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DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

ULTRA WIDEBAND IMPULSE RADIO TRANSCIEVER
PROJECT NO: PRJ085

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Department of Electrical and Information Engineering
DEDICATION

I dedicate this work to my mum and dad, who have been priceless gems in my life. I’m happy that you have stood by me even when I messed up. Indeed your love has been unconditional.
ACKNOWLEDGEMENTS

In my life I have found there are several constants, which I feel should be acknowledged first and foremost because without which, this project would not have been a success. The most significant is my Almighty Savior, Jesus Christ, who has not only given me the strength and ability to achieve my goals, but has surrounded me with the greatest family, friends, and professionals. I have learned in my life that "for with God all things are possible" (Mark 10:27).

Secondly I would like to express my sincere gratitude to my supervisor, Dr. V.K Oduol, who went out of his way to ensure that I complete this project through the advice that he offered, the times that he never tired of seeing me, going through my progress report and making corrections and recommendations. His advice and help were absolutely invaluable.

Last but not least would also like to thank my friends and colleagues for supporting and encouraging me during my studies in the University of Nairobi, in particular, my classmates. Finally, I reserve the most special gratitude for my family. Without your unconditional support and love, this could not have been possible.


ABSTRACT

Ultra Wide Band (UWB) is a new spectrum allocation which was recently approved by the Federal Communication Commission (FCC) and is under study in Europe and Asia. It has emerged as a solution to provide low complexity, low cost, low power consumption, and high-data-rate wireless connectivity devices entering the personal space. For a wireless system to qualify to be a UWB its fractional bandwidth should be greater than 20% and its total bandwidth larger than 500MHz. At the emission level, UWB signals have a mask that limits its spectral power density to -41.3dBM/MHz between 3.1 GHz and 10.6GHz, which is 7.5GHz bandwidth.

UWB systems are implemented in two techniques. These are the orthogonal frequency division multiplexing (OFDM) used to cover the whole spectrum, also called multi-band UWB (MB-UWB) and the other approach is the impulse radio technique in which ultra short duration baseband pulses are generated to cover the whole spectrum. With a variety of modulation schemes data transfer is performed.

The objective of this project is to study, design, and simulate a low power, high data rate Ultra Wideband Impulse Radio(UWB-IR) transceiver. The Direct Sequence (DS) UWB transceiver architecture was selected for the system design. The transmitter uses second derivative Gaussian pulses that are modulated using a binary phase shift keying (BPSK) modulation technique. The pulse rate of the system is 156MHz and the bit rate under investigation was 156Mbps. A matlab code was used to simulate the transmitter and the receiver of the ultra wideband impulse radio transceiver system.
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CHAPTER 1
INTRODUCTION

Radio is the art of wirelessly sending and receiving electromagnetic signals from transmitters to receivers. [2] The transmitters are required for generating signals, and receivers for translating the received information. Both use antennas for sending the signals as electromagnetic energy at the antenna and for collecting that energy at the receiver.

The concept of Ultra-Wideband (UWB) was formulated through research in time-domain electromagnetic and receiver design in the early 1960. This was primarily performed by Gerald F. Ross. Through his work, the first UWB communications patent was awarded for the short-pulse receiver which he developed while working for Sperry Rand Corporation [4]. Throughout that time, UWB was referred in broad terms as "carrier-less" or impulse technology. The term UWB was adapted in the late 1980s to describe the development, transmission, and reception of ultra-short pulses of radio frequency (RF) energy.

UWB-IR communication systems have an unprecedented opportunity to impact communication systems. This is because of the enormous bandwidths available, the wide scope of the data rate/range tradeoff, and the potential for very-low-cost operation. In the past 20 years, UWB has been used for radar, sensing, military communications, and niche applications. In February 2002 the US Federal Communications Commission (FCC) ruled that UWB could be used for data communications as well as radar and safety applications. [1] The band the FCC allocated to communications is 7.5GHz between 3.1 and 10.6GHz; by far the largest allocation of bandwidth to any commercial terrestrial System. [3] However the available power levels are very low. If the entire 7.5 GHz band is optimally utilized, the maximum power available to a transmitter is approximately 0.5mW [1]. The power limitation relegates impulse radio systems to high data rates for indoor, short range communications.

The potential of UWB is in the ability to move between the very high data rate, short-link distance applications and the very low data rate, longer-link-distance applications. The tradeoff is
facilitated by the physical layer signal structure. The very low transmit power available means that multiple, low energy UWB pulses typically must be combined to carry one bit of information. In principle, trading data rate for link distance can be attained by increasing the number of pulses used to carry one bit. The more pulses per bit, the lower the data rate, and the greater the achievable transmission distance.

1.1 Problem Definition

The project problem was to study Ultra Wideband impulse radio transmission systems for as use in wireless sensor networks as a means of providing low power data transmission over short distances. It also required the design and demonstration of the working of an Ultra wideband impulse radio transceiver.

1.2 Problem Justification

The theoretical motivation why UWB-IR technology is so attractive can be better explained using the Shannon theorem which relates the capacity of a system with its bandwidth and signal to noise ratio. It is expressed as: [4]

\[ C = B \log_2 (1 + P / (BN_o)) \]  

Where:
- C is the channel capacity (bps)
- B is the channel bandwidth (Hz)
- P is the signal power (W)
- No is the noise power spectral density (W/Hz)

From equation 1.1 the capacity of a communication system increases faster as function of the channel bandwidth than as function of the power. However, traditional wireless systems have evolved using narrowband systems that are power limited and therefore have a limited channel capacity. [2] On the other hand, the increasing need of high data rates in wireless communication applications will require the use of wide band systems capable of handling several GHz in order to accomplish the demands. Therefore, UWB-IR technology has emerged as a solution for high data rates systems.
The UWB-IR systems are inherently resistant to multi-path fading due to the fact that it is possible to resolve differential delays between pulses on the order of 1ns. [1] Furthermore, as the signals are spread in a wide bandwidth, they show a low power spectral density which makes them suitable for Low Probability of Detection (LPD) systems. [4] The system characteristics justify their applications in low complexity, low cost, low-power consumption, and high data rates wireless connectivity of devices in short range communication. These properties make the UWB attractive to several applications.

### 1.3 Project Objectives

The overall objective of the project was to study the Ultra Wideband impulse radio transmission system for as use in wireless sensor networks as a means for providing low power data transmission over short distances and then design and demonstrate the working of a UWB impulse transceiver.

The design objectives for the impulse radio UWB wireless communication system are as follows:

1. High data rate
2. Pulse waveform: Gaussian Monocycle
3. Modulation Schemes: Bi-phase shift key (BPSK) Modulation
4. Receiver topologies: Correlator receiver

These design goals were to increase data rate, transmission range, and modulation schemes when the system is designed.

### 1.4 Scope of the Project Report

This report has been divided into 7 chapters. Chapter 2 presents an analysis of UWB-IR systems. This covers the characteristics, regulation and application of the systems. The signal processing is also covered in this chapter. Pulse generation, modulation and multiple access schemes are discussed. The transmitter, propagation channel, antenna, path loss and shadowing and the receiver are also presented in this chapter. The design of the UWB-IR system transceiver is covered in chapter 3. The transmitter and the receiver design of the system are carried out here.
The correlation receiver is selected and its blocks are defined. A matlab code to simulate the system is proposed. Chapter 4 presents the verification of the design. The system simulation proposed in chapter 3 is executed, and its results are presented. Results are discussed in detail and compared to theoretical results in Chapter 5. The recommendations for future work in the field covered and the conclusions made in the project report are also contained in this chapter. The references for this report are in chapter 6. Chapter7 is the appendices. It contains the matlab code used to simulate the system and the and results obtained.

1.5 Software Support

The transmission and reception of the impulse radio data signals was done using the matlab software, to demonstrate the working of UWB-IR transceiver. The software-defined implementation provides tremendous flexibility in the capability to utilize one of several different popular UWB modulation schemes. Also one can vary the pulse rate, use different receiver topologies. All of these different situations can be controlled more easily in software, which makes a software implemented UWB-IR system more adaptable to a variety of real world environments. This type of flexibility led to the UWB system design presented in this report.
CHAPTER 2
LITERATURE REVIEW

2.0 Introduction

Ultra wideband Impulse radio communication systems are carrier free. These systems utilize very short, low duty cycle pulses with high bandwidth in transmission that results in an UWB spectrum. This communication method is also classified as a pulse modulation technique since the data modulation is introduced by manipulating pulse shape and position. The UWB-IR signal is noise-like making interception and detection quite difficult. Due to the low power spectral density, UWB signals cause very little interference with existing narrowband radio systems. [1]

2.1 Characteristics of Impulse Radio UWB signals

Time modulated impulse radio(TM-IR) signals are carrier less baseband transmission. The absence of carrier frequency forms the fundamental characteristic that differentiates impulse radio transmission from narrow band applications that are sometimes considered ultra wide band.

The key benefits of UWB-IR communication systems can be summarized as below;

1. Have potentially low complexity;
2. Have potentially low cost;
3. Have a noise-like signal spectrum;
4. Have multipath immunity;
5. Have very good time-domain resolution allowing for precise location and tracking applications
6. Have high data rates

The low complexity and low cost of UWB-IR systems arise from the baseband nature of the signal transmission. Unlike conventional systems, the UWB-IR transmitter produces a very short time-domain pulse which is able to propagate without the need for an additional radio frequency(RF) mixing stage. The RF mixing stage takes a baseband signal and "injects" a carrier frequency or translates the signal to a frequency which has desirable propagation
characteristics. The signal will propagate well without the need for additional up-conversion. The reverse process of down-conversion is also not required in the UWB-IR receiver. Again, this means the omission of a local oscillator in the receiver, and the removal of associated complex delay and phase tracking loops. Consequently, UWB-IR systems can be implemented in low cost, low power integrated circuit processes. UWB-IR technique also offers grating lobe mitigation in sparse antenna array systems without weakening of the angular resolution of the array. [1]

Due to the low energy density and the pseudo-random (PR) characteristics of the transmitted signal, the UWB-IR signal is noise-like which makes unintended detection difficult. Also, the low-power, noise-like UWB-IR transmissions does not cause significant interference to existing radio systems. [1]

UWB-IR systems offer high data rates for communication, hundreds of Mbps. The number of users in an impulse radio communication system is much larger than in conventional systems. This is valid for both high- and low-data rate communications. [3]

Very high multipath resolution is achieved because of the large bandwidth of the transmitted signal. The large bandwidth offers huge frequency diversity, which together with the discontinuous transmission makes the UWB-IR signal resistant to severe multipath propagation and interference. UWB-IR systems offer good low probability of interception/detection (LPI and LPD) properties making it efficient for secure and military applications. The very narrow time-domain pulses mean that UWB-IRs are potentially able to offer timing precision much better than GPS (global positioning system) and other radio systems. [2]

2.2 Regulation
Frequency of operation is one of the important issues in UWB communication. Due to the use of very wide spectrum range, UWB systems are not intended to operate under any specific allocation. There are many systems operating under allocated bands in the UWB signal band.
In the USA the Defense Advanced Research Projects Agency (DARPA) defined UWB signal based on the fractional bandwidth \( B_f \) of the signal. A signal can be classified as an UWB signal if its fractional bandwidth \( B_f \) is greater than 0.20. The fractional bandwidth is determined using the formula. [1]

\[
B_f = \frac{2(f_H - f_L)}{(f_H + f_L)}
\]  \hspace{1cm} 2.1

Where \( f_L \) is the lower and \( f_H \) is the higher \(-3\)dB point in the spectrum, respectively. Also, according to the FCC UWB rulings, UWB radiators must be designed to guarantee that the 20-dB bandwidth of the emission is contained within the UWB frequency band. The minimum bandwidth measured at points 10dB below the peak emission level is 500 MHz and the permissible emission levels for UWB signals in the UWB band are set at \(-41.3\) dBm/MHz. In the above formula, \( f_H \) and \( f_L \) are now the higher and lower \(-10\)dB bandwidths, respectively. [2] The center frequency is given by \( f_C = (f_H \times f_L)^{1/2} \), denoting -10dB cut-off frequency of the power spectrum [7].

![Image](image_url)
The FCC regulations permit indoor UWB systems and handheld devices. The emission limits for indoors and handheld devices are shown in Figure 2.2, and are compared to their limits in Table 2.1.

Table 2.1  FCC limits for indoor and handheld systems [2]

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Indoor EIRP (dBi)</th>
<th>Handheld EIRP (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 960</td>
<td>Section 15.209</td>
<td>Section 15.209</td>
</tr>
<tr>
<td>960-1610</td>
<td>-75.3</td>
<td>-75.3</td>
</tr>
<tr>
<td>1610-1990</td>
<td>-53.3</td>
<td>-63.3</td>
</tr>
<tr>
<td>1990-3100</td>
<td>-51.3</td>
<td>-61.3</td>
</tr>
<tr>
<td>3100-10600</td>
<td>-41.3</td>
<td>-41.3</td>
</tr>
<tr>
<td>Above 10600</td>
<td>-51.3</td>
<td>-61.3</td>
</tr>
</tbody>
</table>
According to compatibility studies undertaken by the CEPT (the European Conference of Postal and telecommunication), the limits for emissions from UWB devices for communication applications should be lower than the FCC limits in order to avoid harmful interference to some of the radio communication applications in CEPT countries. [2]

2.3 Applications of UWB-IR

UWB-IR technology is flexible enough to work in many different ways while still maintaining its characteristics. This diversity enables UWB-IR communication systems to be applied in many areas. These applications are distributed amongst three categories:

1. Communications and sensors

One of the major potential advantages in UWB-IR based systems is the ability to trade data rate for link distance by simply using more or less concatenated pulses to define a bit. Without dramatically changing the air interface, the data rate can be changed by orders of magnitude depending on the system requirements. This means however that high-data-rate (HDR) and low-data-rate (LDR) devices will need to coexist. [1] The high-data-rate personal area networks (PANs) can be applied in transmission of digital TV signals via a wireless link. Such high data rates, in conjunction with the limits on the power spectral density, can be performed only over short distances (on the order of 10m), and are of interest mostly for residential and office environments. Another application of interest is sensor networks. As the data rates are much lower in this context, longer ranges are possible. Furthermore, sensor networks can be of great interest in factory environments, where "indoor" distances can be larger, and the abundance of metallic reflectors can lead to quite different propagation conditions. [1]

2. Position location and tracking

The narrow time domain pulse means that UWB-IR technology offers the possibility for very high positioning accuracy. However, each device in the network must be "heard" by a number
of other devices in order to generate a position from a delay or signal angle-of-arrival estimate.\[1\] The power limitation effectively relegates UWB-IR systems to indoor, short-range communications for high data rates, or very low data rates for longer link distances. Applications such as wireless USB and personal area networks have been proposed offering hundreds of Mbps to several Gbps with distances of 1 to 4 meters. For ranges of 20 meters or more, the achievable data rates are very low compared to existing wireless local area network (WLAN) systems. [1]

3. Radar.
Together with good material penetration properties, UWB-IR signals offer opportunities for short-range radar applications such as rescue and anti-crime operations, as well as in surveying, and in the mining industry. However, UWB-IR does not provide precise targeting and extreme penetration at the same time, but the UWB waveforms present a better tradeoff than many conventional radio systems. [2]

2.4 UWB-IR Signal Processing
This technique is a baseband signal approach based on discontinuous transmission of very short pulses or pulsed waveforms (monocycles) having the corresponding ultra-wide frequency-domain. This type of transmission does not require the use of additional carrier modulation as the pulse will propagate well in the radio channel. One transmitted symbol is spread over $N$ monocycles to achieve a processing gain that may be used to combat noise and interference. The processing gain derived from this procedure can be defined as [1]

$$PG_1=10\log_{10}(N)$$

2.2

The monocycle waveform can be any function that satisfies the spectral mask regulatory requirements. Common pulse shapes include Gaussian, Laplacian, or Rayleigh pulses. Data modulation is typically based on pulse position modulation (PPM) although pulse amplitude modulation(PAM) and Bi-Phase shift key(BPSK) modulation schemes can also be used. The UWB-IR receiver is typically a homodyne cross-correlator that is based on an architecture that utilizes a direct RF to baseband conversion. Intermediate frequency conversion is not needed, which makes the implementation simpler than that in conventional heterodyne systems. [1]
The UWB pulse does not necessarily occupy the entire chip period, meaning that the duty cycle can be extremely low. In a low delay spread channel, the receiver is only required to “listen” to the channel for a small fraction of the period between pulses.[1] The impact of any continuous source of interference is therefore reduced so that it is only relevant when the receiver is attempting to detect a pulse. This leads to processing gain in a similar manner to a spread spectrum system’s ability to reduce the impact of interference. Processing gain due to the low duty cycle is given by [1]

$$PG_2=10\log_{10}(T_p/\tau_p)$$  \hspace{1cm} (2.3)

Where
\begin{align*}
T_p & = \text{chip period} \\
\tau_p & = \text{impulse width}
\end{align*}

The total processing gain \(PG\) is the sum of the two processing gains

$$PG=PG_1+PG_2$$  \hspace{1cm} (2.4)

In a discontinuous time-hopped system, consecutive pulses are transmitted according to a pseudorandom (PR) time-hopping code. Since the transmitted signal is not continuous, UWB-IR communication is resistant to severe multipath propagation. With a short pulse width and a relative long pulse repetition time (compared to pulse width), the multipath components associated with the transmitted pulse are attenuated before the next pulse is sent, reducing the inter-pulse interference. If the time between pulses is greater than the channel delay spread, there is no inter-symbol interference (ISI) between pulses and so no ISI between bits. [4]

One technique of generating a very wideband signal is based on fast frequency chirps, which are commonly used in impulse radar applications. It is possible to generate a wideband transmission by sweeping the transmitter’s oscillator in the frequency domain. A bandwidth of several hundred MHz can be achieved with ~ 10 nanosecond sweep time. Wider bandwidths can be achieved using this technique.

Pulse Generation, modulation, and multiple accesses are time domain dependent functions. Therefore the behavior of most wireless systems is well defined in the time domain. These systems are described using their impulse response. Hence, they are known as impulse radios.
The output of a system in the time domain is defined with the convolution formula: [4]

\[ y(t) = \int_{-\infty}^{+\infty} h(u)x(t-u)\,du \]  

2.5

Where

- \( x(t) \) is the input of the system and
- \( y(t) \) is its output.

When \( x(t) \) is equal to a Dirac pulse, the output is equal to \( h(t) \) which is defined as the impulse response of the system.

2.4.1 Ultra Wide Band Pulses

The baseband pulses used by UWB-IR signals have very short time duration in the range of a few hundred picoseconds. These signals have frequency response from nearly zero hertz to a few GHz. The shape of the signal is not restricted, but its characteristics are restricted by the FCC mask. A good candidate shape for the UWB signal is the Rayleigh monocycle which is the first derivative of a Gaussian pulse, which has the time-domain representation, \( P_R(t) \), given by; [1]

\[ P_R(t) = A_R((t-\mu)/\sigma)^2\exp(-(1/2)((t-\mu)/\sigma)^2) \]  

2.6

Where:

- \( \hat{\mu} \) is the pulse width and
- \( \epsilon \) is the centre of the pulse.
- \( A_R \) is a scaling factor

Thus by adjusting \( \sigma \), the bandwidth can be controlled. The scaling factor is introduced such that the total energy in the pulse is normalized to unity. The frequency spectrum of the Rayleigh monocycle, \( P_R(f) \), is; [1]

\[ P_R(f) = A_R(2\pi)^{1/2}(2\pi\sigma f)^{-1/2}\exp(-(1/2)(2\pi\sigma f)^2)\exp(-j(2\pi f\mu + 0.5\pi)) \]  

2.7

The effective time duration is defined as the time duration of the waveform that contains 99.99% of the total monocycle energy. Rayleigh monocycles do not have a DC component enabling them to be used in impulse radio systems since they facilitate the design of components such as antennas, amplifiers and sampling down converters. The time and frequency domains of an
example Rayleigh monocyte are shown in Figures 2.1 and 2.2 where the monocyte has been normalized for unit energy. [1]

![Figure 2.3 Rayleigh monocyte in time domain [1]](image1)

![Figure 2.4 Rayleigh monocyte in frequency domain [1]](image2)

The second derivative of the Gaussian pulse is Gaussian monocyte and it is also used in UWB-IR communication since it does not contain DC term. The time domain representation of the Gaussian monocyte is:[1]

$$P_G(t) = \frac{1}{\sqrt{2\pi \sigma}} \left\{ \left(1-(t-\mu)/\sigma \right) \right\} \exp\left(-\frac{1}{2}\left((t-\mu)/\sigma \right)^2\right)$$

Where the effective time duration of the Gaussian monocyte is $T_P = 7\mu$ with center frequency $\mu = 3.5\sigma$. The frequency spectrum of the Gaussian monocyte is given by; [1]

$$P_G(f) = (2\pi \sigma f)^2 \exp\left(-\frac{1}{2}(2\pi f)^2\right) \exp(-j2\pi f \mu)$$

2.4.2 Pulse Modulation

Essentially, UWB communications systems are either single-band or multiband UWB(MB-UWB). UWB-IR systems are single-band UWB systems. In UWB-IR systems, the signal that represents a symbol consists of serial pulses with a very low duty cycle. The pulse width is very narrow, typically in nanoseconds, giving rise to a large bandwidth and a better resolution of
multipath in UWB channels. The MB-UWB modulation is accomplished by using multicarrier or OFDM modulation with Hadamard or other spreading codes. [3]

The pulse position modulation, PPM and bi-phase shift key(BPSK) modulation schemes are the most used for UWB-IR systems due to the fact that from the theory point of view they have a better bit energy performance than pulse amplitude modulation, PAM or on-off keying, OOK modulation schemes. [5]

2.4.2.1 Pulse Position Modulation

This modulation technique involves changing the delay between the transmitted pulse according to the binary data; transmitting impulses at high rates. However, the pulses are not necessarily evenly spaced in time, but rather they are spaced at random or pseudo noise (PN) time intervals [5]. The timing of each pulse is altered to transmit data. Binary PPM is the simplest form of PPM, where a pulse in a uniformly spaced pulse train represents a 0 and a pulse offset in time from the pulse train represents a 1. Conceptually, the binary PPM technique is shown in Figure 2.5, the Bit Error Rate (BER) vs. Eb/No curve of PPM can be seen in figure 2.6 and the constellation diagram of PPM is shown in figure 2.7. Stated mathematically, the modulated data is;

\[
y(t) = \sum_{j=0}^{\infty} W(t - jT - \delta \times dj)\]

2.10

Where:

- W is the pulse waveform
- T is the bit time
- \( \delta \) is a fixed delay
- dj is the binary data
The error probability, $P_F$ of the pulse position modulation in additive white Gaussian noise (AWGN) follows approximately given by; [5]

$$P_F = \frac{1}{2} \text{erfc}\left(\sqrt{\frac{p}{2}}\right)$$

Where

$p$ is the received signal-to-noise ratio (SNR) per information bit.

The most advantageous feature of PPM is the orthogonality in signal present in its data. The pulses in time are independent of one another, thus the time during the symbol period can be broken up to look for each pulse within a specified time slot. PPM modulation scheme provides better error performance than PAM and also has the advantage of permitting non-coherent reception. [5]

The disadvantage of PPM is its BER performance. This lack of signal energy causes binary PPM to have a probability bit error of 3 dB worse than BPSK modulation. Also PPM is susceptibility to inter-symbol interference, which limit data rate when using it in impulse-radio UWB applications. [5]

2.4.2.2 Bi-Phase Shift Key(BPSK) Modulation
This modulation scheme involves changing the polarity of the transmitted pulses according to the incoming data as shown in the figure 2.8. It is also referred to as antipodal modulation. The BER vs. Eb/No curve for BPSK is shown in figure 2.9.

The bi-phase modulation is expressed as: [5]

\[
y(t) = \sum_{j=-\infty}^{j=\infty} w(t - jT)(2d_j - 1)
\]

Where:
- \( w \) is the pulse waveform
- \( T \) is the bit time
- \( d_j \) is the binary data

The error probability \( P_E \) of BPSK modulation is given by:

\[
P_E = \frac{1}{2} \text{erfc} \left( \frac{\sqrt{P}}{\sqrt{2}} \right)
\]

Where
- \( p \) is the SNR per information bit.
The BPSK modulation has the advantage of improved BER performance, as the $E_b/N_0$ is 3 dB less than PPM for the same probability of bit error. Another benefit of BPSK modulation is its ability to eliminate spectral lines due to the change in pulse polarity. This minimizes the amount of interference with conventional radio systems.[4]

The disadvantage of bi-phase modulation is that its physical implementation is more complex, as two pulse generators, with the opposite polarity, are necessary instead of one. [5]

2.4.3 Multiple Access Methods

Continuous pulse transmission leads to strong lines in the spectrum of the transmitted signal. These regular energy spikes may interfere with other communication systems over short distances. A randomizing technique is applied to the transmitted signal in order to minimize the potential interference from UWB transmission, making the spectrum of the UWB transmission more noise-like. The pulse train in impulse radio systems is randomized by time-hopping (TH) and direct-sequence (DS) techniques.[5] The DS uses the technique found in spread spectrum systems to produce a sequence of pulses with pseudorandom inversions where as the TH technique randomizes the position of the transmitted UWB pulses in time. Neither the DS nor the TH techniques lead to further spectrum spreading. Both techniques use pseudo-noise codes to separate different users. [1]
The use of spreading codes in DS-UWB systems is solely for accommodating multiple users as UWB systems are spread spectrum systems. In TH pulsed UWB systems, the pulse duty cycle is very small. Thus, the transmitter is gated off for the bulk of a symbol period. Multiple access can be implemented by employing appropriately chosen hopping sequences for different users to minimize the probability of collisions due to multiple accessing. Each receiver can detect a signal during its own unique hopping pattern, mitigating interference. DS can also be used for multiple access in a PPM-UWB or PAM-UWB system. This is done by representing each symbol by a series of pulses that are pulse-amplitude-modulated by a chip sequence. Input symbols are modulated onto either the amplitude or the relative positions of each sequence of pulses. [3]

2.4.3.1 Time Hopping UWB(TH-UWB)

Data modulation is typically based on PPM using TH-UWB as the basis for a communication system. This approach allows matched filter techniques to be used in the receiver. The optimum time shift depends on the cross-correlation properties of the pulses used. [1] The TH-UWB signal using PPM can be defined as: [4]

\[
S_{tr}(t) = \sum_{j=-\infty}^{+\infty} W_{tr} \left( t - jT_f - C_j T_c - \vartheta \frac{d}{Na} \right)
\]

2.14

Where:

- \( W_{tr} \) is the pulse waveform
- \( T_f \) is the pulse repetition time
- \( C_j \) is a pseudorandom code different for each user
- \( \vartheta \) is a fixed delay
- \( d \) is the binary data

The transmitted signal for one user using BPSK is defined as: [4]

\[
S_{tr} = \sum_{j=-\infty}^{+\infty} W_{tr} \left( t - jT_f - C_j T_c \right) \left( 2d_j N_a - 1 \right)
\]

2.15

Where:

- \( W_{tr} \) is the pulse waveform
- \( T_f \) is the pulse repetition time
C\textsubscript{j} is a pseudorandom code different for each user

T\textsubscript{c} is a slot time

d is the binary data

Ns is an integer which indicates the number of pulses transmitted for each bit

An example of the BPSK modulation using TH multiple access technique is as shown in figure 2.11 and for the PPM modulation is as shown in figure 2.12

Figure 2.11 Example of TH-UWB with BPSK modulation[4]

Figure 2.12 Example of TH-UWB using PPM [4]

\begin{align*}
S_{tr} &= \sum_{j=-\infty}^{j=+\infty} W_{tr}(t-jT_{f})n_{j}(2d_{j}/N_{s} - 1) \\
& \tag{2.16}
\end{align*}

Where:

W\textsubscript{tr} is the pulse waveform

T\textsubscript{f} is the pulse repetition time

n\textsubscript{j} is a pseudorandom code which only takes values of +1

Ns is an integer which indicates the number of pulses transmitted for each bit

DS-UWB with BPSK modulation is shown in figure 2.13.
The transmitted signal for one user using PPM modulation in DS-UWB can be expressed as:

\[
S_{tr}(t) = \sum_{n} W_{tr}(t - jT_f - d_j Na \oplus n_j)
\]

Where:
- \( W_{tr} \) is the pulse waveform
- \( T_f \) is the pulse repetition time
- \( n_j \) is a pseudorandom code which only takes values of 1 or 0
- \( d \) is the binary data
- \( \delta \) is a fixed delay
- \( N_s \) is an integer which indicates the number of pulses transmitted for each bit

An example of DS-UWB with PPM can be seen in figure 2.14.

**2.4.4 Multiple Access Capability**

The overall performance of UWB-IR system deteriorates with increase in number of users sharing the channel. In order to meet the performance specification of bit error rate (BER), the signal to noise ratio in the receiver must be controlled. Moreover, the number of users that can share a channel is limited. For TH-UW the number of users is a function of the fractional increase in the power required to maintain a fixed BER, and is expressed as: [4]
\[ N(\Delta P) = M^{-1} \text{SNR}^{-1}(1-10^{-\Delta P/10})+1 \]

Where:
- \( N \) is the number of users
- \( M \) is the modulation coefficient
- \( \text{SNR} \) is the signal to noise ratio of the specifications
- \( \Delta P \) is the increase in required power to maintain a constant BER

The maximum number of users in a TH-UWB system can be calculated as: \[ N_{\text{max}} = \lim_{\Delta P \to \infty} N(\Delta P) = M^{-1} \text{SNR}^{-1} + 1 \]

The crucial parameter in establishing the performance of a receiver in a digital communication system operating in an additive white Gaussian noise (AWGN) channel is the ratio between the bit energy and the power spectral density of the noise, different modulation techniques and channel coding, give different curves of BER vs. Eb/No. However, in the design and implementation of the impulse radio communication system SNR is the parameter commonly used. These are related as: \[ \frac{E_b}{N_0} = \frac{(P_s \times T_b)}{(P_N/B)} = \text{SNR} \times \frac{B}{r} \]

Where
- \( \text{SNR} \) is equivalent to \( \frac{P_s}{P_n} \)
- \( T_b \) is equal to \( \frac{1}{r} \),
- \( r \) is the bit rate (bps)
- \( N_0 \) is the noise power spectral density (W/Hz)
- \( E_b \) is the average energy of a bit (J)
- \( P_N \) is the power of the noise (W)
- \( B \) is the bandwidth of the signal (Hz)
- \( P_s \) is the average power of the signal (W)
- \( T_b \) is the duration of one bit (s)

The bit energy is referred to as the thermal noise, \( N_0 \) which is described as a white noise process with a Gaussian distribution. In the case of multiple users sharing the channel, the addition of users using different orthogonal pseudo noise codes appears as an increase in the noise level during the detection process, thus having additive characteristics that are Gaussian in nature. As
a result, $N_0$ can be renamed $I_0$, which is the power spectral density of the thermal noise and the interference produced by other users. In multi user environment equation 2.20 can be written as:

$$\text{(Eb/Io)}_{dB} = (\text{SNR})_{dB} + (B/r)_{dB}$$  \hspace{1cm} 2.21

Where

$B/r$ is the processing gain.

The maximum number of users can be found by expanding the SNR. It is assumed that all signals arrive with the same power and that the power of the noise is dominated by addition of multiple interferers. This expression can be expressed as: [4]

$$\text{SNR} = Ps/Pn = Ps/ (N-1)Ps = 1/(N-1)$$  \hspace{1cm} 2.22

The maximum number of users is thus inversely proportional to the SNR. It was assumed that the pseudo noise codes are orthogonal, and that some kind of power control is available in the system. Practically, this is difficult to achieve and as a result the SNR required to maintaining a target BER is larger than that described in equation 2.22. In any communication system, the information can be coded using block or convolutional Forward Error Correction (FEC) codes in order to improve the gain at expenses of reducing the bit rate. [4]

The structure of multiple access channel is as given; [1]

$$H(\tau) = \sum_{n=1}^{N} \delta_n(\tau) \delta(\tau - \tau_n)$$
Where;

\[ n \] is path delay

\[ A_n \] is scattering amplitude

\[ h_n \] is the transfer function.

### 2.4.5 Ultra Wide Band Transmitter

The functional structure of the TH-PPM UWB-IR transmitter can be described using figure 2.16

In the TH-PPM UWB, the blocks of modulation and code generation control the programmable time delay, which determine the time at which the pulse generator is triggered. This block causes the time-hopping of the signal that permits the multiple access and it is also used as data modulator in this scheme. [4]
In Bi-Phase modulation, the block of modulation controls the pulse generator. The programmable delay is only used in the DS-PPM UWB. In DS-UWB with Bi-phase modulation, the programmable time delay is omitted, and the block of modulation and code generation directly control the pulse generator. [4] This implies that no carrier modulation is required in any stage, and, since power level is very low, power amplifiers are not needed resulting in a simplified architecture. The antennas behave like filters, and therefore their effect was considered. [4]

2.4.6 The Propagation Channel

The channel determines the information-theoretic performance limits, as well as the practical performance limits of various transmission schemes and receiver algorithms. A radio channel is an arrangement of two or more antennas, of which at least two are coupled by far field radiation. If the total number of connectors of all antennas is N, the corresponding radio channel can be viewed simply as an N-port giving rise to SISO, SIMO, or MIMO channel. Changing the antenna characteristic may change the properties of the channel as well. Therefore, a radio channel can be viewed as the result of combining antennas and propagation. [1]

Propagation channel is a channel concept that is independent of the antennas used; its ports are not related to feed lines of antennas, rather they are directly related to the propagating fields. Deriving propagation channel characteristics from measured radio channel data is a de-embedding problem that can be solved if sufficient measurement data and a complete characterization of the antennas are available. [1] However, the UWB radio channel may exhibit certain frequency dependencies even for frequency-independent antennas, which are due to the fact that an antenna cannot be frequency-independent in both transmission and reception; which in turn are caused by constraints imposed by reciprocity. Mobile radio channels are assumed to be linear. For a time invariant linear system, the basic measurement approaches can be directly related to several of these system functions. For example, the response w(t) of a time-variant linear system to a stimulus z(t) can be written as [1]

\[
W(t) = \int z(t - \xi) g(t, \xi) d\xi = \int z(t - \xi) h(t - \xi, \xi) d\xi,
\]

Where
\( g(t, \xi) \) is the input delay-spread function

\( h(t, \xi) \) the output delay spread function.

Using an input signal that is localized in time, for example, an impulse \( z(t) = \delta(t - t_0) \), the output signal \( w(t) = g(t, t_0) = h(t, t_0) \) is directly related to these system function. This type of measurement is referred to as a "time-domain" measurement. [1]

2.4.7. The Antenna

To ensure the transmission of pulses, the UWB-IR system antenna should be non dispersive having a flat frequency response and linear phase over the frequency band used. The antenna should have a bandwidth of a few Gigahertz. Achieving low return losses for such a channel bandwidth is extremely difficult. The Vivaldi antenna which has a beam width of approximately 45 degrees is a good choice for UWB-IR transceiver. This antenna has a very simple construction, a wide bandwidth, and high gain and allows for high data rates. The Vivaldi is essentially a differentiator with relatively flat, yet strong, frequency response over a broad range of spectrum.

![Figure 2.17 Impulse response of a Vivaldi antenna](image)

2.4.8 Path Loss and Shadowing

Path loss models constitute the basis for link budget calculations; giving an accurate estimate of the power levels as a function of the transmitter-receiver separation distance as they allow the calculation of the SNR in the different locations in the area in which the assumed path loss
model holds. Impulse radio systems are interference limited. Propagation losses have two counteracting effects: [1]

1. They reduce the interference power detected by the victim receiver; thus facilitating coexistence of UWB systems with other RF systems.
2. Compromising the UWB communication link by degrading the UWB signal since transmitted power cannot exceed the threshold imposed by current regulation.

The path loss (PL) gives the local average received signal power relative to the transmitted power. The free-space path loss, \( PL_{FS} \) is a function of the distance, \( d \) between the transmitter and receiver and the wavelength \( \lambda \) of the radiated signal. It is expressed as; [7]

\[
PL_{FS}(d) = 20 \log_{10}(4\pi d/\lambda)
\]  

Shadowing is the variation of the local attenuation around the deterministic mean value given by the path loss law. The large scale fading in UWB is fairly similar to that in narrow band. When the variations of the mean of the power measurements (in dB) have been fitted to a straight line, representing the path loss model as a power of distance. The characteristic distribution of the samples \( P_i \) in terms of the residual errors, \( e_i \), around their mean \( P_i \) at a given radial distance is given by;

\[
P_i = P_i + e_i.
\]  

### 2.4.9 Ultra Wideband Receiver

The most common UWB receivers currently used are the correlation receiver and the RAKE receiver. This is because detection of extremely short pulses requires highly specialized receivers. In impulse radios, up/down conversion is not required. [4] The general block diagram of the receiver is as shown in diagram 2.18
2.4.9.1 The Rake Receiver

The received UWB signal experiences as many as 30 multipath components and an rms delay spread of about 5-15ns as a result of the characteristics of the channel. [4] The delays of the components can be resolved using a RAKE receiver due to the wide bandwidth of the signal. Example of this is shown in figure 2.19.

![RAKE Receiver Block Diagram](image)

Figure 2.19 RAKE Receiver with N fingers [4]

The RAKE receiver combines the energy of the different multipath components of a received pulse in order to improve the performance. Each correlator is synchronized to a multipath component and the results of all correlators are added. The Decision device finally decides which symbol was transmitted after analyzing the output of the adders. This technique maximizes the
amount of energy received per symbol, however it is complex in that the several J components have to be synchronized and their gains adjusted.

2.4.9.2 The Correlation Receiver

The correlation receiver is simple to implement, but its performance is reduced in comparison to the RAKE receiver. The coherent detection of the main component of the signal is the basis on which the correlation receiver is designed. A local signal called template or reference must be generated in the receiver and correlated with the received signal. [4] The structure of the correlation receiver is shown in figure 2.20:

![Correlation Receiver Diagram](image)

The template signal presents the expected signal. The correlator is formed by a mixer and an integrator. The concept of correlation is to compare the received pulse with the expected corresponding to a $\tilde{f}_l \hat{0}$ or $\tilde{f}_l \hat{1}$. The output of the integrator is fed to a decision device which decides whether a one or zero was transmitted, for example a comparator. Ideally, the local signal should be the same signal that was transmitted. However, due to the fact that the medium is not perfect, the received pulses are modified versions of the transmitted ones. The performance of the system is highly dependent on an accurate selection of the local reference signal. [4] The higher the resemblance of the template and the received signal, the higher the probability that the received pulse is a $\tilde{f}_l \hat{1}$.
3.0 Introduction

The design the UWB transceiver was done using Bi-Phase modulation and Direct Sequence multiple access. This scheme presents theoretical and practical advantages for this project. First, the synchronization in DS-UWB is easier to achieve than in TH-UWB. This situation can get worse if PPM is used since timing precision in the order of a few picoseconds is needed to maintain an acceptable performance. Furthermore, the implementation of the programmable time delay with these requirements brings a lot of complexity for an off-chip solution. On the other hand, the BER vs. Eb/No curves show that bi-phase modulation has a better performance than PPM. Also, bi-phase modulation has an easier implementation.

3.1 Transmitter Analysis

The BPSK modulation mode together with the Gaussian monocycle which is the second derivative of the Gaussian pulse was used to implement the ultra wideband impulse radio transmitter system. Adjustment factors were used to correct for inaccuracies in the second derivative equations. For the second derivative Gaussian pulse, the adjustment factor is approximately between 1 and 3, and for this design it was selected at 1.24. the corrected pulse width is given by
\[ P_W = \frac{P_{W1}}{C_F} \] 

Where

- \( P_W \) is the corrected pulse width
- \( P_{W1} \) is the pulse width and
- \( C_F \) is the adjustment factor

The actual pulse width was considered from tail to tail on the time waveform of the Gaussian monocycle. The effective time duration is defined as the time duration of the waveform that contains 99.99% of total monocycle power. For the Gaussian monocycle, 99.99% of the energy is contained in the; [1]

\[ T_{eff} = 7 \times P_{W1} \] 

and centered at

\[ P_C = 3.5 \times P_{W1} \]

Where

- \( T_{eff} \) is the effective time duration
- \( P_C \) is the center of the pulse

In the generation of signal to be transmitted, the following parameters were used;

- Pulse width, \( P_{w1} = 0.2 \text{ ns} \)
- Corrected pulse width, \( P_w = \frac{P_{W1}}{1.24} = 0.1613 \text{ ns} \)
- Sampling frequency, \( F_s = 100 \text{ GHz} \)
- Nyquist frequency, \( F_n = \frac{F_s}{2} = 50 \text{ GHz} \)
- Time vector sampled at \( F_s \), \( t = -1\text{ns} < \frac{1}{F_s} < 30\text{ns} \)

The AWGN noise added by the transmitter antenna has SNR of 7DB

The generated second derivative of Gaussian pulse signal is given by equation 3.4

\[ y = (1 - 4\pi (t/pw)^2)e^{(-2\pi (t/pw)^2)} \]

The BPSK modulation used in the system is given by equation 2.12 and the signal after the modulation is given by equation 2.16; both of which are in chapter 2. The pulse repetition frequency (PRF) was set at 156MHz, thus waveform repeated every 6.41ns. A modulated bit stream of 5 pulses, (10101) with bit rate of 156Mb/s where a \( 1=0 \text{ degrees(right side up)} \) and a \( 1 \text{ bit} \) and a \( -1=180\text{degrees(upside down)} \) a 0 bit. was used. The number of pulses could be expanded but this would give a lower bit rate. A series of redundant pulses improves the processing gain of the receiver by giving more voltage out of the integrator in a correlation
receiver. The appropriate sequence when using BPSK can also produce nulls in the spectrum which would be useful for interference rejection or to keep the UWB spectrum from interfering with other communication systems.

3.2 Receiver Analysis

3.2.1 The Correlator Receiver

The basic correlation receiver was designed with an integrator showing the demodulated output information from a comparator. The correlation receiver was assumed to be perfect synch. Noise is added with a variance of 1 and a mean of 0. It was assumed that the transmitting antenna produced a 2nd derivative doublet and that the receiving antenna passed the doublet through to the mixer without integrating or differentiating the signal, leaving a doublet.

In simulation, the received signal is first added with additive white Gaussian noise (AWGN). The signal is then amplified and mixed with a template (reference) signal. The signal is integrated over a period of time, $T_b$, and then sampled. A comparator to zero then takes the output and produces a digital output that is fed to the baseband processing. This method permits maximization of the energy of the signal during detection and thus maximizing the SNR. The reference signal is formed of pulses that are modulated with pseudo noise code that is particular for each user and makes possible the multiple access.[4]
The output of the filter can be defined in the frequency domain as
\[ Y(f) = X(f) \times H(f) \quad (3.5) \]
and in the time domain it is given by
\[ y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x(t)h(t-\tau)\,d\tau \quad (3.6) \]
where
* Is the convolution operation
\( h(t) \) is the impulse response of the filter

The correlation function is defined as
\[ R(\tau) = \int_{-\infty}^{\infty} x(t)h(t-\tau)\,d\tau \quad (3.7) \]
Where
\( \tau \) is the delay between the two signals that are correlated.

When the signal \( h(t) \) is the same as the input signal of the mixer, this signal produces the maximum SNR and when used in the correlation, the detector is called maximum likelihood, optimum correlator or matched filter. The output of the correlation function becomes autocorrelation as the signals are the same. Peak of this function occurs when \( \tau = 0 \) and is equivalent to the energy of the signal.

### 3.2.2 Noise Analysis

It was assumed that there was no interference signals in the ultra wideband system other than the thermal noise. The amount of degradation of noise introduced by each stage is quantified by the noise figure parameter which is given by [4]

\[ NF = \frac{SNR_{in}}{SNR_{out}} \quad (3.8) \]

Where
- \( NF \) is the noise figure(dB)
- \( SNR_{in} \) is the signal to noise ratio of input signal
- \( SNR_{out} \) is the signal to noise ratio of output signal

The thermal noise referred to the input of the radio system is referred to as noise floor and is given by [4]

\[ Noise = -174\text{dBm/Hz} + NF + 10\log B \quad (3.9) \]
Where

Noise is the power of the noise in the channel(dBm)
B is the bandwidth of the channel(Hz)

The minimum level of power that the receiving signal must have in order to accomplish SNR is referred to as the sensibility of the radio system, and is given by: [4]

\[ \text{Pin}_{\text{min}} = \text{Noise} + \text{SNR}_{\text{min}} \]  
3.10

Where

\text{Pin}_{\text{min}} \text{ is the minimum power of the received signal(dBm)}
\text{SNR}_{\text{min}} \text{ is the minimum signal to noise ratio to keep the specifications of BER(dB)}

The power of the received signal is given by[4]

\[ P_{\text{in}} = P_t + G_t + G_r - L_t \]  
3.11

Where

\text{P}_{\text{in}} \text{ is the available power of the received signal(dBm)}
\text{P}_t \text{ is the power of the transmitted signal(dBm)}
\text{L}_t \text{ is the path loss for a specific distance and heights of the antenna(dB)}

The ratio of the channel bandwidth to the bandwidth of the information signal at the receiver output is referred as the processing gain. Assuming that the bit rate is the same as the information signal rate, the processing gain is given by: [4]

\[ \text{PG} = 10\log(B/r) \]  
3.12

Where

\text{B} \text{ is the total bandwidth of the UWB signal(Hz)}
\text{R} \text{ is the bit rate of the system(bps)}

For the UWB system, \( N_s \) pulses are integrated every \( T_b \) seconds, so the bit rate is defined as[4]

\[ r = \frac{1}{(N_s T_f)} \]  
3.13

where

\( T_f \) is the repetition time

The bandwidth of the pulse is almost equivalent to \( 1/T \) where \( T \) is the pulse width. The propagation gain is then given by: [4]

\[ \text{PG} = 10\log(T_f/T) + 10\log(N_s) \]  
3.14

Where \( \text{PG} \) is the parameter that influences the \( \text{SNR}_{\text{min}} \) required to maintain a specific performance.
The channel bandwidth of the system is defined by the width of the UWB pulse and the absence of the filters by the frequency response of the antennas. The processing gain depends on the target application, thus high data rates results in low processing gain.[4]

CHAPTER 4

SYSTEM SIMULATION AND RESULTS

The matlab simulation proposed in the design was run to simulate the working of the UWB-IR transceiver system. A UWB signal meeting the FCC requirements of bandwidth greater than 500Mhz and fractional bandwidth of more than 20% was generated in the transmitter, transmitted in an AWGN channel and received in the receiver. The simulation code is contained in appendix A and the results of the simulation are contained in the appendix B.
5.1 Discussion

The number of pulses used were only 5 per symbol. This number could be expanded to modulate for a longer series, but this would lower the bit rate. The system simulation was designed for only one user, thus the pseudo noise code generation was not included. The shape of the second derivative Gaussian pulse at the receiver is a little bit changed from the expected signal; this is due to the differentiation effects of the transmission and reception antennas. In order to keep power consumption minimum, a high sampling rate was used. The information rate of the system was determined by the pulse repetition frequency.

5.2 Recommendation and Future Work

The field of ultra wideband impulse radio transceiver is very diverse and it is still developing. The results obtained in the simulation of the designed transceiver were encouraging. Some of the future work that conducted on the same includes:

The software ultra wideband impulse radio transceiver system was designed to be flexible. Future design modification of the wireless communication system can be made based on future simulation and implementation results desired. The matlab code of the receiver can be improved in order to execute other system level simulations such as: investigating Other pulse waveforms
that may be as template in the receiver, including multi-user interface so as to confirm the theoretical multi user capability and implementing of a phase detector to find the time that the receiver needs to achieve pulse synchronization.

The designed system was just software simulated to give the results. In the future a schematic and PCB layout of the system should be created and fabrication of the same be done. The ultra wide band impulse radio transceiver should then be tested and hence physically implemented.

5.3 Conclusion

This project report presents a Ultra Wideband impulse radio transmission system that can be used in wireless sensor networks as a means of providing low power data transmission over short distances. The design and simulation of the UWB-IR transceiver demonstrated the working of the system. The system was implemented using BPSK modulation of the second derivative Gaussian pulses. The designed system achieved a high data rate of about 156Mhz and low power consumption. The UWB-IR system design was simplified, eliminating some of the components required in baseband signal processing with carrier, thus low power consumption. The UWB-IR communications system presented was based on discrete sequence. This system utilizes baseband components, and meets the FCC requirements. The system can be applied in wireless sensor networks, since it has been shown that the transmitted signal from the transmitter can be accurately received at the receiver.
CHAPTER 6

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CHAPTER 7
APPENDICES

Appendix A

The Matlab code

```matlab
% ULTRA WIDEBAND IMPULSE RADIO TRANSCEIVER
% pulse width in nanoseconds
pw1=.2e-9;
Pulse Adjustment factor for inaccurate pulse width, PWs
%(approx. 1-3 for 2nd derivative, in this case 1.24 is used)
pw=pw1/1.24;
% sample frequency
Fs=100e9;
% Nyquist frequency
Fn=Fs/2;
% time vector sampled at Fs Hertz. zoom in/out
t=-1e-9:1/Fs:30e-9;
% EQUATIONS
```
% 2nd derivative of Gaussian pulse = doublet (two zero crossings)

\[ y = 1 \times (1 - 4\pi \times ((t) / \text{pw})^2) \times \exp(-2\pi \times ((t) / \text{pw})^2); \]

% NOISE SETUP FOR BER AND SNR

% Noise - AWGN (0.2 gives approx Eb/No = Es/No = SNR = 7DB)

% for 2 volt peak to peak BPSK signal. Set to 1e-50 to disable

noise = (1e-50) * (randn(size(t)));

figure(1)
plot(t, noise);
title('Additive White Gaussian Noise (AWGN) Added to the Signal to be Transmitted ');
xlabel('Time'); ylabel('Amplitude');

% BPSK MODULATION USING SECOND DERIVATIVE DOUBLET WITH 5 PULSES

% The following series of equations sets the pulse recurring frequency (PRF) at 156MHz

% waveform repeats every 6.41e-9 sec

% The modulated bit stream is made of 5 pulses 10101

% where a {1 = 0 degrees (right side up) and a 1 bit} and a {−1 = 180 degrees (upside down) a 0 bit.}

% The modulated bit stream (bit rate = 156Mb/s)

% unmodulated doublet (yum)

B = 1;

yum = B * y + ...

B * (1 - 4\pi \times ((t - 6.41e-9) / \text{pw})^2) \times \exp(-2\pi \times ((t - 6.41e-9) / \text{pw})^2) + ...

B * (1 - 4\pi \times ((t - 12.82e-9) / \text{pw})^2) \times \exp(-2\pi \times ((t - 12.82e-9) / \text{pw})^2) + ...

B * (1 - 4\pi \times ((t - 19.23e-9) / \text{pw})^2) \times \exp(-2\pi \times ((t - 19.23e-9) / \text{pw})^2) + ...

B * (1 - 4\pi \times ((t - 25.64e-9) / \text{pw})^2) \times \exp(-2\pi \times ((t - 25.64e-9) / \text{pw})^2);

% BPSK modulated doublet (yp) is given by
yp=1*y+ ...
-1*(1-4*pi.*((t-6.41e-9)/pw).^2).*exp(-2*pi.*((t-6.41e-9)/pw).^2)+ ...
1*(1-4*pi.*((t-12.82e-9)/pw).^2).*exp(-2*pi.*((t-12.82e-9)/pw).^2)+ ...
-1*(1-4*pi.*((t-19.23e-9)/pw).^2).*exp(-2*pi.*((t-19.23e-9)/pw).^2)+ ...
1*(1-4*pi.*((t-25.64e-9)/pw).^2).*exp(-2*pi.*((t-25.64e-9)/pw).^2);
%BPSK modulated doublet with noise
ym=yp+noise;
%Correlated output(yc)=Modulated(ym) multiplied by Unmodulated doublet(yum).
%This correlation of the signals occurring at the mixer stage of the receiver.
yc=ym.*yum;
%FFT
%new FFT for BPSK modulated doublet(ym)
NFFYM=2.^ceil(log(length(ym))/log(2));
%pad with zeros
FFTYM=fft(ym,NFFYM);
NumUniquePts=ceil((NFFYM+1)/2);
FFTYM=FFTYM(1:NumUniquePts);
MYM=abs(FFTYM);
MYM=MYM*2;
MYM(1)=MYM(1)/2;
MYM(length(MYM))=MYM(length(MYM))/2;
MYM=MYM/length(ym);
f=(0:NumUniquePts-1)*2*Fn/NFFYM;

%new FFT for unmodulated doublet(yum)
NFFYUM=2.^ceil(log(length(yum))/log(2));
%pad with zeros
FFTYUM=fft(yum,NFFYUM);
NumUniquePts=ceil((NFFYUM+1)/2);
FFTYUM=FFTYUM(1:NumUniquePts);
MYUM=abs(FFTYUM);
MYUM=MYUM*2;
MYUM(1)=MYUM(1)/2;
MYUM(length(MYUM))=MYUM(length(MYUM))/2;
MYUM=MYUM/length(yum);
f=(0:NumUniquePts-1)*2*Fn/NFFYUM;

% new FFT for correlated pulses(yc)
% yc is the time domain signal output of the multiplier in the correlation receiver.
% A simple comparator instead of high speed A/D's may be used to recover the 10101 signal.
NFFYC=2.^(ceil(log(length(yc))/log(2)));
FFTYC=fft(yc,NFFYC); % pad with zeros
NumUniquePts=ceil((NFFYC+1)/2);
FFTYC=FFTYC(1:NumUniquePts);
MYC=abs(FFTYC);
MYC=MYC*2;
MYC(1)=MYC(1)/2;
MYC(length(MYC))=MYC(length(MYC))/2;
MYC=MYC/length(yc);
f=(0:NumUniquePts-1)*2*Fn/NFFYC;

% PLOTS
% plots for modulated doublet(ym)
figure(2)
plot(t,ym);xlabel('Time');ylabel('Amplitude');
title('Modulated Pulse Train in Time domain');
grid on;
%axis([-1e-9,27e-9 -1 2])
figure(3)
plot(f,MYM);xlabel('Frequency');ylabel('Amplitude');
title('Modulated Pulse Train in Frequency domain');
%axis([0 10e9 0 1]);
%zoom in/out
grid on;
figure(4)
plot(f,20*log10(MYM));xlabel('Frequency');ylabel('20LOG10=DB');
title('Modulated Pulse Train Frequency Spectrum');
%axis([0 20e9 -120 0]);
grid on;

%plots for unmodulated doublet(yum)
figure(5)
plot(t,yum);xlabel('Time');ylabel('Amplitude');
title('Unmodulated Pulse Train in Time Domain');
grid on;
axis([-1e-9,27e-9 -1 1])
figure(6)
plot(f,MYUM);xlabel('Frequency');ylabel('Amplitude');
title('Unmodulated Pulse Train in Frequency Domain');
axis([0 10e9 0 1]);%zoom in/out
grid on;
figure(7)
plot(f,20*log10(MYUM));xlabel('Frequency');ylabel('20LOG10=DB');
title('Unmodulated Pulse Train Frequency Spectrum');
%axis([0 20e9 -120 0]);
grid on;
%plots for correlated pulses(yc)
figure(8)
plot(t,yc);xlabel('Time');ylabel('Amplitude');
title('Receiver Correlator Output-no LPF In Time Domain');
grid on;
%axis([-1e-9,27e-9 -1 1])

figure(9)
plot(f,MYC);xlabel('Frequency');ylabel('Amplitude');
title('Receiver Correlator Output-no LPF In Frequency Domain');
%axis([0 7e9 0 .025]);%zoom in/out
grid on;

figure(10)
plot(f,20*log10(MYC));xlabel('Frequency');ylabel('20LOG10=DB');
title('Receiver Correlator Output-no LPF Frequency Spectrum');
%axis([0 20e9 -120 0]);
grid on;

%CORRELATION RECEIVER COMPARATOR(before lowpass filter)

%Threshold level where the comparator device triggers was set
pt=.5
%(volts)

H=5;
%(volts)

L=0;
LEN=length(yc);
for ii=1:LEN;
    if yc(ii)>=pt;%correlated output(y2) going above pt threshold setting
        pv(ii)=H;%pulse voltage
    else;
        pv(ii)=L;
    end;
end;
po=pv;%pulse out=pulse voltage

figure(11)
plot(t,po);
axis([-1e-9 27e-9 -1 6])
title('Comparator output');
xlabel('Frequency');
ylabel('Voltage');
grid on;

% CORRELATION RECEIVER LOW PASS FILTER(INTEGRATOR)
%time constant
rc=.2e-9;
%impulse response
ht=(1/rc).*exp(-t/rc);
% Reduces integrated output voltage greatly.
ht=.2e-9*ht;
%use this instead of ycfo=conv(yc,ht)/Fs for proper dimension.
ycfo=filter(yc,1,ht)/Fs;
%Filtered noise
yn=filter(noise,1,ht)/Fs;
%new FFT for filtered correlated pulses(ycfo)
NFFYCFO=2.^ceil(log(length(ycfo))/log(2));
FFTYCFO=fft(ycfo,NFFYCFO);%pad with zeros
NumUniquePts=ceil((NFFYCFO+1)/2);
FFTYCFO=FFTYCFO(1:NumUniquePts);
MYCFO=abs(FFTYCFO);
MYCFO=MYCFO*2;
MYCFO(1) = MYCFO(1) / 2;
MYCFO(length(MYCFO)) = MYCFO(length(MYCFO)) / 2;
MYCFO = MYCFO / length(ycfo);

f = (0:NumUniquePts - 1) * 2 * Fn / NFFYCFO;

% new FFT for filtered noise(yn)
NFFYN = 2.^(ceil(log(length(yn)) / log(2)));

% pad with zeros
FFTYN = fft(yn, NFFYN);

NumUniquePts = ceil((NFFYN + 1) / 2);
FFTYN = FFTYN(1:NumUniquePts);
MYN = abs(FFTYN);

MYN = MYN * 2;
MYN(1) = MYN(1) / 2;
MYN(length(MYN)) = MYN(length(MYN)) / 2;
MYN = MYN / length(yn);

f = (0:NumUniquePts - 1) * 2 * Fn / NFFYN;

% plots for filtered correlated pulses(ycfo)
figure(12)
plot(t, ycfo); xlabel('Time'); ylabel('Amplitude');
title('Receiver Filtered Correlator Output in Time Domain');
grid on;

figure(13)
plot(f, MYCFO); xlabel('Frequency'); ylabel('Amplitude');
title('Receiver Filtered Correlator Output in Frequency Domain');

figure(14)
plot(f, 20 * log10(MYCFO)); xlabel('Frequency'); ylabel('20LOG10=DB');
title('Receiver Filtered Correlator Output Frequency Spectrum');
%axis([0 20e9 -120 0]);
grid on;

%CORRELATION RECEIVER COMPARATOR (after low pass filter)
%setting level where threshold device comparator triggers
pt1=.1e-8
%(volts)
H=5;
%(volts)
L=0;
LEN=length(ycfo);
for ii=1:LEN;
    if ycfo(ii)>=pt1;%(correlated output(ycfo) going above pt threshold setting
        pv1(ii)=H;%(pulse voltage
    else;
        pv1(ii)=L;
    end;
end;
po1=pv1;%(pulse out=pulse voltage
figure(15)
plot(t,po1);
axis([-1e-9 27e-9 -1 6])
title('Comparator output');
xlabel('Frequency');
ylabel('Voltage');
grid on;

%plots for filtered noise(yn)
figure(16)
plot(t,yn);xlabel('Time');ylabel('Amplitude');
title('Receiver filtered Noise Output in Time Domain');
grid on;
axis([-1e-9,27e-9,-1,1])
figure(17)
plot(f,MYN);xlabel('Frequency');ylabel('Amplitude');
title('Receiver filtered Noise Output in Frequency Domain');
axis([0,7e9,0,.25]);%zoom in/out
grid on;
figure(18)
plot(f,20*log10(MYN));xlabel('Frequency');ylabel('20LOG10=DB');
title('Receiver filtered Noise Output Frequency Spectrum');
axis([0,20e9,-120,0]);
grid on;
figure(19)
plot(t,ht);xlabel('Time');ylabel('Amplitude');
title('Impulse Response(ht) in Time Domain');
grid on;
axis([0,1e-9,0,1])
Appendix B
The Simulation Results

Figure 1: Additive White Gaussian Noise added to Transmitted Signal
Figure 2: The generated Second Derivative Gaussian Pulse in Time Domain

Figure 3: The Generated Second Derivative Gaussian Pulse in Frequency Domain

Figure 4: The Generated Second Derivative Gaussian Pulse Frequency Spectrum
Figure 5: The Modulated Second Derivative Gaussian Pulse in Time Domain

Figure 6: The Modulated Second Derivative Gaussian Pulse in Frequency Domain

Figure 7: The Modulated Second Derivative Gaussian Pulse Frequency Spectrum
Figure 8: The Received Correlator Output Signal Before Filtering in Time Domain

Figure 9: The Received Correlator Output Signal Before Noise Filtering in Frequency Domain

Figure 10: The Received Correlator Output Signal Before Filtering Frequency Spectrum
Figure 11: The Comparator Output

Figure 12: Received Filtered Correlator Output in Time Domain

Figure 13: The Received Filtered Correlator Output Signal in Frequency Domain
Figure 14: The received Filtered Correlator Output Signal Frequency Spectrum

Figure 15: The comparator Function

Figure 16: Received Filtered Noise Output Frequency Spectrum
Figure 17: Received Filtered Noise Output in Time Domain

Figure 18: Received Filtered Noise Output in Frequency Domain

Figure 19: The Impulse Response of the System in Time Domain