TDMA for Low Sampling Rate IR-UWB Receivers

Muhammad Adeel Ansari

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Abstract

In UWB communication sampling plays a key role in detection of the transmitted data. There are various methods of data transmission and detection at the receiver. Mostly, the detection methods are based on frequency domain methods. The popular method to lower the sampling rate is the sub-sampling technique, based on frequency of the transmitted signal. A special method like orthogonal frequency division multiplexing (OFDM) is needed to reduce inter symbol interference for a frequency based method. The power consumption associated with higher sampling rates is also a big challenge. Therefore some simple techniques are required to detect data on lower sampling rates without ISI in the multiple user environments and with lower power consumption. If selection of the sampling frequency would be flexible to detect data from multiple users then it could relax the UWB receiver design requirements. In this thesis we developed a transmission and reception methodology with reduced sampling frequency for data detection.

In the proposed work, transmitted data is distributed using TDMA frames for all users within fixed time slots for each user. The TDMA technique is being used to achieve low sampling rates and to avoid multiple access interference (MAI). The sampling rate to detect the data of each user can be selected according to number of users and transmission bandwidth. For this purpose each data bit of a user is arranged once in a transmission frame. The data can be detected on frame repetition rate depends on the total number of users. The data of each user can be accessed directly by calculating the total time of each user place within each frame. Since each data bit of one user occurs once in a frame therefore it could be claimed that ISI within the same user has been avoided. The proposed scheme has been tested with 50 MHz, 100 MHz and 500 MHz sampling frequencies for 50 users, 25 users and 5 users respectively by using 2.5 GHz bandwidth. 8-bits of data was transmitted and detected for different users using Matlab and Simulink Models. The results were analyzed in perfect synchronization condition and compared between integrated window energy detector UWB receiver and an UWB receiver using a matched filter. The performances are evaluated on the basis of BER. To observe the impact of synchronization, both receivers were evaluated with some timing mismatch. It is concluded that the scheme works well for the lower sampling rate for both types of UWB receivers stated above. It can also be concluded by observing the results that the UWB receiver using matched filter has better performance in noisy environment compared to energy detector UWB receiver with integrated window. The performance of energy detector UWB receiver with integrated window and UWB receiver with matched filter were also evaluated with timing mismatch. It can be concluded that the UWB receiver with integrated window has better performance compared to UWB receiver using matched filter if the synchronization is not achieved properly. The UWB receiver with matched filter is more vulnerable against timing mismatch compared to UWB receiver with integrated window.
Dedication

Dedicated to my parents, my wife, my son and all other family members.
Acknowledgements

The research work presented in this thesis has been done in the Department of Communication Systems (CoS), at the Royal Institute of Technology (KTH), Stockholm, Sweden, during my studies. The work was supervised by Dr. Svante R. Signell which has been ended with the completion of my licentiate. As I have finished my licentiate work therefore I have an opportunity to acknowledge all the people who have supported me during my work.

First of all I would like to express my gratitude for the support of my supervisor Dr. Svante R. Signell, who helped me during my licentiate work and guided me with his fruitful suggestions to improve my work. I really appreciate his generosity in sharing his knowledge, time and expertise during the frequent discussions throughout the whole period of my studies. He supported me well and encouraged me to develop this work with his productive inputs which made my job little bit easier.

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Many special thanks to my friends and their families as we shared wonderful moments here in Sweden.

I wish to express my gratitude to my family who supported me and encouraged me. Their support during my whole studies and my whole life is irreplaceable.

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Muhammad Adeel Ansari, June 2012.
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<td>Inter Symbol Interference</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
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<tr>
<td>UWB</td>
<td>Ultra-wideband</td>
</tr>
<tr>
<td>DoD</td>
<td>Department of Defense</td>
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<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
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<td>WLAN</td>
<td>Wireless Local Area Networks</td>
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<tr>
<td>FBW</td>
<td>Fractional Bandwidth</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>NTIA</td>
<td>National Telecommunications and Information Administration</td>
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<tr>
<td>ECC</td>
<td>European Communication Commission</td>
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<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
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<tr>
<td>CEPT</td>
<td>European Conference of Postal and Telecommunications</td>
</tr>
<tr>
<td>DAA</td>
<td>Detection and Avoidance</td>
</tr>
<tr>
<td>IDA</td>
<td>Infocomm Development Authority</td>
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<tr>
<td>IR-UWB</td>
<td>Impulse Radio Ultra-wideband</td>
</tr>
<tr>
<td>HDR</td>
<td>High Data Rate</td>
</tr>
<tr>
<td>LDR</td>
<td>Low Data Rate</td>
</tr>
<tr>
<td>PDP</td>
<td>Power Delay Profile</td>
</tr>
<tr>
<td>DS-CDMA</td>
<td>Direct Sequence Code Division Multiple Access</td>
</tr>
<tr>
<td>TH-IR</td>
<td>Time Hop Impulse Radio</td>
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<td>BEP</td>
<td>Bit Error Probability</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>LGW</td>
<td>Locally Generated Waveform</td>
</tr>
<tr>
<td>TR</td>
<td>Transmitted Reference</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communication</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
</tr>
<tr>
<td>CRLB</td>
<td>Cramer-Rao Lower Bound</td>
</tr>
<tr>
<td>ZZLB</td>
<td>Ziv-Zakai Lower Bounds</td>
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<tr>
<td>ML</td>
<td>Maximum Likelihood</td>
</tr>
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<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<tr>
<td>MAI</td>
<td>Multiple Access Interference</td>
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<tr>
<td>MB-UWB</td>
<td>Multiband Ultra-wideband</td>
</tr>
<tr>
<td>FH</td>
<td>Frequency Hop</td>
</tr>
<tr>
<td>NBI</td>
<td>Narrowband Interference</td>
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<tr>
<td>PPM</td>
<td>Pulse Position Modulation</td>
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<tr>
<td>OOK</td>
<td>On-Off Keying</td>
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<tr>
<td>PAM</td>
<td>Pulse Amplitude Modulation</td>
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<td>OPM</td>
<td>Orthogonal Pulse Modulation</td>
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<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
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<tr>
<td>BPM</td>
<td>Bi-phase Modulation</td>
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<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>SiGe</td>
<td>Silicon - Germanium</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium- Arsenide</td>
</tr>
<tr>
<td>InP</td>
<td>Indium Phosphide</td>
</tr>
<tr>
<td>SiC</td>
<td>Silicon Carbide</td>
</tr>
<tr>
<td>GaN</td>
<td>Gallium Nitride</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<tr>
<td>MPC</td>
<td>Multipath Component</td>
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<tr>
<td>ARAKE</td>
<td>All Rake</td>
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<tr>
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<td>Selective Rake</td>
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<tr>
<td>PRAKE</td>
<td>Partial Rake</td>
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<tr>
<td>MRC</td>
<td>Maximum Ratio Combining</td>
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<td>MMSE</td>
<td>Minimum Mean Square Error</td>
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<tr>
<td>ED</td>
<td>Energy Detector</td>
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<tr>
<td>BPF</td>
<td>Band Pass Filter</td>
</tr>
<tr>
<td>SDR</td>
<td>Software Defined Radio</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>IFI</td>
<td>Inter Frame Interference</td>
</tr>
<tr>
<td>SB-TDMA</td>
<td>Single Band Time Division Multiple Access</td>
</tr>
<tr>
<td>MWC</td>
<td>Modulated Wideband Converter</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>S/H</td>
<td>Sample and Hold</td>
</tr>
<tr>
<td>IUI</td>
<td>Inter User Interference</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>IW</td>
<td>Integrated Window</td>
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<td>MF</td>
<td>Matched Filter</td>
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Chapter 1: Introduction

1.1 History and background

All animals and humans have been using wireless communication from the beginning of this world. They were communicating their feelings, expressions and thoughts with the symbols and signs within the optical region to convey it to others without wires. As time passes on, people became more knowledgeable and they started thinking to communicate with others on long distances away from their optical range. First electrical communication was done in 1809 by Samuel Soemmering [1]. In 1828, the first telegraph in the USA was invented by Harrison Dyar who sent electrical sparks through chemically treated paper tape to burn dots and dashes [1]. Heinrich Hertz's did his experiment of transmission and receiving signal wirelessly in 1887 within VHF/UHF range (60 to 500MHz) [2]. The First successful experiment in wireless communication was done by Marconi and his assistant George Kemp in 1901 [2]. It was a milestone in the history of radio communication. Then an era came where wireless communication gained popularity and researchers started to think on fast communications means. For communicating safely without interfering to others, wireless communication bands were introduced according to the frequency and their applications, as shown in figure 1.1 [3]. Among the radio communication electromagnetic spectrum showing different frequency bands, there is a band called ultra wideband (UWB), whose range is defined as 3.1GHz to 10.6GHz to communicate within short distances [3].

![Electromagnetic Spectrum](image)

Figure 1.1: Radio Communication Spectrum with Band allocation
As discussed earlier, Marconi used wireless communication technology in 1901, to transmit Morse code sequences across several thousand of kilometers using spark gap radio transmitters but multiuser implementation and fruits of large bandwidth were not considered at that time.

It was 1962 when the work started in time domain electromagnetic pulses which is considered as the foundation of modern Ultra-Wideband (UWB) technology but until decade of 1980’s this technology was referred as carrier free communication. In 1989 the U.S department of defense (DoD), first used the term ultra-wideband (UWB) for this type of communication. The work in UWB was restricted to USA during 1960s to 1990s under classified programs for military needs to utilize the technique and technology for secure communication. Advanced developments in semiconductor technology during the last decade made it possible that the UWB is emerging as a fast growing field for commercial products. In recent times UWB usage increasing due to relaxation in rules from the regulatory authorities all over the world which is opening opportunities for researchers to approach towards new applications. Some of these applications for UWB systems are short range communication, sensor networks, radar systems, wireless personal area networks (WPAN), wireless local area networks (WLAN) and tracking or positioning of objects listed in various literatures available on the internet. Other fields which could be explored for UWB communication are bio medical, agriculture, industrial safety systems and industrial process systems. Equipments for monitoring different kind of parameters and measurements instrumentations can also be implemented by using UWB communication but it requires more attention from researchers and designers.

UWB communications technique is unique among the available radio communications as communication between transmitters and receivers are being done with extremely narrow RF pulses. Due to its narrow pulses it has some advantages over all other types of radio communications such as high data rate, difficult to intercept unintentionally, coexistence with the other users of different radio services, difficult to jam and low intercept probability etc. Some special features of UWB are given as:

- It is useful for radar applications since it can locate objects with good accuracy.
- Due to wide instantaneous bandwidth it has fine time resolution for network time distribution.
- It is useful for military applications due to low spectral power density, as it reduces the interception probability as well as allows coexistence with other RF signals.
- Multipath components can be resolved which increases working efficiency in dense environment.
- If the wireless medium has low loss and is free from multipath reflections then high data rate communication can be achieved.
1.2 UWB Definition

UWB communication can be defined as low power wireless communication for short range with high bandwidth using a large portion of the radio spectrum. The typical bandwidth for UWB wireless communication is between 3.1 GHz to 10.6 GHz. It can also be defined in terms of fractional bandwidth (FBW) i.e. FBW of a signal larger than 20% or signal bandwidth larger than 500 MHz is considered as UWB signal. FBW can be defined as the ratio of total bandwidth to the center frequency of the signal, given as:

\[ \text{FBW} = \frac{\text{BW}}{f_c} \]

Here “BW” is bandwidth of UWB and “fc” is center frequency of the signal.

\[ \Rightarrow \text{FBW} = \frac{2(f_h - f_l)}{f_h + f_l} \]  

(1.1)

Here “f_h” is the highest frequency within interested band and “f_l” is the lowest frequency within interested band. Small duration pulses of a few nano seconds are used by the designers of UWB system to carry information for UWB communication. The Gaussian pulse or its derivatives can be used for UWB communication in which the pulse width defines the central frequency as well as the bandwidth [4]. The allowable transmit power for UWB communication is less than -41dBm/MHz in most of the regions all over the world [5]. Regulatory authorities of respective regions strictly monitor the ranges of UWB transmission to prevent it not to become an interferer for other existing services.

1.3 Regulations for UWB Transmissions

Regulatory conditions are important to establish for applications of UWB technology to encourage the development of economically feasible commercial products. These regulatory conditions also provide significant benefit to harmonize UWB products all over the world which leads to introduce these devices around the world without service interruption.

UWB systems operate on an unlicensed frequency band of 3.1GHz to 10.6 GHz whereas in most of the world partial frequencies within this band are already in use, as shown in figure 1.1. It can be concluded by observing the bands that the frequency spectrum is limited and should be used efficiently. Existing systems operating on the same frequencies should not be interfered by new systems. That is why the strict regulation for UWB is needed to use it commercially.

1.3.1 Regulations in USA for UWB Communication

The regulatory authority of USA is called Federal Communications Commission (FCC) which is an independent agency of US government. It was established in 1934 and is responsible to regulate interstate and international communications by radio, television, wire, satellite and cable. There is another organization in USA called
National Telecommunications and Information Administration (NTIA). FCC and NTIA are responsible for frequency spectrum regulation and they define the legal boundaries of communication for each frequency band to operate in USA. In USA, FCC approved the UWB communication with no license requirement within a band of 3.1 to 10.6 GHz band in 2002 [6]. According to the FCC policy, the average Effective Isotropic Radiated Power (EIRP) is restricted at the emission to $-41.25$ dBm/MHz or 75 nW per MHz. It is free for all users, designers or researchers to use the entire UWB band or divide it into sub bands within the EIRP limits approved by the FCC. Designers or engineers should design and develop an equipment which could operate within UWB band over permissible conditions allowed by the FCC, as shown in figure 1.2 and figure 1.3 for indoor and outdoor applications respectively.

![Figure 1.2: UWB Spectral Mask Approved by FCC for Indoor [6]](image)

![Figure 1.3: UWB Spectral Mask Approved by FCC for Outdoor [6]](image)

1.3.2 Regulations in Europe for UWB Communication

Radio communication all over the world is regulated by the respective authority of that region. In Europe, European Communication Commission (ECC) authorizes and regulates the UWB standards developed by the European Telecommunications
Standards Institute (ETSI). ETSI works since 2001 to develop a European standard for UWB systems. ETSI and the European Conference of Postal and Telecommunications (CEPT) are studying and analyzing harmful interference with existing radio communication services [7], [8].

ECC authorized an UWB spectrum for UWB communication in Feb. 2007, is shown in figure 1.4. Outdoor application of UWB in Europe is not allowed for location measurement or tracking due to existing systems like GPS and Galileo. Tracking equipment must operate indoors and should stop transmission within 10 seconds unless it receives an acknowledgement from receiver. These studies were carried out by ETSI and CEPT by using appropriate mitigation techniques (including detect-and-avoid or low-duty-cycle approaches) and specified a maximum mean EIRP density of −41.3 dBm/MHz can be allowed within 4.2 to 4.8 GHz and 6 to 8.5 GHz band as shown in figure 1.4 [9].

![UWB Emission Limit](image)

**Figure 1.4: UWB Spectral Mask Approved by ECC [10]**

### 1.3.3 Regulations in Asia for UWB Communication

Departments of home affairs and Post & telecommunications under the ministry of Public Management of Japan which are the Japanese spectrum regulators, proposed UWB spectral mask for wireless communication in 2005, as shown in figure 1.5. The regulators allowed the UWB communication for indoors only. The bands 3.4-4.8 GHz is allowed for the products which should use some additional implementation in products to coexistence with other existing services. It requires the implementation of Detection and Avoidance (DAA) technique to avoid any interference with existing services. The limit of -41.3 dBm/MHz has been imposed for unlicensed UWB communications devices operating between 3.4-4.8 GHz and between 7.25-10.25 GHz for indoor applications [10].

Korea adopted a modified mask similar to Japan, as shown in figure 1.6. They imposed additional requirements of DAA for the UWB communication products which operate between 3.1 to 4.2 GHz and 4.2 to 4.8 GHz to avoid interference with
other existing services. These requirements were imposed from 2007, for devices operating between 3.1-4.2 GHz and from 2010, for devices operating between 4.2-4.8 GHz. The limit of -41.3dBm/MHz has been imposed for unlicensed UWB communications devices operating between 3.1-4.8 GHz and between 7.2-10.2 GHz for indoor applications [10].

The regulatory authority of Singapore called “Infocomm Development Authority” (IDA), published details about UWB communication bands in 2003. Initially they permitted UWB communication on trial basis. The IDA permitted controlled UWB emissions within a specific area (named as the UWB Friendly Zone or UFZ) to introduce UWB communication in Singapore. IDA released a new emission mask with its technical specifications for UWB products in 2007. Similar rules are specified in their 2007 release as are being imposed by Europe within the frequency bands from 3.4 to 4.8 GHz and 6 to 9 GHz. The spectral mask allowed by IDA, Singapore for UWB communication is shown in figure 1.7.

![UWB Spectral Mask](image)

**Figure 1.5:** UWB Spectral Mask Approved by Ministry of Public Management, Japan [10]
1.4 Research Motivation

Most of the communication over UWB is digital in nature. Modulated UWB signal carries digital information from different users in the form of pulses with very small time duration. To detect the data corresponding demodulation technique is used with suitable sampling rate to process the digital data at the UWB receiver. In UWB
communication sampling plays key role in detection of data. Since transmission of data via UWB is digital mostly therefore the digital detection should be enough and there is no issue of reconstruction for this type of UWB communication. Therefore the current trend is to make an UWB receiver with minimum number of analog blocks and the maximum processing should be done digitally. There are so many different challenges to make all digital UWB receiver. Since the UWB pulses have small duration with high frequencies within the range of several GHz therefore rapid synchronization is an issue to detect data from the received signal. If the received signal is not properly synchronized then it could lead to performance degradation of UWB system. In addition to synchronization issue in UWB receivers, for all digital UWB receiver achievement of higher sampling rate is also an issue to convert signal into information. The conventional sampling technique requires Nyquist rate to detect the data from the received signal. The Nyquist rate reaches to several GHz for UWB receiver which is almost impossible to achieve with low cost existing technology due to integrated circuit process constraints. The power consumption associated with higher sampling rates is also a big problem, therefore simple and power efficient techniques are required which could be achieved lower sampling rates or flexible sampling rates and can avoid multiple access interference (MAI) in the multiple user environment. If selection of the sampling frequency would be flexible to detect data from multiple users then it could relax the UWB receiver design especially the requirements of ADC would be improved. The Intel research and development report [11] also indicates towards this goal. The research is being carried on [12] by the researchers, to reduce sampling rates so that the power consumption of the ADC may be reduced and the performance of UWB receivers could be improved. For MAI cancellation so many different techniques are being used such as Time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA) and etc. In this thesis a research is carried out to address the issues stated above particularly lower the sampling rate and multiple user access. Therefore a transmission and reception methodology is developed to reduce the sampling frequency for data detection with TDMA. Usually TDMA is used to avoid MAI but in this research the proposed method is using TDMA to lower the sampling rate in addition to its conventional property which is MAI cancellation. In the proposed work the data transmission of all users, distributed in time slots specifies in each frame. The sampling rate to detect the data of each user can be selected according to need from 1 Hz to 7.5 GHz for 7.5 Giga number-of-users to only 1-user respectively if one pulse is used to transmit one bit of data within the entire UWB band i.e. 3.1 GHz to 10.6 GHz. To proof the workability of the scheme, the transmission bandwidth of 2.5 GHz is selected within UWB range. The scheme is tested for 50 MHz, 100 MHz and 500 MHz sampling rates to transmit 8-bits of data from 50 users, 25 users and 5 users respectively. The data of each user is arranged in respective time slots within the frame to achieve a desired sampling rate. For this purpose each data bit of a user is arranged once in a transmission frame. The data can be detected on frame repetition rate which can be
selected according to number of users. The data of one user is divided into different frames and can be accessed directly by calculating the time delay of each user place within each frame. Since each data bit of single user would occur once in each frame, it could be claimed that ISI has been avoided. The detail of the proposed scheme is presented in chapter 5 and chapter 6 of this thesis, but here we claim that the scheme is working properly and data detection is being achieved with a low sampling rate without ISI.

**1.5 Author’s Contribution**

UWB wireless communication is popular due to low cost and non coherent detection of the signal makes it more simple than other communication methods. Therefore the research was focused on non coherent UWB receiver. As discussed earlier, the sampling rate for UWB signal is hard to achieve with low cost technologies therefore the main focus of the research is to develop a low sampling rate non coherent UWB receiver for multi user application. The architecture of IR-UWB receiver is proposed with its simulation results which show that low sampling rate IR-UWB receiver could be implemented. The advantage of proposed architecture is that the transmitted data can be sampled at any sampling rate and the sampling rate is independent to transmission bandwidth. Secondly the proposed IR-UWB receiver can also be implemented for multiple users by dividing the transmission bandwidth among required number of users. The proposed method uses TDMA for low sampling rate to detect data in addition to avoid multiple access interference. Here it should be noted that the multiple access is possible via single transmitter which takes information from different users and transmit those information bits to the UWB receiver in sequence as proposed. Another architecture of UWB receiver is also proposed for multiple transmitters with some modification in the proposed UWB receiver. Finally the proposed UWB receiver is also implemented with matched filter configuration and results are compared to UWB receiver implemented with integrated window configuration.
Chapter 2: Overview of UWB Communication Systems

2.1 Impulse Radio UWB (IR-UWB)
Due to its unique features and properties UWB communication has become popular for RF communication. IR-UWB systems are simple and easy to implement therefore researchers are focusing on them to improve its performance and to make it more feasible. Based on published theory, research focused on the coexistence of IR-UWB with other narrowband and already existing systems. High data rate receivers (HDR) and low data rate receivers (LDR) are being developed. Research is also being done on modeling. New scenarios are being tested for modeling the signal transmission through channels and the challenges offered by the signal passing through the channel. Due to very wide bandwidth and low transmission power of UWB, signals behave differently compared to other types of RF communications. In the following sections of this chapter we present an overview of the UWB communication based on published research.

2.2 Channel Model
A general overview about propagation of UWB signal is presented by Molish [13]. The author discussed about the basic differences between UWB channel and conventional wideband channels due to frequency selectivity. A group developed the first IEEE 802.15.3a standard for channel models which specified the physical layer extension to achieve high data rate for wireless personal area networks (WPAN) [14], [15] developed channel models for indoor wideband communication with ranges up to 10 meters. These models were modified by the group stated above to make an IEEE 802.15.3a standard. Channel models of low data rate communication for distance range up to 30 meters in different indoor and outdoor environments, were developed by another group who proposed IEEE 802.15.4a standard [16]. These standards are being accepted among the researchers to design communication network. Nakagami fading phenomena was studied and specified in [17]. In this study the authors showed that Nakagami fading gives a good fit to the fading of each UWB channel component. This work concludes that the Nakagami distribution can be developed and analyzed very easily with its mathematical models. In [18] an UWB channel model with space variant multipath for indoor communication is proposed. The authors of [19], investigated the channel power delay profile (PDP). In this work they estimated the value of time decay constant for channel PDP.

The UWB frequency response is investigated in [20] where a second order auto-regressive model with random parameter is proposed. Channel modeling is very important in UWB communication to estimate the signal to noise ratio, signal
strength, shape and phase calculations. Channel modeling is also helpful for performance estimation of UWB systems.

2.3 Path Loss

Path loss model describes the signal power attenuation as a function of distance. In UWB communication it is an important issue as the transmitted power is so small compared to other frequency bands for radio communication. In [21] and [22], statistical models are proposed to estimate path loss with the help of different time dispersion parameters.

Similar path loss models are presented in [23] and [24]. In these papers, additional attenuation of signal power due to reflections experienced by UWB signal is considered. The path loss models considered for UWB signals, estimate different power loss coefficients for each multipath component to calculate the signal power and the amount of power loss during propagation of UWB signal beyond the line of sight distance. Path loss models help to estimate the received power of the UWB signal propagated under different ambient conditions and passed through different physical phenomena.

2.4 Data Detection and Synchronization

Synchronization of time for data detection is an important and challenging problem in UWB communication systems. The reasons are low duty cycle of the signal and multipath components.

The synchronization of high data rate (HDR) devices based on direct sequence code division multiple access (DS-CDMA) were studied in [25]. Homier and Scholtz [26], [27] developed a framework for code acquisition and proposed a new synchronization algorithm. Suwansantisuk [28] presented a theoretical framework for synchronization and code acquisition in the presence of multipath reflections. In [29] a synchronization scheme was implemented on chip for time hop impulse radio (TH-IR) based systems which used post detection integration technique. In [30], a Cramer-Rao lower bound for the synchronization of UWB signal in multipath channels is presented.

A comparison between differential and auto-correlation UWB receivers with coherent receivers is presented in [31], where authors discussed the robustness of these receivers against synchronization errors compared to coherent UWB receivers. A transmission protocol for blind synchronization with low complexity receivers like energy detectors receivers is proposed in [32]. In [33], an energy detector UWB receiver is proposed with a synchronization stage based on spontaneous decision related to energy of the received signal. An auto-correlation receiver is proposed in [34] with synchronization algorithms based on noisy template. The synchronization algorithms stated above are very important to reduce energy loss of the received UWB signal for data detection. Without synchronization correct data detection is nearly impossible with acceptable performance.
2.5 Performance of UWB Systems

Performance of the UWB system can be evaluated by estimating the bit error probability (BEP) or bit error rate (BER). Initial studies were focused on the BEP of UWB wireless systems for high data rate (HDR) devices based on locally generated waveform (LGW) techniques, presented in [35], [36]. The challenges about the implementation of LGW based UWB receiver designs, are discussed in these studies. The authors of these studies also showed the robustness against fading of these types of receivers. In [37], the authors estimated the performance of digital RAKE receiver structures with different sampling rates as stated in IEEE 802.15.3a. If the sampling rate is chosen such that the chip rate is higher than the sampling rate then serious degradation can be observed. The performance of digital RAKE receiver structures with different levels of complexity, were also investigated in [37]. The effects of timing jitter and tracking related to IR signal detection on the performance of UWB communications were discussed in [38]. The study showed that the performance of IR-UWB coherent receivers is sensitive to timing jitter and signal tracking errors. The advantage of reduced complexity and other advantages offered by IR-UWB implementation could be shadowed in terms of performance degradation caused by timing jitter and tracking errors. This issue can be resolved by using an autocorrelation architecture of the UWB receiver [39], in which a delayed copy of the signal is provided to the receiver directly from the received signals. This method also known as differential detection which could resolve timing jitter and tracking errors issues of a UWB receiver as tracking operation is not required if this technique is used. In [40] and [41] the performances of transmitted reference (TR) UWB receivers are estimated. In [41] multiuser capability is added in addition to TR-UWB scheme by using time hop (TH) modulation.

Performance estimation of IR-UWB receivers in [42], [43], [44] suggested that IR scheme is very useful for dense environment where multipath signals can be received by the UWB receiver. In a multipath environment long time channel estimation is required. Therefore longer scanning and synchronization of the signal is required which increases the power consumption and complexity of the IR-UWB receivers. Solutions of these problems are stated in [45] and [46], where authors presented the energy detectors receivers also known as radiometer. The energy detector UWB receivers were proposed due to their lower complexity and lower power consumption. After these energy detector receivers, several studies were conducted to estimate auto correlation receivers’ performances in presence of channel fading [47] and in the presence of narrowband interference [48]. In [49], authors focused on channel models presented in the IEEE 802.15.4 and evaluated the performance of energy detector UWB receiver based on these models. Performance of the optimized energy detector receivers was evaluated in [50].

2.6 Coexistence and interference

The UWB transmission within the range of 3.1 GHz to 10.6 GHz is unlicensed in most of the world. Due to this unlicensed spectrum more and more devices are being
designed but the UWB signal can be either distorted or corrupt due to other existing services like narrowband or wideband interferences. Similarly narrowband or wideband services can be distorted by the UWB signal. Therefore interference from the UWB system to narrowband and wideband systems should be considered in the design. Similarly interference from narrowband or wideband systems can corrupt the UWB signal. Therefore these interferences should be considered in the UWB system design to avoid these interferences. The coexistence of Global Positioning System (GPS), Global System for Mobile Communication (GSM), Universal Mobile Telecommunication System (UMTS) and wireless local area network (WLAN) with UWB systems needed to be studied and proper actions needed to be taken to avoid the interference among these systems to achieve better performance. From these systems different studies were conducted and related results were presented in [51]–[54]. The Impacts of UWB on narrowband systems were modeled and results were presented in [55], [56]. The investigations suggested that the impact of UWB systems is smaller over narrowband and it can be further reduced with selection of a proper pulse waveform. On the other hand, narrowband interference affects the portion of UWB systems as well as other existing services also affect UWB systems at their respective spectrum location. In [57] authors showed that the narrowband interference effect can be minimized by designing a good UWB pulse. The Narrowband interference effects were also discussed in [48] related to TR-UWB receivers. In [58] the performance of coherent receivers in presence of narrowband interference was estimated and the impacts of narrowband interference on coherent receivers were discussed.

2.7 Ranging estimation

The benefit of UWB communication due to the large bandwidth of the UWB signal in addition to other advantages is its accuracy of sequential data propagation. This accuracy is due to the high time resolution of UWB signals. These properties of UWB signals allow it to develop UWB wireless devices which could perform accurate range estimation. The theoretical limits on range estimation are discussed in literature as Cramer-Rao lower bounds (CRLBs) and Ziv-Zakai lower bounds (ZZLBs) [59]. Practical range estimation requires good algorithms to achieve these limits. Range estimation on maximum likelihood (ML) estimation is discussed in [60]. The theoretical values may not be reached by the algorithms implemented practically but these practical algorithms provide good results to estimate the ranging of UWB devices.

2.8 Conclusions

In this chapter, a review over different UWB systems has been presented. IR-UWB, channel modeling, path loss, data detection and synchronization techniques, performances of UWB receivers and UWB systems, coexistence of UWB and other services and ranging estimation are studied. The approach of the study is to develop an understanding about the major challenges associated with UWB coherent receivers and non coherent receivers including their related issues belong to design and operation. Previous work related to energy detectors receivers is also discussed. In
this thesis energy detection receiver is discussed with time division multiple access (TDMA). The TDMA technique is used to lower the sampling rate for detection with the advantages that the design of the analog-to-digital converter could be relaxed and the associated power consumption will be reduced. Additionally an advantage of the TDMA technique related to avoiding multiple access interference (MAI). The UWB receiver using matched filter is also designed and simulated in Matlab using the same TDMA approach to reduce the sampling rate and the results are compared with the energy detector UWB receiver using integrated window technique for detection of data. The proposed design methodology and modifications suggested will be discussed later in chapter 5.
Chapter 3: Modern UWB Modulation Techniques and Methods

Modulation is a process of conveying an information signal (digital bit stream or analog) into another other signal to transmit it to the receiver. Demodulation is a process to extract the transmitted information into the original signal.

There are some differences between UWB radio transmission and classical radio transmission in terms of modulation methods due to the properties and shape of the signals.

Classical radio transmission systems use sinusoidal wave as carrier and the information may be transmitted via this carrier by alternating its power, frequency, amplitude or phase whereas UWB systems transmit information over small duration pulses by alternating the amplitude of the pulse, polarity of a pulse, position of a pulse or an orthogonal pulse can also be used to transmit information. Therefore it can be stated here that for UWB transmission, pulse generation is very important. Therefore modulation techniques will be discussed later.

Pulse generation and the pulse propagation are key factors for UWB communication. Different methods can be applied for pulse generation. It should be kept in mind that while generating pulses for UWB the regulatory authorities critically monitor the limits and standard suggested by them in the native regions. They have strict limits on transmission bandwidth and signal transmission power.

UWB systems are also called impulse radio systems, which mean that the pulse generation for the UWB transmission will have very low duration. The duration of the UWB pulse could be several hundred picoseconds. As the transmission power limits are very small within UWB range therefore multiple pulses are used to carry one information bit depending upon the distance to travel between transmitter and receiver for communication.

In this chapter we are focusing on different types of generated pulses and different modulation schemes being used by the researchers for data transmission between UWB devices.

3.1 Generation of UWB Pulses

The representation of a message via an analog pulse is the basic problem in UWB communication. Therefore generation of pulses is an essential function for communication between transmitter and receiver. For UWB communication the message or message symbols are transmitted through small duration modulated pulses with very low transmission power. Classically sinusoidal waves were used to communicate between the devices but nowadays for UWB communication different
types of waves are being used such as Gaussian, Rayleigh, Laplacian, cubic and modified hermitian mono cycles [61].

UWB pulses with message encoding via various techniques of modulation, can be sent to the receiver either individually or in the form of sequential streams. The information can be encoded either in pulse position, polarity, shape or in amplitude. It is being observed that a single pulse cannot communicate too much information. To transmit the message, data should be modulated onto a stream of pulses sequentially, called a pulse train. Therefore the designer or the researcher should know which type of pulse could be used to transmit information to the UWB receiver for further processing [62].

Given below are some pulse shapes which could be used for UWB communication.

![Figure: 3.1: Different Pulse Train for UWB communication [62]](image)

(a) Square Pulse (b) Gaussian Pulse (c) 1st Derivative Gaussian Pulse (d) Gaussian Doublet

Three different types of pulses are most commonly used for UWB communications mentioned in published literature. These are Gaussian pulse, Gaussian monocycle, and Gaussian doublet as shown in figure 3.1.

The pulses can be described by the mathematical formulas, given as:

\[
p_0(t) = e^{-2\pi \left[ \frac{(t-t_0)}{\tau} \right]^2}
\]

(3.1)

\[
p_1(t) = -2\pi \left[ \frac{(t-t_0)}{\tau} \right] e^{-2\pi \left[ \frac{(t-t_0)}{\tau} \right]^2}
\]

(3.2)

\[
p_2(t) = \left[ 1 - 4\pi \left[ \frac{(t-t_0)}{\tau} \right] \right] e^{-2\pi \left[ \frac{(t-t_0)}{\tau} \right]^2}
\]

(3.3)
Here “τ” is time constant, “t₀” is pulse offset time and “t” is instantaneous time of communication pulses.

As shown in the figure 3.1(b), Gaussian pulse is like bell shape which is also known as Gaussian distribution. A Gaussian pulse will remain Gaussian and it can be stated that it does not change its shape while passing through a linear system. It can be seen that there is no zero crossing in Gaussian pulse shape. Gaussian pulses can be generated by the equation (3.1). From the equation (3.2), it can be seen that it is a first derivative of equation (3.1) and is known as Gaussian monocycle. As shown from the figure 3.1(c), Gaussian monocycle has one zero crossing point. Similarly equation (3.3) is the second derivative of a Gaussian pulse. While observing figure 3.1(d), it can be concluded that it has two zero crossings therefore it is known as Gaussian doublet.

The PSDs of the three pulses are examined and shown in figure 3.2. It can be stated while observing the spectrum of all three pulses shown in figure 3.2 that the PSD is centered at zero frequency for the Gaussian pulse and the PSDs are skewed to higher frequencies for Gaussian monocycle and Gaussian doublet. It can also be observed that the PSD of a Gaussian doublet is skewed to higher frequencies than the PSD of a Gaussian monocycle pulse.

![Figure 3.2: PSD of Gaussian pulse, Gaussian monocycle and Doublet](image)

### 3.2 Types of UWB in Terms of Signaling

UWB communication can be divided into two major categories, given as:

#### 3.2.1 Impulse Radio UWB (IR-UWB)

IR-UWB is a time based signaling technique which uses time hopping (TH), direct sequence (DS) or combination of both methods to transmit or receive signal to avoid collision during multiple access [63]. We can define a transmitted IR-UWB signal for “kth” user given as:

$$S^{(k)}(t) = \sum_{j=-\infty}^{\infty} \frac{E_s}{N_s} d_j A. p(t - jT_f - c_jT_h)$$

(3.4)
Here “Es” for energy per symbol, “Ns” for number of pulses per symbol, “dj” is binary code, “j” is frame index, “A” is the amplitude, “Tf” is the interval between two pulses, “cj” is code for time hopping, “t” is the instantaneous time and “Th” the chip duration.

Similarly, we can define receive IR-UWB signal given as:

\[ r^{(k)}(t) = \sum_{j=-\infty}^{\infty} \frac{E_s}{N_s} \cdot d_j \cdot A \cdot p(t - jT_f - c_jT_h) + n(t) \]  \hspace{1cm} (3.5)

Here all parameters are defined above except \( n(t) \) which is AWGN having double sided power spectral density of \( N_0/2 \).

To avoid multiple access interference (MAI), a TH scheme can be used, which improves performance of a UWB system. TH-UWB is more popular than other techniques for multiple access. This technique is being used by the UWB system designers and researchers to design typical UWB system stated as equation (3.4) and (3.5) [64]. The compound values here can be expressed as “\( c^{(k)}_j \cdot T_h \)” pseudo random time hopping, and “\( jT_f \)” uniform pulse train spacing, respectively.

Collision between the desired user and an interfering user is shown in figure 3.4 [65]. This situation occurs when same time slots are used and shared by different users. If two or more users occupy the same time slot (user “1” and user “k-1”) as shown in figure 3.4, then a collision will occur because the pulses are uniformly spaced.

These collisions of pulses can be avoided by assigning an individual code to each user. This code is known as periodic pseudorandom time hopping code \( \{ c^{(k)}_j \} \). According to the code, each pulse will be randomly shifted with \( c^{(k)}_jT_h \), which reduces the probability of a collision of pulses and improves the performance of UWB system. The randomness associated with the code helps smoothing the spectrum (i.e., less peak power) and consequently less interference may occur to other communication systems [65] as well.
We have discussed multiple access via TH-UWB. Instead of this method direct sequence (DS) spreading scheme can also be used as shown in figure 3.5.

To achieve DS-UWB from the IR-UWB system stated as equations (3.4) and (3.5) “c_j=0” and T_f=T_h (it means pulses are processed consecutively as chip duration is equal to frame duration) now “d_j” can be used to change the polarity of the pulses to achieve pure DS-UWB as the researcher did in [66]. TH-UWB and DS-UWB can also be used simultaneously which improves the spectrum smoothness [63].

### 3.2.2 Multiband UWB (MB-UWB)

In multiband UWB scheme, the available UWB bandwidth is divided into multiple frequency bands. These sub bands should be larger than 500 MHz to comply with the federal communication commission regulation. Frequency hopping (FH) is used to transmit and detect the data using multiband UWB signaling to avoid collisions during multiple accesses [65]. FH can be defined as the switching from one frequency band to another frequency band or for multiple user one user frequency to another user frequency whereas the communication is known as FH-UWB communication [63] within UWB range.

Several benefits can be achieved by dividing the UWB spectrum into small parts.

(i) The UWB device could operate all over the world as the spectrum allocation can be different in different parts of the world.

(ii) It provides better co-existence with other technologies.

(iii) It provides ability to avoid narrowband (NB) interference.
Pulse-based, single-carrier-based and multiple-carrier-based are some possible solutions for multiband UWB communication. In pulse-based multiband UWB, information is transmitted via pulses within its corresponding sub-band [63]. These pulses are shown in figure 3.6 (top) whereas the corresponding power spectral densities are shown as figure 3.6 (bottom).

In single-carrier-based and multi-carrier-based multiband UWB signaling, spectrum is divided into different sub-band as shown in figure 3.7. The only difference between single-carrier-based multiband signaling and multi-carrier-based multiband signaling is the number of carriers in each sub-band. Single-carrier-based multiband signaling is done via one carrier in each corresponding sub-band whereas multi-carrier-based multiband signaling can have more than one carrier in each sub-band. Orthogonal frequency division multiplexing (OFDM) [65] is an example of multi-carrier-based multiband signaling.

![Figure 3.6: Pulse-based Multiband UWB](image)

![Figure 3.7: Multiple Frequency Band Allocation within UWB Range [65](image)

### 3.3 Modulation Methods for UWB

In UWB systems information should be added into the analog pulse train. This information can be added in digital form i.e. either 1 or 0. To add this digital information with each pulse of a pulse train we need some techniques, called modulation methods. Modulation schemes for UWB are shown in figure 3.8 [62].
### 3.3.1 Pulse Position Modulation (PPM)

A pulse is displaced from its origin in the time domain to show data information either 0 or 1. This technique of modulation is called pulse position modulation (PPM). This technique uses pulses of uniform height and width. This technique is shown as figure 3.8 (b). As the detection of data is based on the correct time displacement rather than the amplitude therefore it has better noise immunity.

The delay of the pulse is an important parameter in PPM. If $s_i(t)$ is a modulated pulse train signal with a pulse shape defined by $p(t)$ then the modulated pulse train can be defined as equation (3.6):

$$s_i(t) = p(t - T_i)$$

Here “$T_i$” is delay parameter for “$i^{th}$” pulse to define either “0” is transmitted or “1”.

![Figure 3.8: Different Modulation Schemes for UWB](image)

### 3.3.2 Bi-Phase Modulation (BPM)

The pulse polarity is inverted to transmit “0” or “1”. This modulation technique is known as BPM or binary phase shift keying (BPSK). This type of modulation techniques is shown as figure 3.8 (c). The pulse polarity is an important parameter for BPM as the information defines the polarity of a pulse. A pulse $p(t)$ can be inverted using a pulse polarity parameter $\sigma_i$. If $s_i(t)$ is a modulated pulse train signal with shape of a pulse is defined by $p(t)$ then the BPM pulse train can be defined as equation (3.7):
\[
s_i(t) = \sigma_i \, p(t); \quad \sigma_i = 1 \text{ or } -1
\]  
(3.7)

If a positive pulse \( p(t) \) corresponds to a data bit “1” then “\( \sigma=1 \)” and the resultant pulse can be defined as: \( s_1 = p(t) \).

Similarly, If a negative pulse \( p(t) \) corresponds to a data bit “0” then “\( \sigma=-1 \)” and the resultant pulse can be defined as: \( s_2 = -p(t) \).

BPM can produce twice the data rate compared to PPM if the delay of PPM would be exactly equal to one pulse width while the pulse shape would be similar for both modulation schemes.

Since the mean of “\( \sigma \)” is zero therefore spectral peaks or comb lines would be removed and the spectrum will be smoother. There will be no need to calculate a threshold of energy for the energy detectors UWB receivers to detect the data from the BPM pulse train due to zero mean of the pulse polarity parameter.

### 3.3.3 Pulse Amplitude Modulation (PAM)

The amplitude of a pulse is varied to transmit “0” or “1”. This modulation technique is known as pulse amplitude modulation (PAM). To use this technique either voltage or power amplitudes of pulse could be varied. If \( s_i(t) \) is the modulated pulse train signal with a pulse shape defined by “\( p(t) \)” then the PAM pulse train can be defined as equation (3.8):

\[
 s_i(t) = \sigma_i \, p(t); \quad \sigma_i > 0
\]  
(3.8)

Here “\( \sigma \)” is a parameter to vary the amplitude of the pulse \( p(t) \).

If a positive pulse \( p(t) \) corresponds to a data bit “1” then “\( \sigma=2 \)” and the resultant pulse can be defined as: \( s_1 = 2 \cdot p(t) \).

Similarly, If a positive pulse \( p(t) \) corresponds to a data bit “0” then “\( \sigma=1 \)” and the resultant pulse can be defined as: \( s_2 = p(t) \). This technique is shown as figure 3.8 (d). It is not a preferred modulation technique for UWB since higher power is required to transmit higher pulse amplitude which reduces the power efficiency of the UWB application whereas for most of the UWB applications, power efficiency has prime importance.

### 3.3.4 On-Off Keying (OOK)

The pulse is transmit or not to modulate data “1” or “0”. If the pulse \( p(t) \) is transmitted it mean the information data bit is “1” if the pulse is not transmitted it means the information data bit is “0”. This modulation technique is known as ON-OFF keying (OOK).

If \( s_i(t) \) is modulated pulse train signal with shape of a pulse is defined by \( p(t) \) then the OOK pulse train can be defined as in equation (3.9):

\[
 s_i(t) = \sigma_i \, p(t); \quad \sigma_i = 0 \text{ or } 1
\]  
(3.9)
It is also known as pulse shape modulation where the shape parameter “σ” is either 0 or 1.

If a positive pulse $p(t)$ corresponds to a data bit “1” then “σ = 1” and the resultant pulse can be defined as: $s_1 = p(t)$.

Similarly, If a pulse $p(t)$ corresponds to a data bit “0” then “σ = 0” and the resultant pulse can be defined as: $s_2 = 0$. This technique is shown as figure 3.8 (e). This is the simplest technique to implement for UWB wireless communication.

### 3.3.5 Orthogonal Pulse Modulation (OPM)

Different pulse shape is required to transmit “0” or “1” but the pulses should be orthogonal to each other. This modulation technique is known as OPM.

For UWB orthogonal pulses can be designed. A set of orthogonal pulses could be used for multiple accesses.

Here simple pulse shape parameter “σ” cannot solve the purpose to define the orthogonal pulses therefore a set of pulses “$S_i$” is being defined as equation (3.10): assume that pulses are designed so as to be orthogonal pulse shapes.

$$S_i = \{p_1, p_2, p_3, \ldots, p_i\} \quad (3.10)$$

It is assumed that the pulses “p_1, p_2, p_3, \ldots, p_i” are orthogonal to each other. This technique is shown as figure 3.8 (f).

### 3.4 Power Spectral Density

After the choice of a suitable modulation scheme for the transmission, it is very important to measure the power spectral density (PSD) of the UWB transmitted signal. Since the strict rules are applied all over the world on the transmission power of UWB signal to communicate between transmitter and receiver therefore transmission power should be limited for UWB applications and their PSD should be less than -41.3 dbm/MHz.

By definition PSD can be defined as:

The power of a signal distributed along the frequency. It has the unit of watts per Hz or dbm per Hz.

Suppose we have a signal voltage signal $f(t)$ in time domain with 1 ohm resistance then the power spectral density (PSD) of the signal $f(t)$ can be calculated by the equation given as:

$$PSD = [\int_{-\infty}^{+\infty} f(t)e^{-j\omega t} dt]^2 = |F(f)|^2 \quad (3.11)$$

Here $F(f)$ is continuous Fourier transform of $f(t)$. 

3.5 UWB Pulse Generation Circuit

To generate UWB pulses, a number of different circuits are proposed by the researchers [67], [68]. A simple circuit is presented for generation of UWB pulses in [69]. Inductors, capacitors, diodes and transistors are commonly used components to generate pulses for UWB communication systems. The pulse generator circuit presented in [69] is shown in figure 3.9, in which a, b, c, d are the control taps of the four MOSFET (metal oxide semiconductor field effect transistor) transistor, “C” represents a capacitor for DC blocking called blocking capacitor whereas “L” is an inductor. Stated components are configured in an electronic circuit as shown in figure 3.9.

Figure 3.9: A simple pulse generator circuit [69]

To describe the working of the circuit illustrated in figure 3.9, suppose that the control taps a, b, c, and d are set to GND, Vdd, Vdd, and GND, respectively. If the circuit state is stable there is no current flow through the load. As mentioned the initial state of MOSFET, “a” and “d” are in conduction state or “ON” whereas “b” and “c” are non-conducting or “OFF”. Therefore current flows through the RF choke “L” and two conducting transistors. Now suppose that “a” switched to GND or “0” state the current flowing through the respective transistor will flow through the load and will make a positive slope of the current and voltage pulse. In the next step after certain time delay “b” switched to Vdd or “1” will get the corresponding transistor to ON state which will reduce the current flowing through the load and create a negative slope of current and voltage at the load. Similarly, after “b”, “c” will be switched to Vdd or “1” will ON the respective transistor this will further reduce the current through the load will create a negative slope of current and voltage at the load. In the last step “d” will be switched to GND or “0” will OFF the respective transistor and a positive slope of current and a voltage will be created at the load. The switching sequences stated above will create a monocycle UWB pulse. Pulse width depends on the switch ON and OFF time of the transistors “a”, “b”, “c” and “d” as well as the semiconductor materials used for constructing the electronics components used in the circuit.

Figure 3.10 shows the switching sequence waveforms of the transistors “a”, “b”, “c” and “d”.

![Figure 3.9: A simple pulse generator circuit [69]](image-url)
As discussed above, to generate UWB pulses, a pulse width of between 0.094ns (10.6GHz) to 0.3225 ns (3.1GHz) is required and pulse width depends on the ON/OFF timing of the switching components of the circuit and the semiconductor materials, which are used to generate the pulse. Many different kinds of semiconductor materials are available for high frequency application such as silicon (Si), gallium arsenide (GaAs), indium phosphide (InP), silicon germanium (SiGe), silicon carbide (SiC), and gallium nitride (GaN). In general, the compound semiconductors work best for high-frequency applications due to their higher electron mobilities [70].

In general, Si works for less than 10GHz frequency applications and it is the cheapest material to be used. GaAs can work for 10GHz frequencies or higher up till 20GHz. Therefore GaAs is used almost everywhere, where Si does not work properly but Si is always a better choice for applications under 10 GHz due to its low cost and acceptable material properties. SiGe is more power efficient and has better linear performance than GaAs and Si but it is more expensive. It can operate on frequencies more than 20 GHz up to 40 GHz. It is expected that future wireless devices will use SiGe more instead of Si or GaAs to get better performance and high data rates. Indium phosphide (InP) has the lowest noise at very high frequencies more than 40 GHz up till 70 to 80 GHz but InP is also very expensive to be used in wireless devices. The application frequency ranges for solid state technologies based on these materials are summarized in table 3.1.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Material Name</th>
<th>Symbol</th>
<th>Electron Mobility (cm²/V-s)</th>
<th>Hole Mobility (cm²/V-s)</th>
<th>Frequency &lt; GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silicon</td>
<td>Si</td>
<td>1500</td>
<td>600</td>
<td>10 GHz</td>
</tr>
<tr>
<td>2</td>
<td>Gallium Arsenide</td>
<td>GaAs</td>
<td>8500</td>
<td>400</td>
<td>20 GHz</td>
</tr>
<tr>
<td>3</td>
<td>Silicon-Germanium</td>
<td>SiGe</td>
<td>3000</td>
<td>700</td>
<td>40 GHz</td>
</tr>
<tr>
<td>4</td>
<td>Indium Phosphide</td>
<td>InP</td>
<td>4600</td>
<td>150</td>
<td>80 GHz</td>
</tr>
</tbody>
</table>

Since the FCC range is 3.1 GHz to 10.6 GHz for UWB communication therefore Si could be used to develop circuits for UWB wireless applications up to 10 GHz signal frequency.
Chapter 4: Non Coherent and Coherent Communication

In this chapter, different types of UWB receivers are being discussed. There are two major categories of UWB receivers, coherent receivers and non-coherent receivers. Both types of UWB receivers are important to understand with their advantages and disadvantages and their performance over different operating conditions multipath fading channels.

To design coherent receivers require several parameters to be considered carefully, given as:

1. Received signal
2. Radio channel
3. Interference characteristics
4. Multipath delays
5. Channel coefficients for each delayed multipath components
6. Distortion of the pulse shape needs to be estimated for optimal coherent reception.

Coherent receivers are best possible in the sense that they utilize the knowledge of the end-to-end channel response. This information of channel is typically obtained by means of some kind of channel estimation method prior to the symbol recognition step. Coherent receivers consists of a conventional correlator based architecture with good channel knowledge, where a model of the transmitted pulse is used to apply a matched filtering or Rake receiver [71], [72].

The Detection of the transmitted bits for non-coherent receivers depends on less information compared to coherent receivers. In non coherent receivers, pulse shape estimation, synchronization and channel estimation are not as strict as in the fully coherent receivers. Some of the non-coherent receiver designs include transmitted reference (TR) based UWB, an energy detector and a differential detector. Common to all these approaches is that channel estimation and received pulse estimation is not necessary. Also, the timing estimation is easier and receiver performance is more immune to timing mismatch.

Non coherent receivers are preferred over coherent receivers due to their lower cost, lower power consumption, lower complexity and lower computational load.

The decision of using a coherent or non coherent receiver basically depends upon the specification and required performance in terms of signal-to-noise ratio (SNR), modulation scheme, data rate, accuracy and bandwidth.
4.1 **UWB Receiver Architecture**

4.1.1 **Rake Receiver Structures**

Rake architectures belong to the family of coherent receivers. It consists of a tapped delay line that is used to estimate the channel impulse response and a matched filter that is matched to the transmitted pulse train which represents a symbol or series of symbols. The rake structure can be implemented with different number of correlators for each multipath component (MPC) that is sampled at the delay each line related to corresponding MPCs; each of those correlator is called a "RAKE finger" [73]. Three types of Rake receivers are being designed for UWB communication: all-Rake (ARAKE), selective-Rake (SRAKE) and partial-Rake (PRAKE) receivers.

To improve received signal energy in a multipath fading channel, rake receivers are used [73]. It acts as a rake for energy at different time delays due to multiple paths of the transmitted signal to the receiver. All MPCs or some major MPCs are combined in rake receivers to improve the SNR.

![Block Diagram of Rake Receiver](image)

Figure 4.1: Block Diagram of Rake Receiver [63]

A block diagram of rake receiver is shown in figure 4.1. Ideally, the number of fingers equals the number of MPCs to capture all the received signal power. Therefore it is called all Rake (ARAKE) receiver [74], [75], [76]. Due to the infinite or large number of fingers, it is not a feasible option to implement an ARAKE receiver. Therefore
selective rakes (SRAKE) and partial rakes (PRAKE) are being designed [77]. In PRAKE and SRAKE, a finite number of fingers are used to estimate the received signal energy, by combining some initial MPCs as it is being done in the PRAKE or by combining the major MPCs after selecting these with maximum energy magnitude. In [77], the authors compared the performances of ARAKE, PRAKE and SRAKE receivers and they showed that when four fingers are selected either for PRAKE or for SRAKE then received energy difference with ARAKE, is approximated to only 2 dB. This is due to the exponential decay of the average power delay profile (PDP). The exponential decay suppresses the multipath components at large delays, which means that the strongest signal energy component arrives first to the receiver. In [77] it is shown that the performance of PRAKE and SRAKE are comparable to each other for smaller number of fingers.

Maximum ratio combining (MRC) is a technique which combines all of the signal components to obtain optimal performance [78]. MRC requires phase recovery of the received signal and estimating the received power level for each multipath. The distinguishable propagation paths can be separated by the receiver based on the channel estimate. All of the paths that arrive within the receiver’s time resolution will be regarded as a single channel path, while the energy of the single path is a combination of the energy of all the undistinguishable paths. Minimum mean square error (MMSE) scheme is better and effective RAKE receiver scheme which can give better performance but it increases the computational complexity [78].

### 4.1.2 Transmitted Reference (TR) based UWB Receiver

In a TR scheme, two pulses are used to transmit data. The one pulse is used as reference pulse and the other one is used as modulated data pulse. The reference pulse is transmitted before the modulated pulse with a separation of known time delay to estimate the transmission delay which helps in synchronization to the data pulses. To detect the data at the receiver, pulse-pair correlators are used to recover the data after estimating channel conditions with the help of the transmitted reference pulse and the time delay between the reference and data pulses. When the delay is less than the coherence time of the channel, the reference and data pulses can be assumed to be affected similarly due to the channel. Therefore, instead of using a local, the TR scheme uses the reference pulses as the template for correlating the data pulses, and for the demodulation of the transmitted information. A block diagram of TR receiver is shown as figure 4.2 [63].

The UWB receiver based on TR scheme, captures the energy from all multipath components of the received signal whereas it induces high noise power into the detection as the reference and the data pulse both are modified by the noise in the system similarly. However the trade-off compared to noise induction is more advantageous in an environment with dense multipath. It requires less computational power than the rake receivers.
4.1.3 Energy Detector (ED) based Receiver

An energy detector is a non-coherent UWB receiver scheme, which can be implemented with OOK modulations [79], or PPM [80]. An ED receiver consists of a band pass filter (BPF), a squarer, an integrator, a switch for sampling and a sample and hold block. A block diagram of ED receiver is shown as figure 4.3 [63].

Figure 4.3: Block Diagram of ED UWB Receiver [63]

With OOK modulation scheme, a threshold is required to set for the “0” or “1” decision to be taken. It detects “0” when the sampling point at the receiver detects the energy less than threshold value of energy and it detects “1” when the sampling point at the receiver detects the energy is greater than the threshold value.

As discussed ED scheme can be used with pulse position modulation (PPM). With PPM, estimation of a threshold is not required but due to this PPM scheme data rate reduces as the pulses should be separated by a specific time to detect as “0” or “1”. Separation of time between “0” or “1” bit should be more than maximum access delay through the channel.

The UWB energy detector receiver needs only data bit synchronization, which makes it immune against phase nonlinearity of devices (antennas, amplifiers or filters), clock jitter and triggering inaccuracy [79], [81].

4.1.4 Differential Detector based Receiver

Unlike TR receiver, the differential detector does not depend on reference pulse separately. It uses the data pulses one after each other as a reference for the next coming pulse [82]. This scheme needs encoding of the transmitted bits differentially before modulation to save information in the difference of two adjacent pulses. With the differential detector scheme spectral efficiency increases in addition to double
data rate compared to the TR scheme. Similar care and remedy against sources of errors are required as for TR scheme. The disadvantage of the scheme is the accuracy between the data pulses delay is required. A small difference in delay can corrupt the data and affects the performance of the receiver significantly. The transmission from transmitter to the receiver requires a time invariant channel so that inaccuracy of data reception could be minimized.

4.2 UWB Receiver Issues

UWB receiver performance can suffer significantly if some issues are not addressed properly. These issues are being discussed in this section.

4.2.1 Sampling

Sampling of the received signal is one of the major issues to design a UWB receiver. An application like software defined radio (SDR) needs sampling unit as close to the receiver antenna as possible, with a sampling frequency of at least twice the Nyquist rate. As the UWB communication range is between 3.1 GHz to 10.6 GHz sampling at Nyquist rate or above needs a high sampling frequency which is not possible due to available technology constraints. Sampling at a high rate within the UWB band needs sophisticated technology which will increase the cost of the receiver and will make it unaffordable. Sampling with Nyquist rate is almost impossible with existing cost effective technologies. There is another issue associated with sampling at a high rate e.g. the higher rate will consume more power. The higher sampling rate will also require fast digital signal processing which can be managed with field programmable gate arrays (FPGA) or fast digital signal processors. Only fast digital signal processing can be done on the available resources but power consumption should be optimized with suitable algorithms but this is not a cheap solution.

Sampling further away from the UWB receiver antenna is advantageous as it relaxes the sampling requirement. Like the energy detector type UWB receiver uses a sampling unit after squarer and integrate-and-dump to sample the data at signal rate or symbol rate. In this thesis the issue of sampling is being addressed with lower sampling rate below Nyquist limit which could be cost effective and power efficient as well comparable to sampling rates selected for the data processing. The proposed technique is discussed in the following chapter.

4.2.2 Channel Estimation

In UWB, as long as the receiver is able to estimate the channel effects on the signal propagation it is more likely that the signal will recover accurately and the information sent from the transmitter can be recovered without error [63]. If the receiver can estimate the channel parameters such as multipath delays, multipath coefficients, and the received pulse with effects due to the channel then it can recover the data from the received information accurately. The channel estimation is a continuous process due to the nature of the channel which is random and time varying. Therefore any effect from the channel needs to be estimated by the receiver.
properly. Small errors in channel estimation can degrade the performance of UWB significantly. There are several issues which should be addressed properly related to channel estimation. First, very low received signal power leads to inaccurate estimation of data. Secondly, a large number of multipath components will require a large number of parameters to estimate which can lead to inaccuracy of data detection in coherent receivers. Finally, an increase in processing gain can increase the accuracy of the detection. Therefore multiple pulses can be used for data bit transmission. The issue associated with the use of multiple pulses for single data bit transmission is the resulting data rate reduction.

4.2.3 Synchronization

Synchronization can be roughly described as the process of providing the same time reference for the receiver as is used for the transmitter [63]. In other words, synchronization is a process of locking the received signal with the time of the transmitted signal to search the data bit as it was transmitted. The demodulation of data and its detection is not possible without correct timing synchronization.

In RAKE receivers, estimation of each finger positions is a part of the synchronization. A RAKE receiver needs to search and lock onto the correct path positions.

In the TR scheme and in energy detectors, multipath components are not required to be estimated individually. Instead the whole pulse energy is integrated and detected with the synchronization of starting and ending of the pulse. Non coherent receiver schemes are more flexible against synchronization errors compared to coherent receivers. The non-coherent receiver performance does not suffer due to small shifts in integration time whereas coherent receivers do suffer significantly.

In addition to time synchronization, clock synchronization is also important. If the clock is not synchronized with the data integration then it could cause error in detection. The operating clock of receiver and transmitter should be matched and synchronized with each other to reduce detection error and for error free communication between them.

4.2.4 Estimation of Multi Path Coefficients

The estimation of multipath coefficients is very hard from multipath components that have very low SNR [63]. Also the estimation of a large number of multipath coefficients is almost impossible or will induce more computational load and the receiver complexity will increase. Therefore instead of an ARAKE receiver, PRAKE and SRAKE are feasible receivers. Non coherent reception is preferred to avoid estimation of multipath coefficients which make these types of receivers, simple and power efficient.

4.2.5 Estimation of Pulse Shape

Estimation of the pulse shape is important for correlation receivers and RAKE receivers. It is very difficult to estimate all the pulses each time when it received.
Therefore some assumptions need to be taken to get acceptable results. It can be assumed that the distortion is the same all over the channel for each pulse with this assumption the pulse shape can be estimated over all multipath delays. Secondly, it can be assumed that the received pulse shape is similar to the transmitted pulse. These assumptions may induce errors which could degrade the performance of receivers but these are necessary to simplify the receiver design and the analysis will be easier [63]. However, these assumptions can be avoided in non-coherent receivers, as pulse shape estimation may not be needed to detect data bits from the received signal.

4.2.6 Interference

For UWB communication interference plays an important role in addition to AWGN. Multiple access interference (MAI), narrowband interference (NBI), inter symbol interference (ISI) and inter frame interference (IFI) are the example of interferences which could degrade the performance of UWB receivers. To avoid these problems, interference cancellation routines are required. These routines require some advance information about the signal like frequency, power, time and code of the interfering signal.

4.2.6.1 IFI

If the pulse-to-pulse duration is shorter than the maximum delay of the channel [63] then IFI can occur due to frame spaced with these pulses. If the frame information is available to the interference cancellation routine then IFI can be avoided by putting a frame guard time at the beginning and after each frame of course at the cost of data rate.

4.2.6.2 ISI

ISI can occur in high data rate systems where pulses during transmission or reception may interfere to the next or previous pulse. This problem can be solved by putting an equalizer at the receiver [63]. Alternatively an appropriate guard time can be given between the transmissions of pulses. The techniques used for narrowband systems to avoid ISI can also be used with UWB systems as well.

4.2.6.3 NBI

The effect of narrowband interference on the UWB signal can jam the UWB receiver completely [63] and it may not work properly. The UWB signals with its low transmitted power in addition to large bandwidth can coexist with narrowband transmission without interference if the standards of transmissions will be maintained under allowed limits set by the regulatory authorities. The narrowband signal interferes with UWB signal partially but the power associated with the narrowband signal can affect the UWB systems significantly. Therefore suppression of narrowband interference (NBI) techniques should be used by UWB systems. One method is to avoid the UWB transmission within the band where narrowband signals are strong. Another method is to use a bandpass filter and notch filter with peak clipping [83], [84] to suppress the NBI. Minimum mean square error (MMSE) [85]
combining techniques for rake receivers can also be used to suppress NBI. Further research is also needed to suppress NBI.

4.2.6.4 MAI

Multiple access interference is a challenging task in a dense environment with different users. It is even more difficult with orthogonal frequency division multiplexing (OFDM). For OFDM, it is ideal to have an orthogonal signal for each user but in practice the received signal from different users may not be orthogonal because of multipath and asynchronous transmission and due to these phenomena MAI takes place between the UWB communications. To avoid it time division multiple access techniques (TDMA) and code division multiple access (CDMA) techniques are proposed in [86] and [87] respectively. Some more research is needed to avoid MAI from UWB communication.
Chapter 5: Proposed UWB Receiver with OOK

5.1 Introduction

As discussed earlier the sampling with Nyquist rate is very hard to achieve with the existing integrated process technologies within the UWB radio spectrum. Therefore some methods are required to sample the data on lower rates which can be processed by the circuits that could be developed on the existing low cost technology. The UWB receiver being considered in this chapter uses a single band time division multiple access (SB-TDMA) technique to achieve the required low sampling rate to detect data transmitted from multiple users via single transmitter simultaneously. The word Single band is used for the presented technique with TDMA because it could divide the whole UWB band or part of the UWB band in time domain and uses that time divided band as a single band for communication.

There are three popular techniques being used by designers for multiple access. (1) Code division multiple access (CDMA) [88], [89] (2) frequency division multiple access (FDMA) [90], [91] and (3) time division multiple access (TDMA) [86]. For IR-UWB communication TDMA is more suitable than others for multiple access and to avoid MAI. In [92] TDMA is used for multi user application. An UWB system is proposed by the authors using differential TDMA with a novel delay sum scheme to avoid multiuser interference. In [93] the authors presented a review to cop up the interferences in multiple access environment using different methods such as TDMA, FDMA and CDMA etc. The authors of [93] are also showing TDMA for multiple access with no MAI, similarly in [86] TDMA is only used for multiple access communication without interference between users whereas proposed research is showing that TDMA can also be used to lower the sampling rate in addition to avoid MAI. Similarly sampling with lower rates is discussed in several research publications. To address the stated issue, sampling at symbol rate for UWB communication [94] and multiband modulated wideband conversion (MWC) [95] techniques are used to sample below Nyquist rate but these techniques are increasing complexity of the UWB receiver. To reduce sampling rate some other techniques are also used such as in [96] and [97]. In [96], multiple pulses are transmitted which increases the processing gain and reduces the sampling rate. Therefore to achieve the desired sampling rate the number of pulses per bit is being increased accordingly. In [97], PPM is used to modulate the data. Therefore two time slots (T_{int1} and T_{int2}) of “30 ns” each, are used in every frame for a “0” and a “1” to be detected respectively. The total frame time would be equal to “60 ns” which gives a sampling rate of 16.7 Mbps. All the stated low sampling techniques are reducing the transmission data rate to achieve the required sampling rate for detection and the TDMA technique is being
used to avoid MAI only. The proposed technique is using TDMA to lower the sampling rates in addition to avoid the MAI. According to the proposed methodology, users are placed at their defined locations in the TDMA frames to transmit and receive data. As the position of each user is fixed in the TDMA frame, the desired user can be accessed by calculating the respective time location in each frame and sample the data from their location as per user data rate. More details about the technique and the detection method are presented in following sections.

5.2 Single Band TDMA with Low Sampling Rate

The proposed non coherent UWB receiver block diagram is shown in figure 5.1. Like conventional energy detector (ED) UWB receiver mentioned in [98], [99], it consists of a low noise amplifier (LNA), squarer, integrator and sample & hold (S/H) blocks. The integrator timing is being derived by a clock of transmission frequency within the range of UWB. The only difference between stated ED UWB receiver and the proposed model is related to sample & hold (S/H) block which is divided into ‘m’ number of blocks to detect ‘m’ number of users in the proposed model. Each S/H block is driven by the clock of sampling frequency as per user data rate but to access the desired user location in TDMA frame a time delay “td” is needed. The configuration of a TDMA frame with user locations (an, bn, cn, ……mn) and their respective time delays (td1, td2, td3,……. td_m) to access the users are shown in figure 5.2.

![Figure 5.1: Proposed Non Coherent Receiver Block Diagram](image)

On-off keying (OOK) modulation scheme is utilized for the simulation of multiple user data. As stated above that this scheme is based on SB-TDMA therefore it can be described that the user data is distributed on a prescribed time sequence for each user with a fixed user location in each frame apart by a fixed time delay “td” during the transmission as shown in figure 5.2 (c). The “N” number of data bits from “m” number of users are fixed which also indicates the number of frames to communicate.
all “N” bits of data from each users i.e. no. of bit (N) = no. of frames (Nf). During the
detection “kth” user in the first frame can be accessed after calculating the time delay
T_{d,k} for each user. Time delay of “kth” user can be calculated as:

\[ T_{d,k} = k \cdot t_d \]  \hspace{1cm} (5.1)

Here “k=1,2,3,…,m” is the number of desired user in first frame. Each bit of desired
user “k” in “jth” frame can be accessed by calculating total time delay (T_{tot}) up to that
bit, which can be calculated as:

\[ T_{tot} = T_{d,k} + (j - 1) \cdot T_f \]  \hspace{1cm} (5.2)

Here “j=1,2,…,N” and “T_f” is frame repetition time. The sampling rate can be
adjusted by placing the data bits of each user at a distance of different number of
frames between them. Here \( T_f = T_s \) (\( T_s \) symbol time per user per frame) also
corresponds to sample rate of each user as each bit of user data is separated by one
frame between them.

The “N” number of data bits for each user “k” among “m” number of users, can be
denoted by a row vector \( U_k \), for example:

\[ U_k = [u_{k,1}, u_{k,2}, u_{k,3}, \ldots \ldots, u_{k,j-1}, u_{k,j}] \]  \hspace{1cm} (5.3)
Here “j=1,2,3……..N” for “N” numbers of data bits of “kth” user.

The transmission matrix “X” can be constructed by taking transpose of each user row vector $U_k$ and insert them as a column vector into the transmission matrix “X” sequentially, given as:

$$X=[U'_1, U'_2, U'_3, \ldots \ldots \ldots, U'_{k-1}, U'_k]$$  \hspace{1cm} (5.4)

Here “k=1,2,3……..m” for “m” numbers of user.

It can be observed that the transmission matrix “X” is a (N,m) matrix with “N” number of rows and “m” number of columns. Each row vector $X_j$ of transmission matrix “X” is a frame of data stream to be transmitted sequentially. The user data distributed in “N” number of frames for “m” number of users is showing in figure 5.2 (b).

### 5.2.1 Interference

To cope with inter user interference (IUI) and inter symbol interference (ISI) we used already developed techniques given as:

#### 5.2.1.1 Inter User Interference (IUI)

To avoid IUI, user guard time “$t_g$” could be set at the each corner of the pulse. We used “$t_g = 0.1 \text{ ns}$” as guard time at each corner of the pulse to avoid IUI.

#### 5.2.1.2 Inter Symbol Interference (ISI)

The proposed transmission scheme is ISI free inherently for the same user, as each data bit of a user is being placed once in a frame so the two data bits of the same user is at least one frame apart from each other therefore ISI for the same user is being avoided successfully.

![2nd Derivative of Gaussian Pulse](image)

Figure 5.3: 2nd Derivative of Gaussian Pulse
5.3 Methodology

The second derivative Gaussian pulse shown in figure 5.3, is being used to process data bits of each user for modeling the SB-TDMA UWB receiver in Matlab.

5.3.1 Two Users Methodology

The transmission bandwidth of 2.5 GHz is achieved by setting pulse width $t_p$ equal to 0.4 nsec. This transmission bandwidth can be divided between two users to set the sampling frequency of 1.25 GHz for detection of data. N-bits of data are divided into “N” numbers of frames for each user since each bit of user data is separated by a frame. For two users, frame repetition rate $T_f$ can be set to 0.8 nsec, to achieve sampling frequency of 1.25GHz, as shown in figure 5.4. Each user has fixed time delay “$t_d = 0.4\text{nsec}$”, to detect data at the receiver after integration of energy. Therefore “$t_d$” can be used to detect first data bit of the first user in first frame whereas first data bit of other user can be accessed by “$k * t_d$” after integration of energy. Here “k=2” is the index for second user among “m” number of users and the “m=2” as the case of two users is being discussed. Since each data bit of the same user is separated by a frame, it can be claimed that there would be no ISI between the same user data but of course IUI can be depending on the channel.

![Figure 5.4: Two Users Signal Pulse Methodology for Proposed UWB Receiver](image)

5.3.2 Multi User Methodology

The transmission bandwidth of 2.5 GHz is being achieved by setting pulse width $t_p$ equal to 0.4 nsec. This transmission bandwidth can be divided among “m” number of users to set the sampling frequency “$f_s = \frac{2.5\ GHz}{m}$” for detection of data. In each transmission frame “m” bits of data for “m” different users would be placed. To transmit each bit of information 2.5 GHz transmission frequency is required as the
user data in each frame is distributed within its pulse of 0.4 nsec duration and the next bit of the same user is placed after \( k \times t_d + (j - 1) \times T_f \) nsec in the next frame, as shown in equation (5.2). As discussed above, “N” number of frames are used to transmit N-bits data of each user. Here it should be noted that the pulse width of 0.4 nsec is being used to select the bandwidth of 2.5 GHz \([100]\) but the whole UWB bandwidth could be selected by setting the pulse width \( t_p \) accordingly. The number of users in each frame are fixed which depends on bandwidth and sampling rate. To detect each bit of user \( k \) in each frame, the fixed place of user \( k \) in any frame can be calculated by the equation (5.2) for different sampling rate by selecting suitable frame repetition rate \( T_f \). To minimize the risk of IUUI between users, a precaution is taken and a guard time “\( t_g = 0.1 \) nsec” is used with each corner of the pulse.

We constructed the proposed receiver as shown in figure 5.5 by using Matlab Simulink modules.

![Figure 5.5: Proposed UWB Receiver Block Diagram in Matlab Simulink for 5 Users only](image)

### 5.3.3 Threshold Estimation for BER

Threshold estimation for the energy detector receiver plays a key role in estimating BER, which is a parameter to evaluate the performance of an UWB receiver. Researchers are using average of energies corresponding to transmitted bit energy for “0” or “1”. They estimate threshold of energy by transmitting a stream of “0s” and “1s” and calculate the average energy of “0s” and the average energy of “1s” and their variances to estimate the threshold of energy to detect received data bits \([101]\). The methods of estimating threshold energy with average or mean of bit energies can be improved. A different method is being used to estimate the threshold of energy. A stream of “0s” followed by a stream of “1s” and then another stream with alternate...
“0s” and “1s” are transmitted, as a single stream. An AWGN channel is assumed and maximum energy level of “0s” is calculated whenever it occurs in the whole stream of data at the receiver side and stored the value of peak energy for “0s” as \( E_{\text{max}(0)} \). Similarly we calculate the lowest energy level of “1s” whenever it occurs and stored the lowest energy peak for “1s” as \( E_{\text{low}(1)} \). To estimate the threshold of energy \( E_{\text{th}} \), the mean of both values is taken with the equation (5.5), given as:

\[
E_{\text{th}} = \frac{E_{\text{max}(0)} + E_{\text{low}(1)}}{2}
\]  

(5.5)

The simulated results of BER with this method for threshold energy estimation and the technique stated in [101] are compared in following sections.

**5.4 Modeling of Proposed UWB Receiver for Simulation**

A proposed UWB receiver shown in figure (5.1), is simulated using Matlab Simulink and shown in figure 5.5. The blocks used in figure 5.1 are being discussed in the following sub sections.

**5.4.1 The Low Noise Amplifier (LNA)**

A low noise amplifier is a boosting circuit, used as a first component of the radio receiver following the receiver antenna. The LNA provides some gain to the input signal to overcome the effects of noise due to the next stages of the receiver. As almost all the electronics circuits inject some noise, the LNA should be designed such that it boost the signal power to the desired level without inducing too much noise into the signal [102] or create overload problems.

The LNA is not drawn in the figure 5.5, since we assume that the received signal is strong enough to be used by the subsequent blocks to process and detect successfully.

**5.4.2 The Squarer “(.\(^2\))”**

The squarer is an analog block which gives squared value of input at the output. After the LNA, a squarer “(.\(^2\))” block is used in figure 5.1 which is modeled by a multiplier module called “product”. Squaring of the input signal is being achieved by putting same signal at both inputs of the “product” module. An analog squarer or multiplier circuit is not an easy job to design for UWB applications. Researchers have designed many different types of analog multipliers. A squarer could be constructed using an analog multiplier circuit modified for UWB applications by using same input voltage at both inputs of the multiplier. An analog multiplier mentioned in [96] could be used for squaring the input signal.

**5.4.3 The Integrator**

An Integrator circuit is one of the basic building blocks for energy detector UWB receivers to integrate the energy of the received pulse. Normally the squared signal is provided to the integration stage directly. The function of this stage is to estimate the magnitude of integrated energy provided by the squarer and feed it to the next stage of the UWB receiver chain. For this application “Integrate and Dump” type integration
stage is needed, as shown in figure 5.6 [103]. When the clock phase “\( \varphi_I \)” is high and “\( \varphi_R \)” is low, the capacitor “\( C_H \)” starts integration of the energy provided by the squarer current “\( I_{sq} \)”, and dumps the energy when the clock phase “\( \varphi_R \)” is high and “\( \varphi_I \)” is low. The capacitor output voltage \( V_C \) can be calculated by equation (5.6), given as:

\[
V_C(t) = \frac{1}{C} \int_0^T I_C(t) dt + V_C(0)
\]  

(5.6)

Here \( V_C(t) \) is the time varying signal for integration, \( I_C(t) \) charging current for capacitor “\( C_H \)” and “\( T \)” is time for integration respectively.

Figure 5.6: Integration Stage with Integrate and Dump Configuration

5.4.4 The Sample and Hold (S/H)

The analog to digital converter (ADC) uses a S/H block in energy detectors UWB receivers to convert the analog signal into digital data bits. The S/H have to perform signal conversion accurately. The sample and hold times are critical for the conversion. It depends on two parameters, (i) The settling time \( t_s \) and (ii) the acquisition time \( t_a \). The settling time is the time when the output of S/H circuit settles to an allowable error limit with respect to the required output whereas the acquisition time is the time where S/H circuit respond to the input voltage to change its state and removes offset effects. A waveform of a practical S/H circuit is shown in figure 5.7 [104]. The S/H block limits the sampling rate for an ADC and the maximum sample rate can be calculated as:

\[
f_s = \frac{1}{T_s}
\]  

(5.7)

Here “\( f_s \)” is the sampling frequency and “\( T_s \)” can be calculated as:

\[
T_s = \text{ Sampling time } + \text{ Hold time}
\]  

(5.8)

In figure 5.7, the settling time \( t_s \) and acquisition time \( t_a \) are shown. Higher sampling rates can be achieved if the “\( t_s \)” or the “\( t_a \)” would be as low as possible. A switch and a storage element are required to construct a S/H circuit. These are the minimum requirements to implement a S/H circuit. The capacitor is a component that stores the value which means it could be used to hold the sampled value until it would be reset. A switch can be constructed with MOSFET. Therefore sample-and-hold (S/H)
function can be performed by using a simple capacitor in series with a clock synchronized switch, to sample the value from the integrator [105].

Figure 5.7: Sample and Hold Waveform

5.5 Simulation Results

5.5.1 Simulation for 50MHz Sampling Frequency

The transmission bandwidth $B = 2.5 \, GHz$ is divided among 50 users to achieve desired sampling rate of $50 \, Mbps$. Therefore user sampling frequency $f_s$ is $50 \, MHz$ lower than $B/2$ and the frame repetition time $\tau_f$ is set to $20 \, nsec$. Here it is assumed that one pulse is enough to detect one bit at the receiver side. The randomly generated 8-bits of data for each user are transmitted in eight transmission frames using AWGN channel. Simulation is done in Matlab and the received data bits are detected successfully using Simulink model. The successfully received data bits of five users out of fifty users are shown in figure 5.8. The Waveforms of squarer, integrator clock pulse, integrator output, clock pulse waveform of S/H and S/H output are extracted from Matlab Simulink model, are shown in figure 5.9. The type of integrator is “integrate and dump”. The pulse energy is integrated by the integrator and dumped when RESET is initiated automatically after 0.4 nsec duration. The S/H block of respective user initiates sampling signal at user sampling rate before dumping of integrated energy. S/H block samples the magnitude of energy and hold the value until the clock of S/H goes down to RESET it again, as shown in figure 8 (4th window is S/H clock, 5th window is S/H output). Figure 5.10 is showing a comparison of BER among theoretical (BER Cal.), simulated values of BER with mean estimation for energy threshold [101] (BER Mean Th.) and simulated values of BER with proposed estimation for energy threshold (BER Pro Th.). The comparison shows BER with proposed threshold (BER Pro Th.) is lower than BER with threshold method in [101]. BER with both methods are also following the theoretical BER (BER Cal.) plot.
Figure 5.8: 8-Bits Data of 5 Users out of 50 Users with 50Mbps Sample Rate ($f_s = 50$ MHz)

Figure 5.9: Partial View of Squarer Output, Integrator Clock, Integrator Output, S/H Clock and S/H Output for 50MHz Sampling Frequency
5.5.2 Simulation for 100MHz Sampling Frequency

The transmission bandwidth $B = 2.5 \text{ GHz}$ is divided among 25 users to achieve desired sampling rate of 100 Mbps. Therefore user sampling frequency $f_s$ is 100 MHz lower than $B/2$ and the frame repetition time $T_f$ is set to 10 nsec. Here it is assumed that one pulse is enough to detect one bit at the receiver side. The randomly generated 8-bits of data for each user are transmitted in eight transmission frames using AWGN channel. Simulation is done in Matlab and the received data bits are detected successfully using Simulink model. The successfully received data bits of 5 users out of 25 users are shown in figure 5.11. The Waveforms of squarer, integrator clock pulse, integrator output, clock pulse waveform of S/H and S/H output are extracted from Matlab Simulink model, are shown in figure 5.12. Working principle of integrator and S/H is similar as defined in section 5.5.1. Figure 5.13 is showing a comparison of BER among theoretical (BER Calculated.), simulated values of BER with mean estimation for energy threshold [101] (BER Mean Th.) and simulated values of BER with proposed estimation for energy threshold (BER Pro Th.). The comparison shows BER with proposed threshold (BER Pro Th.) is lower than BER with threshold method in [101]. BER with both methods are also following the theoretical BER (BER Calculated) plot.
Figure 5.11: 8-Bits Data of 5 Users out of 25 Users with 100Mbps Sample Rate ($f_s = \text{MHz}$)

Figure 5.12: Partial View of Squarer Output, Integrator Clock, Integrator Output, S/H Clock and S/H Output for 100 MHz Sampling Frequency
5.5.3 Simulation for 500MHz Sampling Frequency

The transmission bandwidth $B = 2.5 \text{ GHz}$ is divided among 5 users to achieve desired sampling rate of $500 \text{ Mbps}$. Therefore user sampling frequency $f_s$ is $500 \text{ MHz}$ lower than $B/2$ and the frame repetition time $T_f$ is set to $2 \text{ nsec}$. Here it is assumed that one pulse is enough to detect one bit at the receiver side. The randomly generated 8-bits of data for each user are transmitted in eight transmission frames using AWGN channel. Simulation is done in Matlab and the received data bits are detected successfully using Simulink model. The successfully received data bits of 5 users are shown in figure 5.14. The Waveforms of squarer, integrator clock pulse, integrator output, clock pulse waveform of S/H and S/H output are extracted from Matlab Simulink model, are shown in figure 5.15. Working principle of integrator and S/H is similar as defined in section 5.5.1. Figure 5.16 is showing a comparison of BER among theoretical (BER Cal.), simulated values of BER with mean estimation for energy threshold [101] (BER Mean Th.) and simulated values of BER with proposed estimation for energy threshold (BER Pro Th.). The comparison shows BER with proposed threshold (BER Pro Th.) is lower than BER with threshold method in [101]. BER with both methods are also following the theoretical BER (BER Cal.) plot.
Figure 5.14: 8-Bits Data of 5 Users with 500Mbps Sample Rate ($f_s = 500$ MHz)

Figure 5.15: Complete View of Squarer Output, Integrator Clock, Integrator Output, S/H Clock and S/H Output for 500 MHz Sampling Frequency
The simulated results were also compared on different sampling frequencies to observe the impact of different sampling frequencies on the BERs. For the purpose BER of “User1” are compared on 500 MHz, 100 MHz and 50 MHz user sampling frequencies as shown in figure 5.17. It can be observed that the BER graphs of “User 1” have small variations on each user sampling frequency. The variations observed in the plot could be due to random data simulated by Matlab. Therefore it can be stated that the performance of the proposed UWB receiver is independent to sampling frequency. Usually performance degraded when the sampling rates increases and vice versa as stated in [106]. This could be due to fact that to achieve the different sampling rates with proposed method do not need to change transmission bandwidth whereas to achieve different sampling rates with other methods transmission bandwidth may also be changed.
5.5.4 Integrator Loading

It can be observed by the figures 5.9, 5.12 and 5.15 that the integrator is loaded quite heavily with the proposed configuration and it has to work for 95% in each cycle with the frequency of 2.5GHz. It means the integrator will have to dump its stored charge during 5% of clock off time. Usually the MOS switches has their own ON resistance which describes the charging or discharging time of the integrator. If the integrator will not discharge its energy completely then a residual energy will be added to the next coming bit. If the transmitted bits would be series of 1’s and then suddenly a “0” will transmit then there is a risk of bit error because of residual energy stored on the integrator capacitor which may lead that “0” could be detected as “1” as shown in figure 5.18. To resolve the issue two integrators are used with the proposed UWB receiver. The simulink model with two integrators is shown in figure 5.19 and the outputs of the integrators are shown in figure 5.20 with the integrators clocks. In figure 5.21 detected data bits using two integrators are shown.
Figure 5.18: Single Integrator and Double Integrator Outputs

Figure 5.19: Simulink block diagram of proposed UWB receiver with two integrators
5.5.5 Clock Jitter

In electronics circuit there are always some imperfections which degrade performance of the circuit due to thermal noise. Clock circuits often shows uncertainties due to thermal noise which translate to jitter in the clock. Since the proposed UWB receiver...
uses clock circuit for integrator to integrate energy and reset to dump its energy therefore clock stability is important. Here we have distributed the integration into two parallel integrators which include one more clock circuit to trigger the new integrator. We are assuming that the clock jitter are not present in any other clock circuit only in added integrator clock. Therefore integrator performance will suffer by the clock jitter and will also disturb the sampling process. We assumed that integrator 1 has no clock jitter therefore the sampling process will be smoothly done by the sample and hold circuit from the output of integrator 1 whereas the output of integrator 2 will be disturbed by the jitter. It is assumed that the jitter is random and occurs in each cycle of the integrator 2 clock. “Δt” is the difference in clock time which produces due to jitter. This “Δt” in clock of integrator 2 will disturb the reset of the integrator 2. Due to jitter the “Δt” is the amount of time which will be added or subtracted randomly from the clock of integrator 2 and it will either reset the integrator 2 quicker by an amount equal to “Δt” or reset of the integrator 2 will be delayed by an amount equal to “Δt”, hence either sample time will come within the integrated window or outside the integrated window which will induce error in detection. These phenomena are modeled in Matlab and result is shown in figure 5.22. Here red lines are showing the samples are disturbed due to jitter in integration clock 2. If jitter reset the integrator with an amount “Δt” (T_{Rj} = T_R + Δt, here T_R is reset time cycle of integrator 2 without jitter and T_{Rj} is reset time cycle with jitter ) time before i.e. Δt < 0, then the sample will be taken from outside the integration window which will give a wrong value to the sample and hold but if the integrator 2 will reset after an amount of “Δt” i.e. Δt > 0 time compared to the actual reset time then the sample and hold will take sample value within the integration window hence it may take correct sample value if a “1” would be transmitted. For a “0” the sample and hold will always take a correct value as we are using OOK for modulation. For other modulation like PPM it could take wrong values for both states. The proposed UWB receiver performance is evaluated using this Matlab model with a clock jitter in integrator 2 while taking integrator 1 as a reference clock. The results of proposed UWB receiver in terms of BER is shown in figure 5.23. The jitter in clock of integrator 2 increases 1 % bit error rate compared to integrator 2 with no jitter between SNR values from 0 db to 1 db and degrades the SNR value to 0.6 db for the same BER value with no jitter in clock of integrator 2. 1% increase in BER means 100 more bits will be detected wrongly if 10,000 bits will be transmitted. The jitter of 40 psec duration was assumed which is 10% of the pulse width or 5% of integrator clock cycle.
5.5.6 Synchronization

Two types of timing synchronizations are needed for IR-UWB receivers [100]: (1) Frame level synchronization (2) Symbol level synchronization.
In this thesis it is assumed that the frame level timing synchronization has been achieved by estimating the channel conditions and random delay estimation. Therefore symbol level synchronization is assumed to be perfect. For energy detector UWB receivers different timing windows are used to integrate energy of each symbol and maximum energy window is searched for each received symbol to achieve perfect synchronization. All the results stated in previous sections are considered with perfect synchronization. Here different windows are being used to integrate energy by using some time offset “t₀” and the impact of mismatching in timing over estimation of the symbol energy is observed. To analyze the performance of the proposed UWB receiver, BERs with different timing offset are estimated. The BERs results with timing offsets of 0.06 ns (15 %), 0.12 ns (30 %) and 0.16 ns (40 %) are compared with perfect synchronization and shown in figure 5.25. It can be observed that the timing offset of 0.16 ns (40 %) degrades the UWB receiver performance significantly and the timing offset impact is being reduced as the perfect synchronization is achieved by reducing the timing offset gradually. In figure 5.26, BERs are plotted on different SNR with respect to percentage of deviation. It can be seen by the figure 5.26 that the BERs are relatively smaller when the deviation is lower and it increases when the deviation increases on all SNR values. According to the figure, bit errors are increasing with higher rate when the deviation increases beyond 30% of the pulse duration. Figure 5.24 shows the methodology of symbol level synchronization. It shows that the black window and red window have the same time duration equal to pulse width $t_p = 0.4$ nsec but the red window corresponds to integration of energy with timing offset whereas black window correspond to perfect synchronization. The blue line on the S/H output image shows the level of energy threshold to decide a “1” or a “0” received. The red windows and their corresponding energy levels shows that there are more chances to have a wrong decision about a “1” or a “0” received, with the timing offset compared to perfect synchronization case.

Figure 5.24: Deviation of Clock with Synchronization Error for IW
5.5.7 Channel Modeling

To achieve good quality of wireless communication it is imperative to estimate the impact of the wireless channel during the transmission. To estimate performance of the proposed UWB receiver, a wireless channel model is used as described in [15] by Saleh and Valenzuela.

\[ h(t) = X_i \sum_{l=1}^{\infty} \sum_{k=1}^{\infty} \beta_{kl} \delta(t - T^i_l - \tau^i_{kl}) \]  

(5.9)
Here “h(t)” is time dependent channel response, “β_кл” are the multipath gain coefficient, “T_кл” is the delay of the “кл”th cluster, “τ_кл” is the delay of the “кл”th multipath component of respective “кл”th cluster and “X_i” is log normal shadowing where “i” represents the “i”th realization. According to [15], “T_кл” and “τ_кл” can be defined by the exponential probability density function of clusters and ray arrival rate, given as:

\[ P(T_l | T_{l-1}) = \wedge \exp[-\wedge(T_l - T_{l-1})], \quad l > 0 \]  \hspace{1cm} (5.10)  

\[ P(\tau_{kl} | \tau_{(k-1)l}) = \lambda \exp[-\lambda(\tau_{kl} - \tau_{(k-1)l})], \quad k > 0 \] \hspace{1cm} (5.11)

Here “\wedge” and “\lambda” are denoted to cluster arrival rate and ray arrival rate respectively.

Since “β_кл” are gain of multipath which decreases monotonically and can be estimated as:

\[ \beta_{kl} = \beta_0 \exp\left(-\frac{T_l}{\Gamma}\right) \exp\left(-\frac{\tau_{kl}}{\gamma}\right) \] \hspace{1cm} (5.12)

Here “\beta_0” is the average path gain, “Γ” and “γ” are decay constant for cluster and ray respectively.

To apply the stated model each frame is a cluster and each pulse of user symbol as ray are considered, since the stated model deals with rays and clusters. I used cluster arrival rate “\wedge” of 2 ns for 500MHz frame repetition frequency and use 2.5 GHz (0.4 ns) ray repetition rate “\lambda” with the power decay time constant for cluster “Γ” and ray “γ” is 0.8 ns. The assumption is that a pulse or ray of each symbol will only interfere with two adjacent user symbols or pulses partially. The standard deviations of fading coefficients for cluster “σ_1” and ray “σ_2” are 2.2 db and 3.4 db respectively. The channel impulse response with the stated parameters is shown in figure 5.27. Five reflection paths are used on each channel to model wireless channel.

A channel model whose impulse response is shown in figure 5.27, was applied on the single UWB pulse and the effect was observed as shown in figure 5.28. After that same channel model was applied on the bit stream of 5 users using 2.5GHz transmission frequency and sampled at 500MHz to collect data of each user at the receiver side. The proposed UWB receiver performance is estimated in term of BERs and the results of each user were compared to over all BER without channel modeling. The comparison of BERs is shown in figure 5.29. As shown in figure 5.29, the BERs of each user are increased after applying channel modeling as compare to overall BERs without channel modeling. The reason of increase in BERs is IUI as the two previous pulses interfere partially with the current user symbol according to the assumption in wireless channel model.
Figure 5.27: Channel Impulse Response

Figure 5.28: UWB pulse with and without channel modeling effect
5.5.7.1 Multi Channel Model with Multipath

Until now, the transmission was assumed from a transmitter which collected information from multiple users and transmit it via a single channel to the receiver as shown in figure 5.2 (a). All users transmit data to a local transmitter and then that local transmitter transmit data in the proposed frames format which could be received by the proposed UWB receiver and demodulated accordingly.

Assuming that multiple transmitters are transmitting information via single channel for each transmitter with multiple paths on each channel, the situation is shown in figure 5.30.

Here two assumptions are being made to evaluate the performance of the proposed UWB receiver. (1) Transmission from multiple transmitters via single channels for each transmitter with multipath on each channel using equal path gains and, (2) Transmission from multiple transmitters via single channel for each transmitter with multipath on each channel using different path gains. The Matlab simulations were done for the two stated cases and performance of UWB receiver under each case were evaluated in term of BERs as shown in figures 5.33 and figure 5.35 respectively. In figure 5.31, BER comparison shows that bit errors are similar on each channel for each user using equal gain for each path. In figure 5.32, comparison of BERs is shown with different number of multipath on each channel. It shows that there are two different slopes. First between no multipath to two multipath and the other is between two multipath to five multipath. It means that the bit error increases with higher rate between no multipath to two multipath compared to second slope region between two multipath to five multipath.
Figure 5.30: Multiple transmitter with direct and indirect path

Figure 5.31: BERs comparison for equal path gains with and without channel effect
In figure 5.33 BER comparison shows that there are different bit errors on each channel with different path gain (DPG). Different path gains are assumed. PG (user 1)=1, PG (user 2)=0.9, PG(user 3) = 0.8 and PG (user 4)= 0.7. The BERs plots are compared with BER using equal gain i.e. BER EG. The bit errors are highest in the channel with lower gain and bit errors are lower in the channel with higher gain as shown in figure 5.33. The bit errors are estimated with same threshold on each channel. To evaluate the impact of different threshold for different channels code is developed with threshold adjustment on each channel. The result with threshold
adjustment is shown in figure 5.34. BERs plot after threshold adjustment are following the same pattern for each user and there is no pattern for higher bit error or lower bit error related to path gains. The comparison shows that the plots are comparable to BER with equal gains.

![BER Comparison after Channel Modeling with DPG with Threshold Adjustment](image)

Figure 5.34: BERs comparison for different path gains with threshold adjustment

The configuration of multiple transmitters is shown in figure 5.30. The main problem with this configuration is synchronization of the data at the receiver end if the UWB receiver would be similar as proposed in figure 5.1. Since the transmitted data from different transmitters on different time slots could be random in nature therefore collision could be possible at the receiver end and different delays of each transmitter will increase error. Therefore proposed configuration in figure 5.1 could not be used. For the system with multiple transmitters, UWB receiver should be modified as shown in figure 5.35. To avoid collision, it could be assumed that the receiver will receive data one by one from each transmitter. For this purpose a triggering pulse could be given to the transmitters when the receiver will be ready to take data from the corresponding transmitter or collision detection and avoid (CDAA) mechanism should be defined. For the new configuration it is very important to estimate the time delay “Δtm” of each transmitter data which should be included with the integrator and S/H clocks for the detection of correct data bits as shown in figure 5.35.
5.5.8 Comparison of UWB Receivers

A system model of IR-UWB receiver given as equation (3.4) is implemented. The system model used in [96] is given as:

\[ S(t) = \sum_{j=-\infty}^{\infty} \sum_{i=0}^{N_s-1} d_j P_{tx}(t - iT_p - jT_s) \]  

(5.13)

Here “P_{tx}” is the transmitted pulse, “T_p” is the pulse repetition interval, “d_j” is the j^{th} information bit, “N_s” is the number of pulses per bit to achieve processing gain and “T_s = N_s * T_p.” The stated UWB receiver performance is compared with the proposed UWB receiver. The simulation results are shown in figure 5.36. The BERs plot shows that the receiver performance in [96] is better in terms of BER mainly due to processing gain. A performance comparison is summarized in table 5.1. From the table we see that with respect to other parameters, the proposed receiver is better.
In figure 5.37 squarer output with 3 pulses per bit are shown to take the advantage of processing gain compared to single pulse per bit like in proposed UWB receiver where only one pulse per bit is being used. Processing gain of proposed UWB receiver can also be achieved of course with the disadvantage of reducing the transmission data rate. The integrator output is also shown in figure 5.37. The square gives the instantaneous energy of a signal at the output in red color as shown in figure 5.37. The integrator gives the total energy of a signal in blue color, as shown in figure 5.37.

Table 5.1: Comparison of proposed UWB receiver with another UWB receiver model

<table>
<thead>
<tr>
<th>Proposed UWB Receiver</th>
<th>Remarks</th>
<th>UWB Receiver in [96]</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>Bandwidth</td>
<td>2.5 GHz</td>
<td>2.5GHz</td>
<td></td>
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<tr>
<td>Sampling Frequency</td>
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<td>Flexible independent of transmission frequency</td>
<td>833.3 MHz</td>
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<td>Processing Gain</td>
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<td>3</td>
<td></td>
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<tr>
<td>Transmission Data Rate</td>
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<td>833.3Mbps</td>
<td></td>
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<tr>
<td>Transmitted Bits</td>
<td>40</td>
<td>Can send longer stream</td>
<td>40</td>
</tr>
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<td>Total UWB Pulses</td>
<td>40</td>
<td>Single pulse communication for a user</td>
<td>120</td>
</tr>
<tr>
<td>Data Detection Time</td>
<td>16ns</td>
<td>48ns</td>
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<tr>
<td>Frame repetition time</td>
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<td>9.6ns</td>
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<tr>
<td>No. of Users</td>
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<td>5</td>
<td></td>
</tr>
<tr>
<td>No. of bits per frame</td>
<td>5</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>No. of users per frame</td>
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<td>1</td>
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<tr>
<td>No. of bit per user</td>
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<td>8</td>
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<td>Modulation</td>
<td>OOK</td>
<td>OOK</td>
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</table>
5.6 UWB Receiver with Matched Filter

5.6.1 Matched Filter

The Matched filter is a method to detect a known signal embedded in the noise content of the received signal. Matched filtering increases the signal to noise ratio for a given shape of signal pulse [107]. It is not a specific name of a specific filter because different types of pulse shapes have their own optimum filters matched to those pulse shapes. The filter which matches to the signal pulse shape and optimize the output of the signal with respect to noise is known as matched filter. It is given as the time shifted, time reversed transmitted pulse i.e. \( h(t) = x_p(t_0- t) \), here \( t_0 = t_0 + \tau \). “\( t_0 \)” is the time shift needed to make \( h(t) \) causal.

Now, \( h(t) = x(t_0+ \tau - t) \)

In figure 5.38 (a), it is shown that the pulse \( x(t) \) is a rectangular pulse which starts at “\( t_0 \)” having duration “\( \tau \)” then the end of pulse will be at “\( t_0 + \tau \)”.

Similarly in figure 5.38 (b), it is shown that the filter response is “\( h(t) \)” has coefficients of a rectangular pulse spread over a width of duration “\( \tau \)”.

Now we can estimate the response “\( y(t) \)” of this filter given as:

\[
y(t) = \int_{-\infty}^{\infty} x(t) \cdot h(t - \tau) \cdot dt
\]  

(5.14)

The output response “\( y(t) \)” is plotted as shown in figure 5.38 (c). It can be seen that the peak output of the filter is achieved at “\( t_0 + \tau \)”.
The output signal power \( P_s \) of the output signal \( y(t_0 + \tau) = A \) is proportional to the square of the output, then the output power we would get:

\[
P_s = A^2
\]

Similarly if \( n_i(t) \) is the noise inducing into the signal then the output noise due to response of the filter \( n(t) \) will be given as:

\[
n(t) = \int_{-\infty}^{+\infty} n_i(t) \cdot h(t - \tau) \cdot dt
\]

Here \( n_i \) is the input noise signal.

We know that the noise spectral density of white Gaussian noise is given as:

\[
N(\omega) = \frac{N_0}{2} \frac{\text{watt}}{\text{Hz}}
\]

Noise power \( P_N \) for the bandwidth can be estimated as:

\[
PN = \frac{N_0}{2} \int \left| h(f) \right|^2 df = \frac{N_0}{2} \int \left| h^2(t) \right| dt = \frac{N_0}{2} \frac{1}{\tau^2} \cdot \tau = \frac{N_0}{2}
\]

Here \( B = 1/\tau \) can be considered as the bandwidth of the signal.

The signal to noise ratio (SNR) after matched filter can be estimated as:

\[
\text{SNR} = \frac{\text{Signal Power (} P_s \text{)}}{\text{Noise Power (} P_N \text{)}} = \frac{2A^2}{N_0B}
\]
5.6.2 UWB Receiver Implementation using Matched Filter with OOK

The proposed UWB receiver with low sampling rate is also implemented with matched filter instead of integrated window, as shown in figure 5.39.

The modeling for simulation results was the same as stated for the integrated window based ED UWB receiver. Simulations are done in Matlab and the results are analyzed for sampling frequencies 50 MHz, 100 MHz and 500 MHz. 8-bits of data were sent for each user and detected successfully. The 2nd derivative of Gaussian pulses was selected with 0.1 volt amplitude and the coefficients of similar pulses were used for the matched filter. The pulse for the matched filter is shown in figure 5.40.

The pulse template with filter coefficients for matched filtering and noisy pulse are shown as figure 5.41.
Figure 5.41: MF Template and Noisy Second Derivative of Gaussian Pulse

Matched filter output for single pulse with noise is shown in figure 5.42.

Figure 5.42: Matched Filter Output for Single Pulse

The UWB receiver performance is evaluated by the bit error rate (BER). In figure 5.43, the BER of Integrated window (IW) energy detectors are compared with the matched filter UWB receiver. Here “BER cal” is for theoretical bit error rate, “BER Mean IW” are for the energy detector UWB receiver using IW, are recorded with an estimated energy threshold with the technique in [101], “BER Pro IW” are for BERs of energy detector UWB receiver using IW recorded with threshold of energy estimated by proposed technique. Similarly “BER Pro MF” are for BERs of matched filter UWB receiver with a threshold by proposed technique and “BER Mean MF” are for BERs of matched filter UWB receiver with a threshold by the technique as stated
in [101]. The OOK modulation scheme is used for the simulation results. It can be observed by figure 5.43 that the BERs of the matched filter receiver is better than IW energy detectors. It can also be stated that proposed technique of energy threshold calculation is better than the technique of threshold calculation mentioned in [101]. The AWGN channel was assumed to observe simulation results.

BERs of MF UWB receiver are also compared with different sampling frequencies and plotted in figure 5.44. It can be observed that the BERs for MF UWB receiver are independent of sampling frequencies and the variations in BERs could be due to random data generation. There is no defined pattern of BERs on any sampling frequency that the BERs are increasing or decreasing. The results with MF UWB receiver are also verifying the comparison of BERs on different sampling frequencies using IW energy detector UWB receiver that the BERs are independent to sampling frequencies.

![Figure 5.43: Comparison of BERs between UWB Receiver with MF and IW](image-url)
5.6.3 Synchronization

The symbol level synchronization is considered for matched filter receiver. For matched filter UWB receiver different sampling points are used to sample magnitude of each symbol. The maximum magnitude of voltage is the center point of the output pulse after matched filter therefore in perfect synchronization condition the sample point will be at the center of each received symbol. All the results stated in previous section (5.6) are considered with perfect synchronization. Here the impact of mismatching in timing over estimation of the symbol voltage magnitude is observed. To analyze the performance of the proposed UWB receiver with matched filter, BERs with different timing offset are estimated. The BER results with timing offsets “$t_0$” of 2.5 % (0.01 ns), 5% (0.02 ns), 7.5 % (0.03 ns), and 10 % (0.04 ns) are compared with perfect synchronization and shown in figure 5.46. It can be observed that the timing offset of 10 % (0.04 ns) and 7.5 % (0.03 ns) degrades the UWB receiver performance with more than 40 % BER and 20 % BER respectively with -3 db SNR. The timing offset impact is being reduced as the perfect synchronization is achieved by reducing the timing offset gradually. Figure 5.45 shows the methodology of symbol level synchronization. It shows that the blue line and red line are at the center of user 1 symbol and user 2 symbol where sampling is performed as perfect synchronization. The blue and red lines from the corresponding centered values are showing the time mismatch with an offset “$t_0$”. The blue and red lines are showing their corresponding magnitudes which are less than perfect synchronization. Therefore it can be concluded that there are more risks to have a wrong decision about a “1” or a “0” received, with the timing offset compared to the perfect synchronization case.
Figure 5.45: Deviation of Clock with Synchronization Error for MF

Figure 5.46: Comparison of BER with timing offsets using 500 MHz sampling frequency for MF
The results to evaluate performance due to timing mismatch in matched filter UWB receiver are shown in figure 5.46 and figure 5.47. In figure 5.46 the BERs are plotted with respect to different SNR values which show that BER are higher with -3db SNR and it decreases when the SNR is increased. In figure 5.47, the BER are plotted with respect to percentage of deviation to see the impact of mismatch on different SNR values. It can be seen that the BER are increasing when the deviation is increased from the perfect synchronization i.e. zero percent deviation whereas the BER is higher than 40% with 10% of deviation on -3db SNR value. Here it should be noted by comparing the figure 5.43 with the figure 5.46 that the UWB receiver with matched filter is more vulnerable against timing mismatch compared to UWB receiver with integrated window because the deviation of 40% (0.16 ns) in integrated window reaches to the BER of less than 40 % at -3db SNR whereas the small deviation of only 10% (0.04 ns) can generate BER of greater than 40 % on -3db SNR using matched filter configuration for the proposed UWB receiver. Therefore it can be stated that the UWB receiver with integrated window is more robust against the timing mismatch whereas the UWB receiver with matched filter is more robust in the higher noise condition compared to integrated window configuration of proposed UWB receiver as shown in figure 5.43.

5.7 Conclusions

The proposed SB-TDMA scheme for low sampling rate is simulated with Matlab for 50 MHz, 100 MHz and 500 MHz sampling frequencies. The energy detector UWB receiver using integrated window and UWB receiver using matched filter were developed and simulated. The 8-bits of data for 50 users, 25 users and 5 users were transmitted with 2.5 GHz transmission bandwidth. The 8-bits of data for first 5 users
out of 50 users using both UWB receivers were detected successfully with the sampling frequency of 50MHz, then the 8-bits of data for first 5 users out of 25 users using both UWB receivers were detected successfully with the sampling frequency of 100 MHz, similarly the 8-bits of data for 5 users using both UWB receivers were also detected successfully with a sampling frequency of 500 MHz. These sampling frequencies are very low compared to the transmission bandwidth. It can be seen that the proposed UWB receiver methodology is working properly. There is an issue when “m” number of S/H blocks are used to detect the data from different users i.e. the design considerations are relaxed for S/H block. The design limitations are shifted to integrator and the integrator loading could be increased which could lead to performance degradation of the proposed UWB receiver. Therefore two integrators are used to distribute the loading of an integrator which could solve the problem associated with single integrator. During research work it is assumed that there is no performance degradation due to clock jitters in any block but after including one more integrator it is assumed that it has jitter problem which means integrator reset has some problem i.e. integrator 2 is reset either before the sampling signal or after the sampling signal. The result shows that the performance of proposed UWB receiver is degraded due to clock jitter of integrator 2 as BER are increased to 1 % and SNR is lowered to 0.6 db between 0 db to 1 db SNR. A wireless channel was modeled and the impact was observed. The comparisons of BER show that the BER is increased with the number of multipath increased. It is suggested that IUI is increased due to delayed copies of user symbols, interfere with the current user but the proposed method is ISI free as each symbol of same user occurs once in a frame. By observing the simulated results with wireless channel modeling, it could be concluded that the proposed scheme of low sampling rate for IR-UWB wireless communication is working successfully to get lower sampling rates for multiple users via single transmitter through single channel. For multiple transmitters communication with multichannel using multiple path on each channel, communication can be done after some modifications. The results of proposed UWB receiver with integrated window and matched filter UWB receiver were compared. By observing the results it can be concluded that the UWB receiver developed with matched filter is better than integrated window UWB receiver in the higher noise environment. It can also be concluded that the UWB receiver with integrated window is better than UWB receiver with matched filter when the timing mismatch became critical and synchronization becomes an issue due to unknown parameters. Synchronization could be a challenge to develop the proposed UWB receiver under good estimation of wireless channel. It can be stated that the proposed scheme has the potential to play an important role and could be used as a substitute of other sampling methods which are being used to achieve lower sampling rates.
5.8 Future Work

In this research issue of sampling at low rate for UWB receivers is addressed. With the help of this research, UWB receivers can be fabricated using low cost technology to achieve desired sampling rate. The research is suitable where sampling rate for S/H block become crucial and higher sampling rate cannot be achieved. This research can be extended further in future.

Some suggestions are being given below for future work:
- A UWB receiver can be designed using suitable circuit simulation software like CADENCE.
- UWB receiver can be implemented with discrete components on printed circuit board to test the feasibility and ability of work of the proposed UWB receiver.
- A silicon chip can be fabricated and tests can be carried out to validate the working of the proposed UWB receiver.
- A complete system with transmitter and proposed receiver can be fabricated after validation of prototype circuits to communicate among multiple users via single transmitter with higher data rate or to monitor and control multi sensors process parameters in an industrial plant.
- Some other suitable applications can also be investigated for the proposed receiver.
References


Appendices


