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Performance of Bit Error Rate and Power Spectral Density of Ultra Wideband with Time Hopping Sequences.

Joseph Martin Peek
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Joseph Martin Peek entitled "Performance of Bit Error Rate and Power Spectral Density of Ultra Wideband with Time Hopping Sequences.." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

Dr. M. Mostofa Howlader, Major Professor

We have read this thesis and recommend its acceptance:

Dr. Paul B. Crilly, Dr. Jack S. Lawler

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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**A Thesis Presented for the
Master of Science Degree
The University of Tennessee, Knoxville**

Joseph Martin Peek
December 2003

Dedication

To my Family and all those who have supported me

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I am sincerely grateful to Dr. Mostofa Howlader for being my advisor, and for all his guidance throughout this thesis. His insight and motivation were very valuable in completing this research. I am also thankful to Dr. Paul Crilly, and Dr. Jack Lawler for being on my graduate committee, and for reviewing and suggesting comments.

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Abstract

This thesis focuses on several modulation methods for an ultra wideband (UWB) signal. These methods are pulse position modulation (PPM), binary phase shift keying (BPSK), on/off key shifting (OOK), and pulse amplitude modulation (PAM). In addition, time hopping is considered for these modulation schemes, where the capacity per time frame of time hopping PPM is studied using different spreading ratios.

This thesis proves that with the addition of time hopping to all types of modulated UWB signals, the performance of power spectral density improves in all aspects, despite the increase of data per time frame. Note that despite the increase of data per frame, the bit error rate remains the same as standard non-time hopping UWB modulated signals.

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Chapter 1
Introduction

The communications industry is growing at a rapid pace. The communications corporations are searching for a way to increase the system capacity, while ensuring the bit error rate (BER) remains low. The answer that they have been looking for might now be in a new system called ultra wideband (UWB). In order to understand this exciting new technology, we must first take a look the definition of UWB, and what a UWB signal consists of.

1.1 Definition of UWB

The definition of UWB is the communication of a series of baseband pulses of a very short duration, generally in the order of nanoseconds. UWB is a periodic signal, of which each period carries information using anywhere from one to millions of pulses per period to transmit data. This allows the system to spread the energy of the signal over several GHz. UWB is a new wireless communication system used to transmit digital data over a wide spectrum of frequency bands with low power usage. The signal does not need a carrier wave to transmit data. This is because generally the only need for a carrier wave is to step a signal up to a higher frequency. Since UWB is already in the GHz range, there is no need for a carrier signal. UWB often operates in highly populated frequencies around a few GHz [1]. Frequently, UWB must deal with interfering signals and avoid narrowband signals. Interfering signals can cause inter-symbol interference, often leading to intense zero power sampling spikes, creating detection problems. Several means to reduce spectral noise for a UWB signal is with data modulation, accomplished by additional pulse position modulation at a pulse rate of a greater number of pulses per bit, and time hopping modulation. Time hopping code will reduce the PSD zero power combs that uniform pulse distribution causes. Additionally, due to the extremely short duration of pulses, UWB signals are immune to multipath effects and other wireless spectrums in a channel. UWB offers many advantages to a communication system, from low probability of detection to low power consumption. UWB can also operate in the lowest possible frequency range. Since a low frequency range emits radiation, the lower the frequency, the better the chance of penetrating materials. Since UWB has a considerable bandwidth, another advantage of UWB is it can handle many users, pending interference. UWB is defined as

$$s^{(k)}(t) = \sum_j A^{(k)}_{j/Ns} w(t - jT_f - c^{(k)}_j T_c - \delta d^{(k)}_{j/Ns}) . \tag{1.1}$$

Where *w(t)* represents the transmitted pulse waveform, which is generally called a monocycle. T_f is the frame time or pulse repetition time. This function is generally a hundred to a thousand times the monocycle width, which will output a resulting signal with a very low duty cycle. A typical monocycle is in the form of the Gaussian first, or second derivative. To avoid collisions of monocycles, each pulse is assigned a time shift location, $T_{f,,}$ and c_j is called the time-hopping sequence, which is an additional time shift. This allocates each user a necessary time shift position during a pulse train sequence. The j^{th} monocycle undergoes an additional shift of c_jT_c seconds, where T_c is the duration of time delay. N_s is the number of pulses modulated in the signal. The data sequence *d(j)* is designed to be modeled as a wide-sense stationary random process. UWB's definition is a communication system that involves the transmission of information via signals with a fractional bandwidth of greater than 25%, or a total bandwidth of greater than 500 GHz [2]. Bandwidth for UWB is defined in [3] and given as

$$B_f = \frac{(f_h - f_l)}{f_c} > 25\% . \tag{1.2}$$

This is different from a narrowband system in that a narrowband system is defined as a system that has a fractional bandwidth less than 1% [3]. Narrowband fractional bandwidth is defined in [2] and given as

$$B_f = \frac{(f_h - f_l)}{f_c} < 1\% . \tag{1.3}$$

As Figure 1.1 displays, the UWB signal can contain a large data signal, as opposed to the narrowband cannot. A graphical analysis of UWB vs narrowband is represented in Figure 1.1. The UWB system is the use of extremely short duration of sub-nanosecond pulses instead of continuous waves to transmit information. These pulses directly generate a very wide instantaneous bandwidth signal according to the time scaling properties of the Fourier transform relationship between time and frequency. UWB also operates at a very low duty cycle, anywhere on the order of 0.01 to 0.001.

1.2 Characterization of UWB

UWB can be characterized as follows: No allocated spectrum is necessary; the low frequency component of UWB offers penetration capability through walls and ground; ultra-short duration pulses that yield ultra-wide bandwidth signals; Transmission with very low power; no interference with existing spectrum users; excellent immunity to interference from other radio waves; a simple and inexpensive circuit; high precision ranging and wide bandwidth results in reducing multi-path interference.

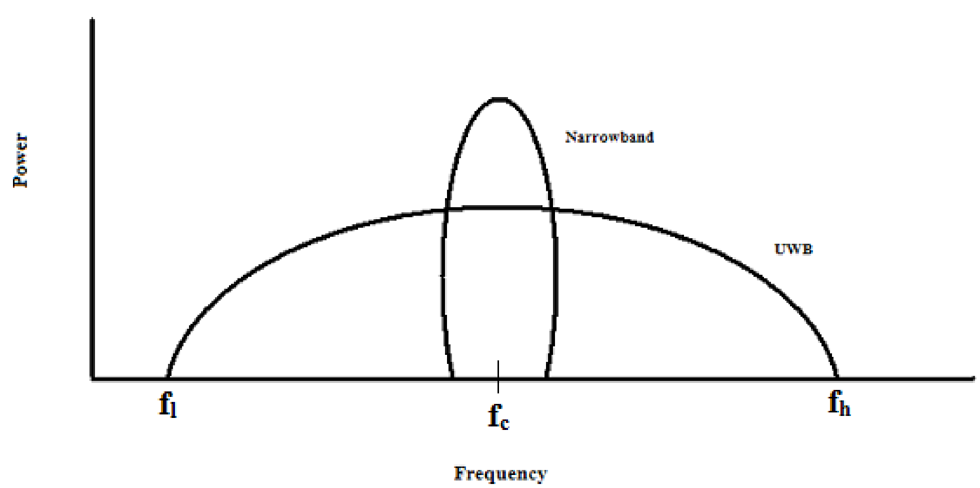


Figure 1.1 Graphical spectrum analysis of UWB

1.3 Outline of the Thesis

Chapter 2 will contain the history of UWB, and offer some additional literature on any work being done on UWB.

Chapter 3 of this thesis will go into detail of implementing a uniform pulse distribution for a UWB transmitter and receiver. The basic structure of the UWB will also be examined, including waveforms for the first and second derivative of the Gaussian pulse.

Chapter 4 will involve a short description of data modulation, followed in detail of PPM modulation and PPM capacity using varying spreading ratios per user. Further in the chapter, the thesis will explain simple types of modulation and give graphical representation of pulse amplitude modulation (PAM), on/off keying (OOK), and binary phase shift keying (BPSK).

Chapter 5 will go into detail of the research for pulse train spacing and time hopping sequences. This chapter will also define a time hopping UWB transmitter and receiver. This chapter will also go into detail of power spectral density (PSD) for time hopping modulation schemes. The final section will involve bit error rate (BER) plots for time hopping modulation schemes defined in Chapter 4. The PSD and BER plots will give results on whether time hopping schemes offer improved performance of transmitting data over free space versus data transmitted using uniform distribution. Chapter 6 will give a final conclusion and summary to the research defined in this thesis, followed by references.

Chapter 2
Literature Survey

2.1 History of UWB

The origin of UWB comes from time-domain electromagnetic studies from the 1960's [4]. It was discovered when the transient output of microwave impulse responses was studied. Instead of exciting a linear-time invariant (LTI) system with an amplitude or phase response, excite the system with a impulse response *h(t)*. By using this idea, an output *y(t)*, with any random input *x(t)*, can be calculated by a convolution integral given as

$$y(t) = \int_{-\infty}^{\infty} h(t)x(t-u)dt \,. \tag{2.1}$$

Since this signal is an impulse generated output, the only way for researchers to analyze the signal was to sample the output. The signal was sampled, the development of techniques for sub nanosecond pulse generation was created. Once it was discovered that that there is a way to design and implement a wideband, short pulse communication system, UWB technology was developed. Through the 1980's, the technology was referred to as a baseband, carrier-free signal, or truly termed impulse band technology. By 1989, UWB was being considered for such applications as communications, radar, and positioning systems. In [5], additional history is researched.

This technology received more attention from the military in the 1960's. The Department of Defense (DOD) discovered the technology and immediately turned the technology top secret. It was discovered that the technology was excellent for radar and low-probability of detection. The DOD liked some of UWB's advantages. Some of the advantages of UWB is the ability to penetrate objects and also the low signal power consumption. It also costs less than the standard carrier-based technologies. Standard carrier-based technologies must modulate and demodulate a complex analog carrier waveform, and corporations must pay for all necessary components to do so. UWB is also the only system that truly offers a binary form of communication.

2.2 UWB Literature Survey

UWB is most likely the technology of the future. Despite being a relatively new technology, an extensive amount of research has been done on UWB. Of all the competing wireless technologies currently available, or under development, UWB shows the most promise. UWB provides the highest data rates with the lowest vulnerability to multipath interference [6]. UWB is a unique signal that implements very low power pulses over a very large bandwidth [6]. In order to become a mainstream technology, concerns about interference with signals currently available must be proven otherwise.

There are many papers that have researched the basic structure of UWB. Reference [7] states that UWB is a viable candidate for short range communications in dense multipath environments. Reference [7] describes the characteristics of UWB using a modulation format that can be supported by currently available technology and gives analytical estimates of multiple access capability under ideal multiple access channel conditions.

There has also been considerable research comparing performance of standard communication systems with UWB. Reference [8] researched and described the performance of several communication systems in terms of achievable transmission rate and multiple-access capability are estimated for several communication systems using data modulation formats under ideal multiple-access channel conditions.

UWB is very important to the military since the signal is not easily detected. Reference [9] states that it is expected that tactical communication systems be capable of operating in a covert and robust manner in the face of various threats related to detection, interception, and jamming of radio communications. Reference [9] investigates the covertness of an impulse radio network in the same environment that employs a simple power control algorithm while using two detection methods, hard decision detection and soft decision detection. Reference [9] also uses a method for quantitatively defining low probability of detection that is based on principles of communication theory, by operating in an environment with dense multiple access interference with large near-far ratios.

Reference [10] is another paper that goes into detail about UWB signal design. The research of [10] presents the design for time hopping, spectral flatness, for rapid acquisition, and for multiple access. Reference [10] also details power spectral density computation. In designing a UWB signal that has a flat and smooth power spectrum, many variables must be considered. According to [10], the flatter the power spectral density of the transmission, the larger the amount of power that can be radiated while still satisfying power spectral density bounds imposed by regulatory agencies. There are also many challenges addressed for certain modulation schemes used for UWB.

Reference [11] outlines the attractive features of direct sequence UWB multiple access systems employing antipodal signaling and compare it with time hopping. An appropriate direct sequence UWB transmitter and receiver are designed, and the system signal processing formulation is investigated. Reference [11] investigates the performance of such communication systems in terms of multiple access capability, error rate performance, and achievable transmission rate are evaluated.

Reference [12] proposes an innovative high performance, high throughput direct sequence spreading UWB system. The proposed system in [12] employs a multi-carrier pulse waveform at the UWB transmit side. At the receiver side, the received direct sequence spreading UWB pulse is decomposed into sub-carriers and recombined to exploit diversity in the frequency domain and provide resistance to inter symbol interference and multi-access interference

Reference [13] offers new results on the capacity of a typical M-ary pulse position modulation time hopping UWB system. Reference [13] makes the case that the influence of multiple user interference (MUI) on capacity is detrimental, especially in the case of high bit-SNR. Based on an extended model containing correlator and soft-decision decoding, the capacity is evaluated in the single user case of a system when the inputs are equally probable.

Reference [14] considers a UWB system using reduced-complexity Rake receiver, which are based on either selective or partial Rake receivers, by combining a subset of available resolved multipath components. Reference [14] investigates the influence of the spreading bandwidth on a system performance using two types of Rake receivers. Reference [14] also investigates that optimal bandwidth increases with the number of Rake fingers, and is higher for a selective Rake, versus a partial Rake receiver. The effects of fading are also included in the results.

There has also been a lot of research on bit timing over multipath channels. Reference [15] takes a look at recovering timing of ultra wideband transmissions over dense multipath channels. This is done by oversampling, which is easy for UWB because the symbol pattern is periodic with all types of UWB modulation. The timing acquisition relies only on frame rate samples. This research is applied in AWGN and also channel fading is looked at.

Reference [16] also takes a look at using UWB for navigation systems. It is important to note that the system in this paper does not involve radar. It works by using active ranging over a code divisible multiple access (CDMA) communication channel with no carrier frequency. Reference [16] conducts this study using pulse position modulation by giving each transceiver a unique pseudo-random noise code. This is done by a type of call and return scheme to measure the time it takes for a signal to reach a certain vehicle. Additionally, the signal provides a very low power due to the fact that the CDMA encoding will provide a megabit per second communication data rate for each vehicle that is being used in the system.

Since UWB has a large fractional bandwidth when it is compared to other types of conventional systems. Reference [17] describes how a large fractional bandwidth will lead to lower worst-case fading in the presence of multipath for many modulated UWB communication systems. Reference [17] also makes measurements made using an actual UWB communication systems showing the magnitude of signal strength variations due to multipath interference. Reference [17] provides analysis on how fractional bandwidth in providing a stout performance when passing through multipath environments for UWB communication systems.

Reference [18] researches the performance of UWB communication in the presence of interference. This paper models interference as a zero mean, random process with constant power spectral density over a certain bandwidth. This paper shows that in the case of narrowband interference, UWB provides more effective interference suppression than direct-sequence spread spectrum (DS-SS). Reference [18] compares the interference suppression properties of UWB and DS-SS. This paper goes into detail of how a DS-SS system propagates a signal, and how it performs with the addition of UWB to the signal.

Since UWB exists at the same frequency range as GPS, the FCC is concerned about activating the system as a mainstream system. Reference [19] researches how UWB might interfere in GPS and navigation bands, as well as cellular bands. Reference [19] carries out analytical results include the cumulative effect that a spatially spread UWB radio system might have on a receiver, and certain BER theoretical results. The theoretical analysis takes into account certain types of modulation schemes using UWB. Reference [19] also determines the spatial distribution of the sources, propagation losses, and receiver models. This paper theorizes that interfering UWB signal structure will cause effects that can differ from certain broadband and thermal signals. This can include pulse repetition rate, duty cycles, and certain waveforms.

Reference [20] investigates multi-user detection in multiple-access communication systems based on ultra-wideband technology. This paper states that as the number of users increase, while the bandwidth to pulse repetition frequency decreases, multiple-access interference is expected to adversely affect system capacity and performance. Reference [20] presents a theory that by designing a multi-user detector, UWB can be more easily detected and demodulated. This paper presents numerical examples proving that the performance of the optimum detector versus that of a single conventional correlation receiver is better for detecting UWB signals.

Reference [21] researches the performance of three impulse train modulated UWB systems in an AWGN channel. This paper describes the mathematical model for a biphase, pulse position and hybrid modulated UWB signal. These systems were created in [21] with decision rules for detecting the UWB signal with only AWGN interference as the proposed noise. Reference [21] follows up by calculating the exact formulas of bit error rates of all the UWB signals with the closed-form approximation being derived. Reference [21] follows up by applying the derived formulas to optimize the modulation parameter of the Gaussian monocycle UWB impulse radio.

Reference [22] researches the implementation of an algorithm for the detection of a direct path signal in the presence of dense multipath environments, using generalized estimation. The models represented in this paper are based on statistical analysis of propagation data and the algorithm is cross correlated to another independent set of propagation measurements. Reference [22] proposes that UWB ranging systems uses correlator and a parallel sampler with high-speed measurement capability. This paper states that each transceiver has the ability to accomplish two way ranging between the incoming signal time, and the transmitter clock. Reference [22] proposes that fine time resolution for UWB signals enables potential applications for long range applications.

Reference [23] will demonstrate the effectiveness of multiuser detection for an UWB baseband pulse DSSS system using code division multiple access (CDMA). This paper conducted several simulations using a frequency range between 2 and 8 GHz. Reference [23] also goes into detail of multiuser detection receivers that can gather multipath energy and reject intersymbol and interchip interference for the frequency range given. This paper also shows that certain interference levels can be filtered out with the use of a rake receiver that has anywhere from 4 to 8 fingers. Reference [23] also states that practical rake receivers were incapable of effectively rejecting either the strong narrowband interference or the heavily loaded wideband interference. This paper also states that even more moderate levels of interference caused the performance of standard rake receivers to degrade the signal.

Reference [24] studies the error probability of ultra wideband spread spectrum multiple access (SSMA) through channels containing additive white Guassian noise (AWGN) in which all active users transmit in the same channel. With the incorporation of M-ary pulse position modulation (PPM) signals the multiple-access performance of bit error rate is studied for multiple users in a system. Additionally, the signal-to-noise ratio, bit transmission rate, and the number of signal levels in an M-ary signal set are also studied. These signals are studied with multiple users.

Some additional work on time hopping with pseudo-chaotic spacing is researched in [25]. The coding system is based on upon controlling the symbolic dynamics of pseudo-chaotic map for encoding the digital information to be transmitted. The chaotic time hopping enhances the spread spectrum characteristics of the system. This is completed by removing most of the periodic, continuous characteristics of a transmitted signal. A detector is proposed for its maximum likelihood scalability features. Additionally, the theoretical soft and hard decision performance bounds are studied. These bounds are decoded by Viterbi simulations. This paper also emphasizes the use of convolutional coding to add flexibility to the receiver.

Some additional time hopping PPM UWB work has been researched by [26]. This paper presents a new method for the evaluation of the bit error probability of a time hopping binary PPM UWB scheme with the presence of multiuser interference. The technique researched predicts that the system performance with high accuracy and rational accuracy. Reference [26] proves the theory with simulation results and compares them to Gaussian approximations. The simulations assume that there are no pulse collisions, due to the time hopping coding. The binary data modulation factor from the standard UWB equation is implemented, due to the fact that the PPM model is in a binary form.

Reference [3] also goes into great detail about many aspects of modulation schemes for UWB. This paper first goes into detail about UWB interference to a coherent phase shift keying (PSK). This section will analyze the bit error rate (BER) performance of a coherent PSK receiver in the presence of several types of modulated UWB signal. The main analysis consists of assuming a non-fading channel that is corrupted by additive white Gaussian noise (AWGN). This paper also goes into detail about frequency shift keying (FSK), and how BER is changed with certain types of intersymbol interference. Some additional work on power spectral density (PSD) using time hopping (TH) UWB was studied. This paper goes into detail on the coexistence that UWB has on narrowband signals. This paper presents a mathematical representation that enables the evaluation of the PSD for UWB.

There is a great amount current and future work constantly evolving for UWB. Reference [27] researches various modulation options for UWB systems in terms of their bit error rate performances, spectral characteristics, modem/hardware complexities, and data rates. The performance of each modulation scheme under realistic conditions, such as multipath, multiple-access interference, narrowband interference, and timing jitter are analyzed using simulation.

Some additional work has been done on many types of rake receivers. The performance of a single-user, ultra-wideband communications system employing binary block-coded modulation with pulse position modulation, or on/off key shifting, while operating in indoor multipath channels is researched in [28]. This paper researches the difference of performance between receiver complexity of a RAKE receiver and a maximal-ratio combining receiver. This paper derives expressions, which are evaluated numerically with UWB channel data.

Reference [29] proposes an efficient method to calculate a multi-carrier, coded system over multipath fading channels. In the future, the system configuration for wideband systems over multipath fading channels will be efficiently examined. Since UWB is being considered for long range communications, more multipath interference will become an issue. The use of a passband system, with pulse position modulation is being considered for long range communications. It has been simulated that pulse position modulation will maintain a high, continuous power over a long frequency range, generally over several GHz.

Reference [30] proposes using RAKE receivers to detect binary block-coded PPM in dense multipath channels corrupted by AWGN. Several designs are explored with various finger selections, all while maintaining maximum energy capture per transfer of each bit stream. Generally, the more finger, the easier it is to filter out any intersymbol interference. Additionally, the increase of fingers will allow a system to receive multiple signals, with different timing sequences.

Reference [31] proposes the use of CDMA for UWB communication. The performance of several DS/CDMA designs are simulated in AWGN, and compared to the performance of TH-PPM. Since PPM and CDMA are both coded, each should give comparable results. Additionally, CDMA is a proven technology, therefore, UWB may be a useful addition to propagate the signal.

2.3 Research

There has been a great amount of research performed on UWB. Reference [7] researches additional channel algorithms, reference [32] and [33] have looked at UWB indoor performance, and research on uniform pulse distribution for UWB. Studies have proven that the power spectral density spectrum often has a large amount of spectral combs when several types of modulation schemes have been used with uniform pulse distribution. Since covertness of a signal is important in every aspect, the spectral combs must be reduced to avoid detection. Reference [8] researches the design and implementation of a covert UWB signal.

This thesis investigates the fact that adding a time hopping sequence to any of the modulation schemes available, the spectral combs will be greatly reduced, maybe even possibly reduced to a negligible level. Spectral combs are known as zero power samples across a frequency range on a PSD plot. The zero power causes a long spectral spike to occur during the spectrum. The smoother the spectral signal, the less detectable a signal will be. This will be accomplished by creating additional samples to occur on the power spectrum, thus not allowing spectral combs to occur. For the communication industry, UWB must not interfere with signals that share the same spectrum. It must be very discrete in passing through a channel. References [9], and [34]-[36] discuss in detail how to create a UWB signal that does not interfere with existing spectrum, and also a UWB signal that is not corrupted by interference. References [10] and [37] address system design and system performance based on UWB design. By adding time hopping to any modulation scheme, it will greatly reduce the probability of pulse collision, allowing an improvement to bit error rate. References [7], [33], and [38] discuss different modulation schemes and how the addition of a time hopping sequence can improve performance of a UWB system.

Additionally, this thesis will determine if, and how time hopping will affect the capacity of a system. Since the pulse spacing will not be uniform, it must be determined if the capacity will increase or decrease. This will be determined by the size of the spreading ratio, which is defined in chapter 4.

This thesis will also examine the results of a bit error rate (BER) performance using time hopping. BER simulations using several modulation schemes of UWB using uniform pulse distribution can be viewed in [39]. The research in this thesis will prove that time hopping improves spectral density, and keeps bit error across a channel low.

Chapter 3
General System Design

3.1 Implementing UWB Transmitter

The first step for transmitting data is to generate a pulse waveform that is Gaussian in nature. This creates individual, equally symmetric pulses to be placed on the baseband signal. The waveform to be generated is mathematically the first derivative of a Gaussian pulse, which creates a monopulse. The Guassian first derivative is given as

$$s(t) = \frac{1}{2}\sqrt{e}A\pi t f_c e^{-2(\pi t f_c)^2} . \tag{3.1}$$

The peak amplitude of the pulse is represented by A, f_c is the center frequency, and t is the time duration. The f_c and t variables actually cancel each other, because f_c is in GHz and t is in nanoseconds, leaving an additional amplitude shift. Once the waveform is created, additional pulse spacing for the UWB signal can be considered pending the application. By subtracting an integer greater than zero to the time duration, *t,* the pulse will be shifted between zero and infinite. This time shift creates the spacing between each pulse of a pulse train signal. The type of modulation scheme, described in Chapter 4, must also be chosen to transmit the pulses across a channel. Each modulation scheme is unique in performance for certain applications. The first derivative of the Gaussian pulse is shown in Figure 3.1. There is no time shift in the pulse and the pulse carries equal distribution on each side. Note that some figures in later sections of this thesis have signals that are shifted in time and have different pulse widths, but each pulse will carry equal distribution. The signal width is defined by the time function, and how many pulses are contained in each time frame. In order to fit large numbers of pulses in a given time frame, each pulse width must narrow, however, this could change the performance of the signal.

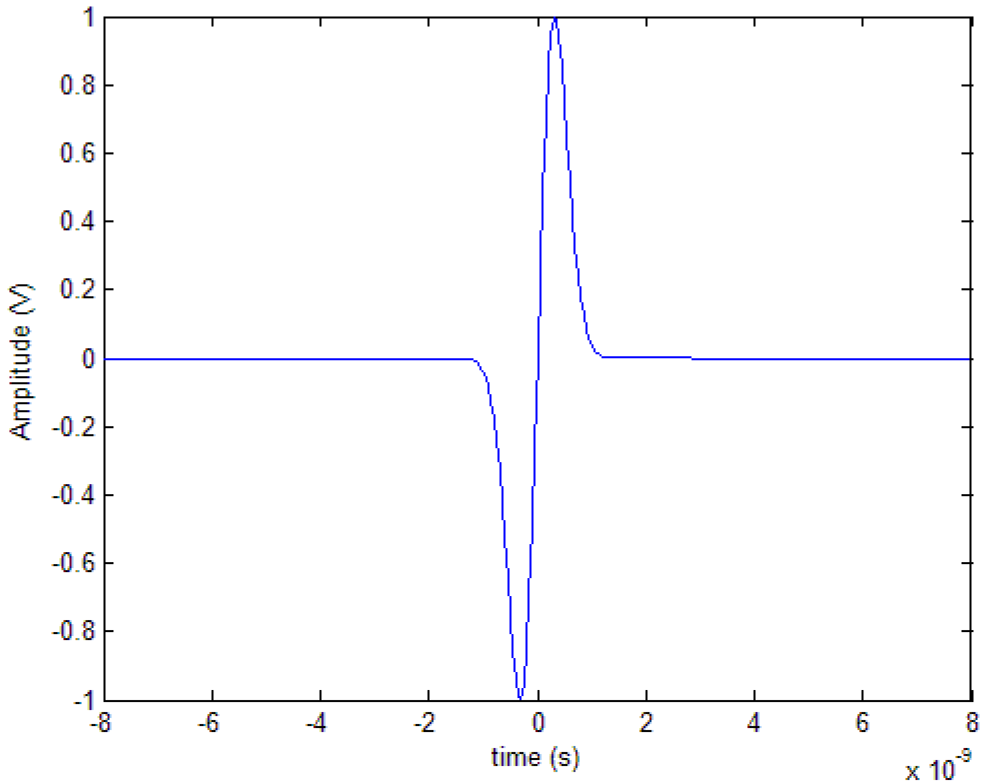


Figure 3.1 Gaussian first derivative pulse.

The time shift, or the position of the pulse, can either be random or pre-set depending on the application. This time shift is called time hopping. Chapter 4 and Chapter 5 will go into detail of random time hopping. The frequency domain of the Gaussian first derivative pulse can be found using

$$S(f) = |s(t)|^2 . \tag{3.2}$$

When (3.2) is simulated, it gives a result in Figure 3.2. The figure clearly shows that the pulse has a smooth spectrum. The result in Figure 3.2 is strictly theoretical, because no noise was added to the system. An ideal signal would have no spectral combs and have a completely smooth spectrum. The simulations in later sections are implemented with additive white Gaussian noise (AWGN).

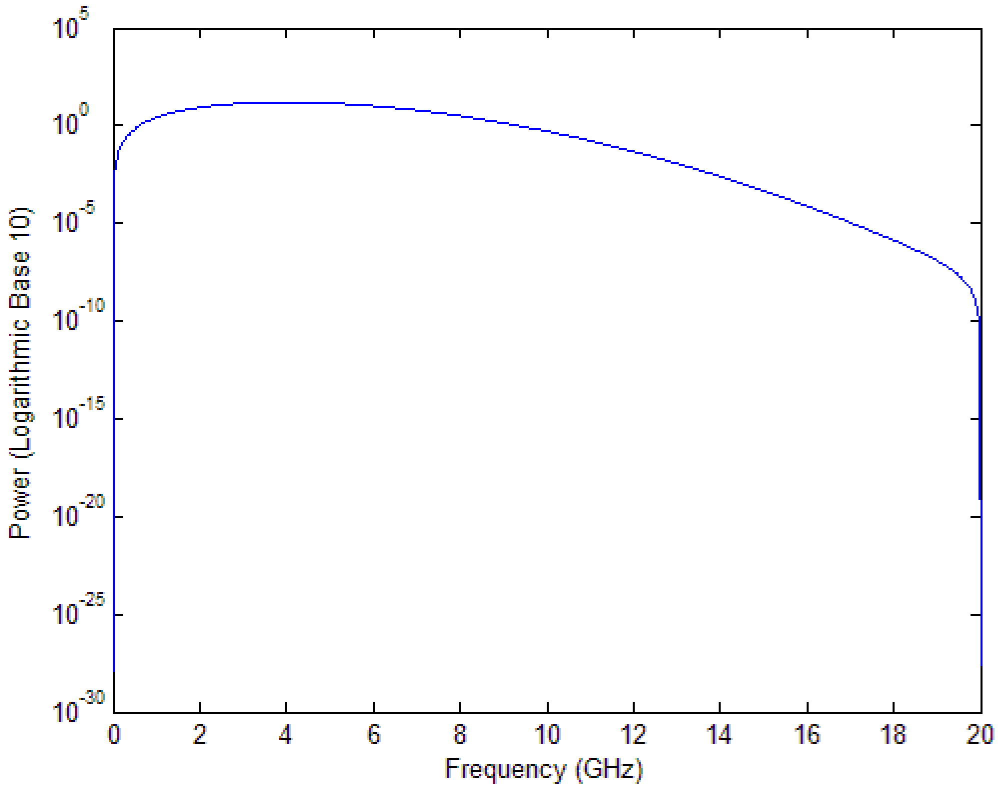


Figure 3.2 PSD of Gaussian first derivative.

The second derivative of the Gaussian pulse can also be configured. This signal can also be used in UWB analysis, and ultimately output to the receiver. Studies have shown that the Gaussian second derivative pulse using certain modulation schemes, will have very different power spectral densities, and bit error rate performances. The second derivative of the Gaussian pulse is shown in Figure 3.3. Note that the pulse is time shifted, yet distribution of the pulse is uniform. The transmission of the signal is capable of transmitting data across a channel at a very low cost of power. Despite UWB having low power transmission, it also has an incredible ability to penetrate walls and buildings, giving it the ability to work in multipath environments. Since UWB is a time configured system, it can allow a large number of users in a system, giving the potential for great use in the communications industry. It also has a low probability of detection, giving the military a use for it also.

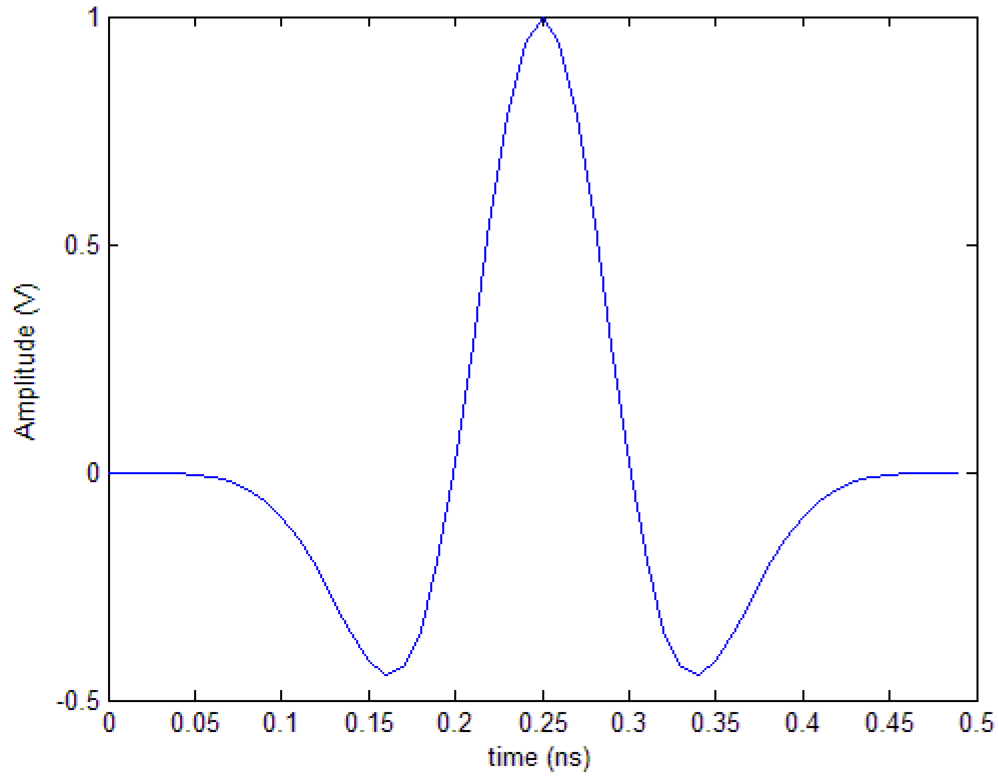


Figure 3.3 Gaussian second derivative pulse.

The performance of UWB in multiple-access environments is totally dependent on the modulation scheme used. Changing certain parameters, such as the pulse spacing, the amplitude, and pulse output will all enhance the performance of the signal. The only advantage to enhancing the performance is to improve the bit error rate or decrease the chance of signal interception, by improving the power spectrum across a frequency channel. Different modulation schemes change the shape of the transmitting signal, which allows easier passage through multi-path areas. Since certain modulation schemes offer improved performance when used in different environments, several specifications must be taken under consideration before designing the signal for application. The next step is to build a receiver that will be able to detect and demodulate the signal. The receiver for UWB is very difficult to implement, due to the large variations of potential UWB signals that can be transmitted.

3.2 UWB System Structure

The most popular and the most researched section of UWB is using time hopping sequences. The time hopping sequence generally has a very low duty cycle, somewhere around $T_f / T_p > 100$, where T_f is the frame time, and T_p is the number of pulse. The first step of design for transmitting data by a UWB signal is to develop a data pulse train. Each pulse contains some amount of data that the user wishes to transmit. Time hopping allocates the system the ability to set the distance between each pulse, either pre-set or random. A uniform pulse train is shown in Figure 3.4. A UWB uniform pulse train signal is represented as a sum of pulses shifted in time as

$$s(t) = \sum_j a_j w(t - t_j)\,. \tag{3.3}$$

Where *s(t)* is the modulated UWB signal, and the transmitted UWB pulse shape is expressed as *w(t)*, the amplitude offset is expressed as a_j with t_j being the time shift offset. Notice that the pulse width of each pulse in Figure 3.4 is equal, and the spacing is uniform. Also, note that despite the decrease in the pulse width and increase in pulses for the given time duration, the amplitude per pulse does not change.

An increase in the pulses in the time duration given in Figure 3.4 will not result the same output, nor will performance remain the same. This is due to the decrease in spacing between pulses. In later chapters, the amplitudes and pulse spacing will not be uniform. The additional time shift will result in a change of performance, due to the new variances. It is important to note that the pulse amplitude variances can have a direct effect on how much data a pulse can carry. In terms of a covert signal, the variances create disruption and confusion to any unwarranted receivers.

The UWB system is described and given as

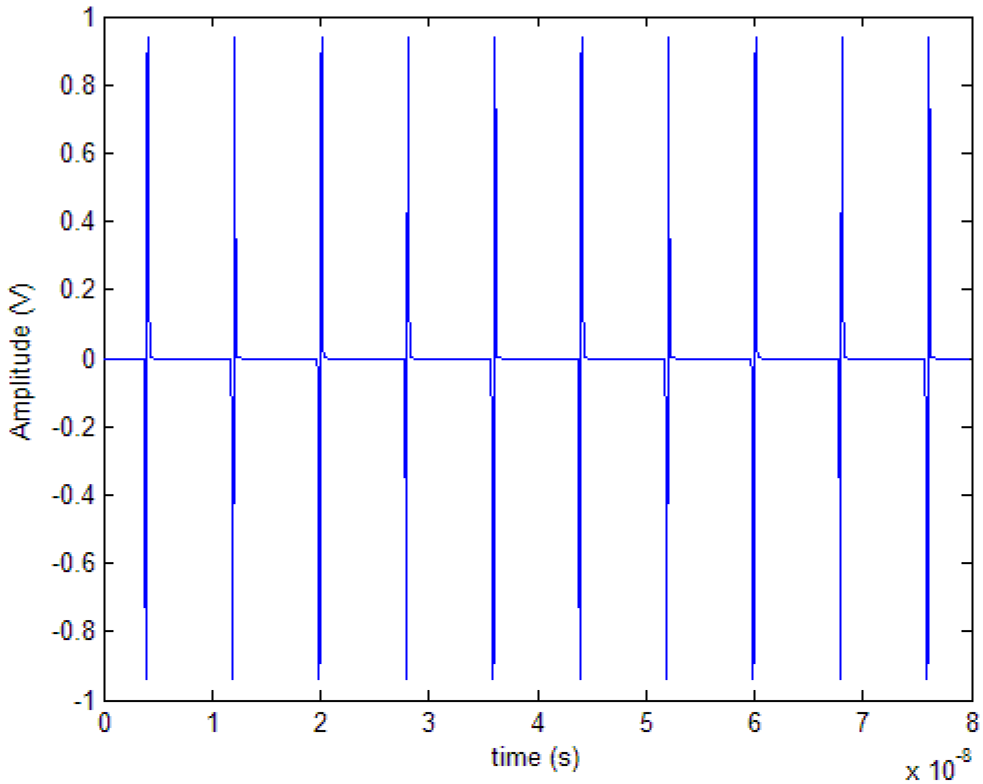


Figure 3.4 Pulse train of Gaussian first derivative.

$$s(t) = \sum_{j}^{Ns} Aw(t - jT_f - c_j T_c - \delta d_j), \tag{3.4}$$

where,

A is the pulse amplitude

w(t) is the normalized pulse shape

T_f is the pulse repetition time, or frame time

c_j is the time hopping sequence

T_c is the additional time hopping delay

δ is a modulation factor

d_j is a binary bit stream

N_s is the number of pulse

Within each time frame, each pulse can be pseudo-randomly positioned in time. This is great for the communications industry, since this allows for multiple users while also smoothing the spectrum. The function T_c is an additional time difference factor between each pulse position. Figure 3.5 displays a single pulse with the position changed by time hopping. Figure 3.5 shows the pulse could be shifted to any of the positions during the given time duration pending the value of c_jT_c. Since data pulses cannot share a position, the greater the time shift between pulses, the fewer number of pulses will fit in a given time frame, resulting in fewer data bits available for each users. Additionally, the smaller the number of time shifts between each pulse, the greater the number of pulses will be allowed during the given time duration, resulting in the increase of users and large data rate. Therefore, the time shift has a direct correlation to the number of pulses able to fit in a given time duration. This will allow the communications industry to give each user a c_jT_c value and assign the receiver the same c_jT_c value. This is ideal for the military because the signal cannot be intercepted without knowing the timing sequence.

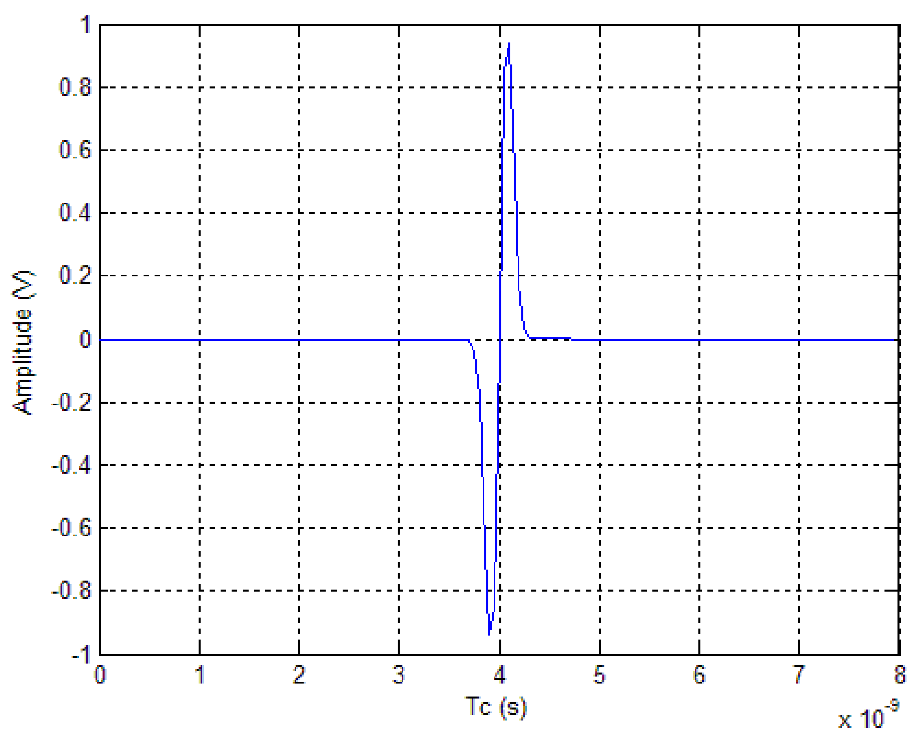


Figure 3.5 Time shift of Gaussian first derivative.

3.3 Designing a Receiver for UWB

The best receiver for a single bit UWB system in additive Gaussian noise is a correlation receiver [40]. The receiver block diagram in Figure 3.6 does not have the ability to receive a pulse train sequence. This receiver can only detect a single pulse signal. The implementation is shown in Figure 3.6.

The receiver design for UWB is extremely difficult. With the addition of time hopping and signal corruption from AWGN, signal detection for the receiver becomes increasingly difficult. To receive a signal and properly demodulate it, the system requires the use of a correlating receiver, such as a spread spectrum receiver design. Signal detection often becomes more difficult as the signal is modulated more. Chapter 5 will go into more detail on how a correlation receiver detects and demodulates UWB signal with all types of modulation schemes.

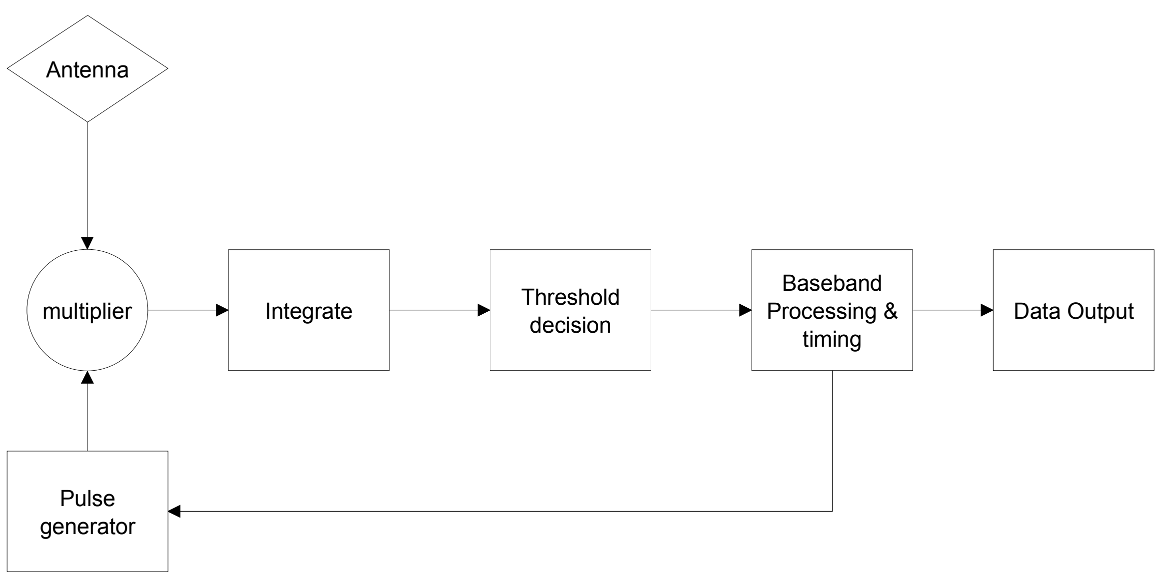


Figure 3.6 UWB receiver without time hopping.

Chapter 4
UWB Modulation

4.1 UWB Modulation Methods

UWB is unique due to the ability to be modulated several different ways. This makes it very constructive for any application. These modulation schemes are pulse position modulation (PPM), using binary or M-ary, bipolar signaling (BPSK), pulse amplitude modulation (PAM), on/off keying (OOK), orthogonal pulse shapes, and a combination of all. Figures in this chapter estimating capacity and number of users is calculated with additive white Gaussian noise (AWGN). The capacity for multiple access channels is calculated with signal-to-noise ratio considerations. The specified bit error probability can only be achieved when the required amount of signal-to-noise is reached. The noise floor also rises as the number of users becomes greater. We assume UWB transmissions utilize a pulse scheme modulation method. A general equation for every UWB modulation scheme is expressed in [41] and given as

$$s(t) = \sum_j a_j w(t - jT_f - c_j T_c - \delta d_j) . \tag{4.1}$$

4.1.1 PPM Modulation

The first modulation type is pulse position modulation (PPM). PPM is given as

$$s(t) = \sum_j a_j w(t - jT_f - c_j T_c - \delta_{opt} d_j). \tag{4.2}$$

A PPM example is shown in Figure 4.1 using time hopping. Figure 4.1 is a binary PPM model. The pulses are placed at 0, or 1. The position is based on the amplitude of the analog signal. Maximum amplitude places the pulse at 1, minimum amplitude is at 0.

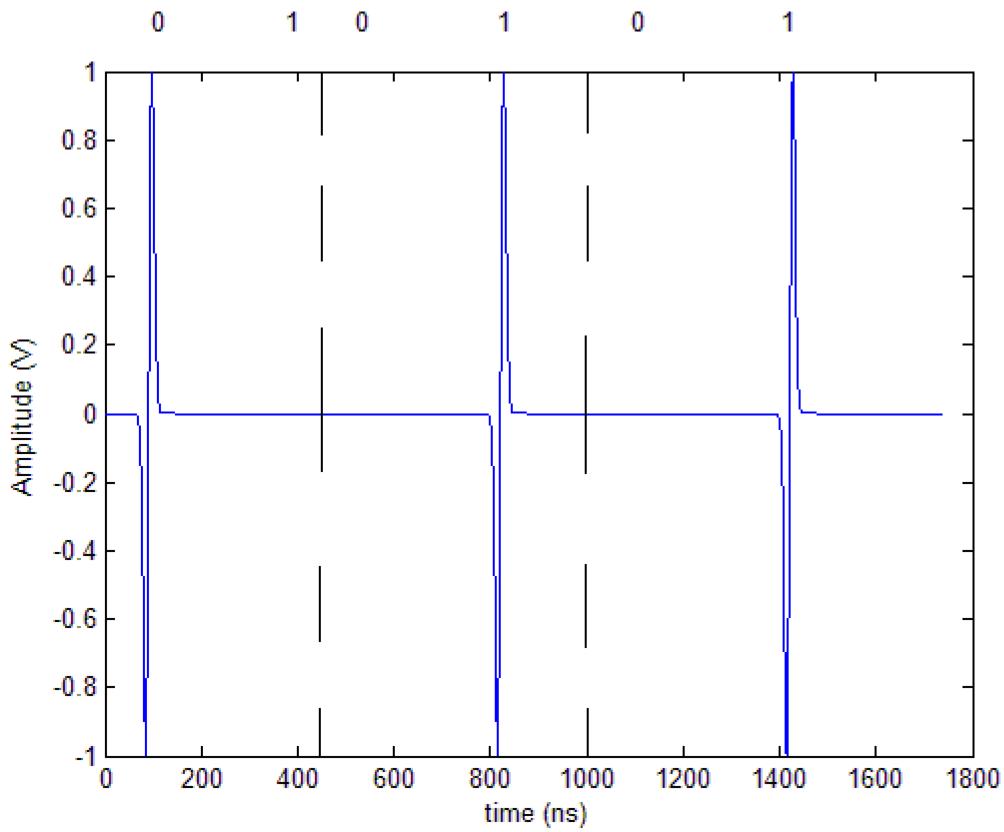


Figure 4.1 PPM model.

Figure 4.2 displays the capacity of an M-ary PPM model. Taking into account AWGN, the SNR per symbol at the output of the correlation receiver is found in [42] and given as

$$\rho_I = \frac{3\beta}{(N_u - 1) + \frac{3\beta}{\rho_o}}. \tag{4.3}$$

Where the variance of the signal, again taking into account AWGN, can be found in [42] and calculated by

$$\rho_o = \frac{2E_p}{N_o}, \tag{4.4}$$

where

$$N_u > \frac{3\beta}{\rho_o}. \tag{4.5}$$

Where N_u is the number of users, E_p is the energy per pulse, β is the spreading ratio, and ρ_o is the variance. The user capacity Cm-PPM as a function of the channel symbol SNR is given by

$$C_{M-PPM} = \log_2 M - E_{v:x1} \log_2 \sum_{m=1}^{M} \exp[\sqrt{\rho_I}(v_m - v_1)] \ . \tag{4.6}$$

Where ρ_I is the symbol channel SNR, and v_m is random variables from m=1,…,m. All M-ary PPM models were created by the method in [42]. Figure 4.2 displays an M-ary system with spreading ratio $\beta = T_f / T_p = 50$, where T_f is the frame interval and T_p is the number of pulses. Figure 4.2 clearly shows that up to ten users, the capacity per user is much greater using a 32-ppm model. The performance between the M-ary models begins to converge as the users increase from ten to one hundred. There is a significant drop in capacity of all M-ary models because the large number of users in

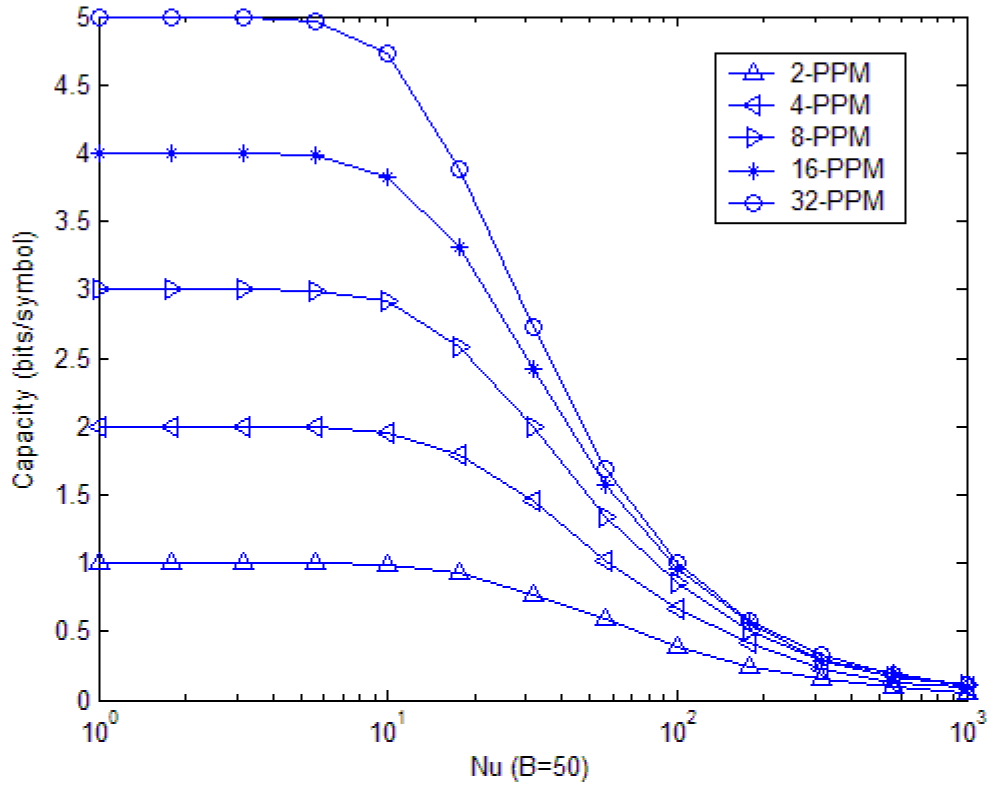


Figure 4.2 Capacity of M-ary PPM at B=50.

each time frame is increasing the total bits in the channel. The system cannot sustain the same performance with high user volume without decreasing the bits per symbol per user. Therefore, for high volume of users, less bits are allocated for each user. One frame time can only contain a certain number of pulses, so once the number of users of each M-ary model max out the frame time, the capacity of all M-ary models become identical. By Figure 4.2, the capacity for M-ary systems is still the greatest between ten and one hundred users when a 32-ppm model is used, but the difference is shown when the users reach one thousand. At that point, all M-ary levels converge to the same point, which draws the conclusion that as the users reach large levels, any level M-ary PPM model will give the same amount of capacity.

Figure 4.3 displays a M-ary PPM model with $\beta = T_f \;/\; T_p$=500. The same equations from [42] used for Figure 4.2 were used to generate Figure 4.3. This figure was simulated from one user to one thousand users. This figure displays how the spreading ratio, β, actually affects the capacity of a system. Clearly the aggregate capacity is constant for all M-ary PPM models from one to ten users. We can also observe that from ten to one hundred users, the aggregate capacity of the M-ary models begin to increase as the number of users increases for each type. This occurs because the frame time is so great, as the number of users for each M-ary model increases, so does the number of bits in the channel, thus allowing a higher data rate and increased aggregate capacity. Once the number of users is at one thousand, we can determine that the capacity at β=500 is greatest for 32-ary PPM. From Figure 4.2, and Figure 4.3, we can conclude that the spreading ratio determines the bit capacity in the system.

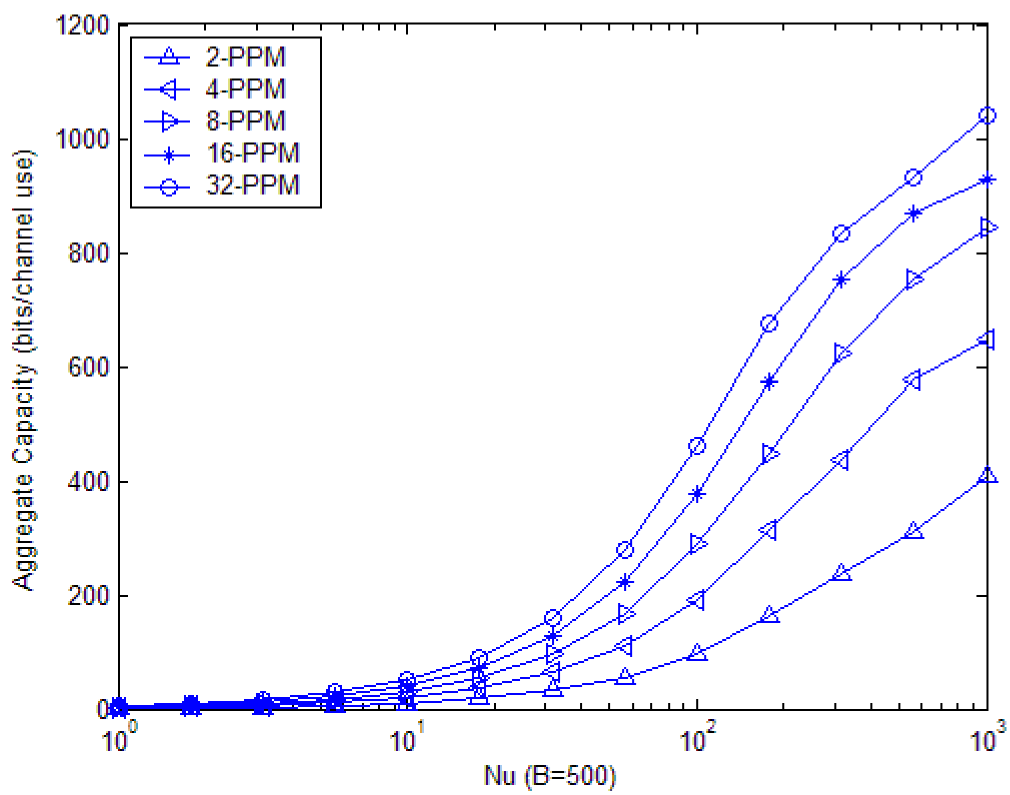


Figure 4.3 Capacity of M-ary PPM at B=500.

Figure 4.4, found using [42], displays a 32-ary PPM model at different spreading Ratios. The 32-ary PPM figure displays that at high user volume, the capacity is the same when a large or small spreading ratio is used. From this figure, we can clearly state that the spreading ratio has a direct result on the capacity. Since the spreading ratio is the frame time divided by the number of pulses, the smaller the frame time, and the greater the number of pulses, the smaller the spreading ratio becomes, resulting in an increased bit capacity. Therefore, the smaller the spreading ratio, the greater the user capacity becomes. This occurs due to the large amount of data bits being packed into each frame. Chapter 5 will go into detail on why increasing or decreasing the bits in a channel will not affect the BER of a system. This is true for all types of UWB modulation schemes. References [43] and [44] can offer additional information into performance and capacity of time hopping PPM.

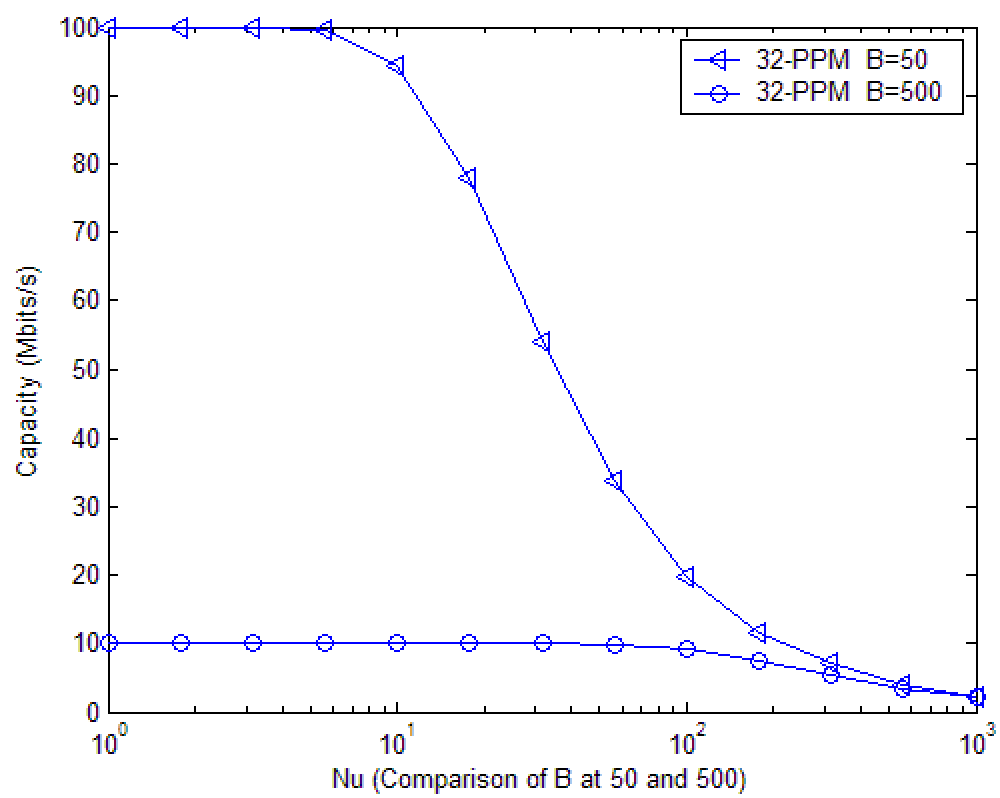


Figure 4.4 Comparison of 32-ary PPM at B=50 and B=500.

4.1.2 PAM modulation

The next type of modulation that is pulse amplitude modulation (PAM). Figure 4.5 displays various pulses that have different amplitudes within the same signal, but the pulse spacing is uniform. The variations of the pulse amplitudes will spread the data about the signal. Therefore the data packet of one pulse will be different from another pulse. This will cause the pulse train to be longer, resulting in a large time frame. Figure 4.5 is a PAM plot configured using the following UWB equation given as

$$s(t) = \sum_{j} j a_j w(t - t_j). \tag{4.7}$$

Note that a_j defines the variation for the pulse amplitudes. Figure 4.5 displays several pulses with a variable binary amplitudes. These pulses with variable amplitudes can be

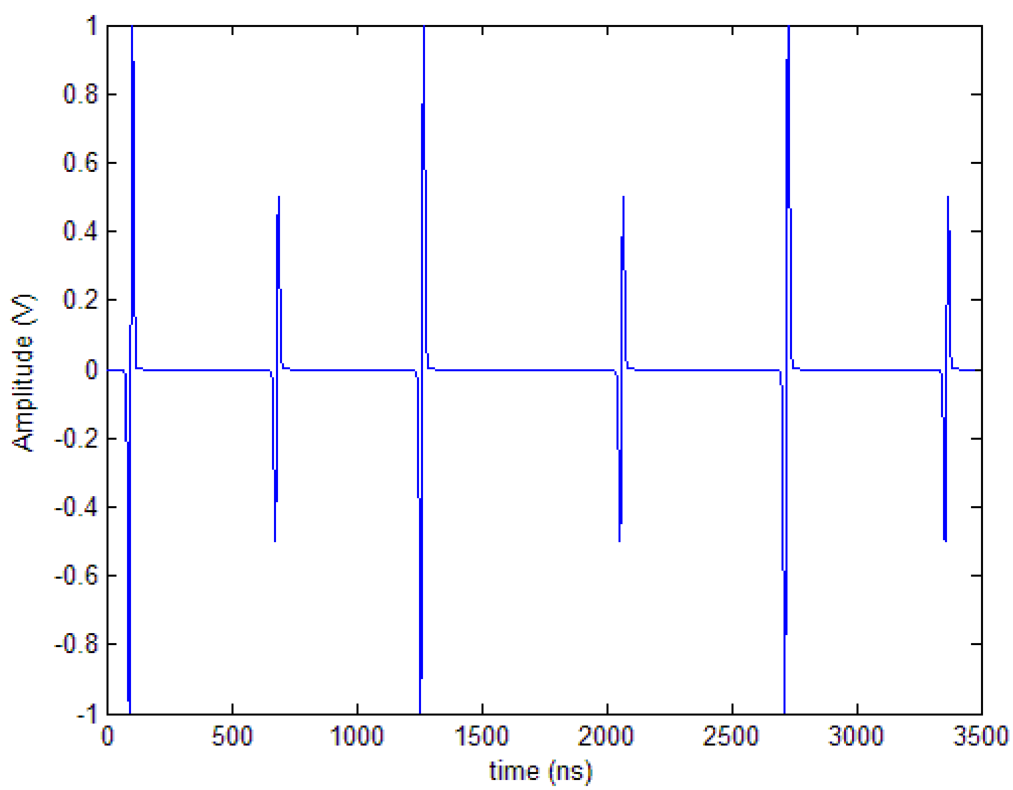


Figure 4.5 Pulse amplitude modulation (PAM) model.

arranged randomly, pending the application. The random amplitudes, combined with random pulse time shifting creates chaos for anyone trying to intercept the signal, thus PAM is getting a great amount of attention from the DOD. Sometimes pulse amplitude modulation can be poorly energy efficient. The random amplitudes combined with random time shifting can improve combs in the spectrum. Since the data is spread amongst random pulses, the time frame can be longer in duration to fit the entire signal. Since spectral combs are created by every new frame time; the less amount of occurring frames, the less spectral combs occur. The receiver also does not need to be adjusted to receive the non-uniform pulses, the template is adequate in processing the signal.

4.1.3 OOK modulation

The next type of modulation is on/off key (OOK) modulation. This type of modulation is the most simple in terms of implementation. The standard OOK data modulation is defined and given as

$$s(t) = \sum_j a_j w(t - jT_f). \tag{4.8}$$

The data sequence in Figure 4.6 is 1, 0, 0, 1. An OOK system is simple and easily defined. It is simply the process of transmitting one pulse, and then having no signal or turning the system off, then transmitting another pulse. When a signal is output, the system is on, as Figure 4.6 displays as a 1.

4.1.4 BPSK Modulation

The next type of modulation is Binary phase shift keying, otherwise known as BPSK. In this modulation method, data is carried by the polarity of the pulse. The phase value of zero degrees means that the data bit is 1, while the phase value of 180 degrees

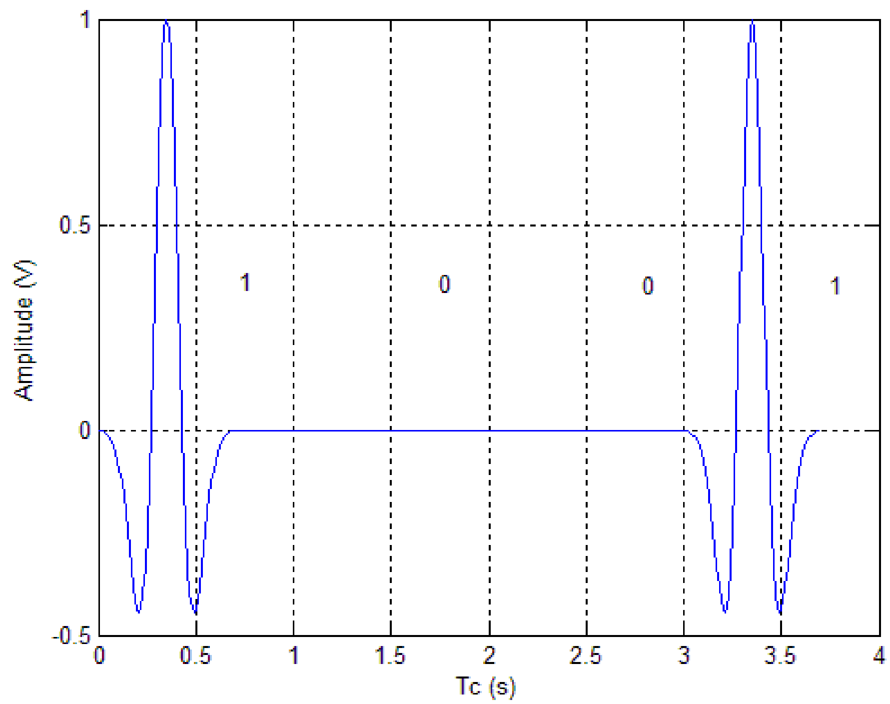


Figure 4.6 On/Off keying model.

indicates the data bit is 0. The standard BPSK data modulation equation is defined by [41] and given as

$$s(t) = \sum_{j} \pm a_j w(t - jT_f). \tag{4.9}$$

Figure 4.7 displays a UWB output with BPSK modulation. Notice that the phase of the second pulse has a different polarity than the first pulse. If a pulse train of BPSK were created, the pulses would follow the same rule as Figure 4.7. A pulse would be created, and an opposite polarity pulse will follow. Basically, BPSK will have a pulse train in pulse sets of two.

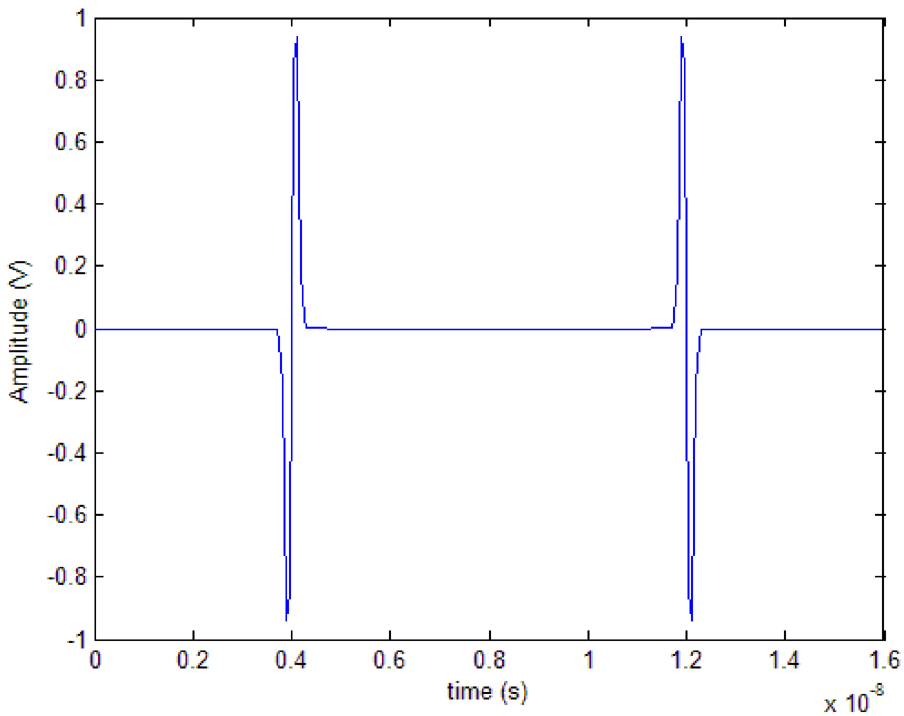


Figure 4.7 BPSK modulation model.

Chapter 5
PSD and BER Comparisons

5.1 Pulse Train with Uniform Spacing

The simplest form of UWB is a signal with uniform pulse train spacing. This type of signal is a long sequence of monopulses spaced across a time distribution, where the pulses are spaced uniformly in time. The standard form for UWB uniform pulse train spacing equation is given as

$$s(t) = \sum_{j} w(t - jT_f), \tag{5.1}$$

where frame time, T_f, is the component for uniform time spacing between each pulse. For a uniform pulse distribution, T_f is constant. Pending on the frame time, the signal can consist of many pulses, or only a few pulses. Figure 5.1 displays the Gaussian first derivative with a frame time of 4 ns (T_f=4 ns), given from (5.1).

Using (5.1), a pulse train of the first derivative is implemented and displayed in Figure 5.2. The pulse train has uniform pulse spacing with ten monopulses. Note that in order to fit all ten pulses in Figure 5.2, a longer timing sequence is needed, due to the uniform spacing of the pulses. Figure 5.2 has a period of 8 ns (T_f=8 ns). The amplitudes of each pulse also remain the same, despite the change in pulse width.

It is beneficial that more pulses can be added to a time frame to increase capacity, but by adding more pulses, the probability of pulse collision increases. If collisions occur, data bits will be lost and the signal will be corrupted. The receiver cannot properly detect and demodulate a corrupted signal.

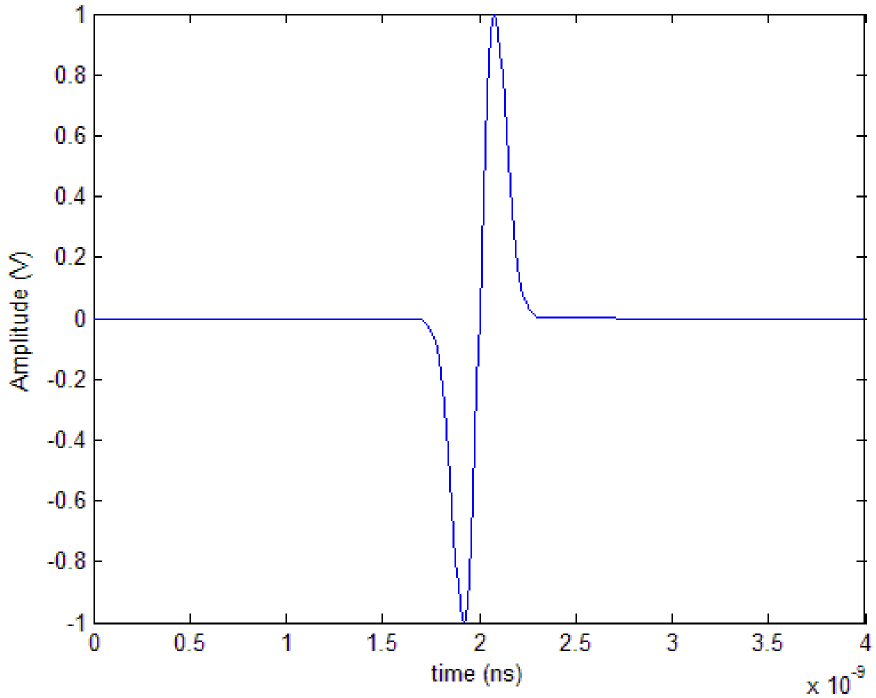


Figure 5.1 Gaussian first derivative pulse (T_f = 4 ns).

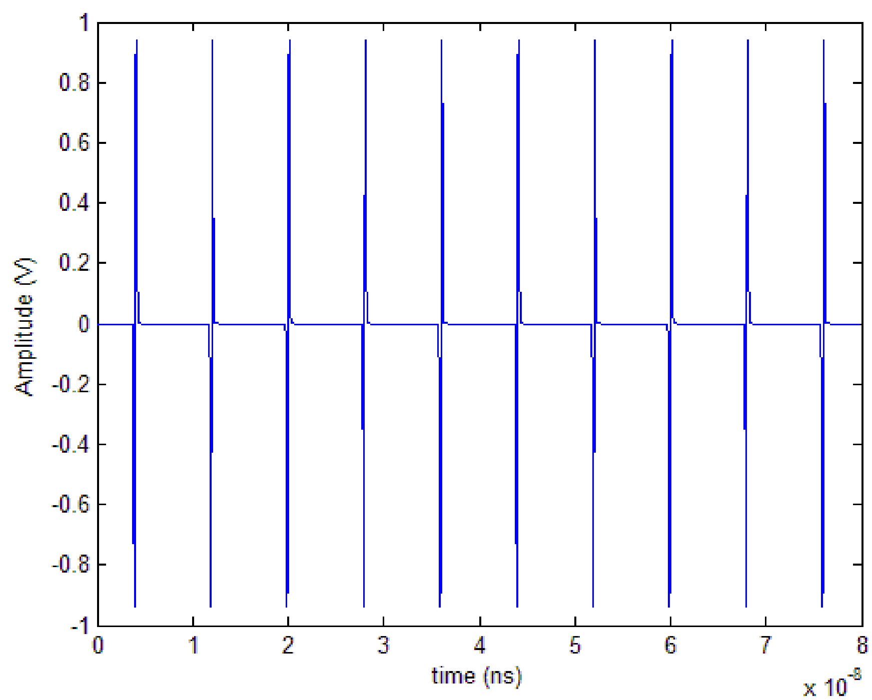


Figure 5.2 Gaussian first derivative pulse train of 10 monopulses.

5.2 Time Hopping

The pulse trains in Figure 5.2 are basic pulse sequences for UWB. If we want to individualize each pulse, we must implement an additional coding scheme to each pulse in the pulse trains. By coding each individual pulse with a timing sequence, the pulse spacing is no longer uniform. This allows multiple access, and will also increase the data rate for each time frame. By coding the pulse train, this will eliminate chances for collisions between pulses [25]. The UWB signal with time hopping implementation can be written as

$$s(t) = \sum_j w(t - jT_f - c_j T_c). \tag{5.2}$$

As (5.2) defines, the pulse train can still be set to a variable number of pulses, but each pulse can be shifted by time to meet the needs of the application. Additional individual time shift coding, c_jT_c, is added to each pulse that is already uniformly shifted in time. The time hopping code, c_jT_c, can be a preset value, or a random code sequence with a period N_p, giving the equation

$$c_{j+iNp} = c_j . \tag{5.3}$$

Since time hopping is periodic with a period N_p, the waveform of (5.2) is periodic with period $T_p = N_pT_f$. The j^{th} monopulse gets shifted by c_jT_c seconds. The time shift is discrete in time between 0 and N_hT_c seconds. The assumption must be made that

$$N_h T_c \le T_f . \tag{5.4}$$

Where N_h is an integer that is greater than or equal to c_j. Figure 5.3 displays a pulse train with time hopping sequences coded into each pulse. It is important to note that since the

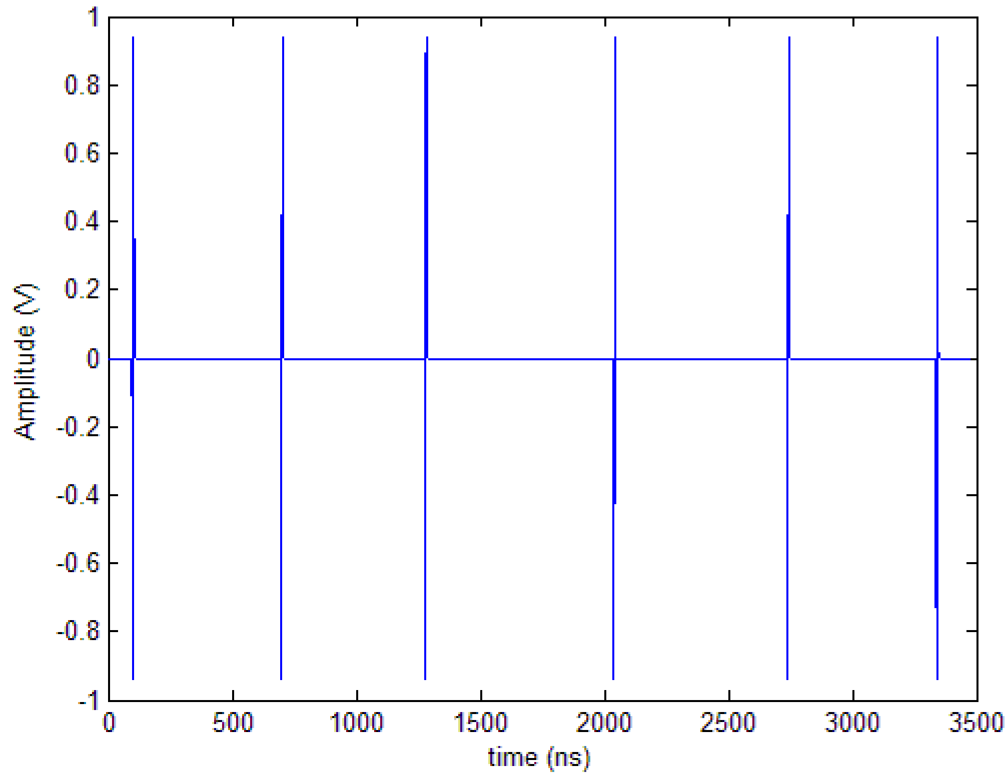


Figure 5.3 Gaussian first derivative time hopping pulse train.

system is transmitting pulses using time hopping, the receiver's template signal must be operating at the same frame time to receive and decode the transmission.

5.3 UWB Transmitter with Time Hopping

In order to transmit a signal, a single pulse or a pulse train must first be constructed and output to the receiver. Once the pulse train is created and modulated by a method from Chapter 4, the code generator, c_jT_c,, is then added to each pulse from the already modulated pulse train. The code generator is generally random in positioning each pulse. A simulated random pulse train will have better performance than a pre-set pulse train. Figure 5.4 displays a UWB transmitter

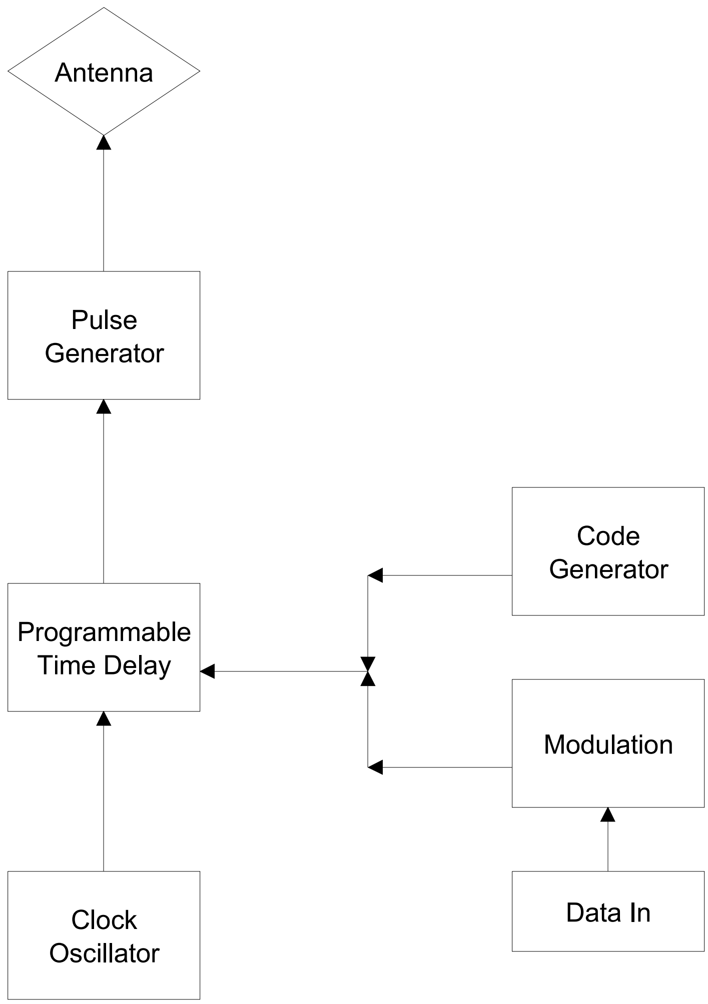


Figure 5.4 Transmitter design.

5.4 UWB Receiver

The UWB receiver is much more difficult to design than the transmitter. In theory the receiver is simple, but implementation proves otherwise. It is standard that every signal passing through a channel will come into contact with noise and interference, which can corrupt the signal. Figure 5.5 displays a fundamental representation of a signal passing through an AWGN channel. The receiver's antenna in Figure 5.5 is defined in [40] and given as

$$r(t) = As(t-\tau) + n(t), \tag{5.5}$$

where A is the attenuation of the signal as it passes through the channel, τ is the time synchronization between the receiver and the transmitter clocks. The additive white noise, *n(t)*, has a PSD given in (5.6) and AWGN has a zero mean and variance given in (5.7).

$$\phi_{nn}(f) = \frac{N_o}{2}. \tag{5.6}$$

$$\sigma^2 = \frac{Eb}{2SNR}. \tag{5.7}$$

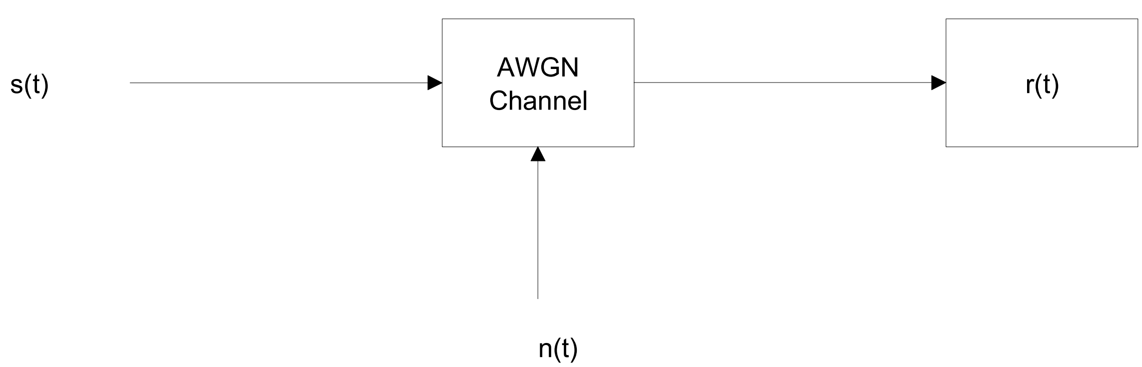


Figure 5.5 AWGN channel representation.

It is imperative that the frame time synchronization of the receiver have identical frame time synchronization as the transmitter. The receiver has an incoming waveform, w_{bit}, given as

$$w_{bit}(t) = \sum_{j=0}^{N_s-1} w_{rec}(t - jT_f - c_j^{(1)}T_c - \tau) \ . \tag{5.8}$$

With an interval duration given as

$$T_s = N_s T_f \ . \tag{5.9}$$

Where N_s is the number of pulses modulated, and T_s is the inverse of the data rate. The preferred receiver for demodulating a UWB signal is a correlation receiver [40]. This type of receiver has a template signal hard coded into the receiver memory. The template signal, v_{bit}, is given as

$$v_{bit}(t) = \sum_{j=o}^{N_s-1} v_{rec}(t - jT_f - c_j^{(1)}T_c - \tau_1), \tag{5.10}$$

where,

$$v_{rec}(t) = w_{rec}(t) - w_{rec}(t - \tau) \ . \tag{5.11}$$

A UWB signal is very difficult to detect, especially when random time hopping coding is involved. A correlation receiver is very unique in how it works. The first step of the receiver is cross-correlate the template signal to the incoming signal. Since the incoming pulse will be corrupted with noise, the UWB receiver must incorporate a method called pulse integration. This is the process of adding numerous correlated samples together, allowing the receiver to demodulate a pulse and the noise. Once the correlated signals are summed, a single pulse with a dc amplitude value remains. The receiver will compare the dc value to a threshold value. Each modulation method has a certain dc value, therefore, the threshold allows the receiver to reject or keep the signal. Figure 5.6 displays a UWB receiver.

5.5 Power Spectral Density (PSD)

The Power spectrum density, PSD, describes how the power, or variance, of a time series is distributed with frequency. Mathematically, it is defined as the Fourier Transform of the autocorrelation sequence of the time series. An equivalent definition of the PSD is the squared modulus of the Fourier transform of the time series. The power spectral density of time hopping UWB signals provides relevant information about the signal, such as coexistence with conventional radio systems. Such aspects as pulse duration, modulation scheme, pulse repetition rate, and the existence of time hopping all determine the shape of the PSD for UWB.

5.5.1 UWB PSD Variations

PSD is directly affected when the pulse duration increases or decreases. Figure 5.7 displays what happens when the pulse duration is decreased to T_f = 0.25 ns with time hopping. The spectrum has a high power at lower frequencies. PSD is also directly affected when the pulse repetition rate changes when time hopping is used. Figure 5.8 displays the effects of the PSD when the pulse rate is increased, with time hopping included. The power of the PSD is uniform, but begins to decrease as the frequency increases.

5.6 PSD of UWB

The PSD spectrum of a UWB signal is very important in analyzing the pulse train performance for UWB. Since UWB is designed to be low in detection and interception,

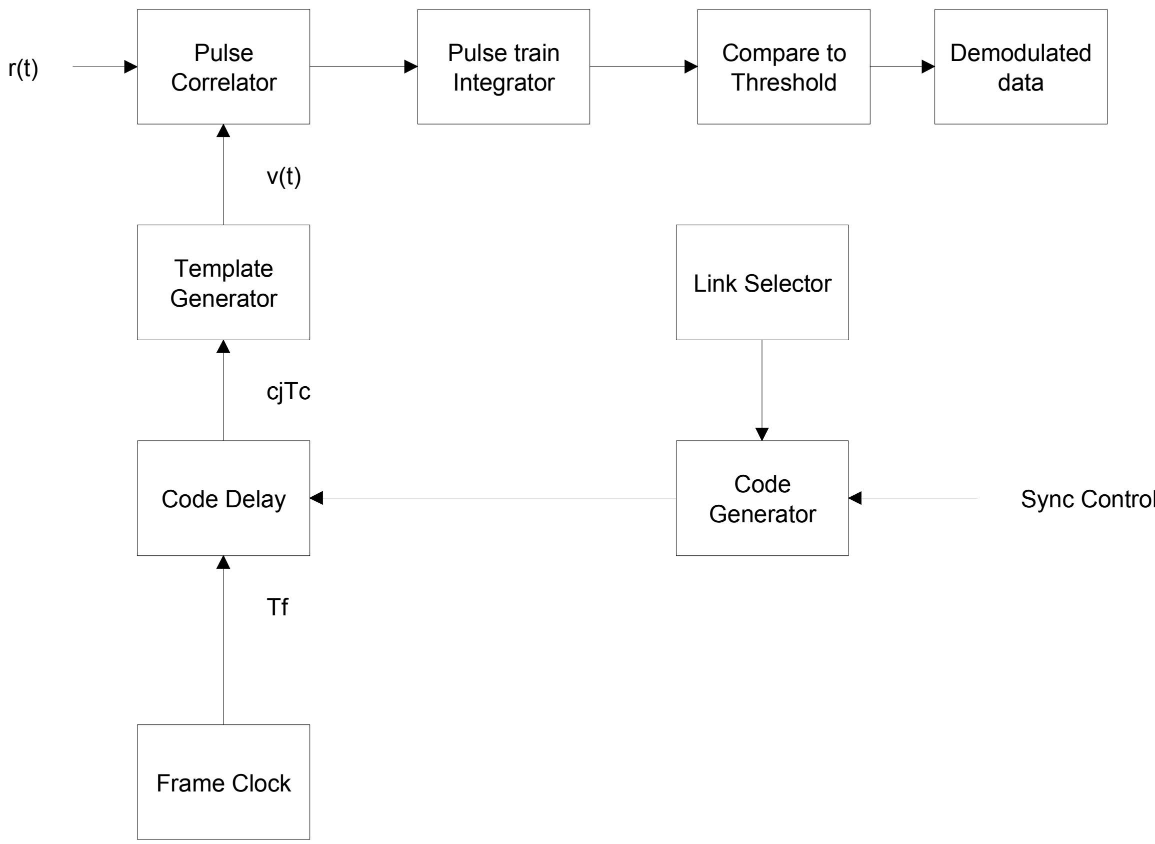
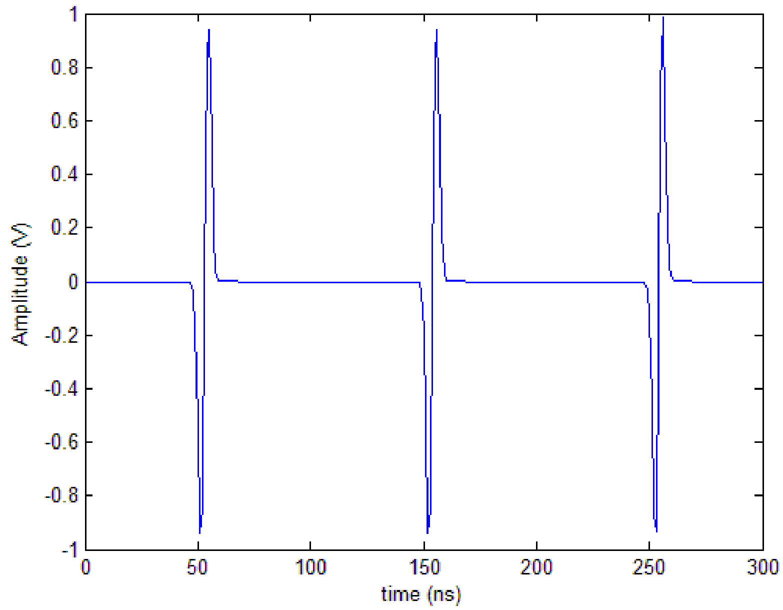
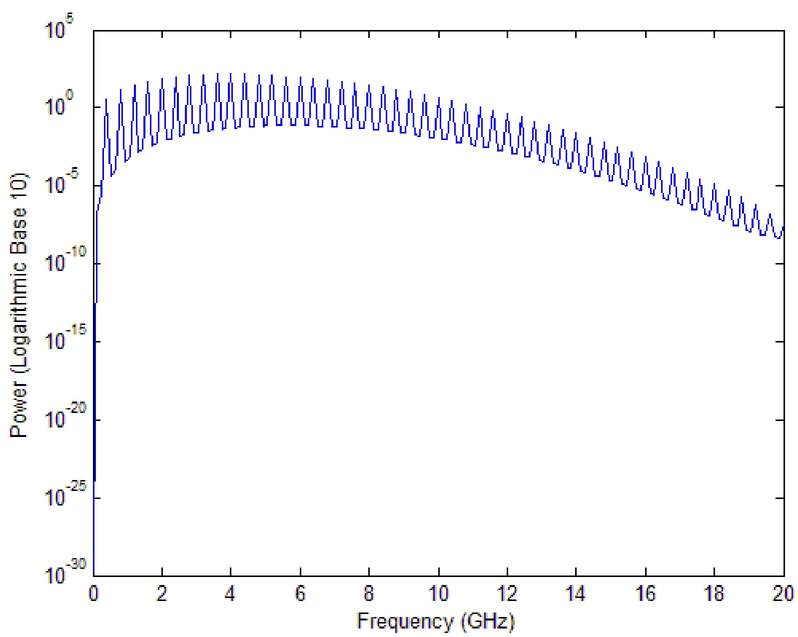


Figure 5.6 UWB correlation receiver.

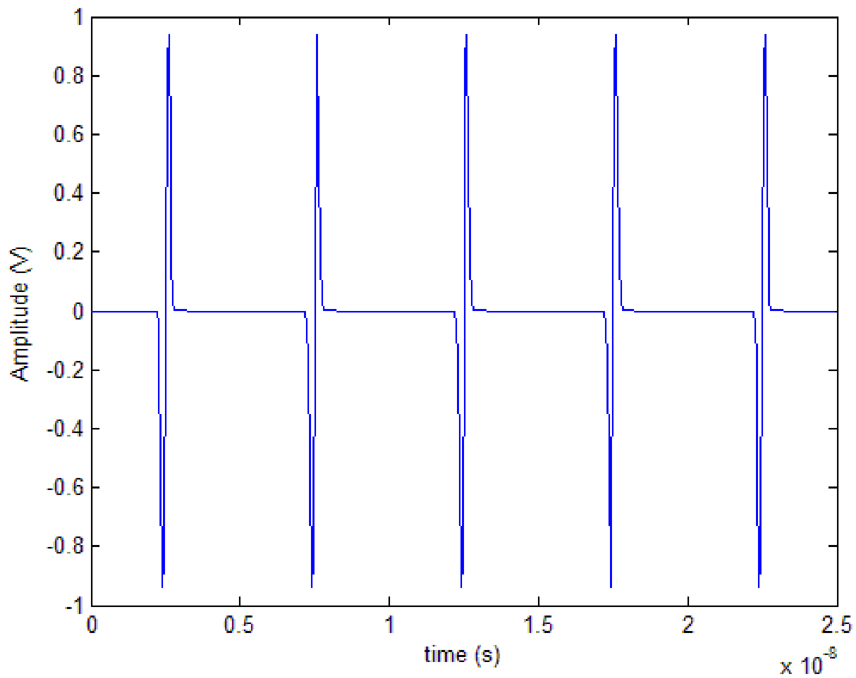


(a) Gaussian first derivative time hopping pulse train at 0.25 ns

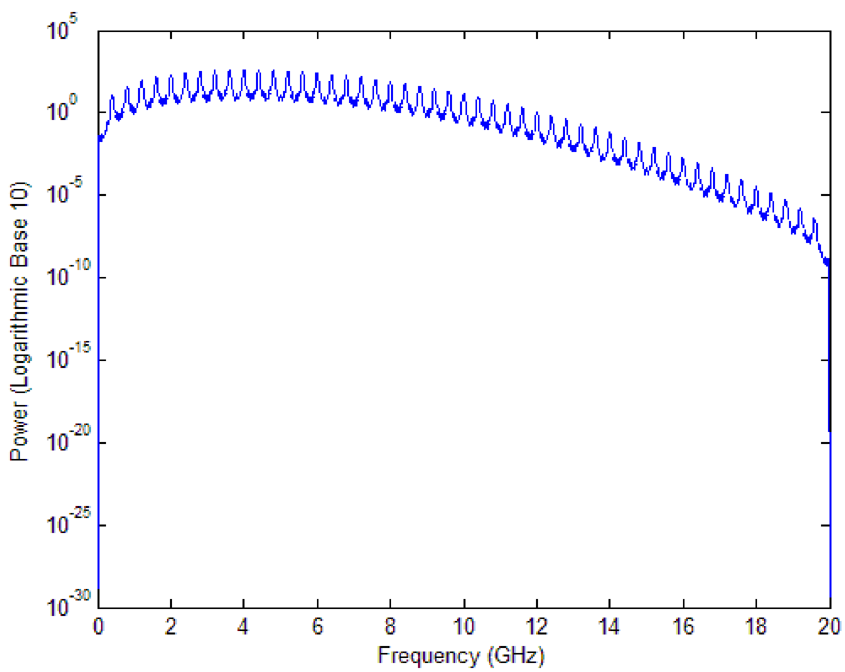


(b) Corresponding PSD of first derivative

Figure 5.7 Gaussian first derivative and corresponding PSD at 0.25 ns.



(a) Pulse repetition change at 0.25 ns



(b) Corresponding PSD of pulse repetition at 0.25 ns

Figure 5.8 Pulse repetition change at 0.25 ns and corresponding PSD.

the spectrum performance is designed to be very smooth. The more spectral combs present in a signal, the probability increases of the UWB signal interfering with other wide band or narrowband signals. References [41],[45]-[48] offer additional derivations of PSD equations and methods for UWB that were used in this thesis.

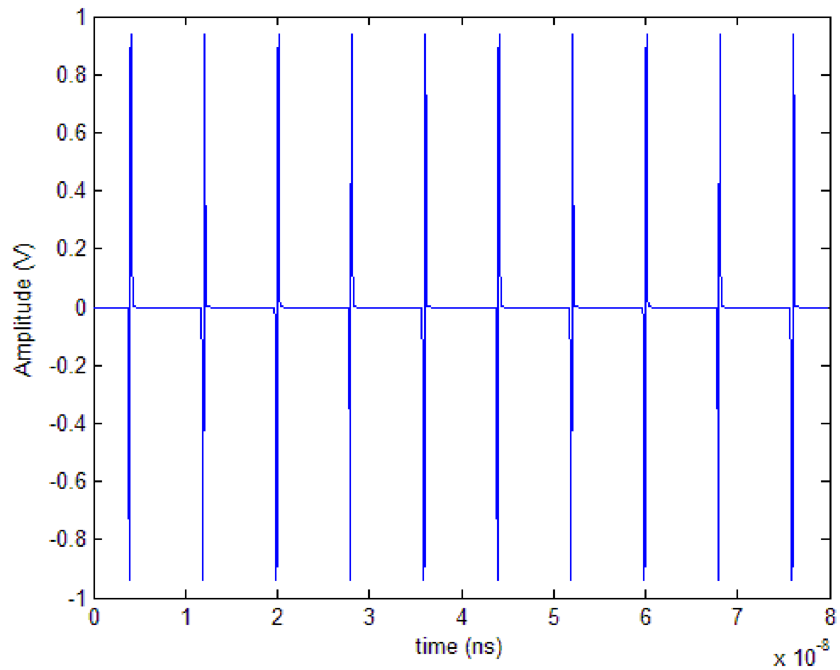
The PSD of a uniform spacing UWB signal can be found by the method in [49] and given as

$$\phi_{ss}(f) = \frac{\sigma_a^{\ 2}}{T_f}|W(f)|^2 + \frac{\mu_a^{\ 2}}{T_f^{\ 2}}\sum_{j=-\infty}^{\infty}\left|W(\frac{j}{T_f})\right|^2 \delta(f-\frac{j}{T_f}), \qquad (5.12)$$

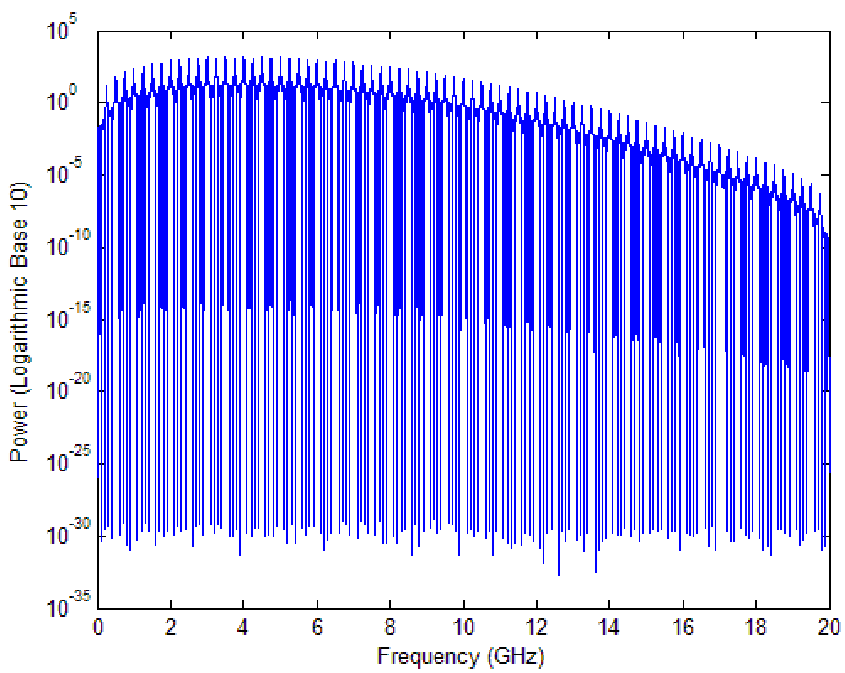
where $\sigma_a^{\ 2}$ and $\mu_a^{\ 2}$ are the variance and the mean squared. A general time hopping plot with the corresponding PSD is displayed in Figure 5.9. Note the deep and continuous spectral combs in the PSD plot for Figure 5.9. The variance can be calculated as $\sigma_a^{\ 2} = E(a^2) - (E(a))^2$, such that the mean from data[01] could be calculated as $\mu_a = (0+1)/2 = 0.5$. Therefore the variance would be $\sigma_a^{\ 2} = (0^2 + 1^1)/2 - (.5)^2 = 0.25$. *$\delta$ (f)* is the unit impulse, which is strictly theoretical in discrete time. *W(f)* is the Fourier transform of *w(t)*, which is continuous in spectrum and time. The discrete function will give the strength and position of spectral combs occurring on a PSD plot.

For the research of this thesis, time hopping is involved for all simulations of PSD for UWB. This thesis will prove time hopping will reduce spectral combs shown in Figure 5.9 for uniform time spacing. Therefore the various PSD of time hopping UWB modulation schemes is given as

$$\phi_{ss}(f) = \frac{\sigma_a^{\ 2}}{T_f}|W(f)|^2 + \frac{\mu_a^{\ 2}}{T_f^{\ 2}}\sum_{j=-\infty}^{\infty}\left|W(\frac{j}{T_f} + c_j T_c)\right|^2 \delta(f-\frac{j}{T_f} - c_j T_c). \qquad (5.13)$$



(a) Pulse train with uniform spacing



(b) PSD for uniform pulse train

Figure 5.9 Uniform pulse train with corresponding PSD.

Where, $c_j T_c$ represents the time hopping sequences. To form a time hopping waveform, a timing pulse position is randomly allocated inside each frame time interval. The position is dictated by the time hopping code. Logically, the time hopping code is a sequence of elements with an integer value between 0 and T_f. Time hopping allows a system to increase the capacity of users in a system and will also smooth the spectrum on a PSD plot while using less power.

5.7 PSD of UWB using Different Modulation Methods

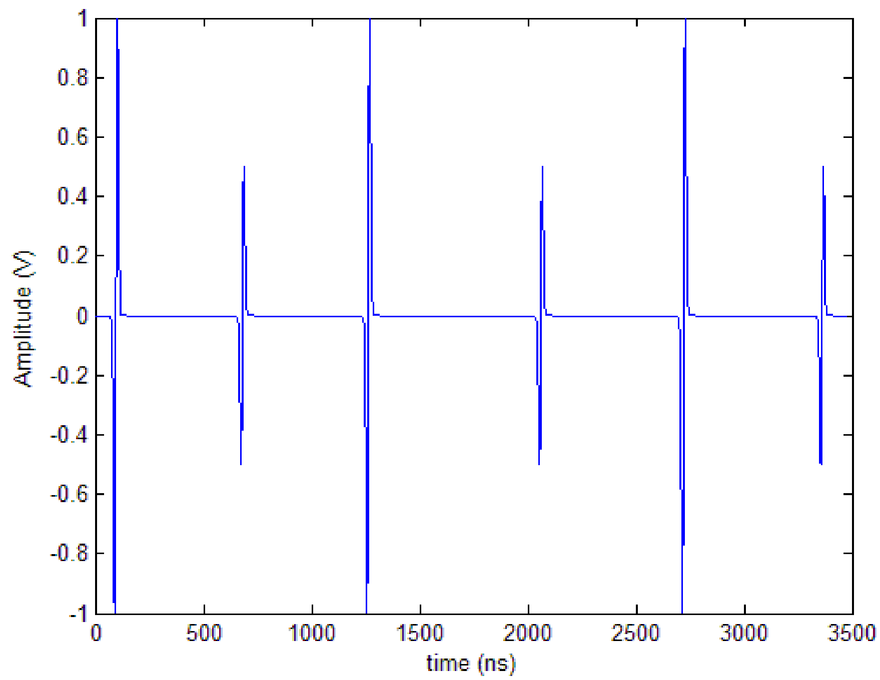
The modulation methods that will be analyzed are PAM, BPSK, OOK, and PPM. A time hopping pulse train of each modulation method will be implemented, and a corresponding PSD of each pulse train will follow. For the simulations in this thesis, the time hopping sequences will be generated as a random value for implementation. The performance of PPM with uniform distribution is studied in [21] and [14]. Reference [14] also offers results for the PSD of uniform distribution using PAM, BPSK, and OOK.

The first UWB system to be implemented is time hopping pulse amplitude modulation, TH-PAM. The PSD for TH-PAM is given as

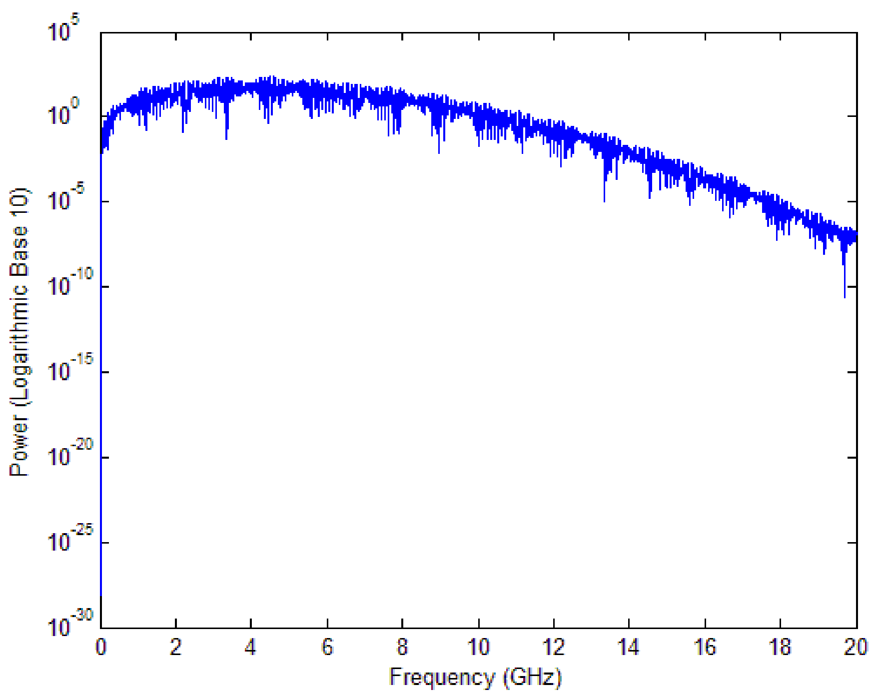
$$\phi_{ss}(f) = \frac{\sigma_a^{\ 2}}{2T_f}\left|W(f)\right|^2 + \frac{\mu_a^{\ 2}}{2T_f^{\ 2}}\sum_{j=-\infty}^{\infty}\left|W(\frac{j}{T_f} + c_j T_c)\right|^2 \delta(f - \frac{j}{T_f} - c_j T_c), \tag{5.14}$$

Figure 5.10 displays the simulation result of a TH-PAM sequence. Note that the pulse train has random amplitudes for each pulse. Another method of UWB is TH-BPSK. Assuming $\sigma_a^{\ 2}$ is equal to 1 and $\mu_a^{\ 2}$ is a random variable with a theoretical value of 0, the PSD of TH-BPSK can be simulated using equation from [14] and given as

$$\phi_{ss}(f) = \frac{1}{T_f}\left|W(f)\right|^2 + \frac{\mu_a^{\ 2}}{T_f^{\ 2}}\sum_{j=-\infty}^{\infty}\left|W(\frac{j}{T_f} + c_j T_c)\right|^2 \delta(f - \frac{j}{T_f} - c_j T_c). \tag{5.15}$$



(a) TH-PAM pulse train



(b) PSD of TH-PAM

Figure 5.10 TH-PAM pulse train and corresponding PSD of TH-PAM.

Figure 5.11 displays two sequences of TH-BPSK with a random time hopping sequence and also the corresponding PSD. Notice the long spectral combs on the PSD plot.

The next method of UWB is time hopping on/off keying, TH-OOK. The PSD of TH-OOK is given as

$$\phi_{ss}(f) = \frac{1}{4T_f}\left|W(f)\right|^2 + \frac{\mu_a^{\,2}}{T_f^{\,2}}\sum_{j=-\infty}^{\infty}\left|W(\frac{j}{T_f} + c_j T_c)\right|^2 \delta(f - \frac{j}{T_f} - c_j T_c)\,. \tag{5.16}$$

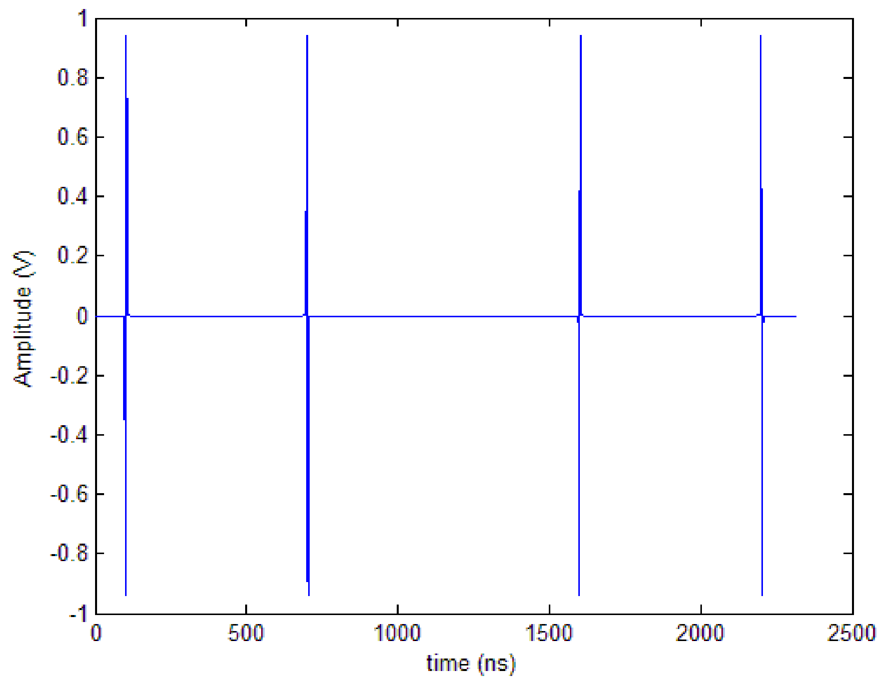
Figure 5.12 displays TH-OOK pulse train with the corresponding PSD. Again, note the spectral combs on the PSD plot.

Finally, the last method of UWB is time hopping pulse position modulation, TH-PPM. Additional TH-PPM performance analysis can be found in [26]. The PSD of TH-PPM sequence is given as

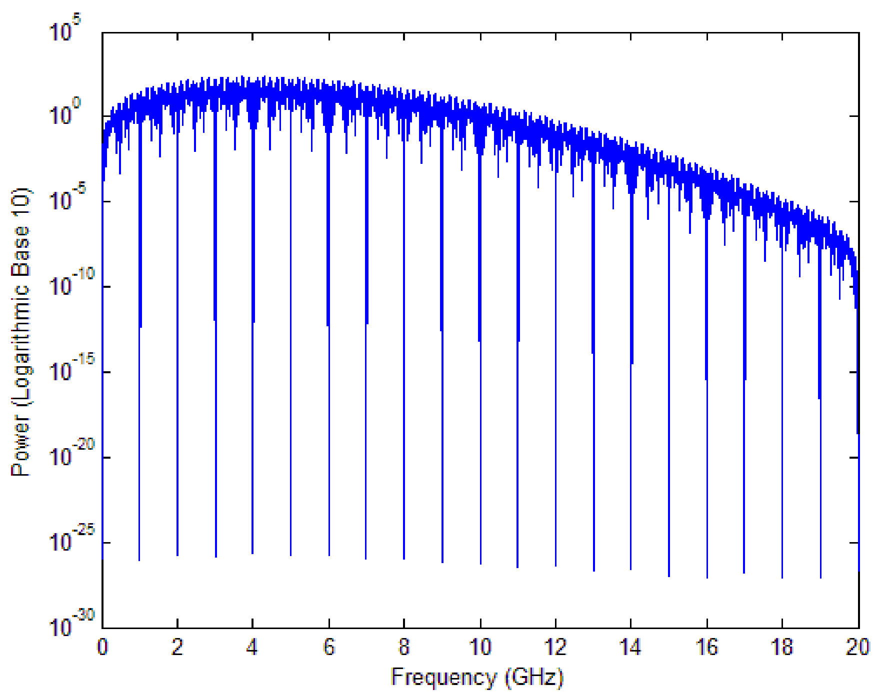
$$\phi_{ss}(f) = \frac{1}{2T_f}\left|W(f)\right|^2 + \frac{\mu_a^{\,2}}{T_f^{\,2}}\sum_{j=-\infty}^{\infty}\left|W(\frac{j}{T_f} + c_j T_c)\right|^2 \delta(f - \frac{j}{T_f} - c_j T_c)\,. \tag{5.17}$$

Figure 5.13 displays a TH-PPM pulse train with the corresponding PSD. The noise level is also very noticeable in the PSD curve for TH-PPM, and it has short, but continuous power combs in the spectrum.

The TH-PAM PSD has the lowest power spectrum spikes; therefore, TH-PAM has the lowest possibility of detection and the lowest possibility of interfering with existing signals. Since TH-PAM has amplitude variations, the time frame is longer in duration to accommodate the longer pulse train. A longer time frame results in fewer periods occurring. This will cause fewer spectral combs.

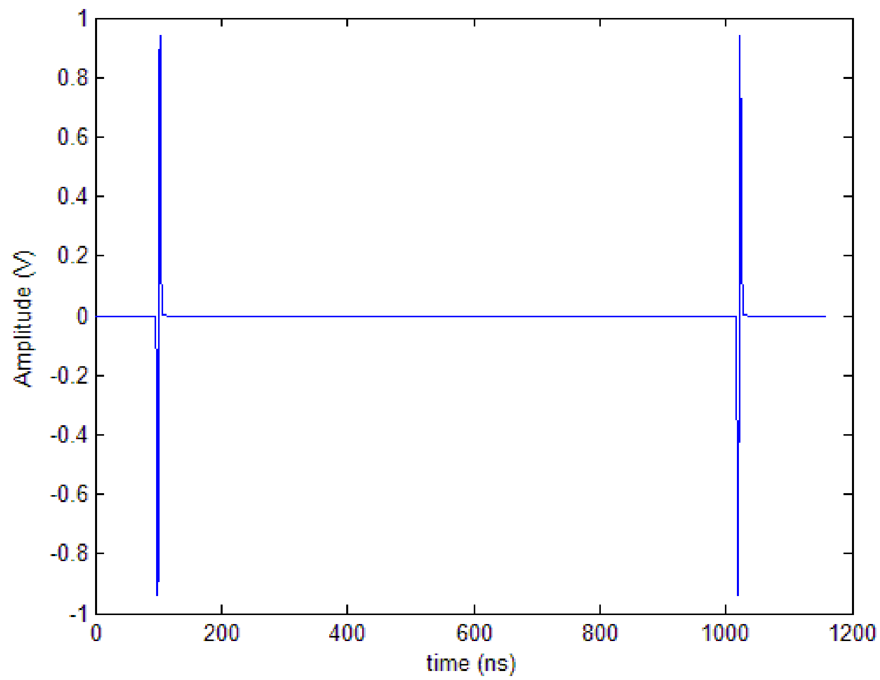


(a) TH-BPSK pulse train

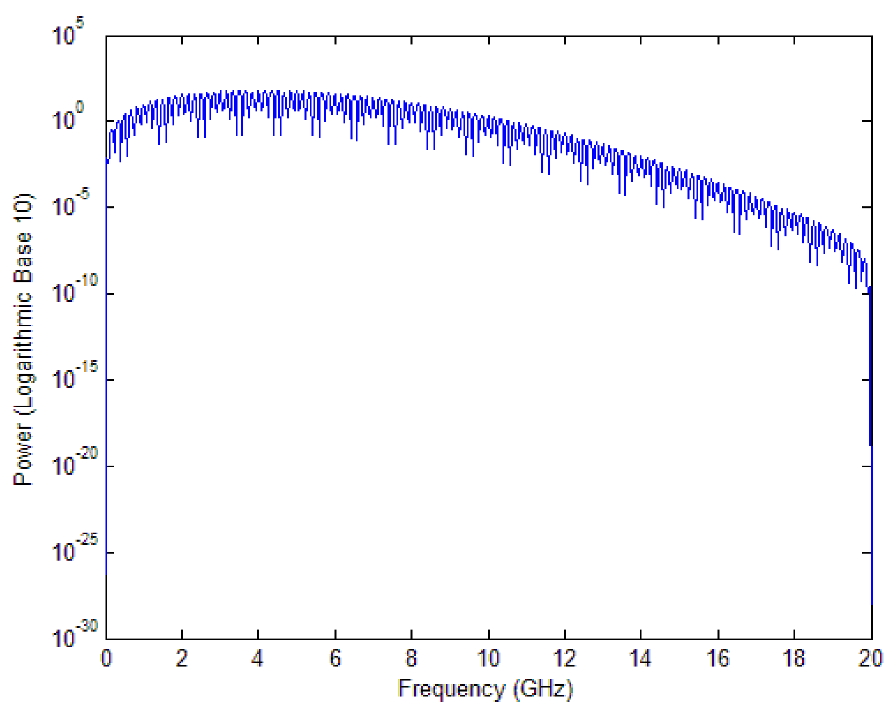


(b) PSD of TH-BPSK

Figure 5.11 TH-BPSK with random time hopping and corresponding PSD.

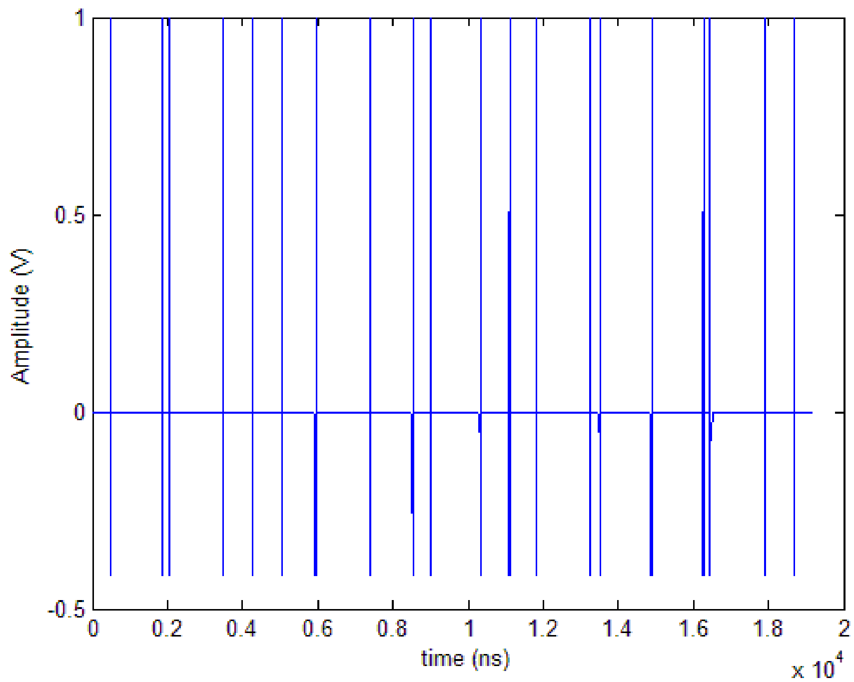


(a) TH-OOK pulse train

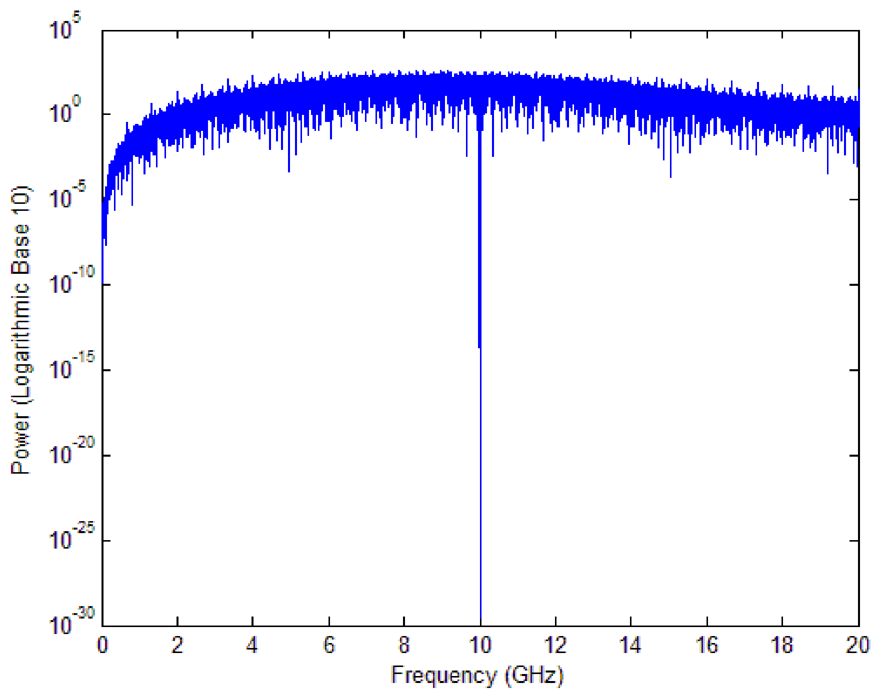


(b) PSD of TH-OOK

Figure 5.12 TH-OOK time hopping pulse train with corresponding PSD.



(a) TH-PPM pulse train



(b) PSD of TH-PPM pulse train

Figure 5.13 TH-PPM pulse train with the corresponding PSD.

TH-PPM and TH-OOK time hopping schemes have the next to lowest power spikes In addition, TH-PPM has the most constant power spectrum over the frequency range of all the UWB PSD figures involved. The power spectrum does not drop for the TH-PPM, but TH-PAM, TH-OOK, and TH-BPSK, all have a decline in power as the frequency increases. TH-PAM also has a relatively low drop in power compared to TH-OOK, and TH-BPSK. TH-BPSK and TH-OOK have relatively the same performance of power drop over the given frequency, but the spectrum of the TH-OOK curve is much smoother when the compared to TH-BPSK. The purpose for TH-PPM having constant power is due to the short, but random time duration between each pulse. This keeps any drops in power from occurring. It is possible that with improved timing sequences of TH-OOK, it could have the potential for the best performance.

Even though TH-BPSK has several power spectrum spikes in the PSD plots, the amount of spikes is considerably lower than the PSD plots of BPSK and OOK when no time hopping is used. This occurs because the data is spread over a larger frame time. Additionally, with more variable time spacing between each pulse within each frame, the more samples occur on the PSD plot. Since the signal is periodic, the more variable time frames, the more samples occur. This will allow fewer spectral combs to occur. Figure 5.14 displays a periodic time hopping pulse train, with the corresponding sampling on the PSD curve. Figure 5.15 displays a periodic uniform pulse train, with the corresponding sampling on the PSD curve. Since time hopping creates multiple timing sequences, there will be more samples. This will allow fewer spectral combs to occur. This fact further proves that when a time hopping sequence is used, there will be less interference with already existing narrowband and wideband systems. All time hopping systems have considerably improved spectrums over uniform spacing.

By the Figures given for the different modulation schemes, it is obvious that each scheme can have advantages to certain applications. TH-PPM will offer high power over a long frequency range, but TH-PAM would be tactically best for covert uses due to almost no power spikes, making detection of the signal very difficult. TH-OOK and TH-

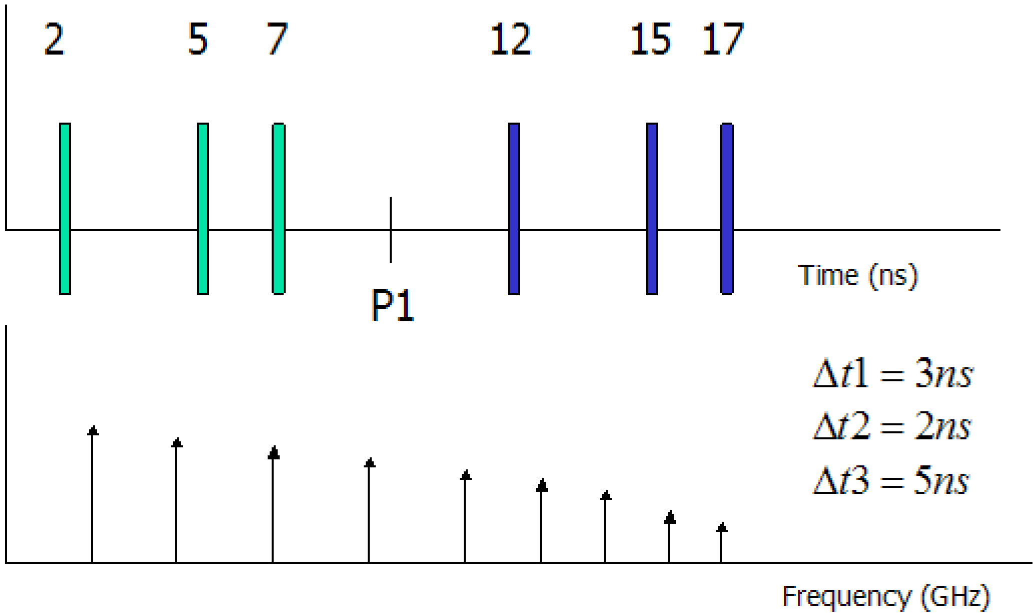


Figure 5.14 Time hopping PSD sampling plot.

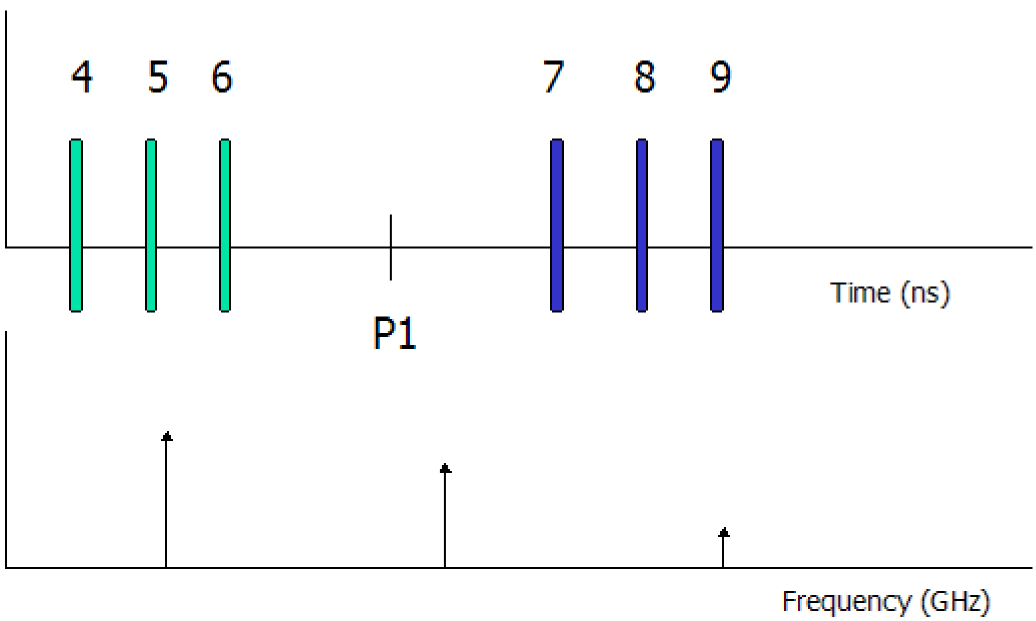


Figure 5.15 PSD sampling of uniform pulse train.

BPSK offer about the same power over a frequency range, but all the modulations offer roughly the same amount of power at low frequencies.

5.8 BER using Time Hopping Modulation Schemes

For a telecommunication transmission, the bit error rate (BER) is mathematically defined as the number of incorrect bits divided by the total number of bits transmitted across an AWGN channel. BER can also be defined as the percentage of bits that have errors relative to the total number of bits received in a transmission, usually expressed as a base ten to a negative power [50]. For example, a transmission might have a BER of 10 to the minus 6, meaning that, out of 1,000,000 bits transmitted, one bit was in error. The BER is an indication of how often a packet or other data unit has to be re-transmitted because of an error. Too high a BER may indicate that a slower data rate would actually improve overall transmission time for a given amount of transmitted data since the BER might be reduced, lowering the number of packets that had to be resent. It is also understood that

$$SNR = \frac{Eb}{No}. \tag{5.18}$$

Figure 5.16 offers a BER representation for TH-OOK. This simulation was created by sending 100,000 bits at random time hopping distribution across an AWGN channel, and received using a correlation receiver.

Figure 5.17 offers a BER representation for TH-BPSK. This simulation was created by sending 100,000 bits at random time hopping distribution across an AWGN channel, and received using a correlation receiver. The spacing between the bi-orthogonal signaling was totally random between all pulse positions, offering a simulated TH-BPSK BER plot.

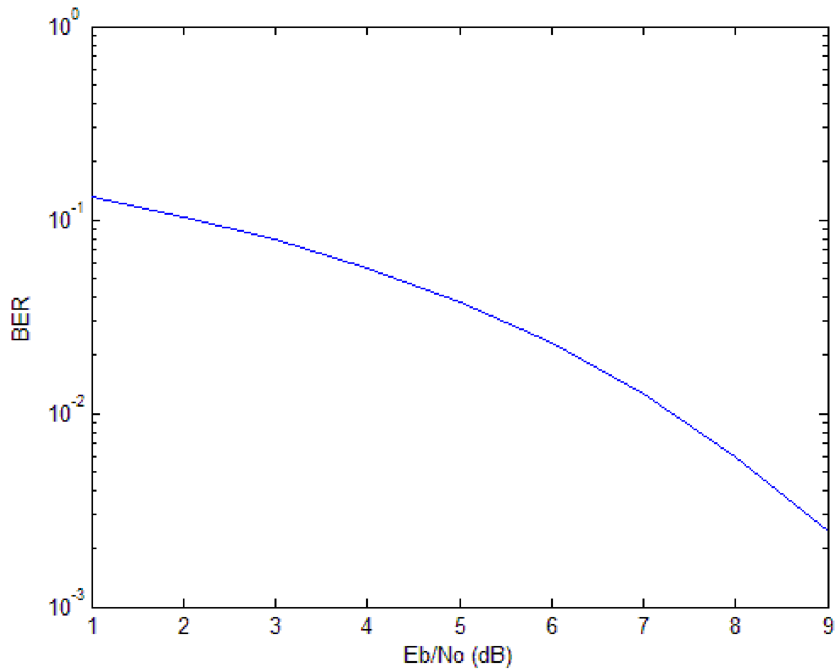


Figure 5.16 BER of TH-OOK.

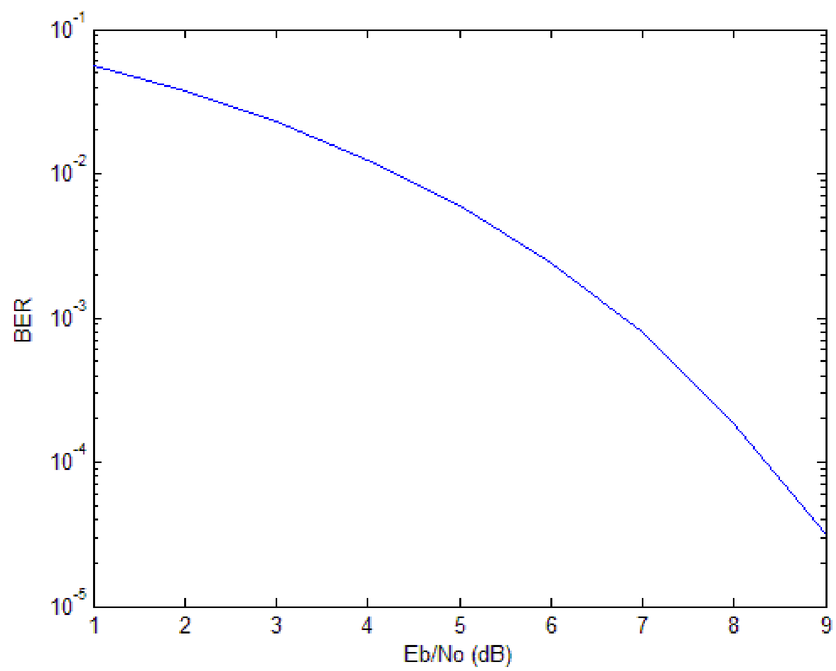


Figure 5.17 BER of TH-BPSK.

Figure 5.18 offers a BER representation for TH-PPM. This simulation was created by sending 100,000 bits at random time hopping distribution across an AWGN channel, and received using a correlation receiver. The performance of TH-PAM was nearly identical to the performance of TH-PPM. Figure 5.19 offers a BER plot of all the time hopping modulation schemes involved. From Figure 5.19, TH-BPSK offers the lowest BER, but as *Eb/No* increases, the BER performance of TH-BPSK improves considerably. For applications that have a low *Eb/No*, TH-PPM, TH-PAM, and TH-OOK will offer the next to best performance. This further proves that time hopping UWB will only improve the performance of a signal, all while keeping a low BER.

For uniform pulse distribution of UWB signals, OOK and PPM have similar BER performance due to similar uses of orthogonal signaling [51]. TH-OOK and TH-PPM offer identical BER results for a single user as uniform spacing offers.

Although the BER of time hopping modulated models have similar performance to standard modulating models, it is important to note that the data rate for time hopping models is considerably higher than standard models. This is due to the longer time frame, and increase of data bits per channel.

Therefore, even though BER is similar, it is beneficial to use a time hopping model. This is because more information can be sent per frame, while keeping a low BER occurring.

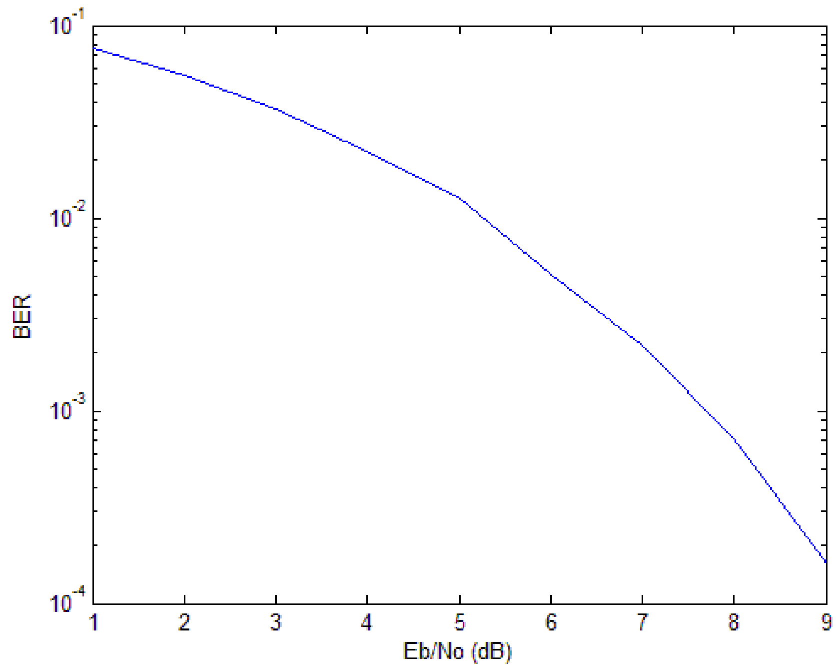


Figure 5.18 BER of TH-PPM.

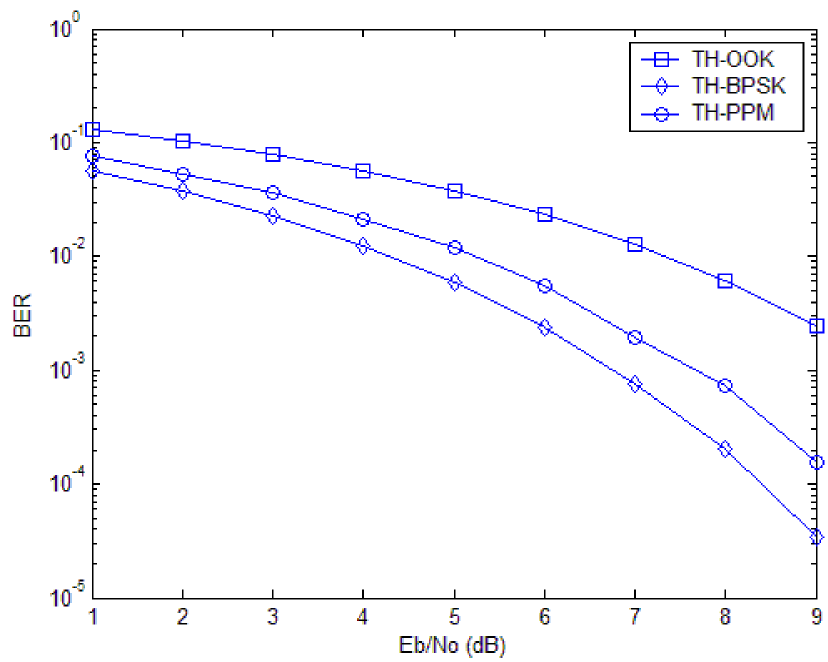


Figure 5.19 BER comparison of all modulation schemes using time hopping.

Chapter 6

Conclusion

The communications industry is growing at a rapid pace. New ways to increase the capacity that a system can sustain, all while keeping the bit error rate low are constantly being studied. UWB might provide the technology that new applications demand. The research that has been done on UWB is still on going and new ideas are constantly evolving. The potential for uses in the military are very exciting because of the incredible low detection rate. Some critics still voice concern because of the fear of UWB interfering with existing systems.

This thesis has gone into detail of basic modulation schemes for UWB. It has also gone into detail of modulation schemes using time hopping for pulse modulation. The spectral analysis was also studied using time hopping modulation for all modulation schemes passing through an AWGN channel, which were reviewed in this thesis. Additionally, the BER performance in an AWGN channel of all time hopping modulation schemes were researched in this thesis.

The simulations in this thesis prove that for spectral analysis, time hopping decreases the amount of spectral combs in all modulation schemes of UWB, offering a lower rate of detection of the signal. This occurs because with the increase of pulses per period, with random time hopping between each pulse, will create more samples on the power spectrum across a frequency range. Using TH-PAM, spectral lines are almost negligible. TH-PAM is hard to have a totally smooth spectrum because of the varying voltage that occurs along the time domain. The voltage of a signal is directly related to the power, therefore, TH-PAM is only as smooth and strong as the number of voltage levels occurring. TH-OOK also improves overall performance of PSD due to the large number of pseudo-random pulses occurring in a UWB signal. TH-OOK has a constant voltage, therefore it should have a smoother power spectrum than TH-PAM. TH-BPSK has the lowest performance of all the modulation schemes that were researched. TH-BPSK can be improve with better random sequencing of pulses, but the phase difference could create possible power inconsistencies to occur. TH-PPM is automatically a good candidate for time hopping since each pulse is shifted on the time domain pending the amplitude of the analog signal. TH-PPM has strong and constant power over a large frequency range. This is one reason PPM is being considered for a long range UWB passband system

This thesis also researched how time hopping will affect the capacity of a system. Since the spreading ratio is dependent on the number of pulses that a period contains, this thesis proved that larger number of pulses, will result in an increased capacity that all systems will apply to a user. It is also easy to vary the capacity with time hopping. This is because by varying $c_j T_{c,}$ the spreading ratio is automatically changed. For uniform spacing, T_f is the only factored changed. With smaller values, the spacing of each pulse could create collisions between pulses. Therefore, time hopping is more versatile, all while increasing capacity.

The BER simulations show that for all values of Eb/No, TH-BPSK offers the best performance, followed by TH-PPM, and TH-OOK has the highest bit error. These results are identical to the BER results that UWB with uniform spacing offers. TH-BPSK has the best performance because of the simple binary baseband signal.

Therefore, with all the results that have been shown in this thesis, there is no reason why time hopping UWB should not be used. This system will improve how discretely a signal passes through a system, increase system capacity or make it easier to set the capacity per user, all while maintaining identical BER to uniform spacing UWB signals.

With FCC approval, UWB will be the future of wireless communications in the United States. UWB is already in use for military applications. Since UWB does not interfere with the GPS weapons technology, then it is possible for use as a mainstream communications technology.

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Vita

Joseph Peek was born in Jackson, Mississippi in 1979. He attended Central High School in Chicago, Illinois until he graduated in 1997. Joseph Peek entered the University of Tennessee, Knoxville as an undergraduate in 1997. He received a B.S. in Electrical Engineering in 2002. In Fall 2002, he entered the graduate program in the Wireless Communications Research Group at the University of Tennessee. He was given a teaching assistantship in the Electrical Engineering department.