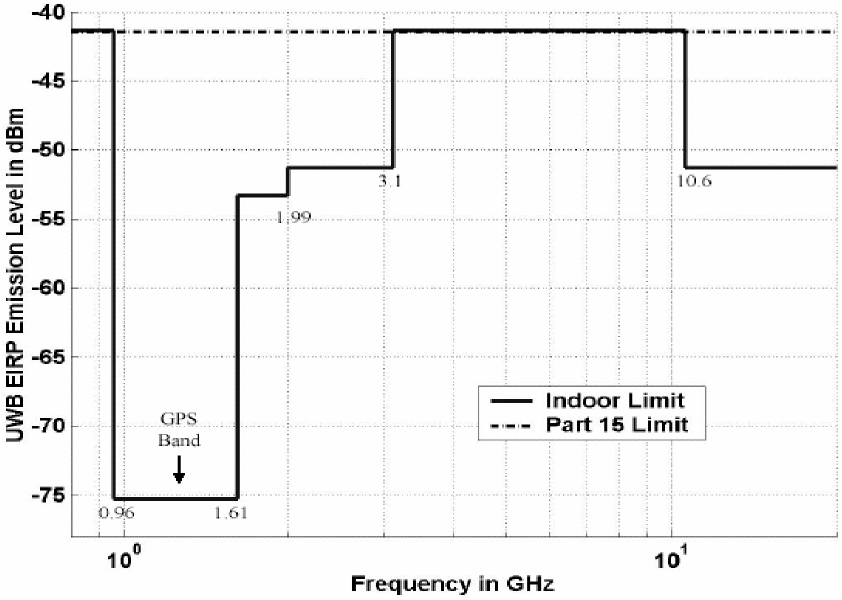


Figure 17 Radiation Limits for Indoor Ultra-wideband Systems

The dotted line in Figure 17 corresponds to the 500 microvolt/meter limit of Table 2. The radiation limit in the GPS band is approximately two thousand times smaller. Nevertheless, this is still about four hundred thousand times larger than the sensitivity of a GPS receiver.

The question arises, “Is the limit shown in Figure 17 for the GPS band small enough to prevent ultra-wideband signals from interfering with GPS receivers?” Part of the answer deals with the amount of degradation experienced by a GPS receiver when subjected to ultra-wideband interference. Figure 18 shows the results of an experiment carried out at Stanford University where an ultra-wideband signal was injected into a GPS receiver along with a GPS signal whose power level was set at the sensitivity level of the receiver.

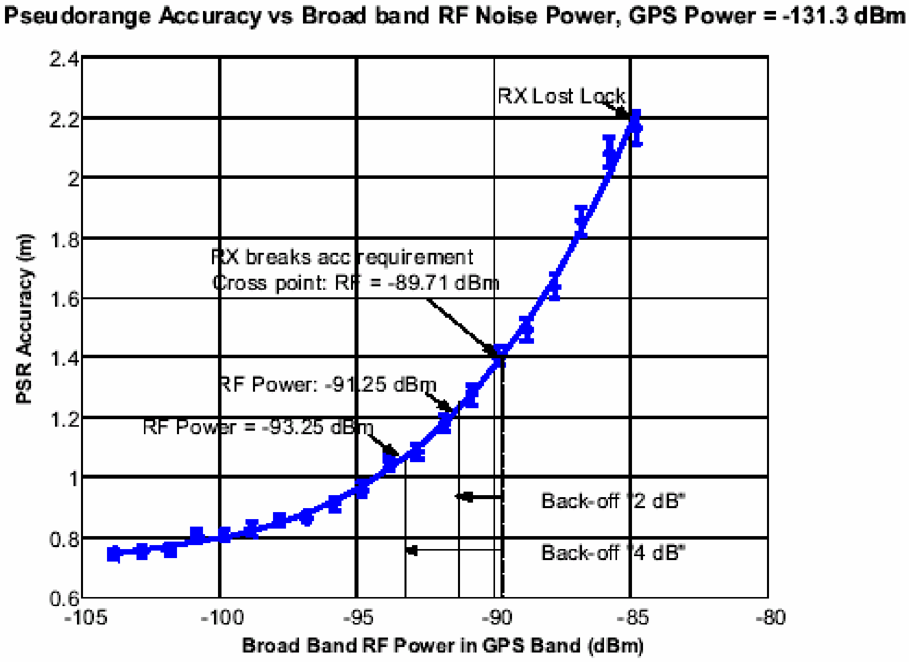


Figure 18 Two Signal Performance Test of a GPS Receiver

The curve of Figure 18 is a plot of the GPS error in position as a function of the ultra-wideband interference power. This error is referred to as pseudo range (PSR) accuracy and is measured in meters. As expected, this error grows as the interference power is made larger. The smallest injected interference power resulted in an error of 0.75 meters. This occurred for a power level which is approximately four thousand times the sensitivity level of the GPS receiver. Hence, the GPS receiver is much more robust to interference than would be predicted by its sensitivity level.

A second consideration one must deal with in evaluation of the limit shown in Figure 17 for the GPS band is the coupling loss, between the ultra-wideband transmitter and the GPS receiver. The limit in Figure 17 is approximately one thousand times larger than the smallest injected interference power of Figure 18 where the error is 0.75 meters. Recall that a radiated signal is attenuated as it propagates through free space. Table 3 tabulates the free space loss at a frequency of 1.58 GHz which is near the middle of the GPS band.

Table 3 Free Space Loss at 1.58 GHz

Separation in Meters	Approximate Free Space Loss 1.58 GHz
0.25 Meters	Approximately 1/250
0.5 Meters	Approximately 1/1,000
1 Meter	Approximately 1/4,000
10 Meters	Approximately 1/500,000

By way of example, the second entry in the table indicates that the power level at the GPS receiver will be attenuated by a factor of approximately 1,000 when it is separated from the ultra-wideband transmitter by a distance of 0.5 meters or equivalently, one an on-half feet. At larger separations, the attenuation is even greater. It is concluded that the two equipments can operate at an acceptable level of degradation provided they are separated by more than one and one-half feet. From the above considerations it appears that the radiation limits of Figure 17 are adequate in the GPS band. However, these conclusions are based on the measurements for the results shown in Figure 18 which did not take into account all of the ultra-wideband signals and GPS receivers likely to be encountered in practice. Additional measurements are required before a conclusive result is reached.

5. Conclusions and Recommendations

The military knows how to build complex systems that are Electromagnetically Compatible. In addition to having specifications similar to the FCC limits, they also perform predictions and analyses to determine whether electromagnetic interference will exist when equipments are placed close together. When interference is encountered, various fixes are possible. For example, filters can be added to transmitters to reduce unintended emissions. They can also be added to receivers to attenuate signals outside the desired frequency band. In addition, carrier frequencies are assigned such that the frequency content of radiated signals does not overlap the desired frequency band of nearby receivers. This is not possible with ultra-wideband signals which do not have carriers. In part II of this report sophisticated methods are discussed that show how the frequency content of ultra-wideband signals can be shaped so that the power within the GPS frequency band is lowered. However, it still remains to learn how low power levels have to be, how far away ultra-wideband transmitters need to be separated from victim receivers (e.g. GPS, cellular telephones, pagers, etc.), and what constraints should be placed on ultra-wideband signal characteristics? These questions can be answered only if all of the components contributing to interference within this complex situation are considered.

In particular, it is necessary to quantify the electromagnetic environment, ultra-wideband emission characteristics, victim receiver susceptibility characteristics, expected coupling loses between equipments, the number of nearby ultra-wideband emitters, and the degree of uncertainty in all of these factors. Figure 18 shows the results of a two signal performance test of a specific GPS receiver with one type of ultra-wideband signal. If another GPS receiver from the same manufacturer was tested, would the same results be obtained? What would be the variability over 30 randomly chosen victim receivers from the same manufacturer? What results would be measured with equipments from 10 different receiver manufacturers? What would happen if the tests were performed by radiating the victim receivers with an ultra-wideband antenna separated by 3 meters in an open office environment rather than by injecting a signal? What would be the impact if five different types of ultra-wideband transmitters were used to interfere with one victim receiver in an open office environment?

The point is that if the interference problem between victim receivers and ultra-wideband transmitters is to be truly understood, the susceptibility of victim receivers from the various manufacturers must be related to the waveform parameters of the different types of ultra-wideband signals. The degree of performance degradation to be permitted or equivalently, the amount of interference to be tolerated must be determined taking into account the many uncertainties associated with the different components of the problem. There is much research and development that needs to be performed in order to achieve this goal.

Research and development needs to be performed to develop simplified testing procedures for measuring the susceptibility of receivers that are either injected or irradiated by various ultra-wideband signals. These procedures must be for signal and two signal susceptibility tests that are performed throughout the frequency band and not just in the unintended frequency ranges, as required in Military Specification 461E. Simple measurement procedures and equipment must be made available for manufacturers of receivers so that they can periodically test their equipment to be assured that they can withstand a defined interference environment with multiple types of ultra-wideband signals present. Research needs to be performed to determine those characteristics of ultra-wideband signals, such as power, pulse shape, pulse width, and time between pulses, for which limits must be set in order to control the effectiveness of these signals in causing interference. This will require that numerous tests be performed on receivers of all manufacturers. This will be a challenge because different manufacturers utilize different algorithms and different implementations. As a result, different receivers may have different susceptibility responses to the same ultra-wideband signals.

6. Technical Study Introduction

Ultra Wide Band (UWB) technology, also referred to as “impulse”, “carrier-free” or “baseband” technology, has been a very popular area of research in recent years [Win98, Mitch01, Win00, Huss02]. Many studies have been conducted to investigate possible benefits of UWB in high throughput, low power, low cost, etc. The design behind this technology is to transmit and receive carrier-free pulses of radio frequency (RF) energy. The pulses are usually in the nanoseconds range. Such signals take only a small fraction of the time domain but are spread over a very large frequency domain. The term “carrier-free” comes from the fact that it is difficult to determine an actual RF center frequency of UWB signals. An important advantage with UWB devices is that their pulses can be used to provide very high data rate performance in multi-user network applications. UWB technology has numerous potential applications such as indoor/office communications, data communications in local area network (LAN) environments, remote monitoring, collision avoidance radar, geolocation, tagging/identification, etc.

One major disadvantage with UWB technology is its potential incompatibility with other devices currently using the radio spectrum. Current Federal Communications Commission (FCC) regulations for intentional radiators can be found in Part 15.209 Subpart C [FCC01]. There has been significant research recently as to how and to what extent UWB waveforms impact other narrowband systems [Telc03, Hama02, Foer02, Swam01]. The impact UWB systems have on Global Positioning System (GPS) receivers has been addressed analytically and in measurements [Stan00, Stan01, NTIA01, UT00, JHU01]. It was shown that parameters such as pulse repetition frequency, the center frequency of the narrowband system, the type of UWB modulation and the structure of the narrowband receiver play significant roles in evaluating the impact UWB has on the performance of a narrowband system.

7. Problem Formulation

Ultra Wideband (UWB) is rapidly emerging as an important technology to provide high performance communications. Similar to the code division multiple access (CDMA), the UWB signal is spread in the frequency domain. However, unlike traditional wireless communication techniques, UWB employs very short pulses (in nanoseconds range) instead of continuous wave transmissions. The result is an ultra wide band, low average power spectral density signal in the frequency domain. The bandwidth of a UWB signal is nominally 25% of the “carrier” or center frequency. Thus, the UWB technology has a tremendous advantage in the relative processing gain. The ideal scenario is to have a wide range and number of UWB systems and users that co-exist with existing systems operating in the same frequency band. For this reason UWB can offer substantial advantages over traditional technologies. Potential advantages over other technologies include low interference, co-existence with existing systems in the same frequency band, increased frequency reuse and capacity, increased robustness to multipath fading, as well as relatively simple low power designs.

A UWB signal is, generally speaking, a sequence of narrow pulses. Pulse widths are usually between 0.2ns and 10ns. The pulses can be modulated and processed in many different ways. This Section provides a description of basic modulation techniques such as on-off keying (OOK), binary pulse shift keying (BPSK), pulse-position modulation (PPM), and some more advanced modulation techniques, such as, direct sequence spread spectrum (DSSS), and time hopping (TH). We also address processing techniques such as gating and dithering.

7.1 General UWB signal model

The UWB signal is a sequence of very short pulses. Let us assume that the basic pulse waveform is $s(t)$. Then the UWB signal can be expressed as:

$$p(t) = \sum_{k=-\infty}^{\infty} a_k s(t - T_k) \tag{1}$$

where T_k is the transmit time and a_k is the amplitude modulation of the k th pulse.

Sequences $\{a_k\}$ and $\{T_k\}$ are random in general and depend on the modulation scheme and type of processing. In this Section we present some examples of UWB signals. More detailed analysis of UWB signals and their spectral characteristics can be found in [Telc03]. Some of the results from [Telc03] are used when we address the problem of interference mitigation.

7.2 Typical UWB signals

UWB pulse waveforms

One of the most commonly used and analyzed UWB pulse waveform $s(t)$ is the first derivative of the Gaussian pulse, Gaussian monocycle, given as:

$$s(t) = 6 s_{\max} \sqrt{\frac{e\pi}{3}} \frac{t}{\tau} e^{-6\pi\left(\frac{t}{\tau}\right)^2} \tag{2}$$

This waveform is shown in Figure 19.

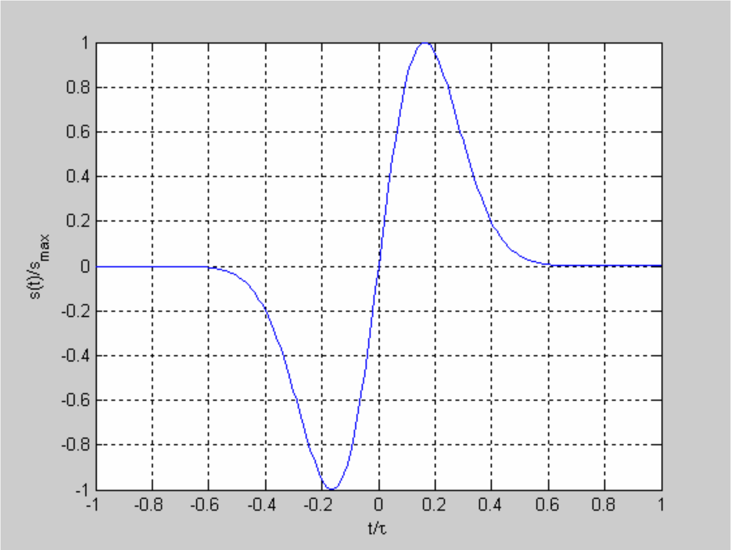


Figure 19 Gaussian monocycle

The Fourier transform of the Gaussian monocycle equals:

$$S(f) = -j\frac{s_{\max} f\tau^2}{3}\sqrt{\frac{e\pi}{2}}e^{-\frac{\pi}{6}f^2\tau^2} \tag{3}$$

As an illustration of how the UWB spectrum spreads over the entire frequency domain let us consider the Gaussian monocycle for a typical value $\tau = 0.5$ ns (note that for this value the x-axis on the previous figure would be 1 ns wide). The corresponding normalized energy spectral density (ESD), $\frac{|S(f)|^2}{|S(f)|^2_{\max}}$, is shown in 20.

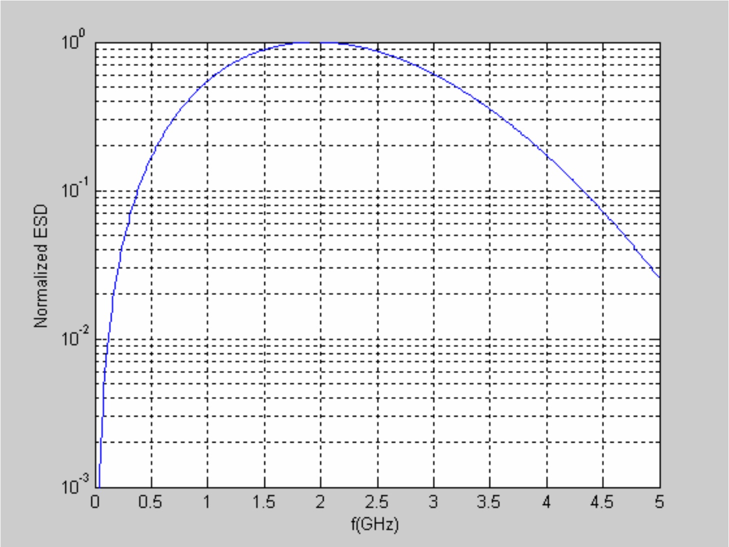


Figure 20 Normalized energy spectral density of the Gaussian monocycle

The selection of UWB waveforms has been addressed in [Hama02, Ghav01, Mich02, Parr03, Corra02]. As it will be shown, the pulse waveform directly determines the continuous part of the UWB spectra and proper shaping of the signal can reduce the UWB interference. At this point we will just mention that other analyzed waveforms include basic Gaussian pulses, Gaussian doublets and Hermite polynomial based pulses [Hama02, Corra02, Ghav01].

Basic UWB modulation schemes

Probably the simplest way of modulating the UWB pulses is an *on-off keying* (OOK) modulation. The pulses are uniformly spaced with $T_k = kT$, $k = 1,2,\ldots$, and $a_k \in \{0,1\}$. Figure 21 shows the typical OOK pulse stream (without dithering and with Gaussian monocycle pulses). Although very simple, this modulation scheme is common in UWB systems and was widely used in measurements that will be presented.

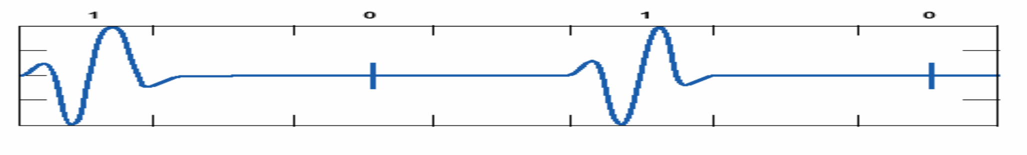


Figure 21 OOK pulse stream

For the case of *binary phase shift keying* (BPSK) modulated pulse stream with uniformly spaced pulses ($T_k = kT$, $k = 1,2,\ldots$) we have that $a_k \in \{-1,1\}$. The BPSK pulse stream is shown in Figure 22.

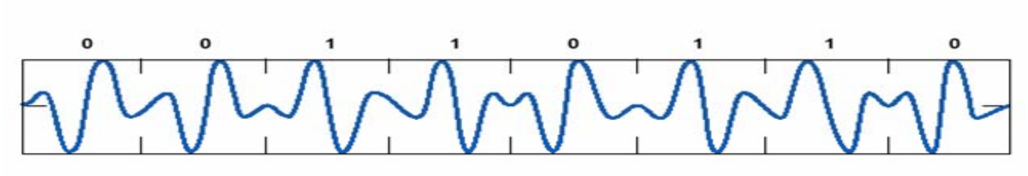


Figure 22 BPSK pulse stream

BPSK modulated UWB signals are very common and possess certain advantages over OOK modulation (see the next section).

For the *pulse amplitude modulated* (PAM) signals, the amplitude of the pulses takes one of the values from the finite set depending on the information carried as shown on the following figure.

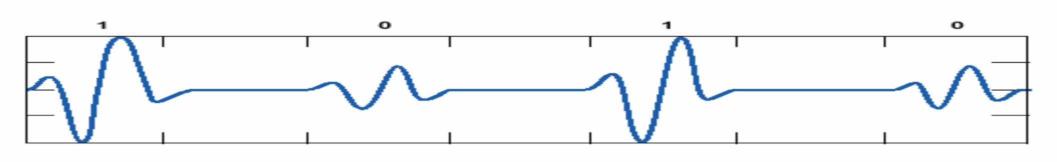


Figure 23 PAM pulse stream

Modulation schemes mentioned so far have assumed uniform spacing between the pulses, that is, $T_k = kT$, $k = 1,2,\ldots$ For the family of modulation schemes called *pulse position modulation* (PPM) we have that $T_k = kT + \Delta_k$, where Δ_k depends on the information bearing signals. Thus, in PPM the information is conveyed by shifting the pulse starting time as illustrated in the Figure 24.

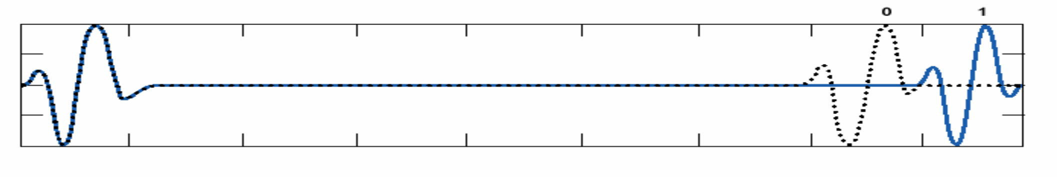


Figure 24 PPM modulation

All above mentioned modulation schemes assume a single access communications system. To allow multi access (MA) communications, a more advanced modulation scheme is required, in addition to the one of the basic schemes described. Some of them include time hopping (TH), direct-sequence (DS) spread spectrum and multi-carrier approaches. For example, UWB system for data communications, impulse radio, employs TH with pulse position modulation (TH-PPM).

The analysis and experimental measurements related to the UWB interference and mitigation techniques that follow consider only the basic modulation schemes and will not address multi access communications issues. However, for completeness, we will briefly describe TH and DS modulations since they are very popular in modern UWB systems. In both the TH and DS systems, one transmitted data bit is spread over multiple pulses in order to achieve a processing gain and enable user separation at the receiver. Let us denote with N the processing gain and with $\{c_j\},\ j = 1,2,...,N$ the spreading code sequence (pseudorandom (PR) code unique for each user). Then the basic UWB signal model from Eq. (1) becomes [Hama02]:

$$p(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N} a_k s\left(t - T_k - jT_f - c_j T_c\right) \tag{4}$$

for a TH signal, and

$$p(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N} a_k s\left(t - T_k - jT_c\right) c_j \tag{5}$$

for a DS signal, where T_c is the chip duration and T_f is the pulse repetition interval.

Note that for the case of no dithering and no PPM, we have $T_k = kNT_f$ for a TH-UWB signal and $T_k = kNT_c$ for a DS-UWB signal.

TH and DS modulations for the case of bipolar code sequences and data are illustrated in the following Figure [Hama02]:

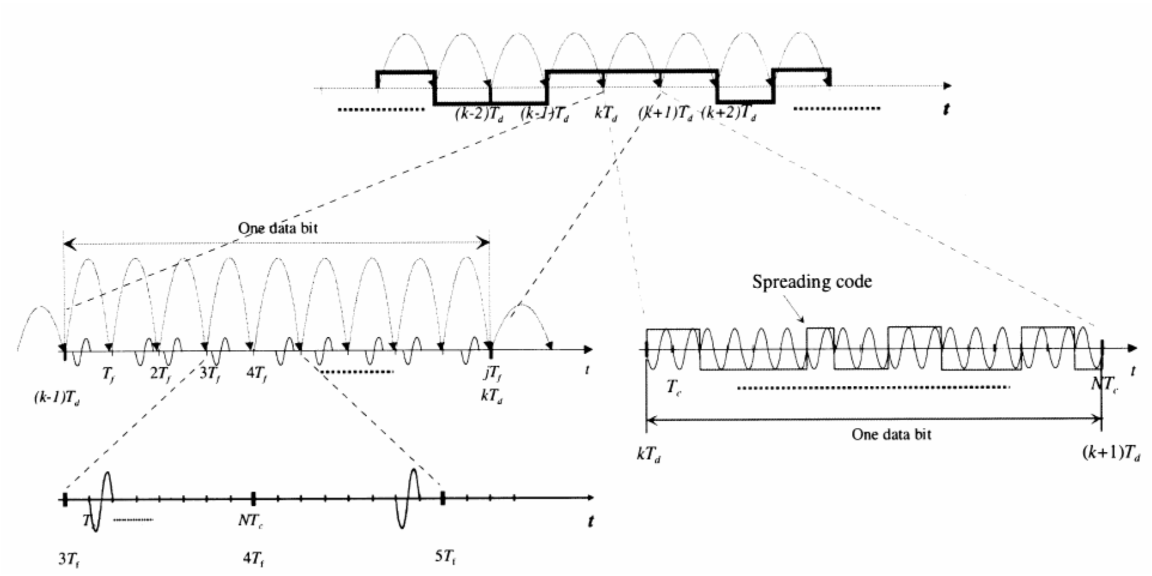


Figure 25 Formation of TH and DS signals (from [Hama02])

In order to improve the characteristics of the UWB signals, two techniques are commonly applied, gating and dithering.

Gating is a higher-level modulation of the UWB output in which the transmitter is quiet during intervals that are long compared to the pulse repetition interval. Thus, when gating is applied the UWB pulses appear in bursts. The goal of gating is to achieve desired spectral characteristics at the expense of a lower effective data rate.

Dithering is random or pseudo-random spacing of the pulses. Two forms of dithered UWB signals were considered in this effort. In the case of *absolute referenced dithered* (ARD) signals, the pulse period is varied in relation to the absolute clock. In the case of *relative referenced dithered* (RRD) signals, the pulse spacing is varied relative to the previous pulse. Dithering of the pulses in the time domain makes the signal appears more noise-like, a property that will be exploited for interference mitigation. Dithering can be mathematically modeled through the sequence $\{T_k\}$ used in the basic UWB signal model (see Eq.(1)). In its most general form we have:

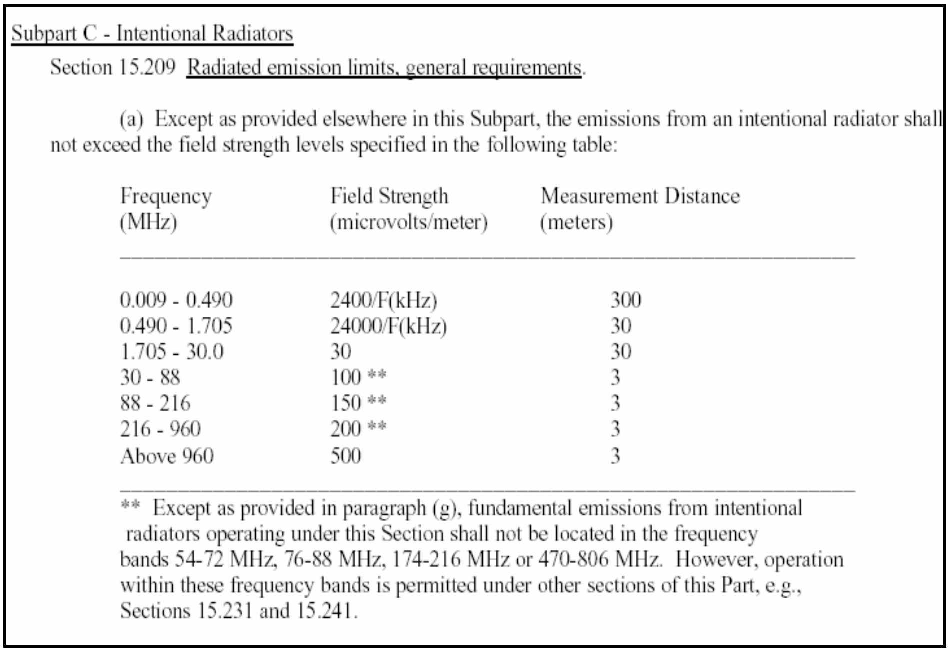
$$T_k = kT + \Delta_k + \delta_k \qquad (6)$$

where the sequence $\{\Delta_k\}$ describes PPM (if applicable) and the sequence $\{\delta_k\}$ describes dithering (if applicable).

Throughout this section, the time-domain representation of the various UWB signals is used. But in addressing the UWB interference, the frequency domain characteristics will be of more interest. Some frequency domain characteristics are directly related to the time domain parameters of the signals and ultimately the impact the UWB signal has on the narrowband receivers will depend on the time-domain characteristics of the UWB signals. For example, the pulse width determines the overall shape of the emission spectrum. If dithering is applied, there will be a smooth component of the emission spectrum in addition to line components. These and other phenomena are described in more detail in the next Section.

7.3 Potential interference and current FCC regulations

One major disadvantage in implementing the UWB technology is its incompatibility with other devices currently using the radio spectrum. In particular, due to its very wide bandwidth, the UWB spectrum overlaps with various narrowband systems. U.S. Federal Communications Commission (FCC) defined UWB emission limits as shown in the following table [FCC01]:



Subpart C - Intentional Radiators

Section 15.209 Radiated emission limits, general requirements.

(a) Except as provided elsewhere in this Subpart, the emissions from an intentional radiator shall not exceed the field strength levels specified in the following table:

Frequency (MHz)	Field Strength (microvolts/meter)	Measurement Distance (meters)
0.009 - 0.490	2400/F(kHz)	300
0.490 - 1.705	24000/F(kHz)	30
1.705 - 30.0	30	30
30 - 88	100 **	3
88 - 216	150 **	3
216 - 960	200 **	3
Above 960	500	3

** Except as provided in paragraph (g), fundamental emissions from intentional radiators operating under this Section shall not be located in the frequency bands 54-72 MHz, 76-88 MHz, 174-216 MHz or 470-806 MHz. However, operation within these frequency bands is permitted under other sections of this Part, e.g., Sections 15.231 and 15.241.

Table 3 FCC's emission limits

The FCC limit in the GPS band that interests us most is 500 μV/m measured at a 3 meter distance. Therefore, the average power at the UWB source measure cannot exceed the following, as measured in a 1 MHz bandwidth:

$$P = 4\pi \frac{\left(500\,\frac{\mu V}{m}\right)^2}{377\Omega}\left(3m\right)^2 = 75nW \qquad (7)$$

In other words, the equivalent isotropically radiated power (EIRP) should not exceed - 41.3 dBm/MHz. In order to ensure protection for very sensitive systems, such as GPS and federal aviation systems, FCC adopted additional emission guidelines [FCCrev], [FCC03]. In particular, several classes of UWB devices based on application and operating conditions (ground penetrating radars and wall imaging systems, through-wall imaging systems, surveillance systems, medical imaging systems, vehicular radar systems, indoor UWB systems, hand-held UWB systems) were considered and assigned different limits. For example, the EIRP restrictions (average limits when measured using a resolution bandwidth of 1 MHz) for indoor UWB systems are shown in Figure 26.

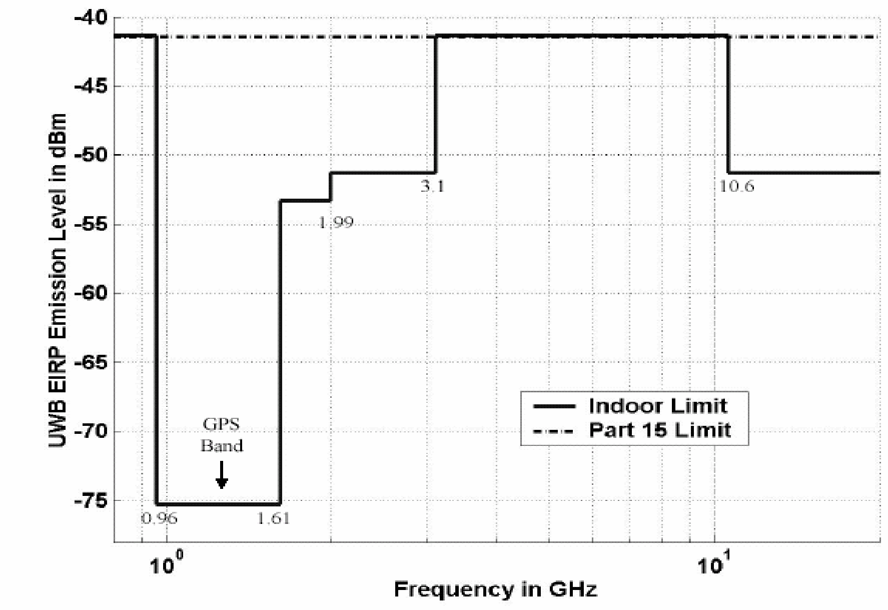


Figure 26 EIRP limits for indoor UWB systems

The EIRP limit in the GPS band for this group of UWB devices is -75.3 dBm/MHz. The UWB emission limit for outdoor hand-held devices in the GPS band is the same.

8. UWB Interference

The frequency domain characteristics of the UWB signals best describe the level and type of the interference UWB causes to the narrowband systems. The reason for this is simple: the distribution of power over the bandwidth gives us direct information of the strength of the UWB signal in the band of interest. The spectral characteristics, on the other hand, are directly related to the pulse waveforms selected and how the pulses are modulated in amplitude and time, characteristics that are described in the previous Section. In this Section we follow the analytical approach in [Telc03] and use the power spectral density (PSD) of the UWB signals to analyze the UWB interference. PSD is usually defined as the Fourier Transform of the autocorrelation of a wide-sense stationary process, the UWB signal in our case. PSD calculations for various UWB signals have been performed in detail in [Telc03], [Win02]. The PSD calculations and expressions for some classes of UWB signals are very complicated. Such signals include amplitude modulated signals, signals with the pulse repetition frequency (PRF) modulation and signals with pulse repetition per information symbol (for example, TH and DS signals). We will use only the major results that apply to the following UWB signal model:

$$p(t) = \sum_{k=-\infty}^{\infty} a_k s(t - kT - \Delta_k - \delta_k) \tag{8}$$

where we assume that sequence the $\{\Delta_k\}$ describes PPM and the sequence $\{\delta_k\}$ describes dithering.

In general, the PSD of the UWB signal consists of two components: continuous and discrete. For the generalized signal model from Eq. (8) they are given as [Telc03]:

$$P_c(f) = R|S(f)|^2 \left(E\{|a_n|^2\} - |\mu_a|^2 |\mu_b(f)|^2\right) \tag{9}$$

$$P_d(f) = R^2 |S(f)|^2 |\mu_a|^2 |\mu_b(f)|^2 \sum_{k=-\infty}^{\infty} \delta(f - kR) \tag{10}$$

where $R = \frac{1}{T}$ is the average PRF, $\mu_a = E\{a_n\}$, $\mu_b(f) = E\{e^{j2\pi(\Delta_n + \delta_n)}\}$ and $E\{\cdot\}$ denotes mathematical expectation.

The last two expressions give us a very good insight into how the UWB signal characteristics influence the in-band interference and can serve as the guideline of how to limit the interference. In particular, the in-band interference can simply be calculated as:

$$I_{f_l, f_u} = \int_{f_l}^{f_u} \left(P_c(f) + P_d(f)\right) df = I^c_{f_l, f_u} + I^d_{f_l, f_u} \tag{11}$$

where f_l and f_u are the lower and upper frequency, respectively, of the narrowband system of interest.

UWB signal generator parameters can be carefully shaped to achieve desired spectral characteristics. The discussion that follows addresses some key UWB signal parameters and how they are treated in the literature. Most of the references mentioned in this section, especially the ones that include measurement results, consider UWB interfering with a GPS receiver. However, in most cases the findings can be easily extended to any narrowband receiver that needs to be protected against a UWB interfering source.

Pulse repetition frequency

According to Eqns. (9-10) the pulse repetition frequency plays a major role in determining the UWB in-band interference. The continuous PSD is proportional to the pulse rate R, while the power of each discrete spectral component is proportional to R^2. It can be concluded that in order to reduce the UWB interference to narrowband receivers, one simple approach would be to reduce the PRF. However, this limits the UWB system throughput and cannot always be achieved in practice. A number of studies have been performed to measure the sensitivity of narrowband receivers (e.g. GPS receivers) as a function of PRF of the UWB interfering signal [Stan01, NTIA01, UT00]. The relevant analysis can be found in [Swam01, Foer02, Telc03, Stan00, Stan01, NTIA01, JHU01].

Center frequency and bandwidth of the narrowband system

The level of the UWB interference also depends upon the center frequency and bandwidth of the narrowband system of interest. This dependence is twofold. First, the continuous component $I^c{}_{f_l,f_u}$ will depend on how the center frequency and bandwidth are related to the pulse waveform Fourier Transform $S(f)$. For example, for the pulse waveform shown in Figure 19, the interference energy will be the greatest for the narrowband system centered around 2 GHz. Second, the discrete component $I^d{}_{f_l,f_u}$ will depend on the number of discrete components that fall into the bandwidth of interest, which in turn will depend on f_l, f_u and R. The effects the center frequency and receiver bandwidth have on the interference were measured in [Stan01, NTIA01, UT00]. Directly related analysis can be found in [Stan00, Stan01, NTIA01, JHU01], while works in [Foer02, Hama02] also have some relevant analysis.

Type of UWB modulation

The type of the UWB modulation selected also plays an important role in determining the interference level. It will influence some of the parameters in Eqns. (9-10). For example, the kind of PPM selected will determine the sequence $\{\Delta_k\}$ and consequently the term, $\mu_b(f)$. The selection of the sequence $\{a_k\}$ will determine μ_a. For example, in the case of BPSK modulated signals with equal probability of one and zero bits, we have $\mu_a = 0$. This property has been exploited to cancel the discrete PSD component (see the next Section). The effects of various UWB modulation schemes on the interference were measured and analyzed in [Stan00, Stan01, NTIA01, JHU01]. Some relevant analysis can also be found in [Telc03, Swam01, Foer02, Hama02 , Mo03].

Type of UWB signal processing

The additional UWB signal processing such as gating and dithering techniques mentioned in the previous section also influences the level of interference. For example, the type of dithering applied will determine the sequence $\{\delta_k\}$ and, consequently, the term, $\mu_b(f)$. Dithering has been shown to be an effective tool in reducing the discrete component of the UWB spectra as is described in the next section. The effects of dithering on GPS receivers have been measured and analyzed in [Stan00, Stan01, NTIA01, JHU01,]. The analysis in [Swam01, Foer02, Hama02, Telc03] could also be used to assess this processing technique.

UWB pulse waveform

As can be seen from Eqns. (9-10), the level of the UWB interference depends on the UWB pulse waveform since the term $S(f)$ is defined by the type of UWB pulses selected for transmission. Some popular waveforms and how their selection influences the interference are described in the next section. The relevant analysis can be found in [Hama02, Ghav01, Mich02, Parr03, Corra02].

Factors other than the parameters listed above can influence the affect UWB devices have on the performance of narrowband receivers. Although they are not related to the PSD parameters of the UWB signals, we mention them for completeness.

Type of the narrowband receiver

The type of the narrowband receiver and its detection process play an important role in determining how sensitive the system is to the UWB interference. Sensitivity of coherent versus non-coherent receivers, FSK versus PSK narrowband systems and performance of C/A versus P(Y) code GPS receivers are just a few comparisons among many that are under investigation. In this study we concentrate mostly on general interference mitigation approaches that are not related to any particular receiver. Measurement results mentioned throughout the report deal with various types of GPS receivers. Some comparison measurement results can be found in [Stan01, NTIA01]. In [Telc03] several digital and analog type receivers were used for UWB interference analysis.

Deployment of UWB devices

Deployment of UWB devices, that is, their number and locations in space also should be considered in evaluating the level of interference that the narrowband receiver of interest is exposed to. Only a very limited number of references take this factor into consideration. Some simulation results can be found in [WP–GIANT].

9. Mitigation of UWB Interference

The efforts to mitigate a UWB interference could be roughly classified into two groups, i.e. mitigating discrete UWB spectral components and broadband spectrum energy. Most of the techniques that will be mentioned do not overlap and can be combined.

9.1 Reduction of the discrete UWB spectral components

The first group of interference mitigation techniques reduces the discrete spectrum components of a UWB signal, which is directly related to the pulse repetition frequency (PRF). PRF has been identified in measurements and analysis as an important parameter in determining the UWB to GPS interference level. It has been widely demonstrated that it is important not only to avoid having discrete UWB spectral components in certain locations (GPS L1 and L2 frequencies, for example) but generally to decrease the discrete portions of a UWB spectrum. Several approaches have been proposed in the literature to accomplish these goals:

- Bipolar signaling ("BPSK")

This approach uses the fact that the discrete component of the UWB spectrum can be (theoretically) completely eliminated if we assure that the UWB pulses employ binary phase shift keying and that there is an equal number of "positive" and "negative" pulses. Let us assume a BPSK modulated transmission with no dithering ($\delta_k = 0, k = 1,2,...$) and no pulse position modulation ($\Delta_k = 0, k = 1,2,...$). Let us also assume that $a_k \in \{-1,1\}$ with:

$$\Pr\{a_k\} = \begin{cases} p & a_k = 1 \\ 1-p & a_k = -1 \end{cases} \tag{12}$$

Then we have $\mu_b(f) = 1$, $\mu_a = 2p-1$, $E\{|a_n|^2\} = 1$, and the PSD expressions in Eqns. (9-10) become:

$$P_c(f) = R|S(f)|^2\left[1-(2p-1)^2\right] \tag{13}$$

$$P_d(f) = R^2 |S(f)|^2 (2p-1)^2 \sum_{k=-\infty}^{\infty} \delta(f - kR) \tag{14}$$

Figure 27 shows the total PSD (theoretical curves) for different values of probability p and a given R ($R = 200MHz$ was selected) and given pulse waveform (Gaussian monocycle with $\tau = 0.5$ ns was selected – see Figure 20 and Eq. (3)).

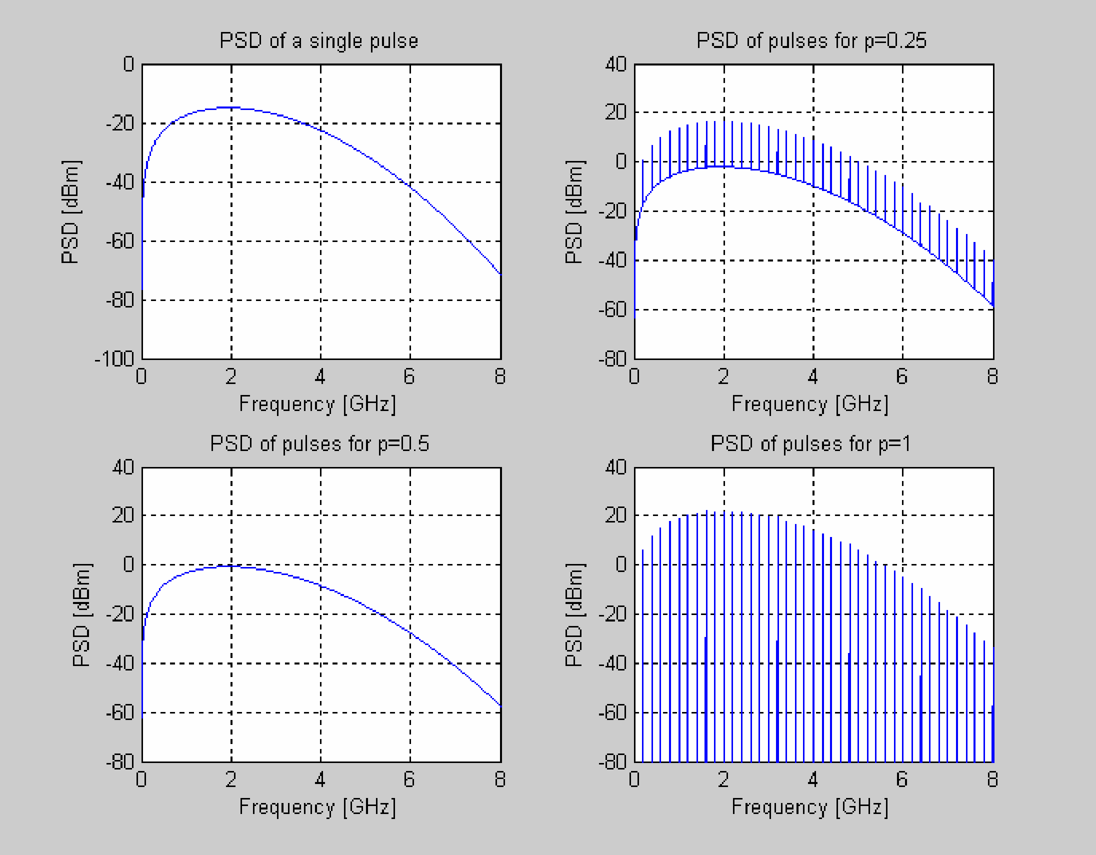


Figure 27 PSD for different p

It becomes obvious from Eqns. (13-14) and from Figure 27, that $P_d(f) = 0$ for $p = 0.5$, while $P_c(f) = 0$ for $p = 0$ or $p = 1$. Thus, for $p = 0.5$ the UWB spectrum is continuous, widely distributed with a low peak value ($PSD_{\max} = 0$ dBm in our example). On the other hand, for $p = 1$ the UWB spectrum is distributed over discrete frequencies separated by R and has a high peak value ($PSD_{\max} = 22$ dBm in our example). Consequently, one way to avoid high peak value in the PSD and mitigate the resulting interference is to ensure that $p = 0.5$ during the UWB transmission. In [Mo03] three different schemes (phase reversion, linear phase shift registers or phase reversion on synchronization (SYNC) bits) have been proposed to achieve this goal. We will briefly comment on the phase reversion approach. Let us assume that another random sequence $b_k \in \{-1,1\}$ is generated at the transmitter such that:

$$\Pr\{b_k\} = \begin{cases} 0.5 & b_k = 1 \\ 0.5 & b_k = -1 \end{cases} \tag{15}$$

Then it can easily be shown that for the sequence $\{c_k\}$ formed as:

$$c_k = a_k \otimes b_k \qquad , \ k = 1,2,... \tag{16}$$

where "$\otimes$" denotes XOR operator, it holds:

$$\Pr\{c_k\} = \begin{cases} 0.5 & c_k = 1 \\ 0.5 & c_k = -1 \end{cases} \tag{17}$$

Thus, instead of transmitting the information bearing sequence $\{a_k\}$, the sequence $\{c_k\}$ is transmitted, which guarantees that the discrete UWB PSD will be eliminated. On the other hand, this should improve the performance of the narrowband receivers that operate in the proximity of the UWB devices, especially ones that are sensitive to interfering spectral lines such as GPS receivers.

The proposed approach for interference mitigation is time-domain based and relatively easy to implement. However, synchronization and "descrambling" at the receiver would be required.

The analysis shown above has been tested in measurements. The US Air Force's Sensors Directorate is performing extensive measurements in order to compare the GPS receiver performance for different values of probability p.

- *Dithering*

Dithering is an approach to introduce randomness in the transmitted signal. The goal is the same as in the previously described approach: to reduce discrete UWB spectral components. This time we achieve this goal by pseudo randomly changing the position of the UWB pulses in the UWB pulse stream. Two types of dithering are possible: absolute referenced dithering (ARD), and relative referenced dithering (RRD). ARD produces pulses that are dithered in relation to the clock tick, while RRD dithers each pulse in relation to the previous pulse position.

Let us again consider the UWB PSD equations and assume the PPM modulated transmission with $\Delta_k \in \{\pm \Delta\}$ and the time hopping code to implement dithering with

$\delta_k \in \{0, \varepsilon, 2\varepsilon, \ldots (M-1)\varepsilon\}$ (code-controlled pulse dithering). With all pulse positions assumed equally likely and $a_k = 1$, the PSD expressions become [Telc03]:

$$P_c(f) = R|S(f)|^2 \left[1 - \left[\cos(2\pi f \Delta) \frac{\sin(\pi f M \varepsilon)}{M \sin(\pi f \varepsilon)} \right]^2 \right] \tag{18}$$

$$P_d(f) = R^2 |S(f)|^2 \cos(2\pi f \Delta) \frac{\sin(\pi f M \varepsilon)}{M \sin(\pi f \varepsilon)} \sum_{k=-\infty}^{\infty} \delta(f - kR) \tag{19}$$

Figure 28 shows the total PSD for different values of ε and M, with no PPM ($\Delta = 0$) and given R ($R = 10$ MHz was selected) and pulse waveform (Gaussian monocycle with $\tau = 0.5$ ns was selected).

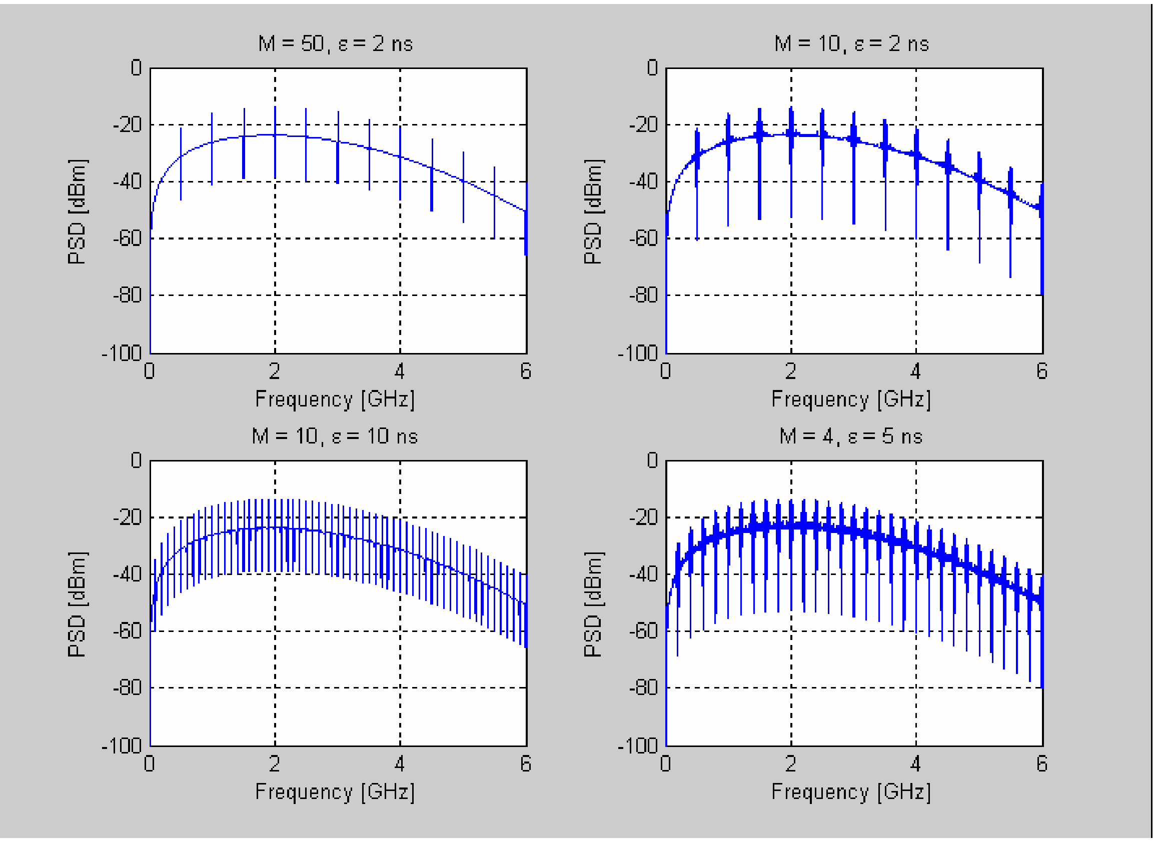


Figure 28 PSD of dithered signals with no PPM

As it can be seen in Figure 28, the occurrence of the main spectral lines is determined by the parameter ε, rather than R. In particular, spectral lines are $\frac{1}{\varepsilon}$ [Hz] apart. The corresponding close-ups are shown in Figure 29.

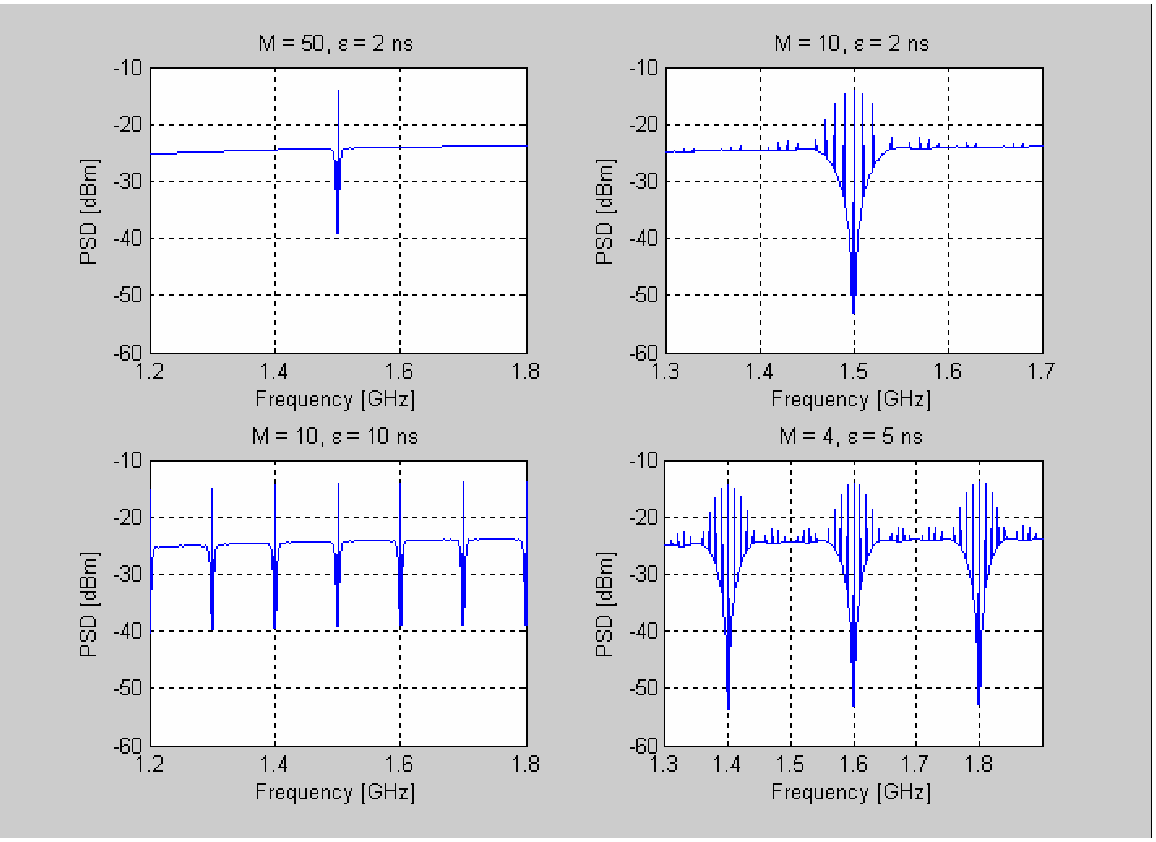


Figure 29 PSD of dithered signals with no PPM (close up)

Let us now assume that PPM is applied. In this case the term $\cos(2\pi f\Delta)$ will influence both the continuous and discrete PSD components. Figure 30 shows PSD results for $\Delta = 0.2\,\text{ns}$ and several different combinations for M and ε.

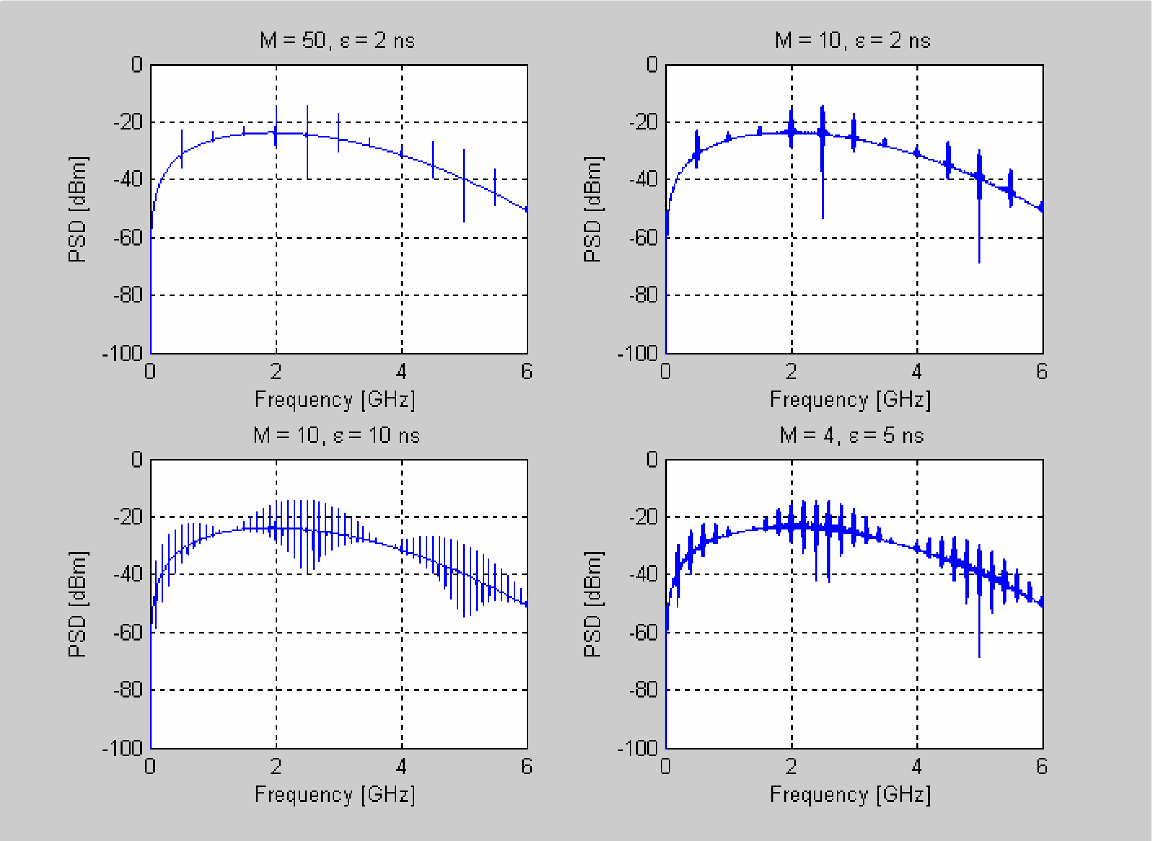


Figure 30 PSD of dithered signals with PPM

This idea has been tested and verified in measurements. Figures 31 and 32 are borrowed from [Stan01] and show a typical UWB spectrum with and without dithering (no modulation was assumed). They demonstrate that dithering is a very effective way to suppress the discrete spectral components.

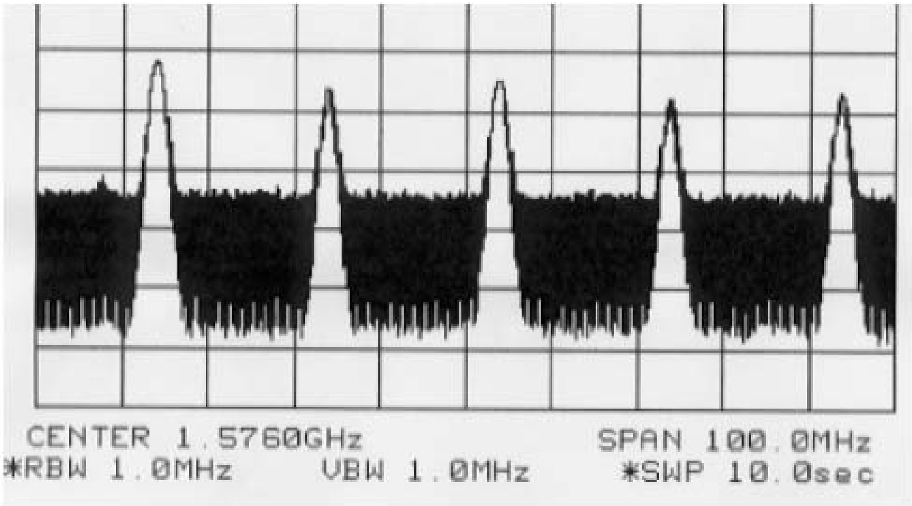


Figure 31 UWB spectrum with no modulation and no dithering

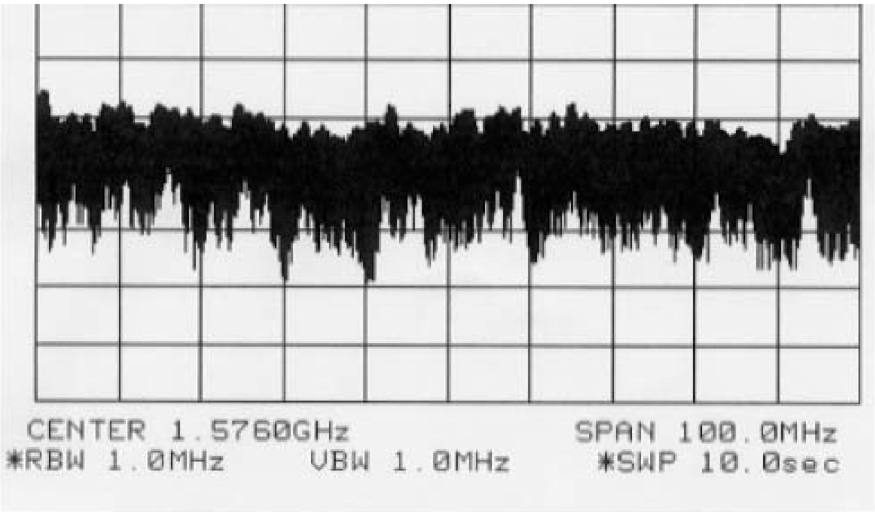


Figure 32 UWB spectrum with no modulation and dithering

Extensive measurements performed in [Stan01] and especially in [NTIA01] have shown that the quality of the GPS reception improves compared to the case with no dithering. As an illustration we will borrow one of the graphs presented in [NTIA01] that shows minimal UWB signal power needed to cause a GPS receiver to lose lock. The results are shown in Figure 33 for one given GPS receiver and several different UWB signals.

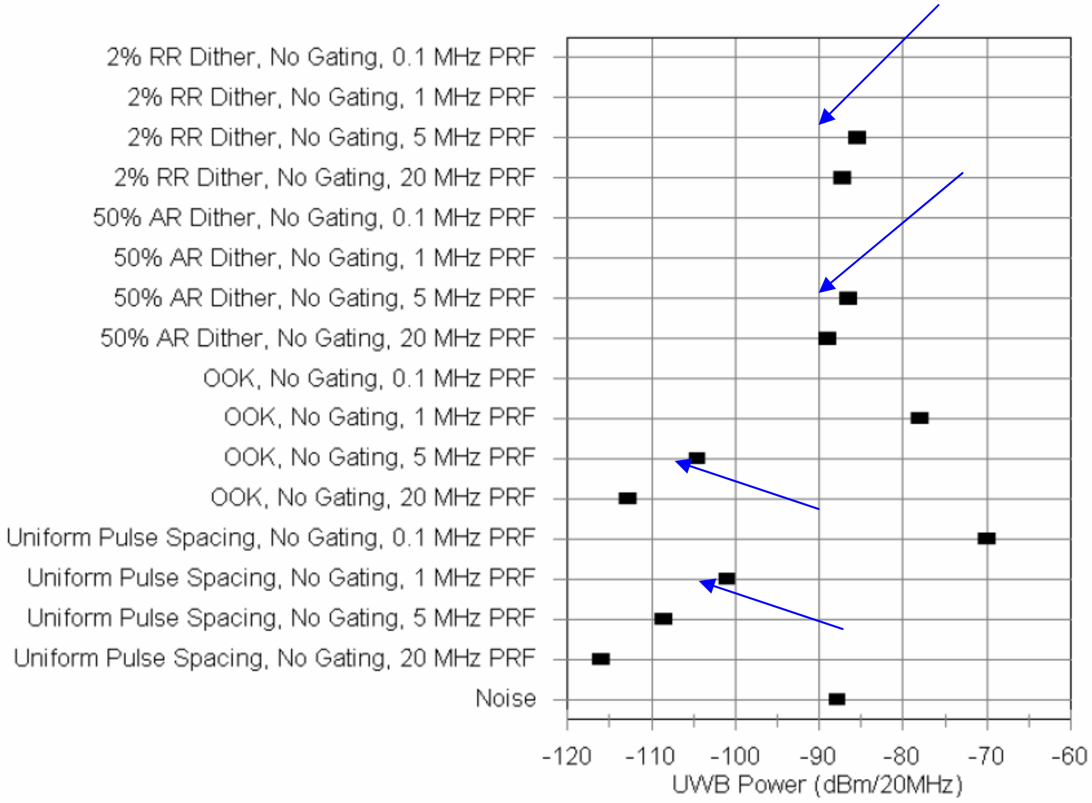


Figure 33 UWB signal power at the GPS break lock point (from [NTIA01])

By introducing dithering the GPS receiver becomes much more robust to the UWB interference. Let us consider four highlighted points that correspond to the 5MHz PRF. Two signals with dithering (2% relative referenced dithering and 50% absolute referenced dithering) require a much stronger UWB signal (between -80 and -90 dBm/20MHz) to break lock at the GPS receiver as compared to the signals with no dithering (OOK and Uniform Pulse Spacing signal).

More results and descriptions of how the experiments were performed can be found in [NTIA01]. Some additional analysis on how the proposed scheme changes the bit error rate (BER) at the generic receiver can be found in [Foer02]. An analysis in [Swam01] can also be applied.

Dithering is a time-domain based approach and is relatively easy to implement, but requires precise synchronization at the receiver.

9.2 Reduction of the UWB pulse energy

The second group of papers concentrates on reducing the UWB pulse energy in the band of interest. By choosing the UWB waveform parameters appropriately, it is generally possible to reduce the main pulse energy inside the narrowband of interest.

Some popular waveforms (Gaussian pulse and its derivatives) were analyzed in the literature [Hama02, Corra02]. The level of UWB to GPS interference as a function of pulse width and pulse shape for two different UWB modulations schemes was illustrated in [Hama02]. In [Corra02] some standard filtering techniques are exploited for shaping the UWB spectrum. A family of orthogonal pulses based on the Hermite polynomials has also been recently proposed in [Ghav01, Mich02]. Spatial techniques that eliminate the energy of the narrow pulse are considered in [Hells00]. The following describes the families of Gaussian pulses and modified Hermite polynomial based pulses.

The Gaussian pulse and its derivatives are currently the most popular waveforms in UWB systems. Let us recall the expression for the Gaussian monocycle $s_1(t)$ (index here denotes the order of the derivative):

$$s_1(t) = 6s_{\max}\sqrt{\frac{e\pi}{3}}\,\frac{t}{\tau}\,e^{-6\pi\left(\frac{t}{\tau}\right)^2} \tag{20}$$

The family of Gaussian pulses is given as:

$$s_{n+1}(t) = \frac{d^n}{dt^n}\left[6s_{\max}\sqrt{\frac{e\pi}{3}}\,\frac{t}{\tau}\,e^{-6\pi\left(\frac{t}{\tau}\right)^2}\right] \tag{21}$$

The corresponding normalized ESD for $\tau = 0.5\,\text{ns}$ are shown in Figure 34.

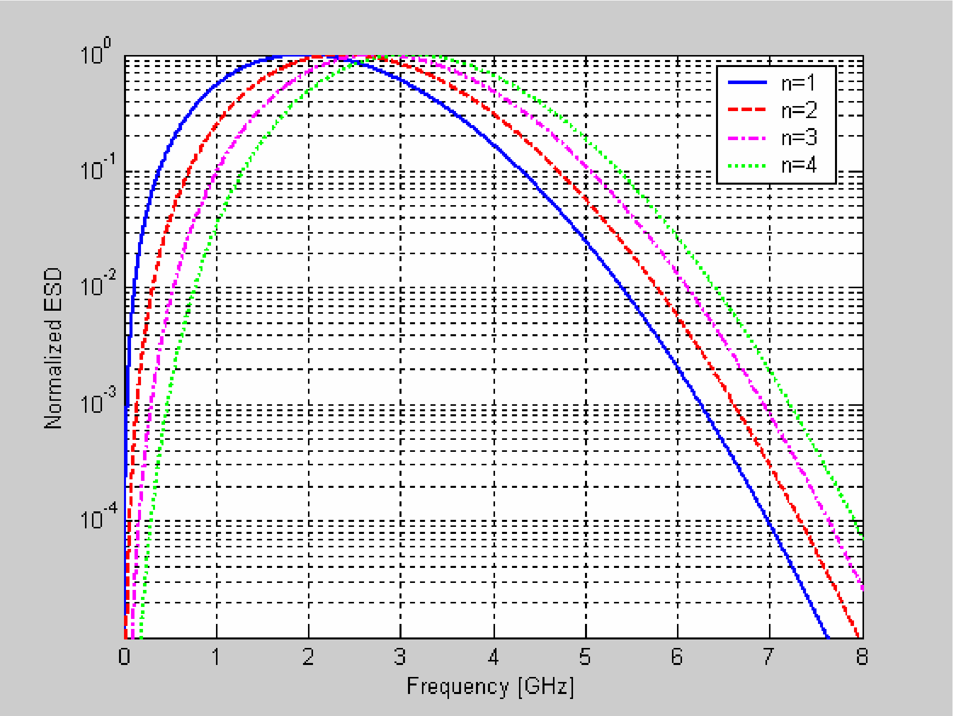


Figure 34 Normalized ESD of Gaussian pulses

Modified Hermite polynomials have recently been proposed for UWB communications in [Ghav01] because of some desirable properties. In particular, they are orthogonal, which makes them a good candidate for multiuser communication schemes, and the pulse width does not change with the pulse order. Modified Hermite polynomials are given as:

$$s_n(t) = (-1)^n e^{\frac{t^2}{4}} \frac{d^n}{dt^n}\left(e^{\frac{t^2}{2}}\right) \tag{22}$$

The corresponding ESD graphs are shown in Figure 35.

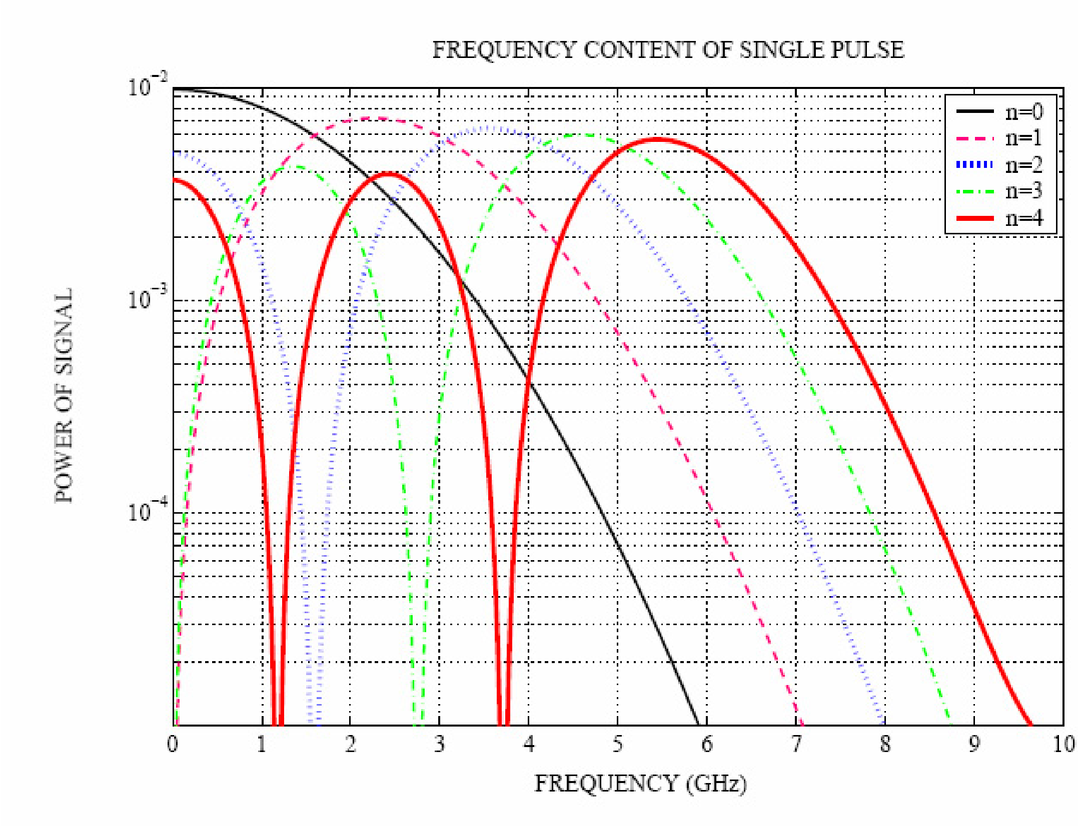


Figure 35 ESD of Hermite polynomial based (from [Mich02])

Figures 34 and 35 show that the proper selection of the pulse waveform can significantly reduce the UWB energy within the narrowband of interest. For example, the energy of some Hermite polynomial based pulses is negligible around certain frequencies.

9.*3 Combined approaches*

Time domain approaches from both reduction of the discrete UWB spectral components techniques and reduction of the UWB pulse energy techniques can be applied together because they do not exclude each other. As a result, additional improvements in reducing the interference can be achieved. Some other processing techniques for reducing both the pulse energy and discrete components of the UWB spectrum are possible. For example, it follows from Eqns. (9-10) that the discrete part of PSD is proportional to R^2 while the continuous part is proportional to R. Thus, one obvious way to significantly reduce both components of the UWB spectrum is to reduce the pulse repetition frequency. However, this generally requires reduction of the throughput of the UWB system. Work presented in [Eshi02] gives some ideas and a potential solution to keep the throughput of the UWB system high, maintain overall quality of service (QoS) requirements for a UWB system and still have reduced the number of monocycles per frame and consequently reduce the interference. As opposed to the binary UWB communication system where many monocycles (depending on the processing gain) are used to transmit one bit of data, in the M-ary UWB transmission proposed in [Eshi02] several data bits are transmitted using the same number of monocycles. Thus, for the same data rate, the pulse repetition time of the M-ary UWB system is higher than the binary UWB system. Having a higher pulse repetition time reduces the PSD of the UWB spectrum. The analysis that illustrates the interference reduction was not performed in [Eshi02] and remains to be done. Multicarrier techniques would have very similar effects once applied to the UWB signals. In [Gera02] the Orthogonal Frequency Division Multiplexing (OFDM) technology was proposed for UWB radio systems. OFDM, already a very popular multicarrier modulation scheme in wireless communications, would be a very promising way of reducing the UWB interference. However, the corresponding analysis and its validations in measurements remain to be done.

References

[Stan00] M. Luo, D. Akos, S. Pullen, P. Enge, "Potential Interference to GPS from UWB Transmitters: Test Plan, Phase I," Stanford University, Version 4.5, May 2000

[Stan01] M. Luo, M. Koenig, D. Akos, S. Pullen, P. Enge, "Potential Interference to GPS from UWB Transmitters: Test Results, Phase II," Stanford University, Version 3.0, March 2001.

[NTIA01] R. Hoffman, M. Cotton, R. Achatz, R. Statz, R. Dalke, “Measurements to Determine Potential Interference to GPS Receivers from Ultrawideband Transmission Systems," NTIA Report 01-384, Version 4.5, February 2001.

[UT00] M. Cardoza, D. Cummings and A. Kerkhoff, “Data Collection Campaign for Measuring UWB/GPS Compatibility Effects,” Applied Research Laboratory report, University of Texas at Austin, February 2001.

[JHU01] “UWB-GPS Compatibility Analysis Project,” Johns Hopkins University/Applied Physics Laboratory, March 2001.

[Corra02] C.A. Corral, S. Sibecas, S, Emami, G. Stratis, “Pulse Spectrum Optimization for Ultra-Wideband Communication,” IEEE Conference on Ultra Wideband Systems and Technologies, May 2002.

[Eshi02] K. Eshima, Y. Hase, S. Oomori F. Takahashi and R. Kohno, “M-ary UWB system using Walsh codes,” IEEE Conference on Ultra Wideband Systems and Technologies, May 2002.

[Foer02] J.R. Foerster, “Interference Modeling of Pulse-based UWB Waveforms on Narrowband Systems,” 55th IEEE Vehicular Technology Conference (VTC 2002), May 2002.

[Gera02] D. Gerakoulis and P. Salmi, “An interference suppressing OFDM system for ultra wide bandwidth radio channels,” IEEE Conference on Ultra Wideband Systems and Technologies, May 2002.

[Ghav01] M. Ghavami, L.B.Michael and R. Kohno, "Hermite Function Based Orthogonal Pulses for Ultra Wideband Communication," The Forth International Symposium on Wireless Personal Multimedia Communications (WPMC01), Aalborg, Denmark, September 2001.

[Hama02] M. Hamalainen, V. Hovinen, R. Tesi, J.H.J. Iinatti, M. Latva-aho, “On the UWB System Coexistence With GSM 900, UMTS/WCDMA, and GPS,” IEEE Journal on Selected Areas in Communications, vol. 20(9), pp. 1712-1721, December 2002.

[Hells00] H. Hellsten and L.M.H Ulander, “Airborne array aperture UWB UHF radar-motivation and system consideration,” IEEE Aerospace and Electronic Systems Magazine, vol. 15(5), pp. 35-45, May 2000.

[Huss02] M. G. M.Hussain, “Principles of space–time array processing for ultrawide-band impulse radar and radio communications,” *IEEE Trans. Veh. Technol.*, vol. 51, pp. 393-403, May 2002.

[Mich02] L.B. Michael, M. Ghavami and R. Kohno, “Multiple Pulse Generator for Ultra-Wideband Communication Using Hermite Polynomial Orthogonal Pulses,” IEEE Conference on Ultra Wideband Systems and Technologies, May 2002.

[Mitch01] T. Mitchell, “Broad is the way,” *IEE Rev.*, vol. 47, pp. 35-39, Jan. 2001.

[Mo03] S.S. Mo, A.D. Gelman, J. Gopal, “Frame Synchronization in UWB Using Multiple SYNC Words to Eliminate Line Frequencies,” IEEE Conference on Wireless Communications and Networking, WCNC 2003. 2003, March 2003.

[Parr03] B Parr, B. Cho, K. Wallace and Z. Ding “A Novel Ultra-Wideband Pulse Design,” IEEE Communications Letters, vol. 7(5), pp. 219-221, May 2003.

[Siwi01] K. Siwiak, “Impact of ultra wide band transmissions on a generic**,**” IEEE Vehicular Technology Conference, May 2001.

[Swam01] A. Swami, B. Sadler, J. Turner, “On the Coexistence of Ultra-Wideband and Narrowband Radio Systems,” IEEE Military Communications Conference, MILCOM 2001, October 2001.

[Telc03] J.E. Padgett, J.C. Koshy and A.A. Triolo, “Physical-Layer Modeling of UWB Interference Effects,” Analysis and Simulation of UWB Interference Effects – NETEX Program, January 2003.

[Win98] M. Z.Win and R. A.Scholtz, “Impulse radio: How it works,” *IEEE Commun. Lett.*, vol. 2, pp. 36-38, Feb. 1998.

[Win00] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. Commun.*, vol. 48, pp. 679-691, Apr. 2000.

[Win02] M.Z. Win, "Spectral density of random UWB signals," *IEEE Communications Letters*, vol. 6(12), pp. 526-528, December 2002.

[WP–GIANT] G. Green, R. Frank, "Ultra-Wideband (UWB) GPS Signal Effects & Hardware-in-the-Loop Assessment," slide presentation, November 4-7, 2003.

[FCC01] Part 15 - Radio Frequency Devices, Technical report, Federal Communications Commission, Washington, DC, December 2001.

[FCCrev] "Revision of Part 15 the Commission's rules regarding ultra-wideband transmission systems," FCC, ET Docket 98-153, 2002.

[FCC03] "FCC regulations, part 15," December 2003. [Online] Available: http://ftp.fcc.gov/oet/info/rules/part15/part15_12_8_03.pdf

Appendix A - Referenced Document Descriptions

Paper Title **Pulse Spectrum Optimization for Ultra-Wideband Communication**

Authors
Corral, C A; Sibecas, S.; Emami, S.; Stratis, G

Keywords
filtering theory; pulse shaping; UWB signals

Publication IEEE Conference on Ultra Wideband Systems and Technologies
Published in May 2002
Pages 31 ***to*** 35

Abstract

Ultra-wideband (UWB) communications employ very short pulses with different modulation that result in extremely wideband spectra for high data-rate links. These spectra are a function of both the spreading operation as well as the pulse shapes. We propose a pulse spectrum optimization technique based on classical filters. Non-ideal impulse characteristics are then considered and the optimum pulse derived for either minimal energy (highest spectral bandwidth). The motivation is to show that filtered pulses can achieve significant spectral control in direct baseband UWB signals for high data-rate communications.

Summary

The paper proposes how to shape the spectrum of the UWB signals. The idea is to use the classical filter theory in order to achieve the desired pulse spectrum. It was pointed out that the use of pre-emphasis filter followed by a low-pass or a band-pass filter could suppress some spectral components. However, no in-depth analysis of interference reduction with respect to any specific radio system was given.

Relevance

The paper directly addresses the problem of shaping the continuous part of the UWB spectra - the results could be used for the interference reduction

Notes

The proposed approach is quite general. It is questionable whether it is possible to achieve resolution good enough to suppress the frequencies in the 20 MHz wide band of a GPS system and still maintain the UWB signal strong enough for quality reception.

Paper Title **M-ary UWB system using Walsh codes**

Authors

Eshima, K.; Hase, Y ; Oomori, S ; Takahashi, F ; Kohno, R

Keywords

M-ary system; UWB system; Walsh codes

Publication IEEE Conference on Ultra Wideband Systems and Technologies

Published in May 2002

Pages 37 ***to*** 40

Abstract

Much attention has been paid to a new form of spread spectrum technique called the ultra wideband impulse radio (UWB-IR) system for future high speed wireless communication services. We present an M-ary scheme that is effective to reduce interference of UWB systems to existing radio systems. The paper presents both theoretic analysis and BER-based computer simulation evaluations of the proposed scheme and shows that the proposed system can overperform the conventional UWB system.

Summary

This paper proposes a novel M-ary UWB system. The proposed system is a modification of time-hopping scheme and use Walsh codes for parallel transmission of M pulses. The motivation is to decrease the number of monocycles during the UWB transmission, which, in turn, should reduce the interference of the UWB systems to existing radio systems. Both theoretical and simulation results are shown to illustrate that the proposed scheme outperforms (BER wise) the normal time-hopping UWB system. However, it was only assumed that the novel M-ary UWB system will have the reduced interference to other systems and wasn't illustrated by simulations. This assumption is consistent with some other studies (some of them mentioned in this summary) that the level of the interference is proportional to the pulse repetition time. The question that interests us and is left unanswered is to what extent this novel approach reduces the interference in the GPS band.

Relevance

The paper directly addresses the problem of UWB interference and how to mitigate it.

Notes

Paper Title **Interference Modeling of Pulse-based UWB Waveforms on Narrowband Systems**

Authors

Foerster, Jeffrey R

Keywords

BER; interference; UWB system

Publication 55th IEEE Vehicular Technology Conference (VTC 2002)

Published in May 2002

Pages 1931 ***to*** 1935

Abstract

Due to the inherent overlay nature of ultrawideband (UWB) systems, it is important to understand and quantify the potential interference caused to narrowband systems that may be located within the bandwidth of the UWB waveform. The simplest way to treat UWB interference is to model it as additive, white Gaussian noise within the bandwidth of the narrowband receiver. However, previous experiments showed that the interference of UWB systems is a function of many factors, including the modulation used, the pulse repetition frequency, the center frequency of the "narrowband" system, and the structure of the "narrowband" receiver. This paper quantifies the effect that a UWB interferer has on the bit error probability of a generic "narrowband" system in order to determine the applicability of the white, Gaussian noise model. These results can also be used to help properly design a UWB system that causes minimal interference to known, overlayed narrowband systems.

Summary

This paper attempts to model and quantitatively measure the interference that UWB causes to the narrowband systems. The author takes into consideration the impulsive nature of the UWB spectrum (instead of simply using the white, Gaussian noise equivalent). The impact of the interference for various UWB scenarios was measured in terms of BER at the receiver (receiver was assumed to use matched root-raised cosine filter and no relation to any particular narrowband system was made).

Key findings:

The UWB interference to narrowband systems increases as the pulse repetition frequency (PRF) decreases in the case of bi-polar modulated pulses (this is very interesting result since it is generally assumed that the interference increases with PRF)

The UWB interference to narrowband systems increases with the PRF in the case of on-off keying

The interference is significantly greater in the case of binary pulse position modulation

(PPM) UWB system, as compared to the random pulse position modulation (R-PPM) UWB system (dithering)

In certain situations, the “real” (theoretically computed) interference is significantly greater as compared to the additive white Gaussian noise approximation case.

Relevance

The paper directly addresses the problem of interference caused by UWB systems - analysis

Notes

The paper considers a generic narrowband receiver and some modifications are needed to apply the analysis on the GPS receiver of interest. It is reasonable to assume, however, that the trends observed in the paper will hold.

Paper Title **An Interference Suppressing OFDM System for Ultra Wide Bandwidth Radio Channels**

Authors

Gerakoulis, Diakoumis ; Salmi, Paola

Keywords

IS-OFDM systems; narrowband interference

Publication 2002 IEEE Conference on Ultra Wideband Systems and Technologies

Published in 2002

Pages 259 ***to*** 264

Abstract

The orthogonal frequency division multiplexed (OFDM) system introduced here, termed interference suppressing OFDM (IS-OFDM), has the capabilities of suppressing narrowband interference in wideband wireless applications. The IS-OFDM encodes each transmitted symbol in all frequency bins. Each frequency bin then "contains" all transmitted symbols which are distinguished and separated from each other by orthogonal Hadamard sequences. The IS-OFDM can provide a point-to-point wireless link without spreading the incoming data rate. In addition, the IS-OFDM has all the advantages of the ordinary OFDM, which is shown to be a special case of the IS-OFDM. We present the IS-OFDM system design and evaluate its performance in the presence of narrowband interference and AWGN channel

Summary

The paper proposes a novel so-called Interference-Suppressing OFDM (IS-OFDM) system. The goal of the proposed approach is to improve the performance of the ordinary OFDM system in the presence of narrow-band interference. The idea is to divide the total number of frequency bins into groups and transmit the same set of symbols in each group using the orthogonal Hadamard sequences. This diversity in frequency domain allows for better symbol reconstruction at the receiver (if one group is seriously affected by the interference, the other groups could be used to keep BER low). The proposed idea is supported by analysis and simulation results.

Relevance

This paper strictly deals with the OFDM systems and how to improve them. No attempt was made to analyze the potential interference to other systems.

Notes

This paper strictly deals with the OFDM systems and how to improve them. The idea is relatively simple and widely known – any type of diversity improves the characteristics of the original system. Aside from the fact that the idea has some drawbacks even from the OFDM system standpoint (for example, it assumes frequency non-selective fading), the approach could introduce significant interference to GPS systems (assuming that the IS-OFDM frequency bins fall into GPS band). Thus, the potential UWB systems that use the proposed idea need to be analyzed and compared with traditional UWB systems.

Paper Title **Hermite Function Based Orthgonal Pulses for Ultra Wideband Communication**

Authors

Ghavami, M ; Michael, L B; Kohno, R

Keywords

Hermite polynomials; impulse radio; orthogonal pulse shapes

Publication The Fourth International Symposium on Wireless Personal Multimedia Communications (WPMC'01)

Published in September 2001

Pages **to**

Abstract

In this paper we propose modified Hermite polynomial functions for use in impulse radio (ultra-wideband) communications. By applying some modifications to Hermite polynomials we can produce pulse shapes which are orthogonal and furthermore have the property of not changing their pulse width. This is in contrast to the majority of orthogonal pulse systems. Another property of the generated pulses is that under the effects of differentiation, while the order of the pulses changes, the property of orthogonality does not change, and the pulse width remains essentially the same. By using these pulse shapes, an M-ary communication system can be constructed which is useful in multi-user systems to achieve lower error rates.

Summary

This paper proposes the use of modified Hermite pulse shapes/wavelets for UWB communications. The constructed pulses were shown to have the following properties:

- pulse duration is almost the same for all values of pulse order (derivative order)
- effective pulse bandwidth is almost the same for every value of pulse order
- pulses are mutually orthogonal
- pulses have zero dc component
- fractional bandwidth can be easily be controlled
- orthogonality of the pulses is preserved despite the differentiating effects of the transmitter and receiver antennas

The orthogonality of the proposed waveforms can be exploited for M-ary signaling and improved data rates and/or for supporting the multiple users.

Relevance

The paper directly addresses the problem of shaping the continuous part of the UWB spectra - the results could be used for the interference reduction

Notes

The ability to relatively easily control spectral characteristics of the Hermite pulses could also be exploited for reducing the UWB interference, that is, for improving its coexistence with narrowband systems.

Paper Title **On the UWB System Coexistence With GSM 900, UMTS/WCDMA, and GPS**

Authors

Hamalainen, V ; Hovinen, V ; Iiatti, J ; Latva-aho, M

Keywords

bit error rate; direct-sequence; interference; time-hopping; ultra-wideband

Publication IEEE Journal on Selected Areas in Communications

Published in December 2002

Pages 1712 **to** 1721

Abstract

This paper evaluates the level of interference caused by different ultra-wideband (UWB) signals to other various radio systems, as well as the performance degradation of UWB systems in the presence of narrowband interference and pulsed jamming. The in-band interference caused by a selection of UWB signals is calculated at GSM900, UMTS/wideband code-division multiple-access (WCDMA), and Global Position System (GPS) frequency bands as a function of the UWB pulse width. Several short-pulse waveforms, based on the Gaussian pulse, can be used to generate UWB transmission. The two UWB system concepts studied here are time hopping and direct sequence spread spectrum. Baseband binary pulse amplitude modulation is used as the data modulation scheme. Proper selection of pulse waveform and pulse width allows one to avoid some rejected frequency bands up to a certain limit. However, the pulse shape is also intertwined with the data rate demands. If short-pulses are used in UWB communication the high-pass filtered waveforms are preferred according to the results. The use of long pulses, however, favors the generic Gaussian waveform instead. An UWB system suffers most from narrowband systems if the narrowband interference and the nominal center frequency of the UWB signal overlap. This is proved by bit-error rate simulations in an additive white Gaussian noise (AWGN) channel with interference at global system for mobile communication (GSM) and UMTS/WCDMA frequencies.

Summary

The paper investigates UWB system coexistence with other radio systems (GPS among them). In particular, the authors measure and compare the level of in-band interference for different UWB signals selected. Two UWB concepts were analyzed – time-hopping and direct-sequence spread spectrum systems. Several pulse waveforms for different pulse widths were analyzed. All the results were obtained based on simulated data.

Key findings:

Direct-sequence spread spectrum introduces less interference as compared to time-hopping for both L1-band and L2-band if all other parameters are kept the same, and assuming a precise code P(Y) (20 MHz wide bandwidth).

Interference strongly depends on the pulse-width used in both cases (TH and DSSS).

The level of interference was calculated for several pulse-waveforms; the least amount of the interference for both the L1-band and L2-band was achieved for the pulse generated as the third derivative of the Gaussian pulse (this conclusion should be taken in perspective, since it might be valid only for the set of parameters used in the simulations).

Relevance

The paper directly addresses the problem of interference caused by UWB systems.

Notes

The methodology for measuring the interference used in the paper is straightforward and the results could be obtained (simulated) for other UWB systems (not just TH and DSSS). However, one should keep on mind that the analysis assumes that the impact the UWB system has on the receiver (GPS receiver in our case) is directly proportional to the level of in-band interference (simple sum of spectral components that fall into the GPS band). Thus, it treats the continuous and discrete spectral components equally, something that could be argued.

Paper Title **Airborne array aperture UWB UHF radar-motivation and system considerations**

Authors

Hellsten, H ; Ulander, L M.H

Keywords

airborne radar; array signal processing; UWB UHF system

Publication IEEE Aerospace and Electronic Systems Magazine

Published in May 2000

Pages 35 ***to*** 45

Abstract

This paper discusses the necessity, feasibility, and technology of FOPEN GMTI. It argues that this functionality may be one mode in a multi-function UWB UHF system, which jointly possesses the capabilities for air target MTI and high resolution FOPEN SAR. The radar platform may be a UAV or an aircraft, whereas, we propose to use the push boom type of antenna mounting previously adopted with the advantage for the CARABAS II UWB VHF SAR. Presently, the push booms will hold a set of UWB UHF antenna elements. This paper relates GMTI to SAR, extended from imaging stationary ground to the 4-parameter set of targets in linear and uniform motion relative to ground. It is recognized that this extended imaging problem depends on one new parameter, i.e., the SAR focusing velocity. The required signal processing may be tackled in an efficient manner by a hierarchical scheme based on iteratively merging subapertures and increasing the resolution. Rejection of stationary clutter and detection occurs on all levels of increasing resolution. This paper also provides a brief presentation of the Swedish FOA efforts to produce an experimental demonstrator of this multi-function radar system.

Summary

Relevance

Notes

Paper Title **Principles of space-time array processing for ultrawide-band impulse radar and radio communications**

Authors

Hussain, M G

Keywords

adaptive antenna arrays; array signal processing; impulse-radio communications; ultra-wide band

Publication IEEE Transactions on Vehicular Technology

Published in May 2002

Pages 393 ***to*** 403

Abstract

The emerging ultrawide-band (UWB) impulse technology has found numerous applications in the commercial as well as the military sector. The rapid technological advances have made it possible to implement (cost-effective, short-range) impulse radar and impulse-radio communication and localization systems. Array beamforming and space-time processing techniques promise further advancement in the operational capabilities of impulse radar and impulse-radio communications to achieve long-range coverage, high capacity and interference-free quality of reception. We introduce a realistic signal model for UWB impulse waveforms and develop the principles of space-time array processing based on the signal model. A space-time resolution function (STRF), a space-frequency distribution function (SFDF) and a monopulse-tracking signal are derived for impulse waveforms received by a self-steering array beamforming system. The directivity peak-power pattern and energy pattern of the beamformer are also derived. Computer plots of the STRF, SFDF and the beam patterns are obtained. The directivity beam patterns of impulse waveforms are sidelobe-free and, therefore, there is no need for sidelobe suppression via amplitude weighting of the array elements. Also, the resolution angle for the beam patterns is derived as a decreasing function of array size and frequency bandwidth. Electronic beamsteering based on slope processing of monopulse waveforms is described.

Summary

Relevance

This is strictly UWB related paper. It does not address the problem of interference.

Notes

Paper Title **Multiple pulse generator for ultra-wideband communication using Hermite polynomial based orthogonal pulses**

Authors

Michael, L B; Ghavami, M ; Kohno, R

Keywords

Hermite polynomials; pulse generator; UWB

Publication IEEE Conference on Ultra Wideband Systems and Technologies

Published in May 2002

Pages **to**

Abstract

We propose a circuit for generation of modified Hermite polynomial functions for use in impulse radio communications. Simultaneous generation of pulses of differing order is developed, reducing circuit complexity. Pulses are produced by applying modifications to Hermite polynomials. Pulses have the properties of orthogonality and not changing their pulse width and pulse bandwidth significantly dependent on pulse order, or under the differentiation effect of the transmitter or receiver antenna. The usefulness of these pulses applied to a multi-user system by orthogonal pulse modulation is shown by comparison with conventional pulse position modulation by computer simulation.

Summary

In this paper the authors develop a method for generating Hermite polynomial based orthogonal pulses that have been recently proposed for ultra-wideband communications in [Ghav01]. The proposed circuitry is based on certain properties of modified Hermite pulses and implements the simultaneous generation of multiple pulses. This work shows that, beside some desirable properties outlined in [Ghav01], the Hermite pulses are also convenient for implementation.

Relevance

The paper directly addresses the problem of shaping the continuous part of the UWB spectra - the results could be used for the interference reduction

Notes

Paper Title **Broad is the way [ultra-wideband technology]**

Authors
Mitchell, T

Keywords
broadband networks; ultra-wideband technology; UWB devices

Publication IEE Review

Published in January 2001

Pages 35 *to* 39

Abstract

Ultrawideband (UWB) systems, which combine bandwidths in excess of 1 GHz with very low power spectral densities (PSDs), are currently attracting growing interest as a means of wresting additional capacity from the already heavily utilized store of wireless bandwidth. If the emissions from UWB devices are regulated to avoid causing significant interference to licensed services, then it becomes possible to allow UWB systems to operate on an unlicensed basis, enabling UWB technology to support a diverse range of applications. As yet, there are no regulations for UWB devices. However, the US is in the process of setting up a regulatory framework, while within Europe, where matters are not quite so far advanced, possible approaches to UWB regulation are under consideration. The author describes the basic principles and the role of regulation in determining the UWB devices destined for commercial deployment.

Summary

Relevance

This is strictly UWB related paper. It does not address the problem of interference.

Notes

Paper Title **Frame synchronization in UWB using multiple sync words to eliminate line frequencies**

Authors

Mo, S S; Gelman, A D; Gopal, J

Keywords

continuous component; discrete component; PSD; UWB

Publication IEEE Conference on Wireless Communications and Networking, WCNC 2003

Published in March 2003

Pages 773 ***to*** 778

Abstract

Ultra wide-band (UWB) is now under consideration as an alternative physical layer technology for wireless PAN. UWB radio uses base-band pulses of very short duration, thereby spreading the energy of radio signal very thinly over gigahertz. The power spectral density (PSD) of UWB signals consists of a continuous component and discrete component. Generally speaking, the discrete component presents greater interference to narrow-band communication systems than the continuous component. Frame synchronization is commonly used in multiple access systems, including wireless PAN systems. The sync word will generate strong PSD. In this paper, we devise a more efficient and better performance mechanism to suppress the discrete component of the PSD of UWB signals by randomizing the pattern of UWB signals. The mechanism can also be applied to payload data to smooth the PSD of USB signals.

Summary

This paper proposes a mechanism for eliminating the discrete component in the PSD of UWB signals by converting it into continuous component. As a result, the reduction of the UWB interference to narrow-band communication systems is achieved. The proposed approach exploits the properties of the PSD expression (its continuous and discrete parts) and is based on the use of multiple sync words for frame synchronization. The idea has been demonstrated in simulations.

Relevance

The paper directly addresses the problem of interference caused by UWB systems and how to mitigate it.

Notes

The paper gives relatively simple and easy to implement guidelines for mitigating the UWB interference. The measurements intended to validate the analytical results are currently underway.

The content of this paper overlaps with "Data Whitening in Base-band to Reduce PSD of UWB Signals" by Shaomin Mo from Panasonic, written as a proposal of base-band processing of whitening data to reduce power spectral density of UWB signals in IEEE 802.15.3 systems.

Paper Title **Measurements to Determine Potential Interference to GPS Receivers from Ultrawideband Transmission Systems**

Authors

Hoffman, R ; Cotton, M ; Achatz, R ; Statz, R ; Dalke, R

Keywords

Publication NTIA Report 01-384, Version 4.5

Published in February 2001

Pages ***to***

Abstract

Summary

NTIA report is very similar in methodology and findings to [Stan01]. The level of UWB to GPS interference was quantitatively described by measuring the break lock (BL) and reacquisition time (RQT), that is, by measuring the GPS receiver's ability to maintain and reacquire lock over a range of UWB interferers. A selected group of UWB signals and their combinations was analyzed: signals with uniform pulse spacing (UPS) and with on-off keying (OOK); 2% relative reference dithering and 50% absolute reference dithering; signals at 0.1, 1.0, 5.0 and 20.0 pulse repetition frequency (PRF). "Gating" of the UWB signals was also considered. Two GPS receivers with different receiving architectures were tested: semi-codeless receiver and general purpose navigation receiver. Different UWB were characterized by their spectra (similar to Stanford study) but also by their amplitude probability distribution (APD). It was illustrated that both characteristics could serve as an indicator what level of interference should be expected. The measurement results were normalized with respect to the broadband noise that would have the same effect on the GPS receiver.

Key findings:

UPS and OOK signals have discrete spectral lines. Time varying Doppler shift due to satellite motion causes these lines to interfere with GPS discrete spectral lines. Test results show that observed parameters degrade at lower UWB signal powers as the approach and recede. Line interference becomes more severe as PRF increases.

APDs of sampled 50%-ARD and 2%-RRD signals approach that of Gaussian noise as PRF increases. Consequently, for dithered signals with high PRF, interference effects are similar to that of Gaussian noise. In general, low-PRF dithered signals generate more impulsive interference which is more benign that Gaussian noise.

Both the BL and especially the RQT value vary significantly with the type of the receiver and the UWB signal parameters selected. General purpose navigation receiver has shown to be more robust to break lock as compared to the other tested receiver.

Relevance

The paper directly addresses the problem of UWB to GPS interference - measurements and analysis

Notes

Paper Title **A Novel Ultra-Wideband Pulse Design Algorithm**

Authors

Parr, Brent ; Cho, ByungLok ; Wallace, Kenneth ; Ding, Zhi

Keywords

impulse radio; pulse design algorithm; UWB multiuser

Publication IEEE Communications Letters

Published in May 2003

Pages 219 ***to*** 221

Abstract

We present a new algorithm to numerically generate pulses that not only have a short time duration for multiple access, but also meet the power spectral constraint of Federal Communications Commission (FCC) ultra-wideband mask. In fact, applying our algorithm to the FCC spectral mask for UWB systems can lead to the design of multiple orthogonal pulses that are compliant. Our algorithm presents a flexible and systematic method for generating UWB pulses that have many advantages over the Gaussian monocycle pulse.

Summary

In this paper the authors present a novel algorithm for UWB pulse design. It utilizes ideas of prelate spheroidal wave functions and allows for fine frequency mask fitting without sacrificing data rate or system capacity. The proposed algorithm was shown to have several advantages over the Gaussian monocycles that are most popular in UWB communication systems. These advantages are:

- the pulses are orthogonal and can be used in multiple access systems
- pulse design is flexible and can fit frequency masks with multiple passbands
- the proposed pulse design allows direct transmitter implementation (no multiplier is needed)

Relevance

The paper directly addresses the problem of shaping the continuous part of the UWB spectra - the results could be used for the interference reduction

Notes

Paper Title **Impact of ultra wide band transmissions on a generic receiver**

Authors

Siwiak, K

Keywords

cellular radio; multipath channel; UWB systems

Publication IEEE Vehicular Technology Conference

Published in May 2001

Pages 1181 ***to*** 1183

Abstract

The noise floor rise in a generic receiver as a basis for the determination of interference levels to a victim receiver is applied to assess interference to systems that are designed to operate in multipath fading environments. The interference levels might be over estimated by as much a 20 dB if fading is not properly taken into account. The impact of potentially interfering sources such as UWB emissions must be treated as an effect on the overall system reliability. Results here show that low power UWB systems operating at the same levels as unintended radiators can comfortably coexist with conventional users of the radio spectrum without significant impact on the performance of those radio services

Summary

This is one of the early papers (as compared to the ones listed) on UWB to GPS interference analysis. The paper performs link budget analysis between an UWB transmitter and a generic narrowband receiver and between an UWB transmitter and generic narrow band base station. For the given set of parameters it was shown that only UWB devices that operate within 1m from the narrowband receiver cause significant interference. The analysis was performed for just one set of parameters and many factors were not taken into consideration. The general observation that “UWB transmissions have a small effect on narrowband system performance” is not in agreement with the findings in other papers and reports.

Relevance

The paper directly addresses the problem of interference caused by UWB systems - analysis.

Notes

Paper Title **Potential Interference to GPS from UWB Transmitters: Test Plan, Phase I**

Authors

Luo, M ; Akos, D ; Pullen, S ; Enge, P

Keywords

GPS receivers; interference measurements; UWB interference

Publication Stanford University, Version 4.5

Published in May 2000

Pages ***to***

Abstract

Summary

The report from Stanford University on potential interference to GPS from UWB transmitters was requested by the U.S. Department of Transportation. The report consists of two parts - Phase I (Test Plan) and Phase II (Test Results). The goal of the Test Plan was to characterize the interference effects of UWB emissions on various types of aviation and non-aviation GPS receivers in a controlled test environment. Pseudorange measurement accuracy, acquisition/reacquisition times, and loss-of-tracking threshold are the four important performance metrics that have been selected for measuring the UWB impact on the GPS receivers. UWB signal design characteristics, such as pulse repetition frequency (PRF), pulse modulation and pulse shaping, that is, how they influence GPS reception, have been chosen to be investigated.

The corresponding measurement results were presented in [Stan01].

Relevance

The paper directly addresses the problem of UWB to GPS interference - measurement plans

Notes

Paper Title **Potential Interference to GPS from UWB Transmitters: Test Plan, Phase I**

Authors

Luo, M ; Akos, D ; Pullen, S ; Enge, P

Keywords

GPS receivers; interference measurements; UWB interference

Publication Stanford University, Version 4.5

Published in May 2000

Pages ***to***

Abstract

Summary

The report from Stanford University on potential interference to GPS from UWB transmitters was requested by the U.S. Department of Transportation. The report consists of two parts - Phase I (Test Plan) and Phase II (Test Results). The goal of the Test Plan was to characterize the interference effects of UWB emissions on various types of aviation and non-aviation GPS receivers in a controlled test environment. Pseudorange measurement accuracy, acquisition/reacquisition times, and loss-of-tracking threshold are the four important performance metrics that have been selected for measuring the UWB impact on the GPS receivers. UWB signal design characteristics, such as pulse repetition frequency (PRF), pulse modulation and pulse shaping, that is, how they influence GPS reception, have been chosen to be investigated.

The corresponding measurement results were presented in [Stan01].

Relevance

The paper directly addresses the problem of UWB to GPS interference - measurement plans

Notes

Paper Title **Potential Interference to GPS from UWB Transmitters: Test Results, Phase II**

Authors

Luo, M ; Koenig, M ; Akos, D ; Pullen, S ; Enge, P

Keywords

GPS receivers; interference measurements; UWB interference

Publication Stanford University, Version 3.0

Published in March 2001

Pages ***to***

Abstract

Summary

The report from Stanford University was requested by the U.S. Department of Transportation. The major goal was to measure UWB impact on the accuracy and loss-of-lock performance of a high-grade GPS aviation receiver. A high-grade, general-purpose GPS receiver and low-cost OEM receiver were also considered during the measurements.

Key findings:

UWB interference to GPS can be successfully described using a noise equivalence factor. The noise equivalence factor is defined as the UWB power level that causes a specified interference effect relative to the broadband-noise power level that causes the same effect. This factor could be used for the computation of link budgets that correspond to a variety of operational scenarios.

The noise equivalence factor is a strong function of the UWB signal parameters. The report quantifies the noise equivalence factor for a large set of UWB waveforms. The factor varies most strongly with the UWB pulse repetition frequency (PRF) and the spectral location of any discrete UWB spectral lines relative to the GPS signal. Observed relations between the UWB signal parameters and the interference impact are:

- Pulse Repetition Frequency (PRF): If UWB pulses are sent at a very low rate compared to the RF front-end bandwidth of GPS receivers, then the interference impact will be smaller than that due to UWB operation at high PRFs. Most GPS receivers have front-end bandwidths between 2 and 24 MHz. If the UWB PRF is less than 500 kHz, then it has been shown that the pulses will still be distinct at the output of the receiver front end, and the interference will be relatively small. If the UWB PRF is higher than the bandwidth, then the GPS front end will smear the pulses together, forming an effectively continuous input to the GPS receiver; thus the interference effect will probably be larger.
- No Modulation Case: In this case, the UWB signal is a pulse train with a constant time

between pulses. The GPS C/A-code also has line spectra. UWB interference will be greatest when the UWB lines fall on top of the GPS spectral lines. UWB interference should be small when the UWB lines fall between the GPS lines or are far away from the bandwidth of the particular GPS receiver under test. The locations of UWB spectral lines will change based on the UWB transmitter parameters; thus the UWB effect on GPS will vary.
- Pulse Modulation: If the UWB pulses are modulated randomly in pre-defined ways and with long codes, then the UWB line spectra will be reduced and may possibly disappear. If modulation is used with sequences that are continuous and have high PRFs, then the interference effect may be similar to that of broadband noise of equal power. (note: random pulse position modulation (R-PPM) (dithering) was shown to be very efficient way of avoiding the appearance of UWB spectral lines)
- Pulse Bursting: UWB pulses may be transmitted in bursts with prescribed on-times and off-times. If the duty cycle (fractional on-time) of these bursts is small, it has been observed that the effect of a single UWB transmitter on a GPS receiver will be reduced.
- Pulse Shaping: The overall UWB spectrum depends on the pulse shape. It may be possible to modify the shape of UWB pulses so that the UWB spectrum avoids certain critical bands (such as the GPS L1 frequency).

Actual UWB degradations are generally greater for the high PRF signals with discrete spectral lines (note: this result was also confirmed in theory, see technical papers listed below)

Under the best circumstances (no in-band spectral lines), UWB signals with high PRFs appear as broadband noise. If the UWB dithering codes or modulation indices are not

Relevance

The paper directly addresses the problem of UWB to GPS interference - measurements and analysis

Notes

Paper Title **On the coexistence of ultra-wideband and narrowband radio systems**

Authors

Swami, A ; Sadler, B ; Turner, J

Keywords

BER; error statistics; UWB interference

Publication IEEE Military Communications Conference, MILCOM 2001

Published in October 2001

Pages 16 *to* 19

Abstract

Ultra-wideband (UWB) signals will encounter many interference sources, primarily from relatively narrowband (NB) systems. In addition, UWB signals will also affect a large number of NB radios; of critical importance is the potential interference with GPS, E-911, and navigation bands, as well as cellular bands. There is a rich and growing literature on UWB radios; however, issues related to interference measurements have only been partially addressed. Here, we assess the interference caused by UWB signals via analysis and simulations. Analytical results include the aggregate effect of spatially distributed UWB radios on a receiver, and theoretical BER expressions.

Summary

The paper tries to assess the interference caused by the UWB using the theoretical analysis. Thus, this is the paper similar to [Hama02] and [Foer02] but with slightly different approach and with some additional factors taken into account. In their analysis the authors take into account waveforms of the interferers, propagation losses and receiver models (matched filter and BPSK signaling was considered). The spatial distribution of the sources was also considered (note: this is the rare paper that analyzes the effect of multiple UWB interferers). The level of interference was measured in the terms of BER at the receiver.

The idea is to simply model the interfering term as additional noise term and use the appropriate BER equations. Thus, this paper uses additive Gaussian noise approximation for UWB interference, which is, according to some other papers and reports, sometimes not an adequate approximation.

Relevance

The paper directly addresses the problem of interference caused by UWB systems - analysis

Paper Title **On the coexistence of ultra-wideband and narrowband radio systems**

Notes

The paper also brings the observation that UWB signals have heavy tailed distribution. Heavy tailed distributions have been relatively popular area of research in the statistical signal processing society but not in the context of UWB signals; something that might be worth investigating.

Paper Title **Physical-Layer Modeling of UWB Interference Effects**

Authors

Padgett, Jay E; Koshy, John C; Triolo, Anthony A

Keywords

Publication Analysis and Simulation of UWB Interference Effects - NETEX Program

Published in January 2003

Pages ***to***

Abstract

Summary

This report gives in depth analysis of the effect of UWB interference on narrowband receivers. The first part of the report provides extensive analysis of the power spectral density (PSD) of the UWB signals. The PSD is very important for understanding and widely used way of describing the impact of UWB interference. The UWB PSD models developed in the report allow the PSD to be computed analytically for a wide range of different UWB signal types and include the effects of parameters such as the pulse repetition frequency (PRF), modulation, dithering, coding, etc. The models could also be used as a basis for developing UWB signals with specific desired spectral properties.

The second part of the report provides set of models describing the impact of UWB interference on several typical receiver types, both digital and analog. The following receivers were investigated: coherent PSK receiver, coherent FSK receiver, non-coherent FSK receiver and analog FM receiver.

Relevance

The paper directly addresses the problem of interference caused by UWB systems - analysis.

Notes

The content of this report overlaps with "Analysis and Simulation of UWB Interference Effects" presented at NETEX Industry Day Workshop.

Paper Title **Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications**

Authors

Win, M Z; Scholtz, R A

Keywords

impulse radio; ultra-wideband; UWB time-hopping spread spectrum

Publication IEEE Transactions on Communications

Published in April 2000

Pages 679 **to** 691

Abstract

Attractive features of time-hopping spread-spectrum multiple-access systems employing impulse signal technology are outlined, and emerging design issues are described. Performance of such communications systems in terms of achievable transmission rate and multiple-access capability are estimated for both analog and digital data modulation formats under ideal multiple-access channel conditions.

Summary

Relevance

This is strictly UWB related paper. It does not address the problem of interference.

Notes

Paper Title **Spectral density of random UWB signals**

Authors
Win, M Z

Keywords
random processes; spectral analysis; time-hopping spread-spectrum signals

Publication IEEE Communications Letters

Published in December 2002

Pages 526 ***to*** 528

Abstract

We derive the power spectral density of time-hopping (TH) spread-spectrum signals in the presence of random timing jitter. Detailed descriptions of different TH schemes, employing a random TH sequence, are given and spectral analysis of such TH signals in the presence of uniform timing jitter is carried out using a systematic and tractable technique.

Summary

Relevance

This is strictly UWB related paper. The UWB spectral analysis provided in the paper can be used for the interference mitigation study.

Notes

Paper Title **Impulse radio: how it works**

Authors

Win, M Z; Scholtz, R A

Keywords

impulse signal technology; multipath channels; ultra-wide bandwidth spread-spectrum signaling

Publication IEEE Communications Letters

Published in February 1998

Pages 36 ***to*** 38

Abstract

Impulse radio, a form of ultra-wide bandwidth (UWB) spread-spectrum signaling, has properties that make it a viable candidate for short-range communications in dense multipath environments. This paper describes the characteristics of impulse radio using a modulation format that can be supported by currently available impulse signal technology and gives analytical estimates of its multiple-access capability under ideal multiple-access channel conditions.

Summary

Relevance

This is strictly UWB related paper. It does not address the problem of interference.

Notes