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An enhanced pulse position modulation (PPM) in ultra-wideband (UWB) systems

Lingxiu Chen
University of Northern Iowa

AN ENHANCED PULSE POSITION MODULATION (PPM) IN ULTRA-WIDEBAND (UWB) SYSTEMS

An Abstract of a Thesis

Submitted

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

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ABSTRACT

Simplicity, transmission rate, and bit error rate (BER) performance are three major concerns for ultra-wideband (UWB) systems. The main advantage of existing pulse-position modulation (PPM) schemes is simplicity, but their BER performance is poorer than that of an on-off-keying (OOK) modulation scheme, and their transmission rate is lower than that of an OOK scheme. In this research project, I will explore a novel PPM scheme, which can maintain the simplicity of the PPM schemes as well as achieve a BER performance and a transmission rate similar to the OOK scheme. During the research, I will thoroughly investigate the relationship between pulse position allocation and the BER performance and the transmission rate of UWB systems through computer simulations and theoretical analysis, and develop a whole set of design rules for the novel PPM scheme.

Index Terms — Ultra wideband, Pulse Position Modulation, On off key modulation, multipath channel.

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Date	Dr. Hong (Jeffrey) Nie, Chair, Thesis Committee
Date	Dr. Jin Zhu, Thesis Committee Member
Date	Dr. Shangzhen Luo, Thesis Committee Member
Date	Dr. Michael J. Licari, Dean, Graduate College

DEDICATION

I dedicate my dissertation work to my family and many friends. A special feeling of gratitude to my loving parents, Zhen Zheng and Qiang Chen whose words of encouragement and push for tenacity ring in my ears.

ACKNOWLEDGEMENTS

There are many people who have given me help and support as I progressed through my education and with this endeavor in particular. I wish to offer them my appreciation.

First, I would like to thank Dr. Hong (Jeffrey) Nie and Dr. Zhimeng Xu for assisting me with this work, and their instruction throughout my graduate courses.

Next, I offer my appreciation to my friends who graciously offered to be test subjects for this research. I couldn’t have finished this without their help.

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INTRODUCTION

Background

Ultra-wideband (also known as UWB, digital pulse wireless and ultra-band) is a wireless technology which uses high bandwidth (larger than 500 MHz) for data communications with low power in a short distance (Khoury & Kamat, 2009) . While traditional narrowband wireless communication technology uses frequency, phase, and amplitude of a sine wave to transmit data, UWB system utilizes pulse (impulse radio) for transmission. What makes UWB different from its competitors is the capacity of low energy (Win & Scholtz, 1998), low cost (Yeap, Chai, & Law, 2004), high interference resistance (Bergel, Fishler, & Messer, 2002), strong multi-path resolution (Lee, Han, Shin, & Im, 2000) and high data rate wireless communication links with license-free band (Allen et al., 2005; Yin, Wang, Liu, & Wu, 2014). Thus, the unique capabilities and potential applications of UWB system have already drawn a huge interest over the world.

The problem addressed in this study is to explore a novel pulse-position modulation (PPM) scheme for ultra-wideband (UWB) systems, which can maintain the simplicity of existing PPM schemes as well as achieve a BER performance and a transmission rate comparable to an on-off-keying (OOK) scheme, and develop a whole set of design rules for the novel PPM scheme.

PPM and OOK schemes are two widely used digital modulation schemes in UWB systems. An OOK scheme simply uses presence or absence of a pulse in a time slot to represent the value of an information bit, i.e. presence of a pulse indicates a ‘1’ and absence of a pulse indicates a ‘0’. When demodulating an OOK signal, a UWB receiver compares the energy of the received signal in the time slot with a predetermined threshold. If the received energy is larger than the predetermined threshold, a ‘1’ is received; otherwise, a ‘0’ is received. For example, as shown in Figure 1, the encoder of an OOK system will modulate bits ‘101’ as a pulse, nothing, and a pulse in three sequential time slots. After the signal is transmitted through a wireless channel, for example, an Additive white Gaussian noise (AWGN) channel, the energy of the received signal in the three time slot is detected as high energy, low energy, and high energy. A predetermined threshold is used to demodulate bit ‘1’ and bit ‘0’ according to the energy of the received signal.

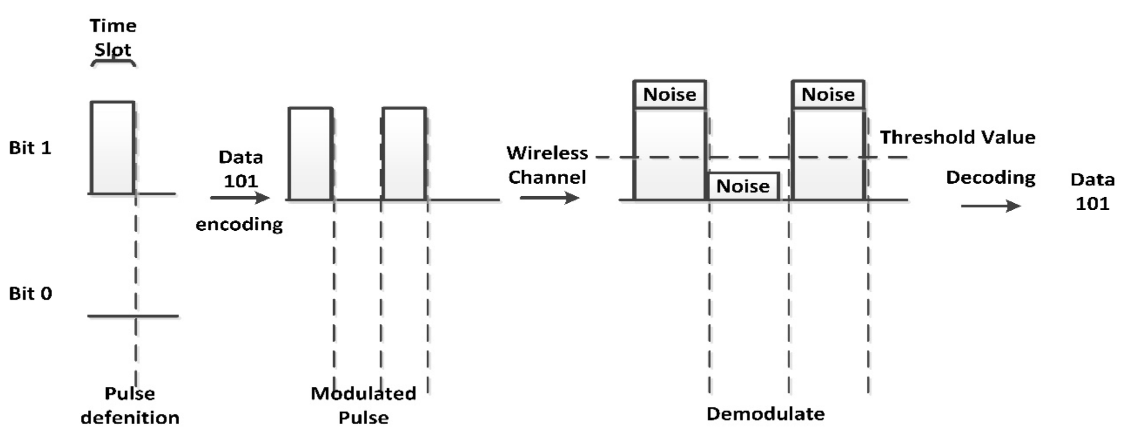


Figure 1. On Off Key Modulation Scheme Overview

In contrast, a PPM scheme uses the position of a pulse in two time slots to represent the value of an information bit, i.e. presence of a pulse in the first time slot indicates a ‘1’ and that in the second time slot indicates a ‘0’. When demodulating a PPM signal, a UWB receiver compares the energy of the received signal in the two time slots. If the energy in the first time slot is larger than that in the second time slot, a ‘1’ is received; otherwise, a ‘0’ is received. As shown in the Figure 2, the encoder of a PPM system will modulate bits ‘101’ as a pulse, nothing, nothing, a pulse, a pulse, and nothing in six sequential time slots. After the signal is transmitted through an AWGN channel, the energy of the received signal is detected as high energy, low energy, low energy, high energy, high energy, and low energy. The receiver compares the first two time slots and identifies that the larger energy appears on the first time slot. Thus, bit ‘1’ is demodulated from the first two time slots. Similarly, the second and third bit is demodulated as ‘0’ and ‘1’.

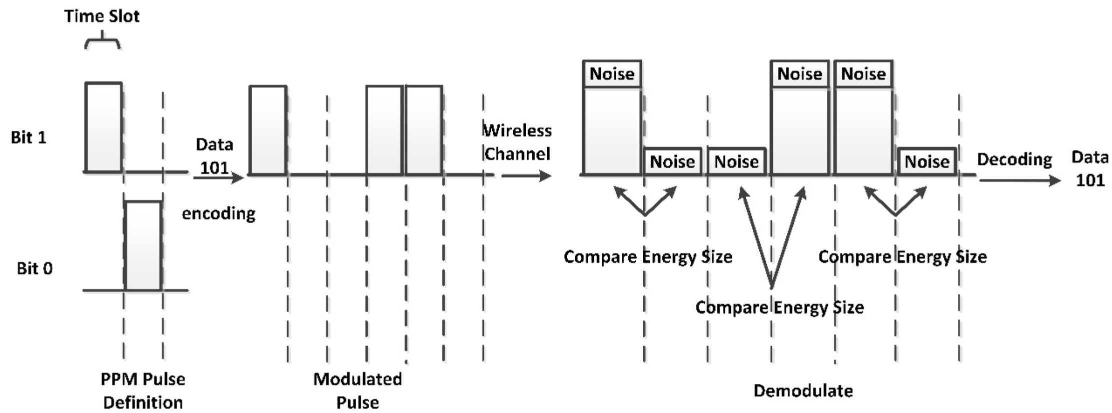


Figure 2. Pulse Position Modulation Scheme Overview

Comparing the two modulation schemes, we can identify the following three differences:

Difference 1: A predetermined threshold is required in receiver side for the OOK scheme, but no threshold is required for the PPM scheme. Thus, the PPM scheme allows easy implementation for UWB receiver, since it is not a trivial job to determine the optimal value for the threshold.

Difference 2: the OOK scheme sends a pulse out only when a ‘1’ is transmitted, but the PPM scheme sends a pulses out independent of a ‘1’ or a ‘0’ is transmitted. Thus, for the same transmitting power, an OOK pulse can have double energy as compared to a PPM pulse. Consequently, the PPM scheme has a poorer bit-error rate (BER) performance than the OOK scheme.

Difference 3: For transmitting each information bit, the OOK scheme uses one time slot, but the PPM scheme uses two time slots. Thus, the OOK scheme provides a higher data transmission rate than the PPM scheme.

There is a need, I believe, to combine the simplicity of the PPM scheme and the better BER performance and high transmission rate of the OOK scheme together. The outcomes of this study will provide a novel approach to maintain the simplicity of the PPM scheme as well as achieve a BER performance and transmission rate similar to an OOK scheme.

The following sections provide some background on the study. These ideas form the basis of the work undertaken for this dissertation.

Research Hypothesis

1. It is assumed that the noise in the UWB channel considered by this project is additive white Gaussian noise (AWGN) and no narrowband interference exists in the wireless channel.
2. It is assumed that no inter-symbol interference exists in the UWB systems considered by this project, i.e. the sum of UWB pulse duration and the maximum multipath delay spread of the wireless channel is shorter than the duration of a time slot.

Statement of Problem

Since it is an exploratory research, the core question to be answered by this study is: "Can a modification from a single pulse to multiple pulses plus pulse position allocation in multiple time slots improve the BER performance and transmission rate of the novel PPM scheme to the same level as the OOK scheme."

Significance of the Study

This project serves three purposes:

1. Improve existing UWB system data communication speed with minor modification on hardware.
2. The conclusion derived from this study can be used in all aspects of UWB applications.
3. The idea for this study can be applied in other pulse-based wireless communication systems.

Limitation

1. The research project only considers the wireless channel without narrowband interference (NBI). NBI may affect the BER performance of the enhanced PPM scheme.
2. The research project only considers the UWB systems without inter-symbol interference. Inter-symbol interference exists when the sum of UWB pulse duration and the maximum multipath delay spread of the wireless channel is

longer than the duration of a time slot, and such interference may affect the BER performance of the enhanced PPM scheme.

Definition

The following terms have been defined to clarify their use in the context of this study.

1. Ultra-wideband System

   It's a telecommunication system that transmits radio signals over a -10dB bandwidth of either at least 20% of its center frequency or at least 500MHz.

2. OOK

   OOK is the simplest form of an amplitude-shift keying (ASK) modulation scheme. It represents digital data with the presence or absence of a carrier wave, or a pulse.

3. Conventional PPM

   Conventional PPM is a form of signal modulation in which M information bits are encoded by transmitting a single pulse in one of 2^M time slots.

4. BER

   BER stands for bit error rate. It is the number of bit errors divided by the total number of bits transmitted during a studied time interval. It is usually used as a performance measurement.

CHAPTER 2

REVIEW OF RELATED LITERATURE

Ultra Wideband (UWB) System Overview

UWB system, with high accuracy on ranging and security, was originally developed for military radar communication. In 2002, Federal Communications Commission (FCC) in the United Stated released a license-free frequency band from 3.1 GHz to 10.6 GHz for commercial use. Since then, UWB technology has been mainly developed as a wireless technology for high-data-rate personal area network (PAN). The typical transmission rate of UWB system is 40 to 60 megabits per second, which is much higher than that of Bluetooth (typically 1~3 megabits per second). Since UWB systems use ultra-wide bandwidth, theoretically the transmission rate of UWB systems can go up to several gigabits per second. In the same time, the emission power of UWB is limited as low as -41.3 dBm/MHz As a result, UWB devices can enjoy a much longer operating time with a battery. Furthermore, short-duration UWB pulses make it easy to implement multiple access schemes for UWB systems. In other words, multiple UWB users can corporate with each other and work at same time without serious interference problem (Kayne, 2014). Aside from these promising features, UWB system, with high penetration of obstacles and accuracy on positioning, is also ideal for indoor position tracking applications (Zhang, Hammad, & Rodriguez, 2011) and medical imaging applications (Yong, Lu, Zhang, & Wang, 2011).

Modulation Method Overview

The design of UWB systems is a two-layer process. The first stage of the process is to design the shape of transmitted pulses and corresponding transmitters; the second stage is to design an appropriate modulation scheme and corresponding receivers. In this study, I am mainly focusing on the second design stage.

Modulation scheme is one of key issues to a wireless system. Selecting a right modulation scheme can not only increase the performance of a wireless system but also reduce the complexity of related hardware. Thus, a considerable amount of time and resources have been spent in designing modulation schemes to fully utilize the benefits of ultra-wide bandwidth.

On Off Keying (OOK) Modulation

The OOK modulation is the first modulation scheme used in UWB systems. In Ghavami, Michael, and Kohno's book, "Ultra Wideband Signals and Systems in Communication Engineering," the OOK modulation for UWB system is defined as a type of pulse shape modulation where the shaping parameter is either 0 or 1.Thus, a threshold value is needed in the receiver side to determine the presence or absence of a pulse (Ghavami, Michael, & Kohno, 2004).

Choi and Stark examined performance of PPM and OOK modulations in the article "Performance Analysis of Rake Receivers for Ultra-wideband Communications with PPM and OOK in Multipath Channels." In the study, they found that OOK modulation outperforms PPM modulation in multipath channels. Furthermore, they examined the tradeoff between receiver complexity and performance for RAKE receivers. Finally, they proposed a suboptimal combining scheme for RAKE receivers (Choi & Stark, 2002).

Because UWB systems are mainly used in low cost applications, the design of the OOK receivers has a stringent limitation on demodulation complexity. Consequently, due to their high complexity, the optimal coherent rake receivers, requiring accurate channel knowledge, are abandoned by most of the real applications. Instead, sub-optimal non-coherent receivers, only requiring energy detection and relaxed channel estimation, have attracted many research interests.

Paquelet and Aubert first came up with the idea to use non-coherent transceiver in OOK modulation, in the article "An Energy Adaptive Demodulation for High Data Rates with Impulse Radio." In this study, authors proposed a high speed non-coherent transceiver using OOK modulation. Although the adoption of non-coherent transceivers would decrease the performance of UWB systems, it was shown that approximated threshold value, calculated by the prior information made of approximate channel delay spread and the available energy level, allows UWB systems perform in a satisfactory level (Paquelet & Aubert, 2004).

Sahin, Guvenc and Arslan pointed out that a joint estimation can be used for optimal threshold estimation in the paper "Optimization of Energy Detector Receivers for UWB Systems." Furthermore, Gaussian approximation can reduce threshold estimation complexity in the expense of some performance degradation (Sahin, Guvenc, & Arslan, 2005).

In summary, the need for threshold estimation brings not only system complexity but also a main disadvantage for OOK modulation: having difficulty in determining the presence or absence of a pulse in a multipath environment which is full of echoes of original and other pulses.

There are some other researches related to the modulation and demodulation of the OOK scheme. In order to reduce the multipath and multi-access interference of the OOK scheme, Cha et al. introduced a new unipolar zero correlation duration (ZCD) code to achieve interference cancellation property in their article “Chaotic-OOK UWB MODEM Using New Unipolar ZCD Codes for Wireless PAN.” They also discussed the history and evolution of IEEE802.15.4a wireless personal area network (WPAN) standard (Cha, Kwak, Lee, Jeong, & Lee, 2006).

In Li et al.’s study, “Equalization Analysis for OOK IR-UWB Using Energy Detector Receiver,” a low-complexity equalization for high data rate OOK modulation was proposed. The study found that a second-order Volterra model equalizer can greatly eliminate intersymbol interference. The study also found that a linear equalizer, instead of non-linear volterra model equalizer, can be used to lower the overall complexity of the receiver (Li, Quan, Zhang, & Lin, 2011).

Pulse-Position-Modulation (PPM) Overview

The PPM scheme is another widely used modulation scheme in UWB systems. As the name indicates, the PPM scheme uses different positions of a pulse in the time domain to transmit information. Thus, the key parameter in pulse position modulation is the time delay of each pulse.

Ross is the first researcher that made the PPM scheme possible for hardware implementation. In his patent named “Transmission and reception system for generating and receiving base-band duration pulse signals for short base-band pulse communication system,” he proposed an impulse radio encoding intelligence, fully utilizing the spread spectrums systems of a wide instantaneous bandwidth, based on the PPM scheme (United States Patent No. 3,728,632).

Win and Schultz introduced the concept called “time-hopping” (TH), which uses different pseudo-noise code in the transmitted signal to distinguish multi users in one system, into the PPM scheme to meet the need of multi-user communication. The study, considering multiple-access channel conditions, estimated the achievable transmission rate and multi-access capability of TH-PPM. The study suggested that a TH-PPM system can support a large numbers of users in an ideal power-controlled AWGN environment (Win & Scholtz, 2000).

Zhan and Haimovich extended the concept of binary PPM to M-ary PPM ($M=2^n$, $n \geq 1$). In their paper “Capacity of M-ary PPM Ultra-Wideband Communications over AWGN Channels,” they computed the capacity of M-ary PPM in AWGN channels under federal communication committee (FCC) power constraint. They also found that M-ary PPM has a significant performance improvement in low signal-noise-ratio environment compared to direct sequence spread spectrum (Zhao & Haimovich, 2001).

Based on the above research, Kokkalis et al. tried to employ M-ary PPM into multiuser TH-UWB systems in their study “Performance analysis of M-ary PPM TH-UWB systems in the presence of MUI and timing jitter.” Furthermore, they provided a semi-analytical method to evaluate symbol error probability performance of this M-ary TH-PPM UWB system. At last, they studied the degradation on overall system caused by Gaussian process model timing jitter (Kokkalis, Mathiopoulos, Karagiannidis, & Koukoulis, 2006).

Kang et al have developed differential PPM (DPPM) in their research report named “Performance analysis of DPPM UWB systems over Nakagami fading Channels.” The DPPM scheme uses a flexible frame length to reduce total time slots of fixed data. Since every frame ends up with a pulse, the DPPM method does not require additional symbol synchronization (Kang, Lu, Zhang, & Zhang, 2001).

When it comes to the receiver side of the PPM scheme, the key factor relate to bit error rate performance is integration time. Since the PPM scheme makes bit decision after comparing energy of two nearby time slots, the optimal integration time can dramatically reduce the influence of channel noise.

Wu, Xiang and Tian described a weighted receiver structure in the article "Weighted Noncoherent Receivers for UWB PPM signals." In this article, the authors integrated the received energy with multiple integration time windows. Then, the results of integration are weighted, and linear combined to generate decision statistic. The output with larger noise would get smaller weight. Finally, the optimal and sub-optimal weighting coefficients are derived to maximize BER performance (Wu, Xiang, & Tian, 2006).

Almodovar-Faria and McNair pointed out that for energy-detection based PPM systems, optimizing integration time can greatly reduce the sensitivity of PPM systems to channel noise, intersymbol interference, and inter frame interference in the conference paper "Optimal Integration Time for Energy-Detection PPM UWB Systems." The study introduced analytical expressions with a simulation result to determine the optimal integration time for energy detectors. Furthermore, they indicated that the equations shown in the paper would simplify calculation and trade-off decision (Almodovar-Faria & McNair, 2012).

Other Modulation Overview

Although the OOK and the PPM schemes are the mainstream to modulate UWB systems, several other modulation schemes also contribute the development of UWB technology.

Bi-phase modulation. Bi-phase modulation is a modulation using 0 degree and 180 degree of to represent bit 0 and 1. The main advantages of bi-phase modulation are smoother power spectral density, higher resistance to jitter, and high data transmission rate. The main drawbacks of the bi-phase modulation are the high complexity for receiver design, because coherent receivers are required to demodulate bi-phase modulated signal. Thus, bi-phase modulation is seldom mentioned in personal area network. Instead, Alomainy et al addressed the bright future of bi-phase modulation applications in on-body radio area (Alomainy, Hao, Hu, Parini, & Hall, 2006).

Pulse amplitude modulation. As the name indicates, pulse amplitude modulation varies amplitude of UWB pulse to transmit data. The main advantage of Pulse amplitude modulation is simplicity, while the main disadvantage of it is noise immunity. It was abandoned just after its poor performance under multipath channels is identified.

Summary

UWB communication system proves its bright future in high-data-rate personal area network (PAN), indoor position tracking applications and medical imaging applications.

Modulation schemes are the key issue for UWB systems. Among all UWB modulations, the OOK and the PPM schemes are the most popular modulation schemes.

For both OOK and PPM schemes, sub-optimal non-coherent receivers can be employed to generate energy decision statistics. In other words, system complexity can be low. The current researches on improving the performance of the PPM schemes are focusing on optimizing the integration time of the energy detector. For the OOK scheme, its bit error rate performance is higher than that of the PPM scheme, but extra threshold estimation is required to make decision statistics. Researchers have been investigating the threshold estimation from every angle in an attempt to reduce the complexity of OOK demodulation. However, none of those articles has ever investigated the possibility to combine the OOK scheme with high performance and the PPM scheme with low complexity. In this study, I have tried the combination and proposed a generalized enhanced PPM scheme to achieve high bit error rate performance, high data transmission rate, as well as low complexity. Furthermore, I have thoroughly examined this generalized enhanced PPM modulation with computer simulations.

CHAPTER 3

METHODOLOGY

Enhanced Pulse Position Modulation (PPM)

The PPM and the OOK schemes are two widely used modulation schemes in UWB systems. In order to maintain the simplicity of receiver structure, I choose the PPM scheme as the fundamental of our enhanced modulation scheme. As I have discussed in last two chapters, for the same transmitting power, an OOK pulse can have double energy as compared to a PPM pulse, and for the same number of time slots, the OOK scheme can transmit double information bit as compared to the PPM scheme, which are two key limiting factors for the conventional PPM scheme. The enhanced PPM scheme tries to encode multiple information bits into one symbol to decrease the total number of pulses and time slots. Thus, enhanced PPM scheme can increase the energy per pulse and reduce the number of time slots per information bit.

For example, if we define two pulses in five time slots as one symbol. According to combination and permutation, there are 10 possibilities for different combinations. Thus, we can pick up eight out of 10 combinations and form a Gray Code table to transmit 3 information bits.

As shown in Table 1, each of the 8 combinations represents one 3-bit symbol. The unused 2 combinations are selected in purpose so as to increase the Hamming distance of the system, which leads to best bit error rate performance.

Table 1. Code Table for 2 Pulses in 5 Time Slots Scheme

Gray code				Time slot				
bit 1	bit 2	bit 3		1	2	3	4	5
0	0	0		0	0	1	0	1
0	0	1		0	1	0	0	1
0	1	1		1	0	0	0	1
0	1	0		1	0	0	1	0
1	1	0		0	0	1	1	0
1	1	1		0	1	0	1	0
1	0	1		0	1	1	0	0
1	0	0		1	0	1	0	0
				Discard time slot scheme				
				0	0	0	1	1
				1	1	0	0	0

According to Table 1, if bits ‘101’ is transmitted by the enhanced PPM scheme, the transmitter will modulate bits ‘101’ with a pulse, nothing, a pulse, nothing, and nothing. As shown in Figure 3, the energy of the received signal through an AWGN channel is detected as high energy, low energy, high energy, low energy, and low energy.

In the conventional PPM scheme, the receiver will compare signal energy between two subsequent time slots. In the enhanced PPM scheme, we will sort the signal energy in five subsequent time slots, and the two time slots with the largest energy are considered as the pulse positions of transmitted signal. Then by looking up the pulse encoding table, the receiver can recover the transmitted information bits.

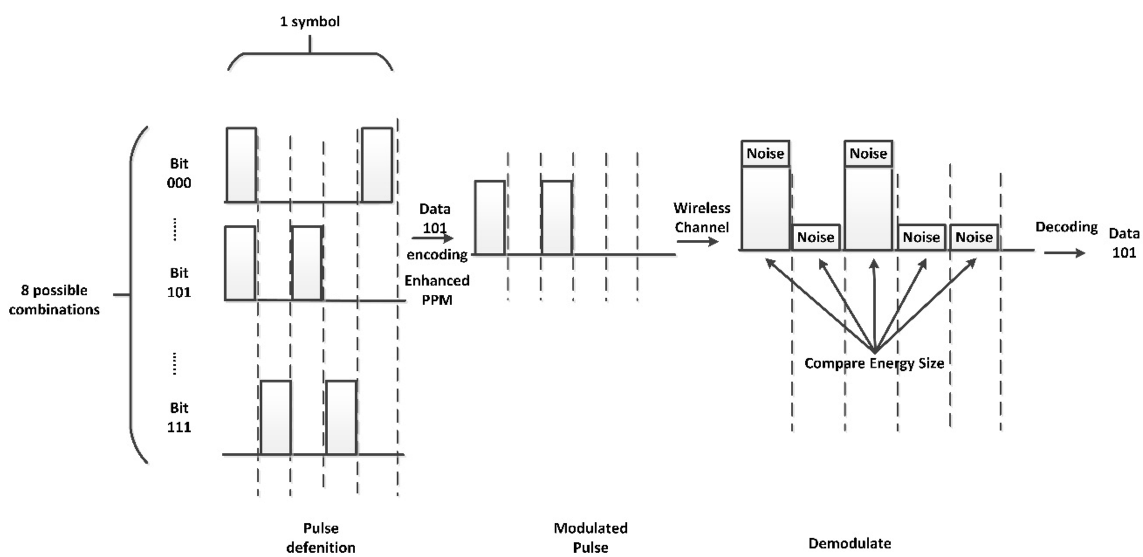


Figure 3. An Example for the Enhanced PPM Scheme.

i. Comparing the enhanced PPM schemes with the two conventional modulation schemes, we can conclude that: the enhanced PPM scheme does not require threshold estimation, so its complexity is low;

ii. with two pulses, the enhanced PPM scheme can transmit three information bits, but the conventional PPM scheme can only transmit two information bits, so its energy per pulse is higher than the conventional PPM and hence its BER performance is also higher;

iii. With five time slots, the enhanced PPM scheme can transmit three information bits, but the conventional PPM scheme can only transmit two and half information bits, so its data rate is higher than the conventional PPM.

Therefore, we can generate the following table to compare the advantages and disadvantages of the modulations schemes.

Table 2. Comparisons among the Three Modulation Methods

Modulation	Complexity	Data rate	BER performance
OOK	High	High	High
Conventional PPM	Low	Low	Low
Enhanced PPM	Low	Medium	Medium

The idea of compressing multiple bits into one symbol is not limited to two pulses in five time slots. By adjusting the number of pulses and time slots, the BER performance (judged by pulse per bit) and the data transmission rate (judged by time slot per bit) of UWB systems can increase dramatically. The brief combination-performance table is shown as below while the complete table is attached in the Appendix A.

Table 3. Brief Combination-Performance Table

Modulation	Pulse	Time Slot	Represent Bit	Pulse/Bit	Bit/Time Slot
PPM	1	2	1	1	1/2
Enhanced PPM	2	5	3	2/3	1/2
	3	6	4	3/4	1/2
	2	6	3	2/3	5/9
	3	7	5	3/5	4/7
	2	7	4	1/2	3/5
	4	8	6	2/3	5/8
	3	8	5	3/5	2/3
	2	8	4	1/2	2/3
	3	9	6	1/2	2/3
	2	9	5	2/5	5/7
	4	9	6	2/3	3/4
OOK	0.5	1	1	1/2	1

Implementation Design:

In order to implement the enhanced PPM scheme, I need to redesign the hardware settings of the conventional PPM scheme, which consist of a generic transmitter and an energy-detection (ED) receiver.

Generic Gaussian Pulse Transmitter

The generic Gaussian PPM transmitter was first proposed by Bagga, De Vita, Haddad, Serdijn, and Long (2004). The transmitter contains a cascaded Modulator and Pulse Generator, the block diagram of which is shown in Figure 4.

As shown in Figure 4, the modulator part is placed before the pulse generator stage to avoid hardware complexity for delaying continuous time signals. It is composed of a variable slope generator which can provide precise phase regulation under variable line voltage and a comparator. The output waveform of the modulator is square waveforms.

The pulse generator part is also divided into two stages: a triangular pulse generator and pulse shaping network. The triangular pulse generator avoids crosstalk and approximates an impulse-like waveform. The pulse shaping network is used to approximate Gaussian signal pulse.

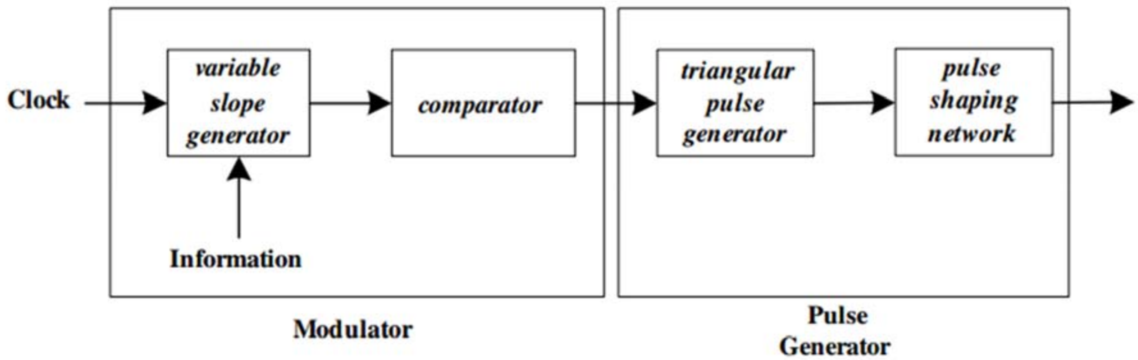


Figure 4. Generic Gaussian Pulse Transmitter Structure

Energy-Detection (ED) Receiver

Due to the simplicity requirement and power consumption concern, non-coherent receivers, instead of coherent ones, are widely used in PPM systems. Among non-coherent receivers, the ED receiver is considered as a primary receiver again for simplicity reason.

As shown in Figure 5, the ED receiver can be divided as a front-end part and a back-end part. In the front end part, the received signal first passes through a cascade of low-noise amplifier, band-pass filter, and variable gain amplifier. Then, the filtered signal will be squared (self-mix) and integrated within a specific time window. The output of the front-end part represents the energy detected in each time slot. In the back-end part, a comparator will compare the detected energy within a symbol (i.e. 2 time slots for the conventional PPM scheme, and 5 time slots for the enhanced PPM scheme) and recover the information bits.

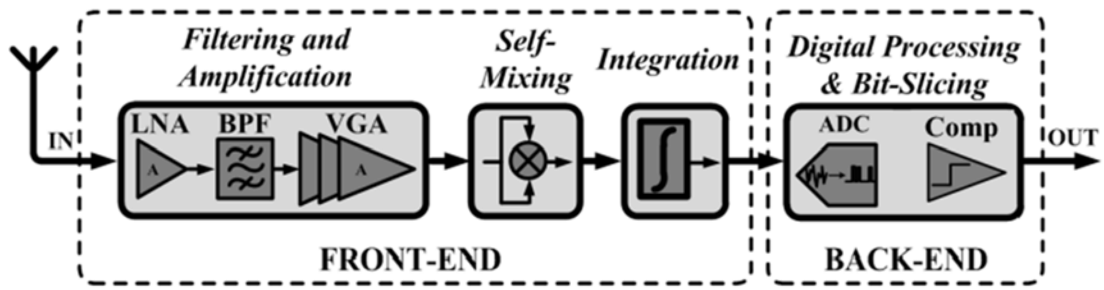


Figure 5. Generic Energy Detector Structure

Simulation Design

Simulation Software

The scientific computation software used in this research is Matlab. As shown in Figure 6, Matlab, developed by MathWorks, is a high-level language and numerical computation environment. The high computation speed and decent accuracy make it popular in engineering and scientific areas.

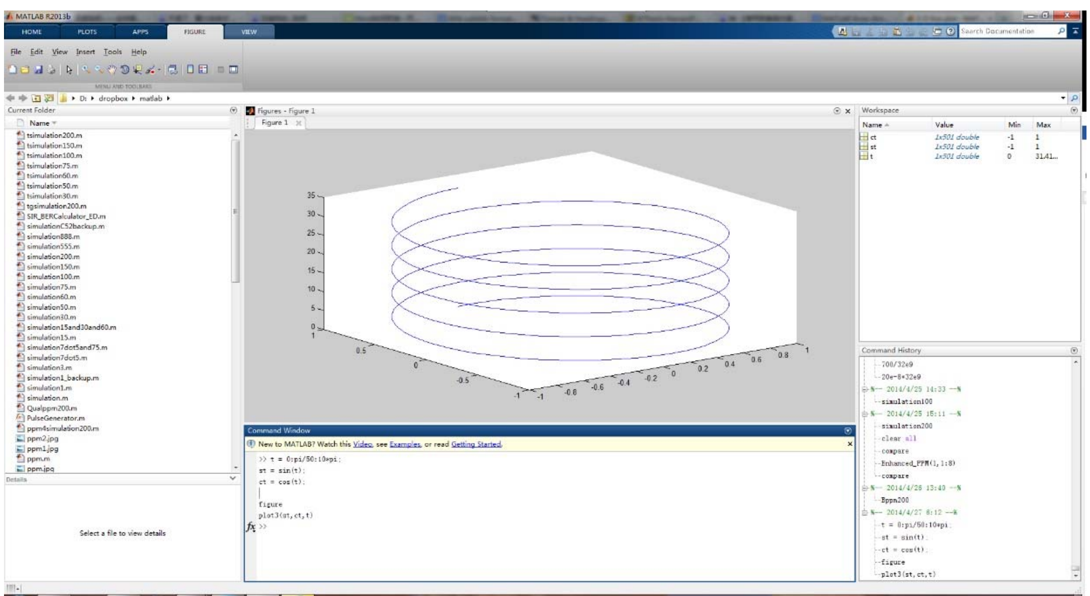
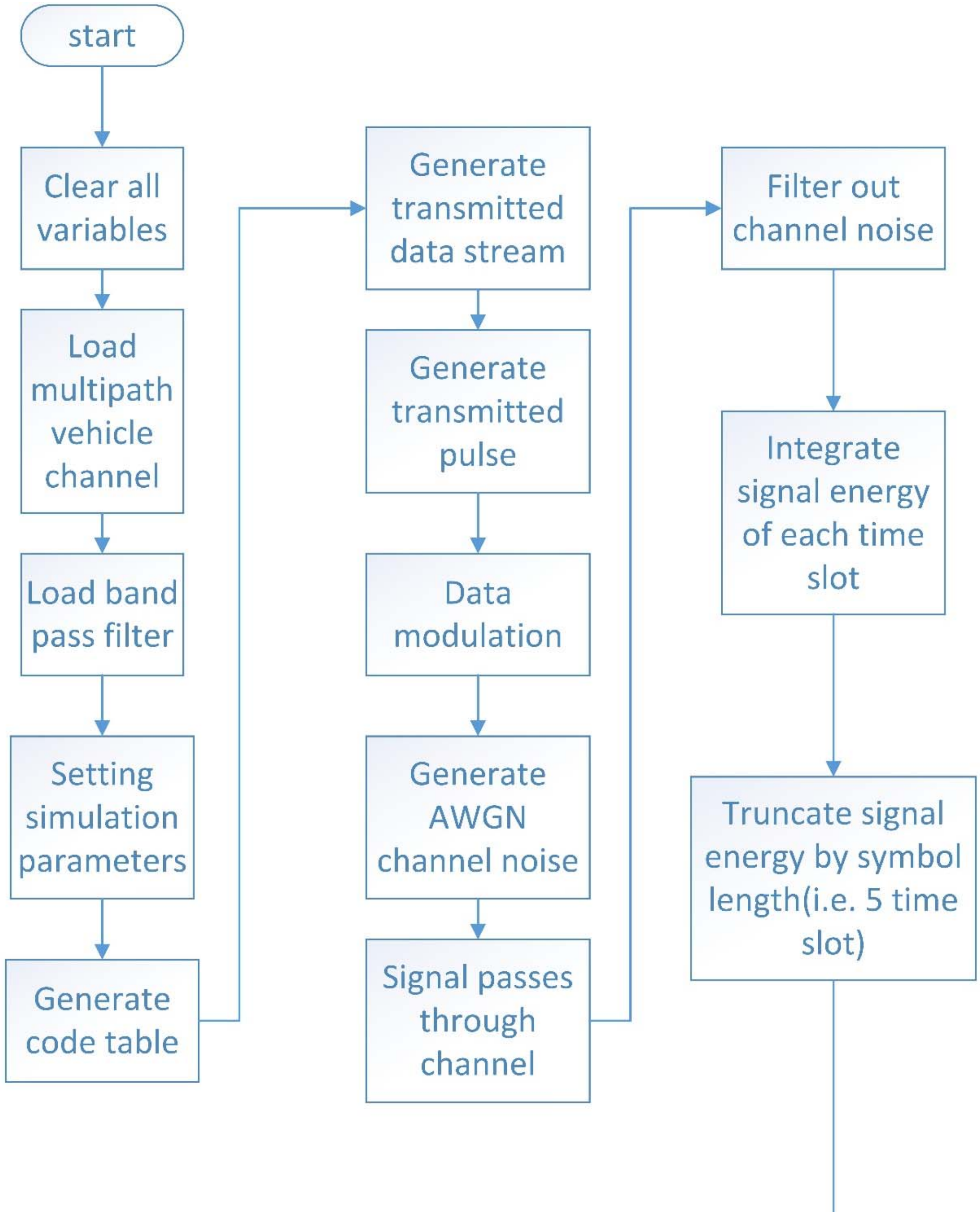


Figure 6. Matlab Software

Flow Chart



(Figure continues)

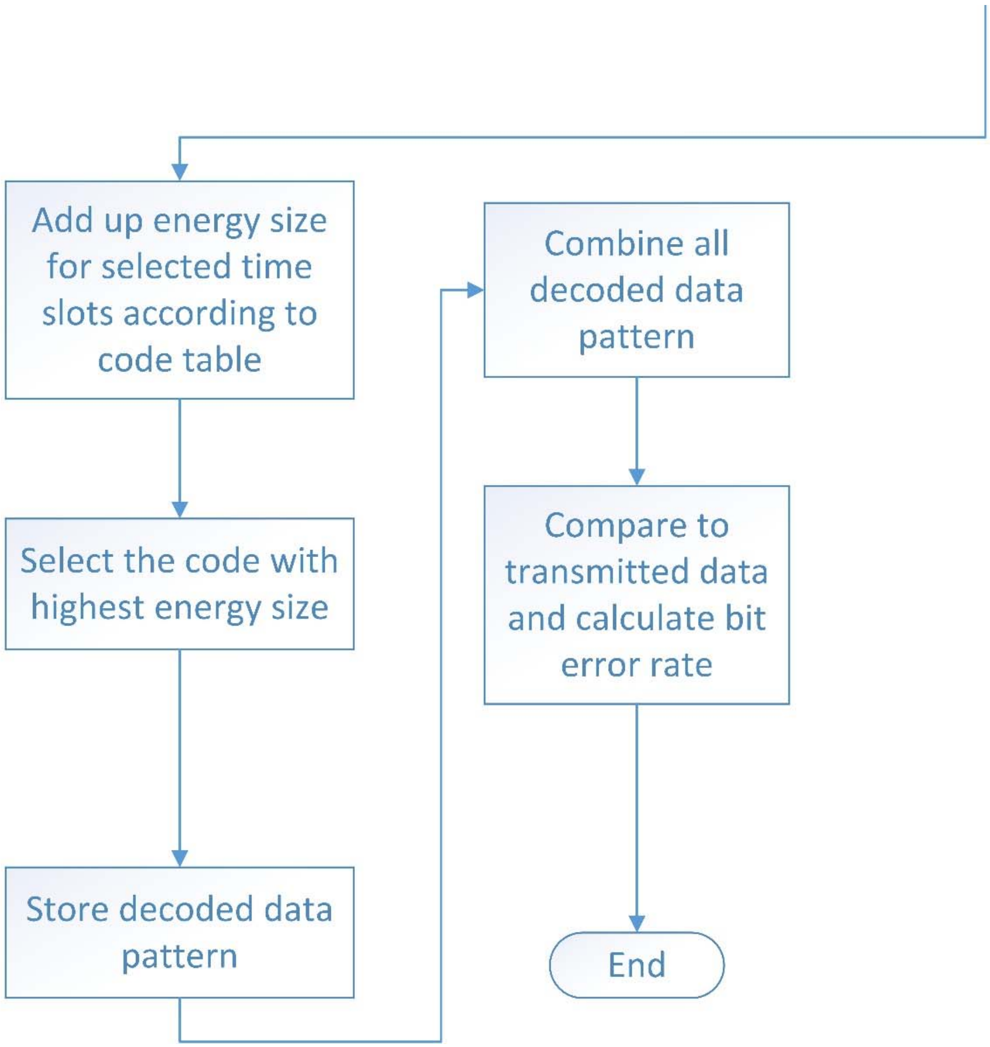


Figure 7. Simulation Program Flowchart

As shown in Figure 7, the simulation program starts with clearing variable data in the memory. Then, it will load multiple IEEE802.15.4a channels and a band pass filter for next stage simulation. Then, several important simulation parameters are defined by user (i.e. system sampling frequency, signal duration, center frequency and bandwidth of the transmitted pulse). After simulation environment is set, simulation program starts to encode data. To encode the data, a predefined coding table is generated and stored in the library. The transmitted data stream is modulated by a PPM pulse generator, and it will be encoded into a pulse position sequence. Then, AWGN noise is generated to simulate noise in the received signal. The modulated signal will pass through an AWGN channel or a multipath channel and add up with AWGN noise. In the receiver side, first the energy in each time slot will be detected from the received UWB signal. Then this detected energy sequence will be grouped by symbol length (e.g. 5 time slots per symbol). This operation will allow the simulation program to decode signal symbol by symbol. In each symbol, the simulation program will sort the energy of selected time slots and identify the time slots with the largest energy (e.g. 2 time slots with the largest energy among 5 time slots). Then according to the coding table, information bits transmitted in this symbol is decoded. After all symbols are decoded into data stream, the bit error rate is calculated by comparing decoded data stream with original transmitted ones.

Multipath Channel Model

The multipath channel model used in this simulation is IEEE802.15.4a industrial line-of-sight (LOS) channel model which is an international standard for an ultra-low complexity, ultra-low cost, and ultra-low power consumption alternate physical layer of the OSI model for IEEE standard 802.15.4 (Ciaran & Michael, 2008).

Parameter Setting

Basic parameters. Several parameters need to be set up before simulation. As shown in Table 4, system sampling frequency, center frequency of transmitted pulse, and bandwidth of transmitted pulse parameters are set to meet the requirements of UWB systems. Pulse duration is set to 20 ns to generate a flat spectrum in the frequency domain. Signal noise ratio parameter is a controlled variable to investigate BER performance of the modulation scheme in different environments. Data number per transmission is set as 500 to reduce memory load for computer.

Table 4 Basic Parameters for Simulation

Parameter Name \ Value	
system sampling frequency	32 GHz
pulse duration	20 ns
center frequency of transmitted pulse	5.35GHz
bandwidth of transmitted pulse	500 MHz
SNR(signal noise ratio)	10 dB to 17 dB
pulse repeat duration	50 ns
bit number per transmission	500

There are also specified parameters for certain modulation schemes. Here 2 pulses in 5 time slots for the enhanced PPM scheme is used as an example. As shown in Table 5, the related parameters are summarized as below:

Table 5. Specified Parameters for Certain Modulation schemes

Parameter Name \ Value	
bit number per symbol	3
pulse number per symbol	2
time slot number per symbol	5
frame time	30 s to 200 ns

<u>Signal generator</u>. The pulse generator used in this simulation is an ideal UWB pulse generator.

<u>Filter</u>. The filter used in this simulation is a FIR bandpass filter. As shown in Figure 8, the pass band of the filter is [5.1 GHz, 5.6 GHz]. The stop band of the filter is [0 Hz, 4.9GHz] and [5.8GHz, infinity]. The attenuation of the filter is 50 dB.

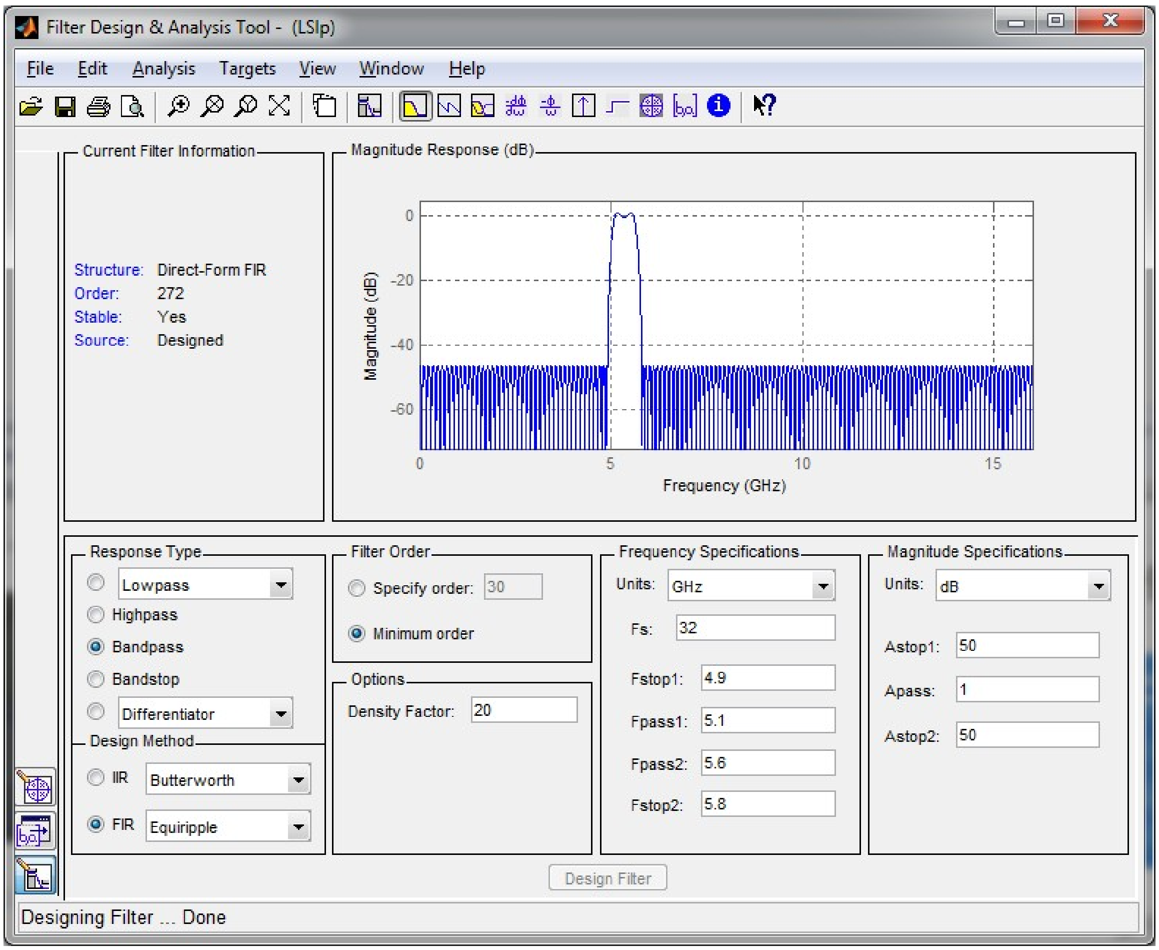


Figure 8. Parameters for Band Pass Filter

CHAPTER 4

ANALYSIS OF DATA

Data Overview

Bit error rate (BER), defined as the ratio between the total error bits and the total bits of the data stream in a communication channel, is mainly affected by noise, interference, multipath distortion or bit synchronization errors. The simulations I did are mainly focused on the multipath distortion and noise effects. In the simulations, it is assumed that the communication system does not suffer from inter-symbol-interference and bit synchronization errors. The multipath distortion mentioned above is caused by IEEE 802.15.4a multipath channels. The noise discussed in the simulations is Additive White Gaussian Noise (AWGN).

Multipath Channel Distortion

If we denote the transmitted pulse as x(t) and channel impulse response of IEEE 802.15.4a channel as h(t), the distorted pulse after channel, denoted as y(t), can be derived from the convolution integral as follows:

$$y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x(\tau) \cdot h(t-\tau) d\tau \tag{4.1}$$

Where * represents the convolution operation.

In this simulation, x(t), shown in Figure 9, is a transmitted pulse generated by a UWB signal generator. y(t), shown in Figure 10, is the distorted pulse after the multipath channel.

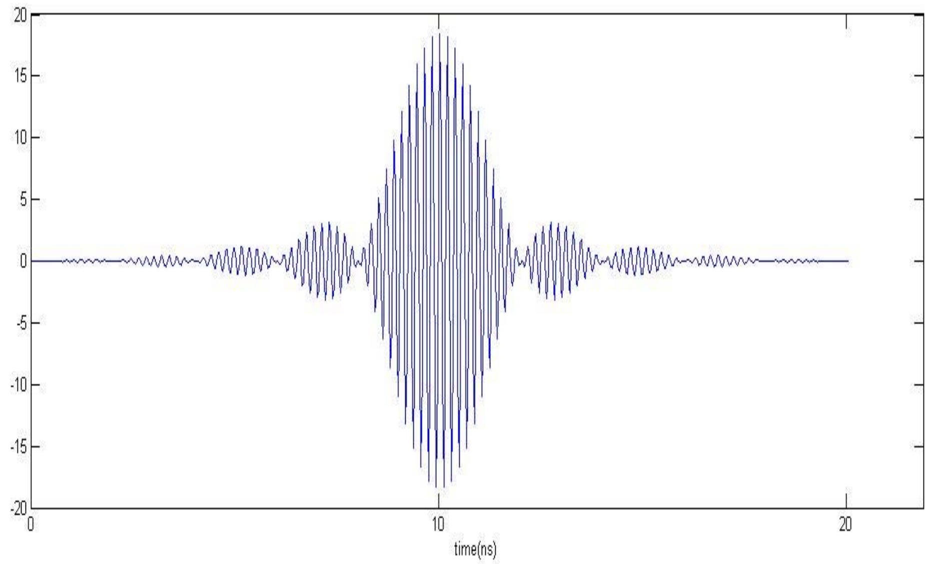


Figure 9. Transmitted Signal

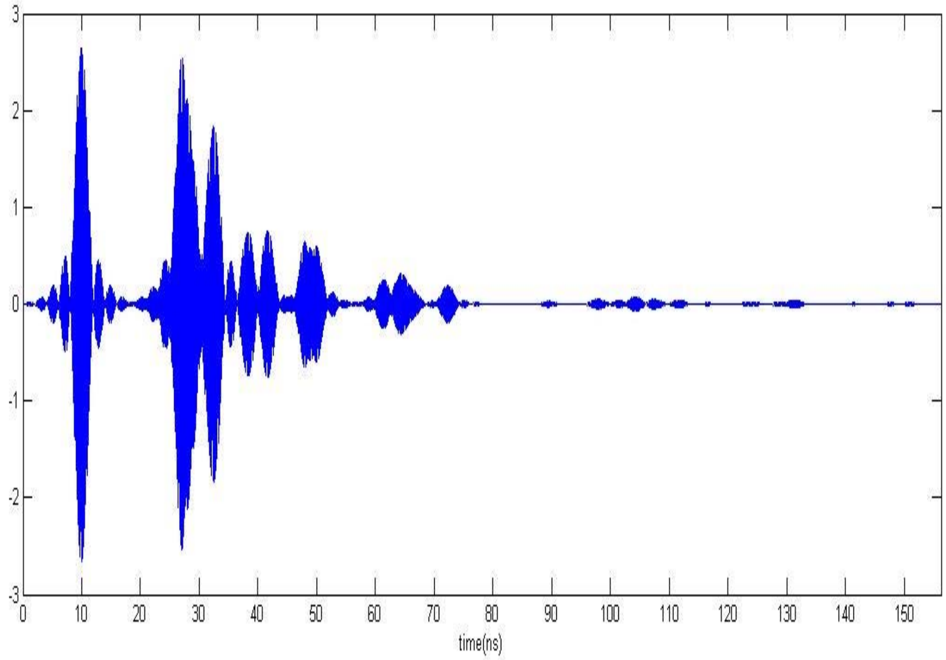


Figure 10. Distorted Pulse after Channel

The duration of the received pulse in Figure 10 is stretched to about 75 ns from less than 20ns (see the transmitted pulse in Figure 9). In the same time, because of multipath distortion, the signal waveform of the received pulse is quite different from that of the transmitted pulse signal in Figure 9. Since the decision statistics for energy detection based modulations are signal energy over an integration time; this stretched signal will lead to less detected energy when the integration time is less than a certain level. As a result, this stretched signal will be more vulnerable to environmental noise.

Additive White Gaussian Noise

Another root cause for BER is noise. AWGN is a fundamental noise model to simulate the random noise in nature. AWGN follows Gaussian distribution, which can be expressed as:

$$f(x,\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\left[\frac{(x-\mu)^2}{2\sigma^2}\right]} \tag{4.2}$$

Where x is the value of a random variable, μ is the mean of the random variable, and σ is the standard deviation of the random variable. Furthermore, the autocorrelation function of AWGN is a delta function, which means the power spectrum of AWGN is flat (or white).

Bit Error Rate for Conventional PPM and OOK

Our approach for data analysis uses the BER of conventional PPM and OOK as reference. It is necessary to get theoretical expression for the BER of conventional PPM/OOK modulation before we start data analysis.

OOK modulation. The Gaussian approximation of OOK performance, derived by Humblet and Azizoglu, assumes finite energy signals with Gaussian probability distribution (Humblet & Azizoglu, 1991). P_0 denotes the probability where a ‘1’ is detected when a ‘0’ (Off) is sent. Similarly, P_1 denotes the probability where a ‘0’ is detected when a '1' is sent. The optimal threshold should be set to make the probability of P_0 and P_1 equal.

The theoretical bit error function can be written as:

$$P_e \approx Q\left(\frac{2\varepsilon/N_0}{\sqrt{M}+\sqrt{M+4\varepsilon/N_0}}\right) \tag{4.3}$$

and the optimal threshold value is given by:

$$\gamma = MN_0 + \frac{2\varepsilon\sqrt{MN_0^2}}{\sqrt{MN_0^2}+\sqrt{MN_0^2+4\varepsilon N_0^2}} \tag{4.4}$$

Where Q(x) denotes a zero mean, unit variance Gaussian distribution function, ε is the average signal energy or ½ of the pulse signal energy, and N_0 is the single-sided power spectral density of the AWGN. In the same equation, M is the approximation integer of (2BT+1)/2, where B is the bandwidth of signals and T is the integration time.

Conventional PPM modulation. The Gaussian approximation for the conventional PPM performance, derived by Carbonelli and Mengali (2006), assumes perfect synchronization and frame period is larger than the channel impulse response.

The theoretical bit error function can be written as:

$$P(e) = Q\left(\left[2\left(\frac{N_0}{E_s}\right) + 4B\Delta\left(\frac{N_0}{E_s}\right)^2\right]^{-1/2}\right) \tag{5}$$

Where E_s is the received energy per symbol.

General Data Information

Modulation performance evaluations for the enhanced PPM schemes have been undertaken for the following three scenarios: i) BER performance with full integration time, ii) BER performance with variable integration time, and iii) BER performance with variable data transmission rate. Three schemes, including the two-pulse-in-five-time-slot scheme, the three-pulse-in-six-time-slot scheme, and the three-pulse-in-seven-time-slot scheme, are used as examples for the performance evaluations. To make it easier to remember, we denote above three schemes as C52 PPM, C63 PPM and C73 PPM.

Table 6. Code Table for C52 PPM Scheme

gray code				time slot				
0	0	0		0	0	1	0	1
0	0	1		0	1	0	0	1
0	1	1		1	0	0	0	1
0	1	0		1	0	0	1	0
1	1	0		0	0	1	1	0
1	1	1		0	1	0	1	0
1	0	1		0	1	1	0	0
1	0	0		1	0	1	0	0
				discard time slot scheme				
				0	0	0	1	1
				1	1	0	0	0

Table 7. Code Table for C63 PPM Scheme

gray code					time slot		
0	0	0	0		1	2	4
0	0	0	1		1	2	5
0	0	1	1		1	2	6
0	0	1	0		1	3	6
0	1	1	0		1	3	5
0	1	1	1		1	3	4
0	1	0	1		1	4	5
0	1	0	0		1	4	6
1	1	0	0		1	5	6
1	1	0	1		2	5	6
1	1	1	1		2	3	6
1	1	1	0		2	4	6
1	0	1	0		2	4	5
1	0	1	1		2	3	5
1	0	0	1		3	5	6
1	0	0	0		3	4	6
					discard time slot		
					1	2	3
					2	3	4
					3	4	5
					4	5	6

Table 8. Code Table for C73 PPM Scheme

gray code						time slot		
0	0	0	0	0		1	2	4
0	0	0	0	1		1	2	5
0	0	0	1	1		1	2	6
0	0	0	1	0		1	2	7
0	0	1	1	0		1	3	7
0	0	1	1	1		1	3	5
0	0	1	0	1		1	3	6
0	0	1	0	0		1	3	4
0	1	1	0	0		1	4	5
0	1	1	0	1		1	4	6
0	1	1	1	1		1	4	7
0	1	1	1	0		1	5	7
0	1	0	1	0		1	5	6
0	1	0	1	1		1	6	7
0	1	0	0	1		2	6	7
0	1	0	0	0		2	3	6
1	1	0	0	0		2	3	7
1	1	0	0	1		2	4	7
1	1	0	1	1		2	4	6
1	1	0	1	0		2	4	5
1	1	1	1	0		2	5	6
1	1	1	1	1		2	5	7
1	1	1	0	1		2	3	5
1	1	1	0	0		3	4	5
1	0	1	0	0		3	4	6
1	0	1	0	1		3	4	7
1	0	1	1	1		3	5	7
1	0	1	1	0		3	5	6
1	0	0	1	0		3	6	7
1	0	0	1	1		4	6	7
1	0	0	0	1		4	5	7
1	0	0	0	0		4	5	6
						discard time slot		
						1	2	3
						2	3	4
						5	6	7

From the coding table given as above, we can see that:

i. With two pulses, the C52 PPM scheme can transmit three information bits. Thus, as compared to the conventional PPM scheme, which transmits one information bit per pulse, for the same E_b/N_o (energy per bit to noise power spectral density ratio, also known as SNR per bit), the energy of each pulse in the C52 PPM scheme is 1.76dB higher than that of each pulse in the conventional PPM scheme;
ii. With three pulses, the C63 PPM scheme can transmit 4 information bits. Thus, the energy of each pulse in the C63 PPM scheme is 1.25dB higher than that of each pulse in the conventional PPM scheme;
iii. With three pulses, the C73 PPM scheme can transmit 5 information bits. Thus, the energy of each pulse in the C73 PPM scheme is 2.2dB higher than that of each pulse in the conventional PPM scheme.

It is well known that in the OOK scheme, one information bit is transmitted with 0.5 pulse, and hence the energy of each pulse in the OOK scheme is 3dB higher than that of each pulse in the conventional PPM scheme. According to the above analysis, the rank of the BER performance from the highest to the lowest for different modulation schemes should be the OOK scheme, the C73 scheme, the C52 scheme, the C63 scheme, and the conventional PPM scheme.

The BER performance for the above five modulation schemes are evaluated through computer simulations, and the obtained results are plotted with Matlab built-in function for each scenario so as to compare the five modulation schemes.

BER Performance with Full Integration Time Interval

BER performance is an important parameter in digital communications. Users want to know what BER performance can one digital modulation scheme achieve under specific received energy level. To ensure every digital modulation is compared fairly, BER performance is investigated under the same signal-to-noise ratio (SNR) level. In the simulations, E_b/N_o is used as a measuring scale for BER performance.

Figure 11 shows the BER performance of the C52, C63, and C73 enhanced PPM schemes, the conventional PPM scheme, and the OOK scheme.

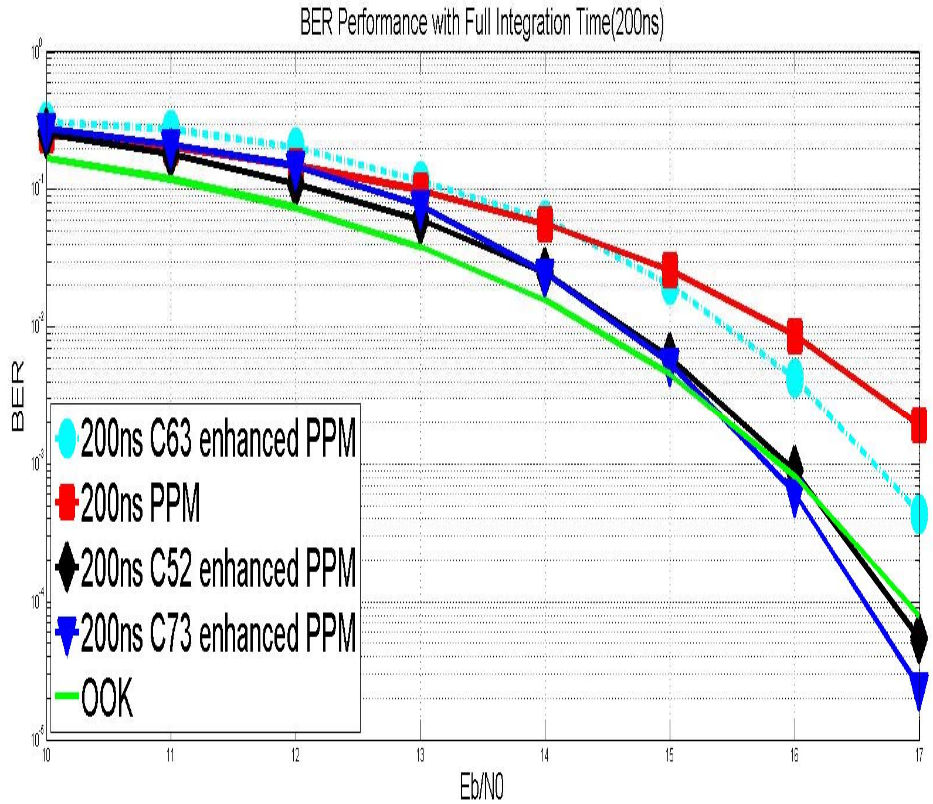


Figure 11. BER Performance with Full Integration Time (200ns)

As showed in Figure 11, for the low SNR scenarios (i.e. E_b/N_o below 13 dB), the enhanced PPM schemes have comparable or even worse BER performance than the conventional PPM. However, for most digital communications, BER must be lower than 10^{-2} or even10^{-3} level. Thus, low BER performance for the low SNR scenarios is acceptable for real world applications.

For the high SNR scenarios (i.e. E_b/N_o is higher than 14 dB), we can clearly see that the enhanced PPM scheme have better BER performance than the conventional PPM scheme. For example, at the 10^{-2} level, the C63 PPM, the C52 PPM, and the C73 PPM schemes have 0.4 dB, 0.8dB and 0.8dB performance improvement, respectively, as compared to the conventional PPM scheme. At the 10^{-3} level, the performance improvement increases to 0.8 dB, 1.4dB and 1.7dB. Theoretically, the OOK scheme should have the best performance among the five schemes. However, a threshold is required to detect the OOK modulated signal, and when the threshold is deviated from its optimal value, the BER performance of the OOK scheme may have serious degradation. As a result, the simulation results show that for the high SNR scenarios, the C52 and the C73 scheme can achieve even better BER performance than the OOK scheme.

From the simulation results, we can conclude that:

i. The enhanced PPM scheme can achieve a decent BER performance improve for high SNR scenarios.

ii. The performance improvement of the enhanced PPM scheme is consistent with the theoretical analysis.

BER Performance with Variable Integration Time Interval

Integration time is another important parameter that affects BER performance of energy detection (ED) based UWB receiver. In the ED- based receivers, if the integration time is longer than the multipath delay spread of the received UWB signal, the last stage of the integration collects no signal energy but noise energy, and consequently the effective SNR is reduced. On the contrary, if the integration time is shorter than the multipath delay spread of the received UWB signal, only a part of energy of the signal is collected, and consequently the effective SNR is reduced as well. Therefore, it is very important to choose an appropriate length for integration time.

Since all five modulation schemes discussed here use the same receiver structure, the C63 PPM scheme is selected as an example to illustrate the effect of the integration time. As discussed in the multipath channel distortion section, the duration of the original UWB pulse is about 20 ns, but the duration of the distorted pulse after the multipath channel is about 75 ns.

As showed in Figure 12, the BER performance of the C63 PPM modulation will improve when the integration time decreases from 200ns to 100ns. In this stage, the reduction on the integration time will only reduce the noise energy collected by the integration, and hence the effective SNR of integration output increases and the BER performance of the C63 PPM scheme improves.

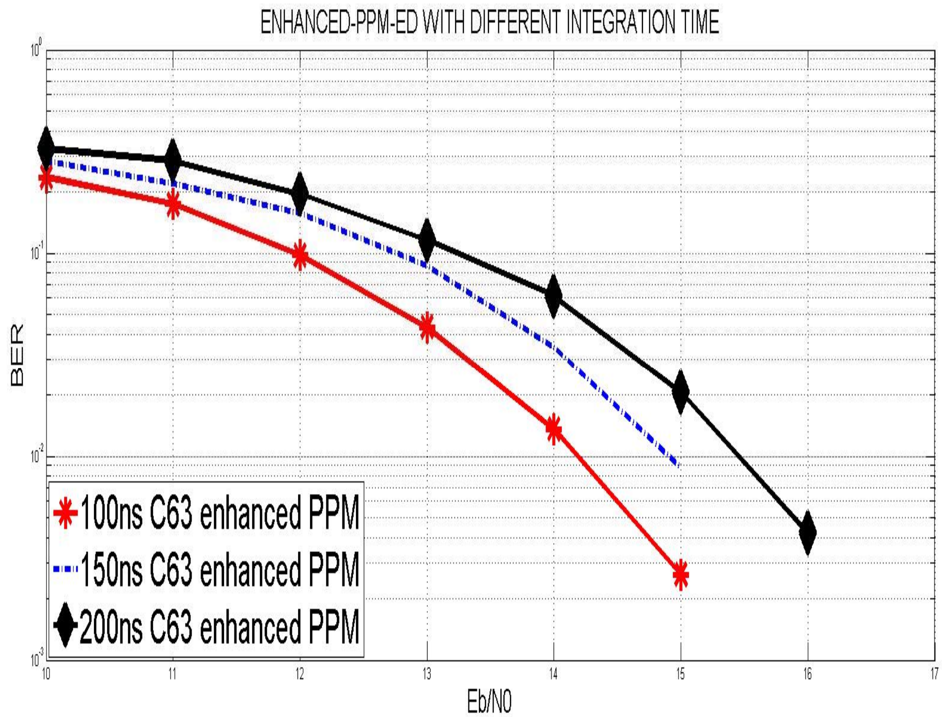


Figure 12. C63 PPM BER Performance

with Integration Time from 100ns to 200ns

If the integration time keeps decreasing to a time interval shorter than the multipath delay spread of the received UWB pulse (around 75ns), the signal energy collected by integration will reduce as well. Consequently, the effective SNR may decrease instead of increasing. As shown in Figure 13, when the integration interval is reduced to shorter than 50, the main energy lobe of the received UWB pulse will be filtered out, and the BER performance will decrease dramatically. The best BER performance appears when the integration interval is round 60ns instead of 75ns. The reason for this phenomenon can be justified as follows: in the range between 60 ns and 75ns, the signal energy starts to fall and is smaller than the noise energy. Thus, reducing the integration time from 75 ns to 60 ns can still bring BER performance improvement.

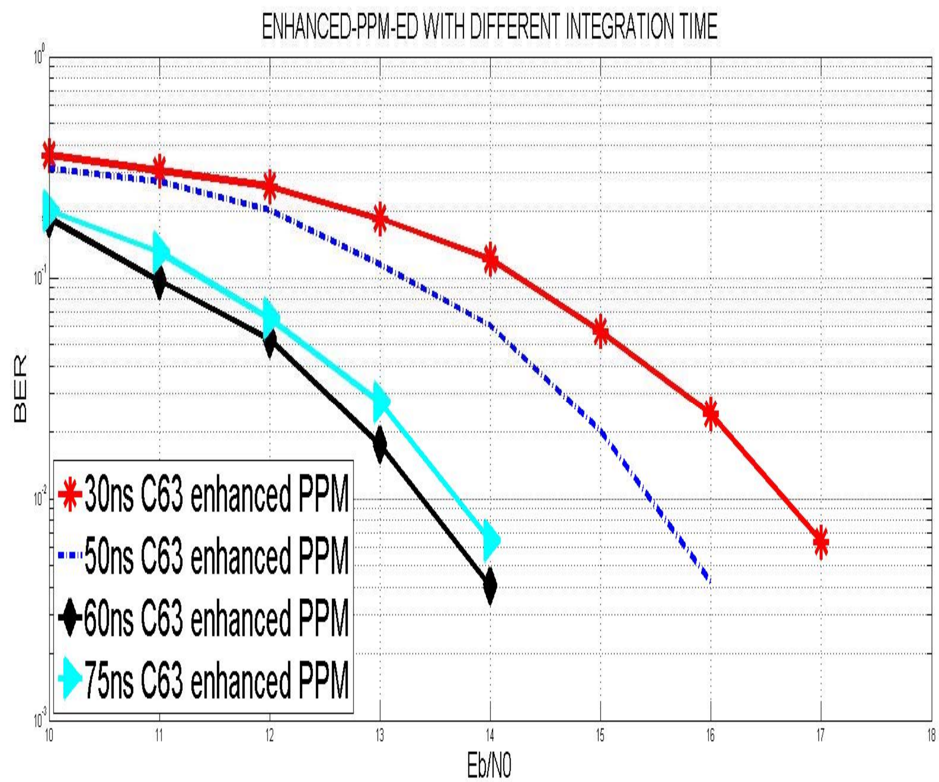


Figure 13. C63 PPM BER Performance

with Integration Time from 30ns to 75ns

Data Transmission Rate

Although BER performance is the main judging factor for digital communication systems, one cannot ignore another importance factor: data transmission rate.

The data transmission rate S can be expressed as:

$$S = \frac{B}{T} = \frac{B}{N_t * T_t} \quad (6)$$

Where B denotes total transmitted bit, T represents total transmission time, N_t means total time slots numbers and T_t stands for the length of each time slot.

Using the conventional PPM scheme as reference, the relative transmission rate of enhanced PPM modulations are shown in Figure 14:

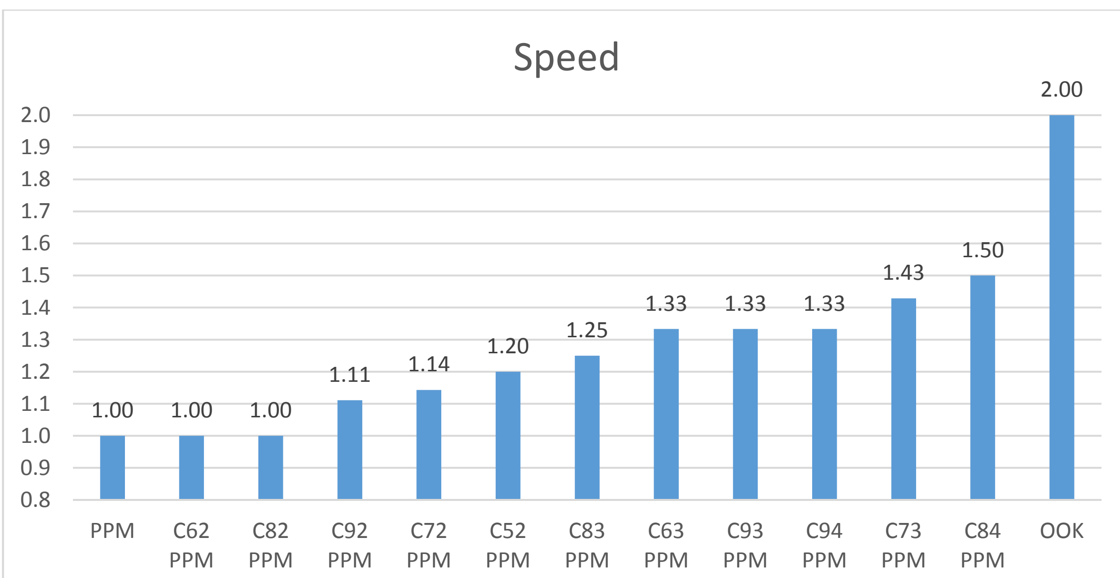


Figure 14. Relative Data Transmission Rate

of the Enhanced PPM Scheme

As showed in Figure 14, the conventional PPM scheme uses two time slots to transmit one information bit, and it is used as the reference transmission rate. The OOK scheme uses one time slot to transmit one information bit, so its rate is twice of the conventional PPM scheme. About the enhanced PPM scheme, the C62 uses 6 time slots to transmit 3 information bits, and the C82 uses 8 time slots to transmit 4 information bits, so they have the same rate as the conventional PPM scheme; the C92 uses 9 time slots to transmit 5 information bits, so its rate is 11% higher; the C72 uses 7 time slots to transmit 4 information bits, so its rate is 14% higher; the C52 uses 5 time slots to transmit 3 information bits, so its rate is 20% higher; the C83 uses 8 time slots to transmit 5 information bits, so its rate is 25% higher; the C63 uses 6 time slots to transmit 4 information bits, and the C93 and the C94 use 9 time slots to transmit 6 information bits, so their rates are 33% higher; the C73 uses 7 time slots to transmit 5 information bits, so its rate is 43% higher; finally, the C84 uses 8 time slots to transmit 6 information bits, so its rate is 50% higher. Among those enhanced PPM schemes, the C73 scheme has both high data transmission rate and high BER performance, so it is considered as a promising modulation scheme.

Discussions

Simulation results in this thesis reveal the benefits of the enhanced PPM modulation. With minor modifications on the existing hardware of PPM transceivers, the enhanced PPM scheme can achieve better BER performance as well as higher transmission rate. Furthermore, some wireless applications may concern more about BER performance, while others may care more about transmission rate. The variety of the enhanced PPM schemes provides a chance for users to select a suitable modulation scheme based on their application scenarios.

The key innovative idea used in this thesis is to extend the conventional 2^M PPM modulation scheme to a general arbitrary size M-PPM modulation scheme. This idea, proved to be useful for the PPM modulation of UWB systems, should not be restricted to UWB systems. Any types of position modulations can be modified according to this idea to get a higher pulse energy efficiency and data transmission rate.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Chapter 1 introduced the history of Ultra-Wideband (UWB) and acknowledged the modulation dilemma of choosing between hardware simplicity and high bit error rate (BER) performance/high data transmission rate. This study addressed the modulation problem and proposed a novel modulation scheme named as enhanced pulse position modulation (Enhanced PPM) to achieve high BER performance and high data transmission rate as well as low hardware implementation complexity. This modulation scheme was demonstrated and validated by scientific simulation tool named Matlab. Chapter 1 also defined special terms used in this thesis along with the assumptions, limitations and general simulation parameters of this study.

Chapter 2 discussed the related literature in the field of Ultra-Wideband (UWB) communication starting with a system overview which covered UWB history, UWB standards, UWB specifications and UWB usage. Chapter 2 went on to speak with two widely used UWB modulation methods: On Off Shift Keying (OOK) modulation and pulse position modulation (PPM). A discussion of reasons why other modulations are seldom adopted in UWB system was followed by a summary of the literature.

Chapter 3 described the methodology used in this study to solve the modulation dilemma. We use two pulses in five time slot PPM modulation scheme as an example for general enhanced PPM modulation. This chapter also discussed, in detail, the coding rules, receiver's implementation, simulation flow chart, simulation tools and simulation parameters for this modulation scheme.

Chapter 4 analyzed the data from computer simulation. The chapter began with a data overview followed by a discussion of the general data information. Matlab and Excel were utilized to test and describe the data in their respective categories. The categories tested were BER performance with full integration time interval (200ns), BER performance with adjustable integration time and data transmission rate. This chapter closed with a discussion of the results collected for analyzing and selection for optimal enhanced PPM modulation.

Hypothesis Findings

The purpose of the hypothesis was to prove that a modification from a single pulse to multiple pulses plus pulse position allocation in multiple time slots allocation improves the BER performance and transmission rate of the novel PPM scheme to the same level as the OOK scheme.

Based on the findings of this study, we can conclude, (1) Modification from a single pulse to multiple pulses plus pulse position allocation does improve the BER performance. (2) Time slot allocation modification does improve data transmission rate. The decrease in total time slot numbers will increase aggregate data transmission speed. (3) The modification of time slot allocation can use the same hardware transceivers as conventional PPM modulation. The implementation complexity is low compared to OOK modulation scheme. Also, the simulation result of novel PPM modulation reveals that different enhanced PPM time slot allocation schemes have the different focus, either on BER performance improvement or data transmission speed. User can select enhanced PPM schemes according to specific scenarios.

Conclusions

The features of the UWB communication system which includes high accuracy, security, low price, low power consumption and high data rate make UWB technology ideal for variety applications such as personal area network (PAN) and intro-vehicle communication (IVC). On-Off-Keying (OOK) modulation and Pulse-Position-Modulation (PPM) are two widely adopted modulations in UWB communications. The advantages for these two modulations are high bit error rate (BER) performance/high data transmission rate and simplicity respectively.

There existed a dilemma problem for above two modulations that high bit error rate (BER) performance/high data transmission rate and receiver structure simplicity cannot be obtained at the same time. In open technical literature, many articles about the OOK modulations are focused on designing an optimal or suboptimal threshold value which requires less pilot channel information to reduce the receiver structure complexity. While researchers for PPM modulation are interested in designing 2^M PPM and DPPM to increase BER performance.

However, none of these articles consider combining the advantage of OOK modulation and PPM modulation. In order to solve this problem, a novel pulse-position modulation (PPM) scheme, with modification from single pulse to multiple pulses in multiple time slots, is proposed to achieve high bit error rate (BER) performance, high data transmission rate as well as low transceiver complexity. Furthermore, we discussed the relation of BER performance with adjustable integration intervals to achieve the optimal BER performance.

This research is based on Matlab simulation. So the simulation result played a very important role in the study. Most of time in this study was dedicated in simulation of BER performance of different enhanced PPM modulations. Firstly, BER performance of enhanced PPM modulations are compared with conventional PPM modulation and OOK modulation in full frame integration time. Then, BER performance of 3 pulses in 6 time slot (C63) PPM modulation is selected to illustrate different integration affection on the BER performance. Finally, data transmission speeds of enhanced PPM modulation are evaluated comparing to conventional PPM and OOK modulation.

The rigorous simulation data enabled meaningful analysis of the study. The analysis of the study was based on the Matlab program. The simulation data is stored on .mat file and plotted in the Figure for easy understanding. The performance of different modulation schemes can be judged by bit error rate level.

Based on the simulation results in both full frame integration time and adjustable integration time, we can conclude, (1) The enhanced PPM scheme can achieve a decent BER performance improve for high SNR scenarios. (2) The performance improvement of the enhanced PPM scheme is consistent with the theoretical analysis. (3) Best BER performance of enhanced PPM scheme appears when the integration interval is round 60ns. (4) The data transmission rate improvement of enhanced PPM scheme compared to conventional PPM schemes varies from 11% to 50%. (5) Among all possible enhanced PPM schemes, the C73 scheme has both high data transmission rate and high BER performance, so it is considered as a promising modulation scheme.

Recommendations for Future Work

So far, the simulation is under the assumption of no inter-symbol interference and no narrowband interference. The reason for ignoring these two interference is for easier calculation and simulation. But I believe the result will be a little bit different when inter-symbol interference and narrowband interference are put into consideration. In next stage research, these two interference should be considered for a more precise result of enhanced PPM modulation.

In addition, this study can only provide a rough prediction for different enhanced PPM modulation according to energy per pulse parameter. There is a need to derive an approximate mathematical model to guide future simulation.

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APPENDIX A

A COMPLETE COMBINATION-PERFORMANCE TABLE

Pulse	Time Slot	Represent Bit	Pulse/Bit	Bit/ Time Slot
2	5	3	2/3	3/5
3	6	4	3/4	1/2
2	6	3	2/3	2/3
3	7	5	3/5	4/7
2	7	4	1/2	5/7
4	8	6	2/3	1/2
3	8	5	3/5	5/8
2	8	4	1/2	3/4
3	9	6	1/2	5/9
2	9	5	2/5	2/3
4	9	6	2/3	2/3
4	10	7	4/7	1/2
3	10	6	1/2	3/5
2	10	5	2/5	7/10
5	10	7	5/7	7/10
4	11	8	1/2	5/11
3	11	7	3/7	7/11
5	11	8	5/8	8/11
5	12	9	5/9	8/11
4	12	8	1/2	1/2
3	12	7	3/7	7/12
2	12	6	1/3	2/3
6	12	9	2/3	3/4
4	13	9	4/9	3/4
3	13	8	3/8	6/13
5	13	9	5/9	8/13
6	13	9	2/3	9/13
4	14	9	4/9	9/13
3	14	8	3/8	9/13
5	14	9	5/9	3/7
6	14	9	2/3	4/7
7	14	9	7/9	9/14
4	15	9	4/9	9/14
3	15	8	3/8	9/14

(Table continues)

pulse	time slot	represent bit	pulse/bit	time slot/bit
5	15	9	5/9	9/14
6	15	9	2/3	3/5
7	15	9	7/9	3/5
3	16	9	1/3	3/8
4	16	9	4/9	9/16
5	16	9	5/9	9/16
6	16	9	2/3	9/16
7	16	9	7/9	9/16
8	16	9	8/9	9/16
3	17	9	1/3	9/16
4	17	9	4/9	7/17
5	17	9	5/9	9/17
6	17	9	2/3	9/17
7	17	9	7/9	9/17
8	17	9	8/9	9/17
3	18	9	1/3	9/17
4	18	9	4/9	9/17
5	18	9	5/9	7/18
6	18	9	2/3	1/2
7	18	9	7/9	1/2
8	18	9	8/9	1/2