IMPLEMENTATION AND EVALUATION OF A MULTIBAND OFDM ULTRA WIDE BAND SYSTEM

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ABRACT OF THE THESIS

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WPAN systems have been receiving significant attention from both industry and academia in the last 10 years and Ultra Wide Band (UWB) technology is one among them. Nowadays, UWB systems can transmit at a data rate as high as 500 Mbps for short distances consuming very little power. When a UWB system moves from the laboratory environment to a real world scenario, several design issues are encountered such as complexity, power consumption, cost and flexibility. In this thesis, a UWB system is designed using a Multiband OFDM physical layer approach which tackles the problems mentioned above while still ensuring high data rates with less power consumption. The reason for choosing this approach over a traditional spread spectrum approach is that the system sends the signal on several sub-bands one at a time making it spectrally flexible while using lesser bandwidth and, hence, preventing the need for high speed RF circuits and ADC's. This will reduce the design complexity and, thereby, reducing the power consumption and making this technology a low cost solution. Since the information on each of these bands uses a multicarrier (OFDM) technique, this system inherits several nice properties of OFDM such as high spectral efficiency, resilience to RF interference, robustness to multi-path, and the ability to efficiently capture multi-path energy.

This thesis focuses on optimizing the Bit Error Rate (BER) performance of the system by making use of symbol diversity and multicarrier diversity techniques. Symbol diversity is implemented by sending an OFDM symbol on different sub-bands and improve the BER by combining the outputs using Maximal Ratio Combining. In multicarrier diversity, the performance is improved further by sending the same data on different subcarriers in an OFDM signal. In addition, a study of the performance by sending the data sensibly on different subcarriers in an OFDM symbol using prior channel information is conducted. The various blocks needed to design the transmitter chain and the receiver chain of the system were implemented using a LabVIEW software testbed and a frequency selective fading channel suggested by the UWB standards committee was simulated to study the performance of the system.

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I would like to express my sincere gratitude to my advisor Prof. Predrag Spasojevic whose guidance helped me a lot at every phase of the project. I would like to thank my family for their constant support throughout the course of the project. I would also like to thank Prof. David Daut and Prof. Zoran Gajic for supervising my thesis defense.

A major reason for my motivation to do a thesis was the project which we worked on as a part of the Digital Communication Systems course under Prof. Predrag Spasojevic. The laboratory sessions on USRP Software Defined Radio conducted by the course TA, Swapnil Mhaske, and the interactions with my project partner Chun-Ta Kung on the practical implementation of a communication system helped me to understand many of the conceptual details and greatly benefitted my research.

Finally, I am indebted to my friends for their invaluable support during the course of graduate study.

Dedication

To my parents, teachers and friends

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Chapter 1

Introduction

ULTRAWIDEBAND (UWB) communication technology is emerging as a leading standard for high-data-rate applications over wireless networks. Due to its use of a high-frequency bandwidth, UWB can achieve very high data rates over the wireless connections of multiple devices at a low transmission power level close to the noise floor. In this order, the FCC allocated the spectrum from 3.1 to 10.6 GHz for unlicensed use by UWB transmitters operated at a limited transmission power of −41.25 dBm/MHz or less. Since the power level allowed for UWB transmissions is considerably low, UWB devices will not cause significantly harmful interference to other communication standards.

A significant difference between conventional radio transmissions and UWB is that conventional systems transmit information by varying the power level, frequency, and/or phase of a sinusoidal wave whereas UWB transmissions transmit information by generating radio energy at specific time intervals and occupying a large bandwidth, thus enabling pulse-position or time modulation. The wide bandwidth and potential for low-cost digital design enable a single system to operate in different modes as a communications device, radar, or locator. These properties give UWB systems a clear technical advantage over other conventional approaches in high multipath environments at low to medium data rates.

The IEEE 802.15.3a High Rate Alternative Physical Layer (PHY) Task Group (TG3a) for Wireless Personal Area Networks (WPAN) has been established to standardize the development of UWB devices. IEEE 802.15.3a task group which deals with high data rate WPAN applications came up with 2 PHY layer proposals: 1) Multi-band OFDM UWB (MB-OFDM) and 2) Direct Sequence UWB (DS-UWB). The orthogonal frequency-division multiplexing (OFDM)-based physical layer is one of the most promising options for the PHY due to its capability to capture multipath energy and eliminate inter-symbol interference. Despite the aforementioned merits, the extremely short range, e.g., 10 m for a data rate of 110 Mb/s, puts UWB at an obvious disadvantage when compared to other competitive technologies, such as the soon coming IEEE 802.11n standard, which supports a data rate of 200 Mb/s for 40 m in indoor environments.

Chapter 2

Background

2.1 OFDM

Orthogonal frequency-division multiplexing (OFDM) is a method of encoding digital data on multiple carrier frequencies. The data are sent over parallel sub-channels with each sub-channel modulated by a modulation scheme such as BPSK, QPSK, 16 QAM etc. The advantage of OFDM is its ability to cope with severe channel conditions compared to a single carrier modulation scheme but still maintaining the data rates of a conventional scheme with the same bandwidth. Furthermore, channel equalization is simplified because OFDM may be viewed as using many slowly modulated narrow band signals rather than one rapidly modulated wide band signal. Also, the low symbol rate naturally makes the use of guard interval between symbols reducing ISI. Orthogonal Frequency Division Multiplexing has become one of the mainstream physical layer techniques used in modern communication systems.

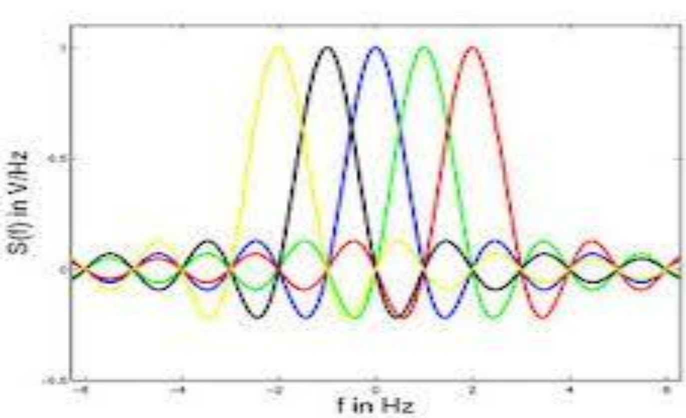


Figure 2.1: Frequency spectrum of an OFDM signal.

2.2 MB-OFDM UWB

MB-OFDM UWB transmits data simultaneously over multiple carriers spaced apart at precise frequencies on more than one band. OFDM signal needs precisely overlapping but non-interfering carriers, and achieving this precision requires the use of a real-time Fourier transform, which became feasible with improvements in Very Large-Scale Integration (VLSI). Basically, MB-OFDM system provides time-domain diversity by time-domain symbol spreading technique and frequency-domain diversity by transmitting OFDM symbols in different sub-bands. Fast Fourier Transform algorithms provide nearly 100 percent efficiency in capturing energy in a multi-path environment, while only slightly increasing transmitter complexity. Beneficial attributes of MB-OFDM include high spectral flexibility and resiliency to RF interference and multi-path effects. Although a wide band of frequencies could be used from a theoretical viewpoint, certain practical considerations limit the frequencies that are normally used for MB-OFDM UWB. Limiting the upper bound simplifies the design of the radio and analogue front end circuitry as well as reducing interference with other services.

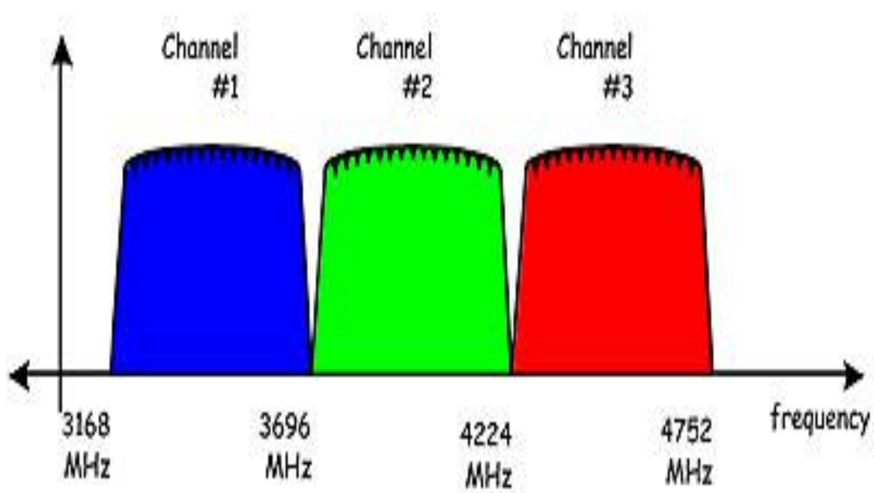


Figure 2.2: MB-OFDM frequency band of operation.

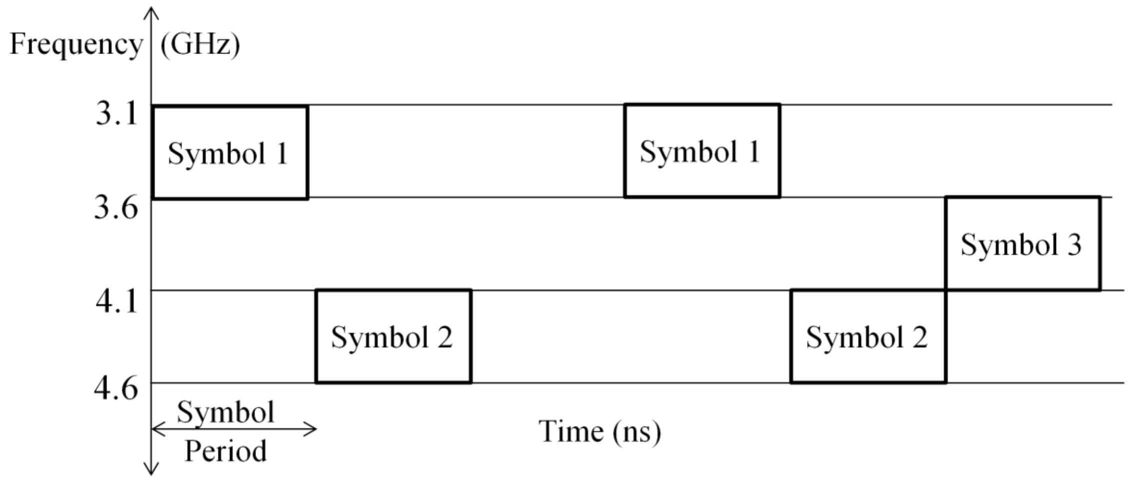


Figure 2.3: Symbol timing of OFDM symbols on different bands

An example of how the OFDM symbols are transmitted in a multi-band OFDM system is shown in figure 2.2. The first OFDM symbol is transmitted on channel number 1 (3168MHz ~ 3696MHz), the second OFDM symbol is transmitted on channel number 3 (4224MHz ~ 4752MHz), the third OFDM symbol is transmitted on channel number 2(3696MHz ~ 4224MHz), the fourth OFDM symbol is transmitted on channel number 1 (3168MHz ~ 3696MHz), and so on.

2.2.1 Advantages

Multipath Robustness

An OFDM system offers inherent robustness to multi-path dispersion with a low-complexity receiver. Adding a Cyclic Prefix (CP) forces the linear convolution with the channel impulse response to resemble a circular convolution. A circular convolution in the time domain is equivalent to a multiplication operation in the frequency domain. Hence, a one-tap frequency domain equalizer is sufficient to undo the effect of the multipath channel. Any multi-path energy outside the CP window would result in inter-carrier-interference (ICI). The length of the CP determines the amount of captured multi-path energy and its length should be chosen to minimize the performance degradation due to the loss in collected multi-path energy and the resulting ICI, while still keeping the CP overhead small.

Tone allocation

Increasing the number of tones in an OFDM system decreases the overhead due to CP. On the other hand, the complexity of the Fast Fourier transform/inverse Fast Fourier transform (FFT/IFFT) block increases and the spacing between adjacent tones decreases. We need to provide the best tradeoff between the CP overhead and FFT complexity. In this system, we use 128 tones. To be compliant with FCC regulation, the 10-dB bandwidth of an UWB signal should be at least 500 MHz and this implies the use of at least 122 tones. Hence, the 128 tones are partitioned into 100 data tones, 22 pilot tones and 6 null tones.

Complexity/Power Consumption

Multiband OFDM system has been specifically designed to be a low complexity solution. By limiting the transmitted symbols to a quadrature phase-shift keying (QPSK) constellation, the resolution of the DAC/ADC and the internal precision in the digital baseband, especially the FFT, can be lowered. This system's lower complexity is also due to the relatively large spacing between the carriers when compared to an IEEE 802.11a system. This large spacing relaxes the phase noise requirements on the carrier synthesis circuitry and improves robustness to synchronization errors. Multiband OFDM has decided advantages over other possible implementations of UWB in terms of the simplicity as well as the efficiency of its multi-path energy capture.

Interference Mitigation

Interference mitigation can be achieved by avoiding a certain part of the spectrum. Since the bandwidth of other technologies such as Bluetooth and 802.11 which act as interferers is very less, it will interfere with only a couple of tones in an OFDM signal. The affected tones can be either erased, or the data rate of the affected tones should be reduced to combat narrow-band interference on the UWB signal. To compensate for the loss in performance, the data rate of the unaffected tones can be increased to a higher data rate. The sub-band in which the narrowband interferer is present can still be used with minimal impact. Frequency hopping also improved the coexistence ability with other technologies by averaging out the aggregating interference.

Chapter 3

Physical Layer Specifications and Features

3.1 Mathematical Representation of a UWB signal

The transmitted signals can be described using a complex baseband signal notation. The actual RF transmitted signal is related to the complex baseband signal as follows:

$$r_{RF}(t) = \mathrm{Re}\left\{ \sum_{k=0}^{N-1} r_k(t - k\, T_{SYM}) \exp\left(j2\pi f_{k(mod)3} t\right) \right\} \qquad (3.1)$$

Where,

Re(·) represents the real part of a complex variable

$r_k(t)$ is the complex baseband signal of the k^{th} OFDM symbol and is nonzero over the interval from 0 to T_{SYM}

N is the number of OFDM symbols

T_{SYM} is the symbol interval and $T_{SYM} = T_{FFT} + T_{CP}$

$f_{k(mod)3}$ is the center frequency for the k(mod)3 band.

$$r_k(t) = \begin{cases} 0 & t \in [\,0, T_{CP}] \\ \displaystyle\sum_{n=-N_{ST}/2}^{N_{ST}/2} C_n \exp((j2\pi n\Delta_f)\,(t - T_{CP})) & t \in [\,T_{CP}, T_{FFT} + T_{CP}\,] \end{cases} \qquad (3.2)$$

The parameters $\boldsymbol{\Delta}_f$ and N_{ST} are defined as the subcarrier frequency spacing and the number of total subcarriers used, respectively. C_n is the complex symbol sent on the subcarrier frequency and the resulting waveform has a duration of $T_{FFT} = 1/\boldsymbol{\Delta}_f$. Shifting the time by T_{CP} creates the "circular prefix" which is used in OFDM to mitigate the effects of multipath.

3.2 Preamble Sequence

The standard PLCP preamble, which is shown in the Figure 3.1, consists of three distinct portions: packet synchronization sequence, frame synchronization sequence, and the channel estimation sequence.

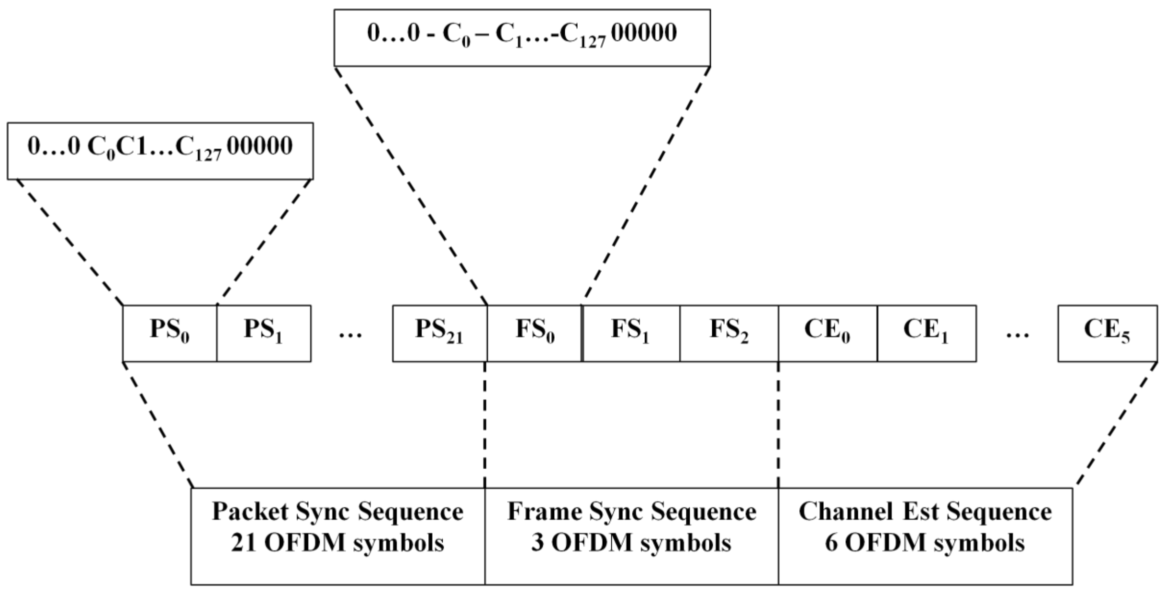


Figure 3.1: Preamble sequence for an OFDM frame.

The packet synchronization sequence shall be constructed by successively appending 21 periods, denoted as $\{PS_0, PS_1, \ldots, PS_{20}\}$, of a time-domain sequence. Each period of the timing synchronization sequence shall be constructed by pre-appending 32 “zero samples” and by appending a guard interval of 5 “zero samples” to the sequences. This portion of the preamble can be used for packet detection and acquisition, coarse carrier frequency estimation, and coarse symbol timing.

Similarly, the frame synchronization sequence shall be constructed by successively appending 3 periods, denoted as {FS_0, FS_1, FS_2}, of an 180 degree rotated version of the time-domain sequence. Again, each period of the frame synchronization sequence shall be constructed by pre-appending 32 “zero samples”. This portion of the preamble can be used to synchronize the receiver algorithm within the preamble. Finally, the channel estimation sequence shall be constructed by successively appending 6 periods of the OFDM training symbol, denoted as {CE_0, CE_1, …,CE_5}. Packet synchronization sequences and frame synchronization sequences have been specified in time domain and channel estimation sequence in frequency domain by the UWB standards committee.

Different types of preambles have been designed to operate in four different environments and they are:

- Preamble 1 for Line Of Sight (LOS) (0–4 m)
- Preamble 2 for Non Line Of Sight (NLOS) (0–4 m)
- Preamble 3 for Non Line Of Sight (4-10 m)
- Preamble 4 for extreme Non Light Of Sight

3.3 Subcarrier Constellation Mapping

The OFDM subcarriers shall be modulated using QPSK modulation. The serial input data shall be divided into groups of 2 bits and converted into complex numbers representing QPSK constellation points. The conversion shall be performed according to the constellation mappings that employ a Gray-coded method.

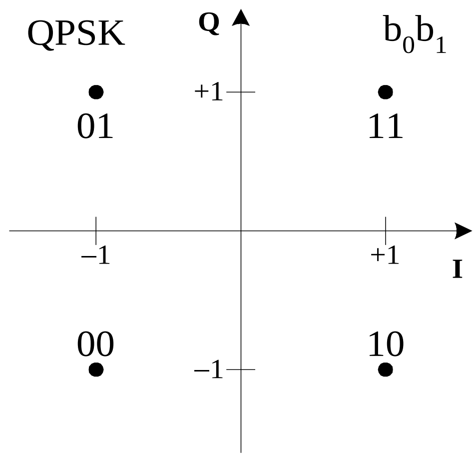


Figure 3.2: Constellation space points for QPSK modulation.

Table 3.1: Bits – Symbol mapping for QPSK.

Input bit (b_0 b_1)	I-out	Q-out
00	-1	-1
01	-1	1
10	1	-1
11	1	1

3.4 Time Domain Spreading

For data rates of 55, 80, 110, 160 and 200 Mbps a time-domain spreading operation is performed with a spreading factor of 2. The time-domain spreading operation consists of transmitting the same information over two OFDM symbols. These two OFDM symbols are transmitted over different sub-bands to obtain frequency diversity. For example, if the device uses a time-frequency code [1 2 3 1 2 3], as specified in table 3.2, the information in the first OFDM symbol is repeated on sub-bands 1 and 2, the information in the second OFDM symbol is repeated on sub-bands 3 and 1, and the information in the third OFDM symbol is repeated on sub-bands 2 and 3. Time-frequency code (TFC) determines the band on which every OFDM symbol has to be sent.

Table 3.2: Time Frequency Code for the band allocation of OFDM symbols.

Preamble pattern	Time Frequency Code (TFC)					
1	1	2	3	1	2	3
2	1	3	2	1	3	2
3	1	1	2	2	3	3
4	1	1	3	3	2	2

3.5 Cyclic Prefix Insertion

Zero padded cyclic prefix refers to the prefixing of a symbol with zero samples. Although the receiver is typically configured to discard the cyclic prefix samples, the cyclic prefix serves two purposes.

- It allows the linear convolution of a frequency-selective multipath channel to be modeled as circular convolution, which in turn may be transformed to the frequency domain using a discrete Fourier transform. This approach preserves orthogonality between the subcarriers in an OFDM symbol and allows for simple frequency-domain processing such as channel estimation and equalization.

- As a guard interval, it eliminates the intersymbol interference (ISI) from the previous symbol.

In order for the cyclic prefix to be effective, the length of the cyclic prefix must be at least equal to the length of the multipath channel.

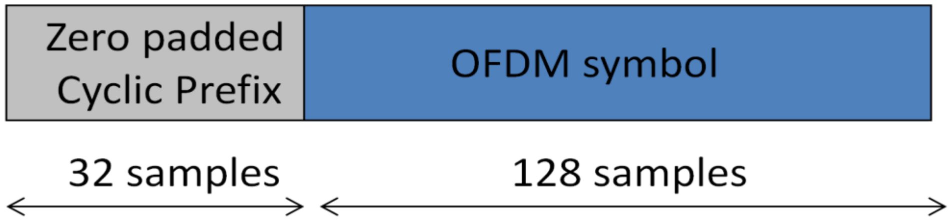


Figure 3.3: Cyclic Prefix of an OFDM symbol.

Chapter 4

System Design

4.1 TRANSMITTER

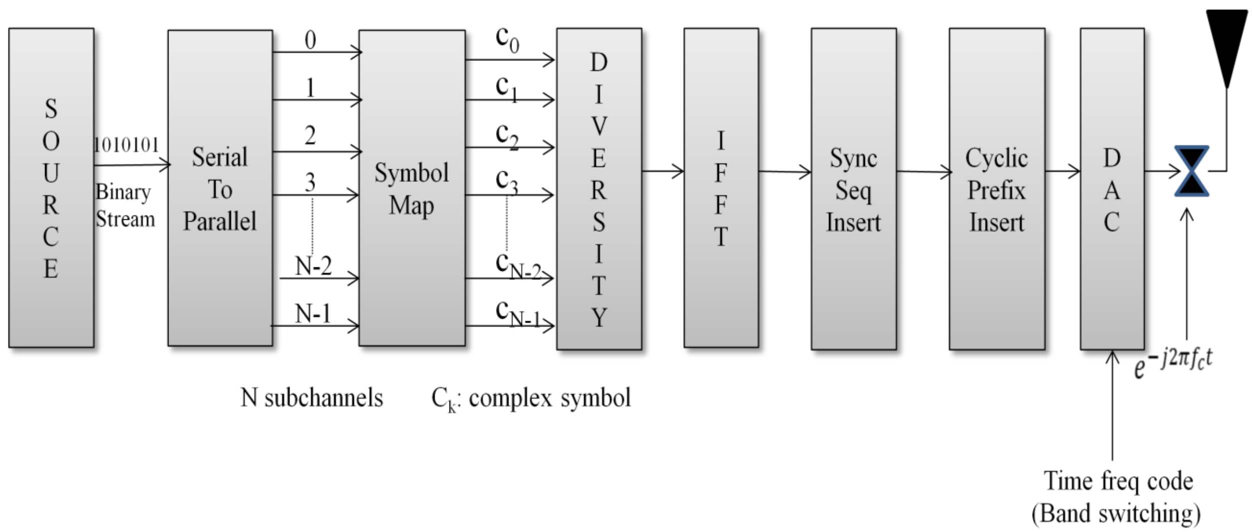


Figure 4.1: Block Diagram of an MB-OFDM Transmitter.

4.1.1 SOURCE

We used a PN sequence generator to generate a random bit stream. The output is a 1-dimensional array of bits. We then perform a serial-to-parallel conversion sending the bits on parallel streams each representing a subcarrier.

4.1.2 MODULATION

We used the QPSK modulation scheme on all the subcarriers. We also have the option of using multicarrier diversity by sending the same bit stream on two different subcarriers.

4.1.3 IFFT

We then perform the IFFT of all the parallel data streams together ensuring orthogonality between the subcarriers and the conversion of symbols to time domain. By orthogonality, it is meant that all the subcarriers on which the data has been sent overlap each other in such a way that they don't interfere with one another and ensure minimum bandwidth usage. IFFT for a set of N complex data points from N orthogonal parallel streams is given by the formula.

$$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k).\, e^{j(\frac{2\pi}{N})nk} \;\; ; (n=0,1,\ldots.N-1) \qquad (4.1)$$

Where,

X(k) is a complex frequency domain data sent on subcarriers of frequency k/N,

k=0,1,….,N

k/N term is orthogonal to every other value of k/N

4.1.4 DIVERSITY/ MULTICARRIER DIVERSITY:

Before sending a signal through the transmitter antenna, we have an option to increasing the BER performance by sending the same signal on different bands or sending the data on multiple subcarriers within an OFDM symbol. When we have more than one copy of the transmitted data i.e. the whole symbol or individual subcarriers of a symbol, we can use a diversity scheme like Maximal Ratio Combining and obtain a lower BER for the same SNR.

4.1.5 TFC ALLOCATION:

After inserting the Cyclic Prefix to all the symbols, we send the symbols on one of the three bands based on time frequency code (TFC). Every TFC corresponds to a specific preamble sequence which in turn corresponds to the type of environment. We can improve the performance by sending the symbol on 2 different bands and make use of diversity schemes like Maximal Ratio Combining at the receiver.

4.2 RECEIVER

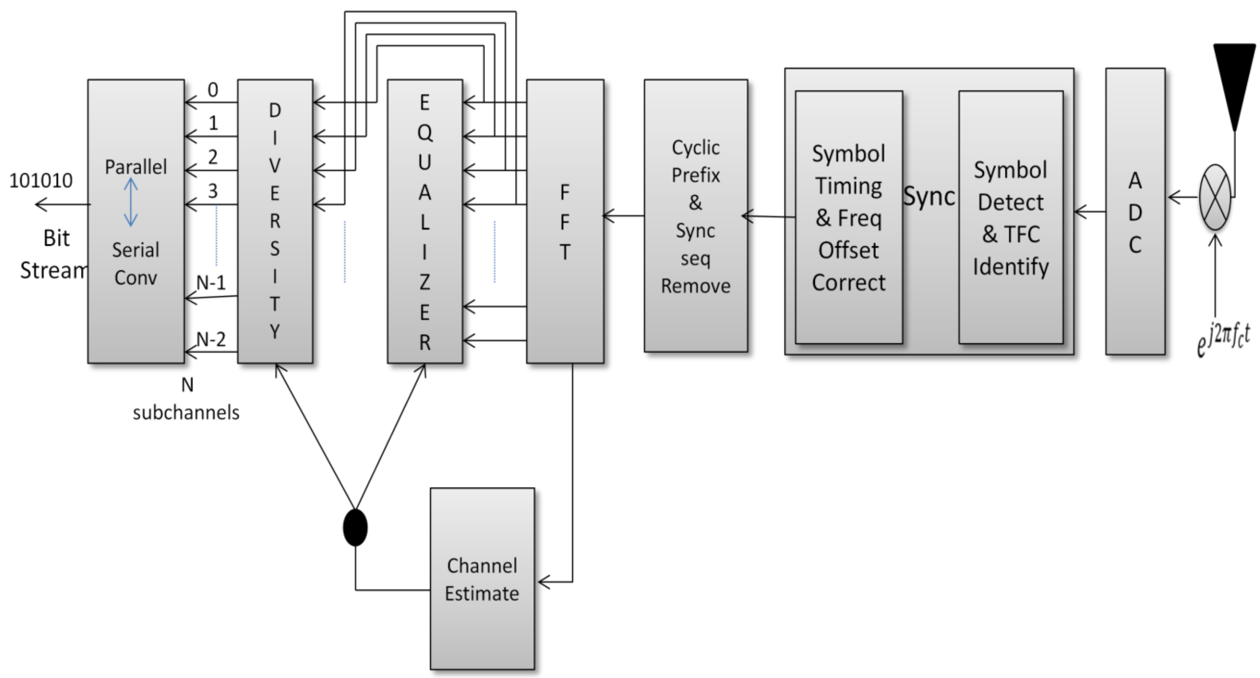


Figure 4.2: Block Diagram of an OFDM receiver.

4.2.1 SYNCHRONIZATION

AUTOCORRELATION BASED SYNCHRONIZER

Since UWB systems are power and cost sensitive, low complexity synchronization should be adopted. Auto-correlator structure performs the autocorrelation of a symbol with symbols delayed by 1, 3, 5 and 6 symbol periods to perform joint symbol detection, TFC identification, timing offset and frequency offset correction.

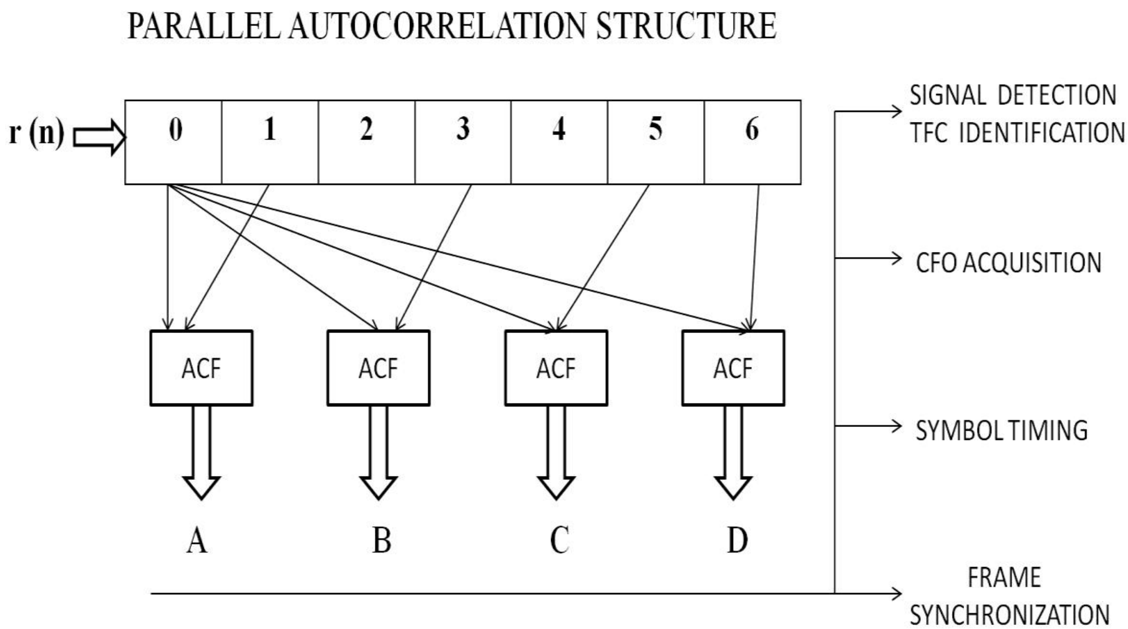


Figure 4.3: Parallel Autocorrelator Structure.

Output A is the result of autocorrelation of a symbol with a symbol delayed by one symbol period, B is the autocorrelation of the symbol with a symbol delayed by 3 symbol periods, C is the autocorrelation of the symbol with a symbol delayed by 5 symbol periods and D is the autocorrelation of the symbol with a symbol delayed by 6 symbol periods.

SIGNAL DETECTION AND TFC IDENTIFICATION

Before synchronization is acquired and TFC identified, a receiver needs to scan through all sub bands, i.e., it stays on one band and “listens” to possible incoming preamble signals for a period of time. If no packet is detected, the receiver switches to a different band and continue listening. For any incoming packet, because of the frequency hopping, only the symbols in the sub-band that the receiver is listening can be “heard”. As an example, for TFC 1, the receiver listening on sub-band 1 receives only one of every three preamble symbols. With the proposed parallel ACF structure, the detection of signal is declared immediately once the ACF outputs (after comparing to a given threshold) matches the ones given in the figure 4.4.

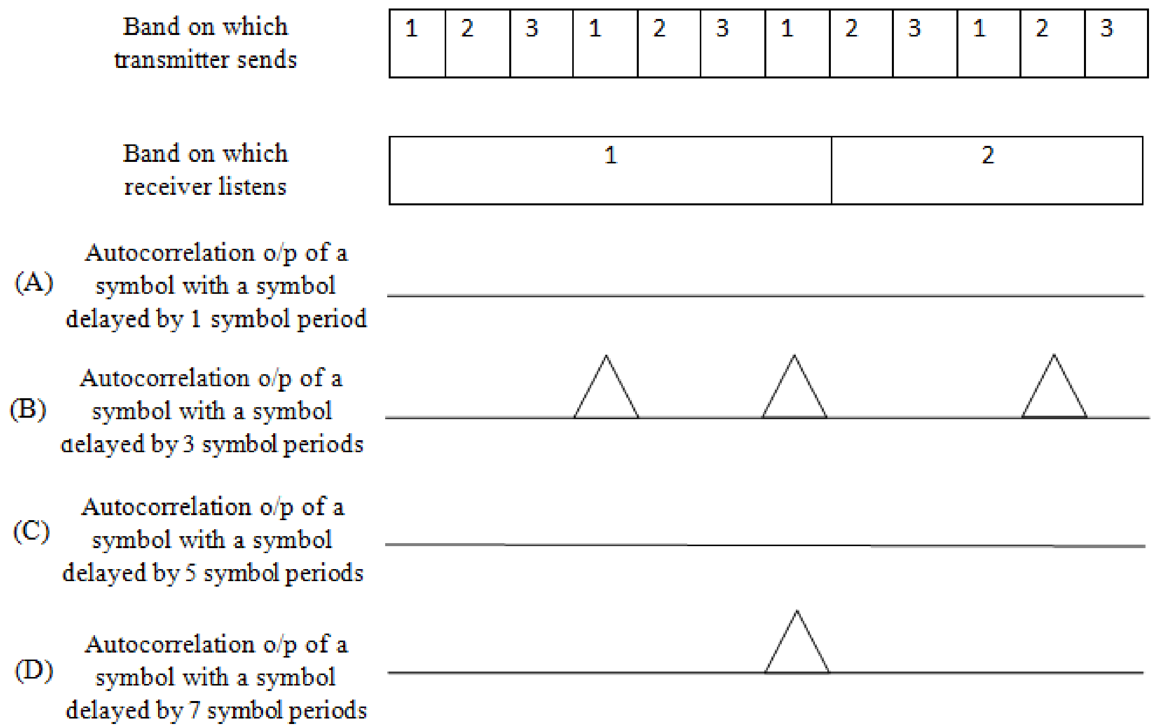


Figure 4.4: An illustration on the Autocorrelation Structure based TFC identification via band switching.

Figure 4.4 shows the correlation peaks when the listener listens to band 1 for a duration of 7 symbol periods and then listens to band 2 for the same duration. The output pattern of the signal detector is assumed to be [0 1 0 1] (B=1, D=1) and the possible TFC is either 1 or 2. The receiver switches to sub-band 2 and continues to do ACF operations on two signal segments with the separation of $3N_s$ T. The peak position of the ACF outputs implies the TFC of the received signal.

OFDM SYMBOL TIMING

After the preamble signal is detected and its TFC identified, the SYNC needs to search for the start of an OFDM symbol. An inaccurate timing not only introduces inter-carrier-interference (ICI) and (possible) ISI, but also affects the quality of channel estimation and the total signal energy collected in the FFT window.

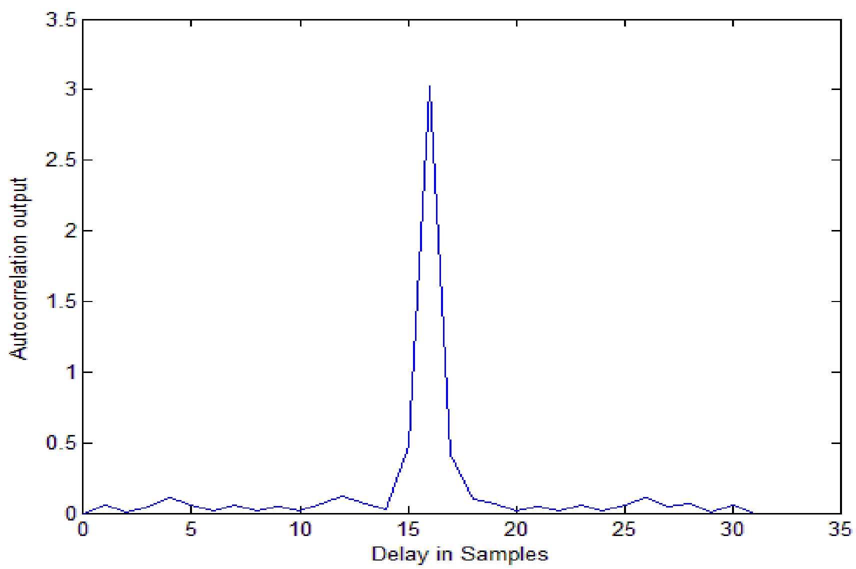


Figure 4.5: Timing metric obtained by correlating 2 preamble symbols together.

The autocorrelation of a known synchronization sequence in the received sequence with itself gives a autocorrelation peak. Since the preamble has high autocorrelation property, we get a high autocorrelation peak when there is perfect autocorrelation.

CARRIER FREQUENCY OFFSET ESTIMATION

Using a unified SYNC structure, frequency offset correction occurs in parallel with symbol timing. The maximum phase difference between two repeated preamble symbols on the same band would not exceed 0.3π. Since the minimum interval between two repeated preamble symbols on the same band in all TFCs would not exceed 3 symbol periods, we estimate the phase of the Autocorrelation value for 2 consecutive symbols

$$\tilde{r}_1 = r_k^* r_{k+3} \qquad (4.2)$$

Where,

r_k is the k^{th} OFDM symbol

r_{k+3} is the symbol delayed by 3 symbol periods

$\tilde{r}_1$ is the autocorrelation output of the first symbol with another symbol delayed by 3 symbol periods

Since the phase of $\hat{r}_1$ is given by $p_1 2\pi N_S f_1 T$, we could get the frequency offset estimate $\Delta f1$ by

$$\Delta f_1 = \frac{1}{2\pi p_1 N_S T} \arg(\tilde{r}_1) \qquad (4.3)$$

Where,

p_k, k=3,6,... is the delay between 2 consecutive symbols on the same band

p_1 is 3

N_S is the number of subcarriers in each symbol

T is the symbol period

Δf_1 is the initial frequency offset estimate

Iterative CFO estimation algorithm takes advantage of different values of p_k to estimate fine carrier frequency offset. The initial phase estimate is then used to compensate for the phase of a autocorrelation value for 2 symbols separated by 6 symbol periods.

$$\tilde{r}_2 = \tilde{r}_1 \, e^{-j\, 2\pi\, \Delta f_1\, p_2\, N_S\, T} \tag{4.4}$$

Where,

p_2 is 6

$\tilde{r}_2$ is the autocorrelation output of the symbol with a symbol delayed by 6 symbols

Though phase offset has already been compensated, we could still get fine carrier frequency offset estimate δf_2 by dividing $\tilde{r}_2$ by the term $p_2\, 2\pi N_S T$

$$\delta f_2 = \frac{1}{2\pi p_2\, N_S\, T} \arg(\, \tilde{r}_2\,) \tag{4.5}$$

The new phase offset obtained is added with the initial phase estimate to get the final phase estimate.

$$\Delta f_2 = \Delta f_1 + \delta f_2 \tag{4.6}$$

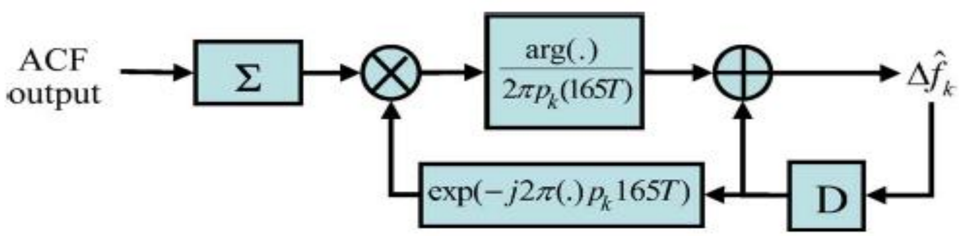


Figure 4.6: Structure of an iterative Carrier Frequency Offset (CFO) estimator.

4.2.2 FFT:

Once Cyclic Prefix is removed from every symbol, it is sent to a FFT block which converts the symbols back to frequency domain. The FFT output takes two paths – one to create a channel estimate and the other as an input to an equalizer.

$$X(k) = \sum_{n=0}^{N-1} x(n).\, e^{-j(\frac{2\pi}{N})nk} \quad (k=0,1,\ldots.N-1) \tag{4.7}$$

Where,

x(n) is complex time domain data sent on k/Nth frequency

k/N, k=0,1,…,N-1 frequency term is orthogonal to every other frequency term

4.2.3 CHANNEL ESTIMATION:

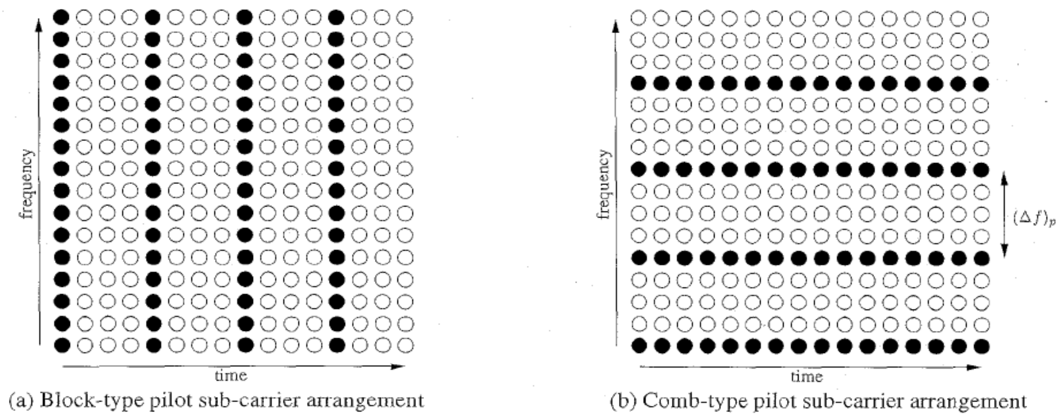


Figure 4.7: Pilot subcarriers arrangement in an OFDM symbol.

Since every OFDM subchannel can be viewed as a flat fading channel, we decided to use Least Squares Channel Estimator with pilot symbols inserted at the head of the packet (in the frequency domain). The received pilot symbol in kth subchannel relates to the transmitted pilot symbol in the same subchannel by the equation:

$$y_k = h_k \times x_k \tag{4.8}$$

In the LS estimator, the goal is set to minimize $(y - Xh)^H(y - Xh)$, where y, h denote the received pilot symbol vector and channel frequency response vector respectively. Matrix X is a matrix whose diagonal elements are composed of the transmitted pilot symbols. Xh is just matrix form convolution equation. By solving the minimization problem above, we can estimate $\tilde{h} = X^{-1}y$

4.2.4 EQUALIZER

OFDM Equalizer is significantly simplified due to the property of narrowband subchannel. For every subchannel, we equalize the symbol by using this expression $\frac{y_k}{h_k}$.

4.2.5 DIVERSITY

Since every OFDM symbol is sent on 2 bands, we could make use of the both the signals using diversity to improve the BER performance. We make use of Maximum Ratio Combining technique where we combine all the signals because of multipath in a co-phased and weighted manner so as to have the highest achievable SNR at the receiver at all times.

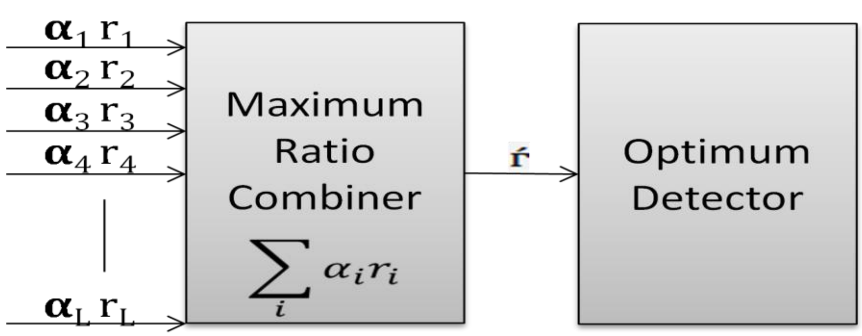


Figure 4.8: Maximal Ratio Combiner.

Where,

$r_1, r_2 \ldots r_L$ are multipath copies of the transmitted signal

$\alpha_1, \alpha_2, .. \alpha_L$ are complex gains associated with each path

α_i is the complex conjugate of the channel estimate $\widetilde{h_i}$

$$\acute{r} = \sum_{i=1}^{L} \alpha_i r_i \Longrightarrow \sum_{i=1}^{L} \widetilde{h_i}\, r_i \qquad (4.9)$$

The output of the combiner ŕ is then decoded to see an increase in BER performance

4.3 SIMULATION

Table 4.1: Simulation parameters.

Parameter	Value
N_{SD} : Number of data subcarriers	100
N_{SG} : Number of null carriers	28
Number of total subcarriers used	128 (= N_{SD} + N_{SG})
Subcarrier frequency spacing	3.906 MHz (= 500 MHz/128)
T_{FFT}: IFFT/FFT period	256 ns (1/Δ_F)
T_{CP}: Cyclic prefix duration	64 ns (= 32/500 MHz)
T_{SYM}: Symbol interval	320 ns (T_{CP} + T_{FFT})
Modulation used in each subcarrier	QPSK
Types of channel	1. AWGN channel 2. UWB channel
Diversity	1. Symbol Diversity 2. Multicarrier diversity (Random subcarriers) 3. Multicarrier diversity (Prior channel information)

4.4 SIMULATOR FRONT PANEL

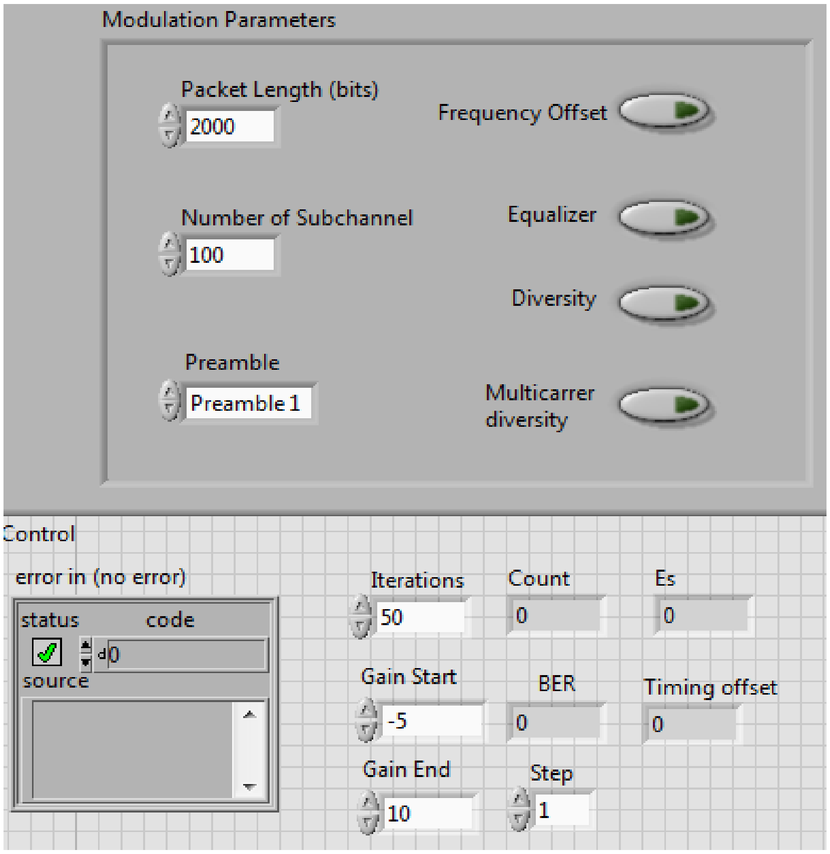


Figure 4.9: Front panel view of Modulation parameters control in LabVIEW.

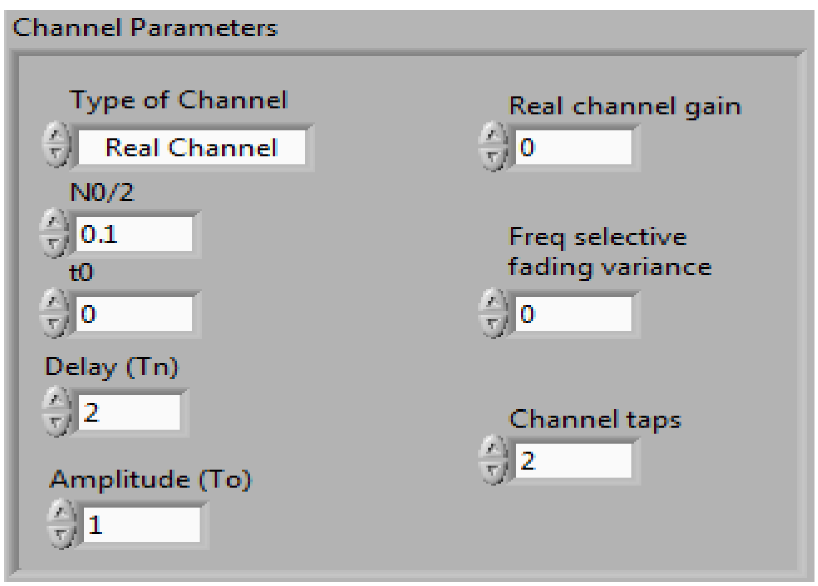


Figure 4.10: Front panel view of Channel parameters control in LabVIEW.

4.5 Channel

There are 2 types of channels defined in this experiment and BER performance has been evaluated for each channel by considering several critical factors.

4.5.1 AWGN Channel

According to the AWGN channel specifications, the received signal y(t) can be expressed as an addition of the transmitted signal x(t) and white Gaussian noise w(t). If we sample the received signal y(t) according to the relation t= nT where n=0,1,....N-1, we can express y(n) as

$$y(n) = x(n) + w(n) \tag{4.10}$$

where,

w(n), n=0,1..N-1 is independent and identically distributed random variable and follows a normal distribution with mean 0 and a deviation of 0.1 $[N(0,(0.1)^2)]$

y(n) is also a independent and identically distributed Gaussian random variable $[N(x,(0.1)^2)]$

4.5.2 UWB Channel (Frequency Selective Fading)

This channel model incorporates a strong multipath, with several overlapped replicas of a transmitted signal. The replicas of the propagating signal are equally spaced in time, with amplitudes that depend on both distance and delay. The model assumes that all channel parameters are random variables with specific, well defined distributions. The channel frequency response can be expressed as follows:

$$H(f) = \sum_{n=1}^{N} \alpha_n (D, \tau_n) e^{j2\pi f \tau_n} \tag{4.11}$$

Where,

$\alpha_n\,(D,\tau_n) = k.\frac{e^{-D}}{D}\,e^{\frac{-\tau_n}{\tau_o}}$ is the gain of each multipath component

τ_n is the delay in samples between any two consecutive multipath components

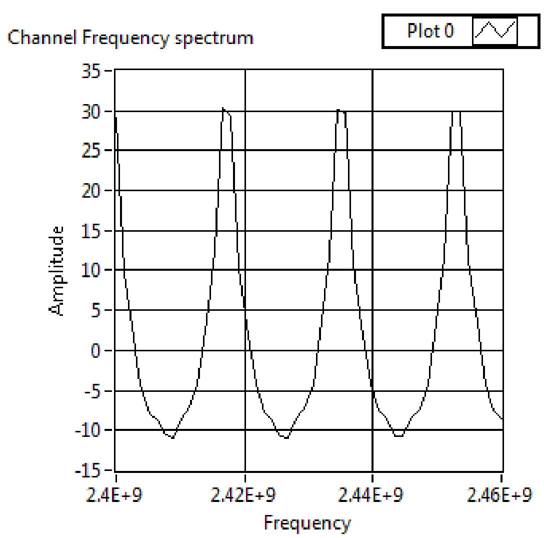
N is the number of multipath components

k and τ_0 are constants

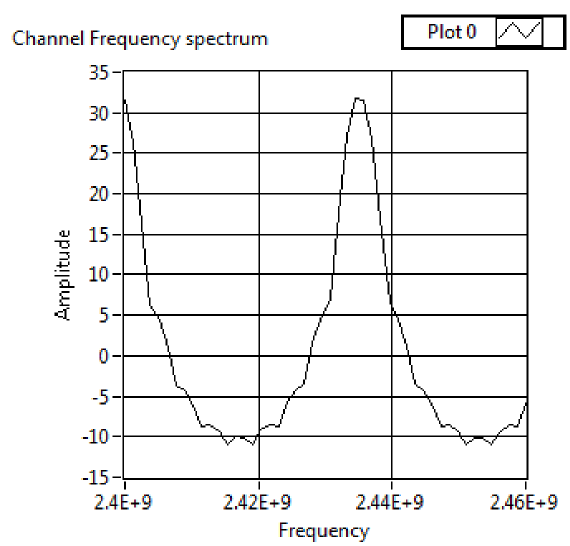
The shape of the channel transfer function depends on 3 critical factors:

- Distance ‘D’, since channel gain ‘α_n‘is inversely proportional to the distance (e^{-D}).
- Relative Delay ‘$\boldsymbol{\tau}_{n}\,/\,\boldsymbol{\tau}_0$ ‘, since increase in delay decreases the multipath effect.

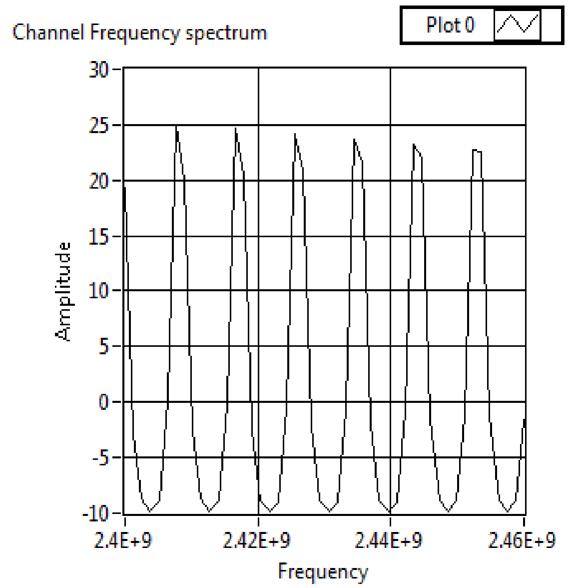
We consider some realizations of the channel frequency response based on the delay between the multipath components ($\boldsymbol{\tau}_n$) keeping $\boldsymbol{\tau}_o$ and D constant.



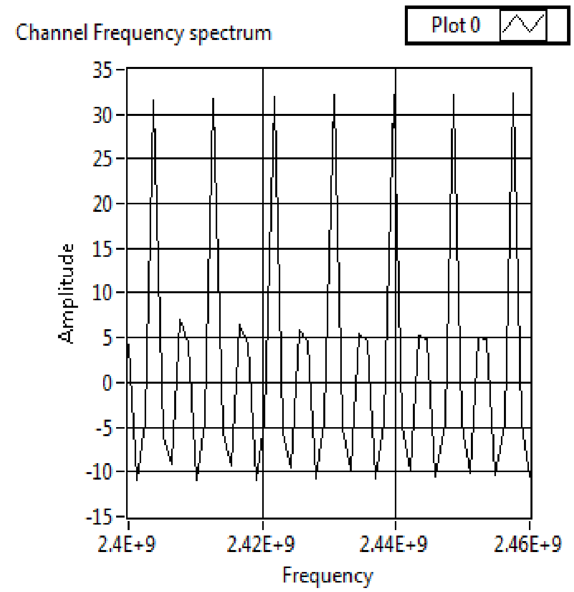
(a) Modulus of channel transfer function $|\,H(f)\,|^2$ with $\boldsymbol{\tau}_n = 2$ ns, $\boldsymbol{\tau}_0 = 15$ ns.



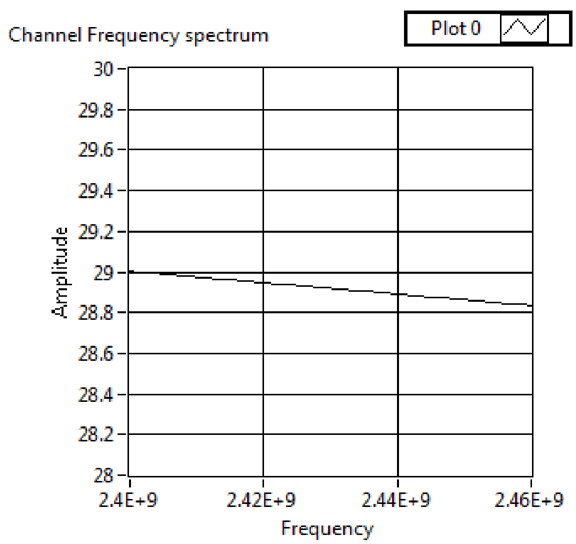
(b) Modulus of channel transfer function $|\,H(f)\,|^2$ with $\boldsymbol{\tau}_n = 4$ ns, $\boldsymbol{\tau}_0 = 15$ ns.



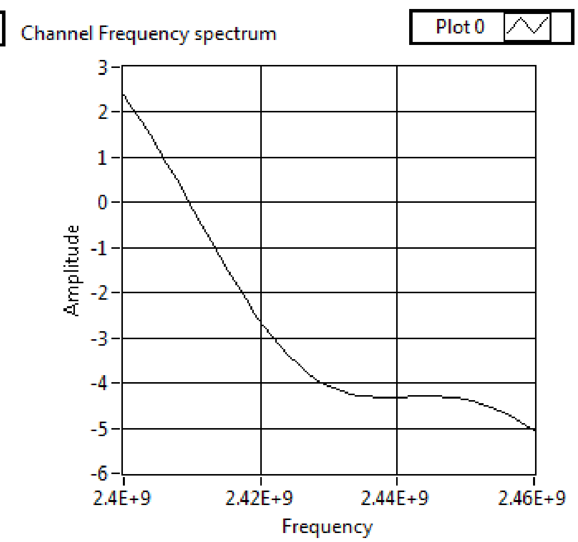
(c) Modulus of channel transfer function | H(f) $|^2$ with $\tau_n = 8$ ns, $\tau_0 = 15$ ns.



(d) Modulus of channel transfer function | H(f) $|^2$ with $\tau_n = 16$ ns, $\tau_0 = 15$ ns.



(e) Modulus of channel transfer function | H(f) $|^2$ with $\tau_n = 32$ ns, $\tau_0 = 15$ ns.

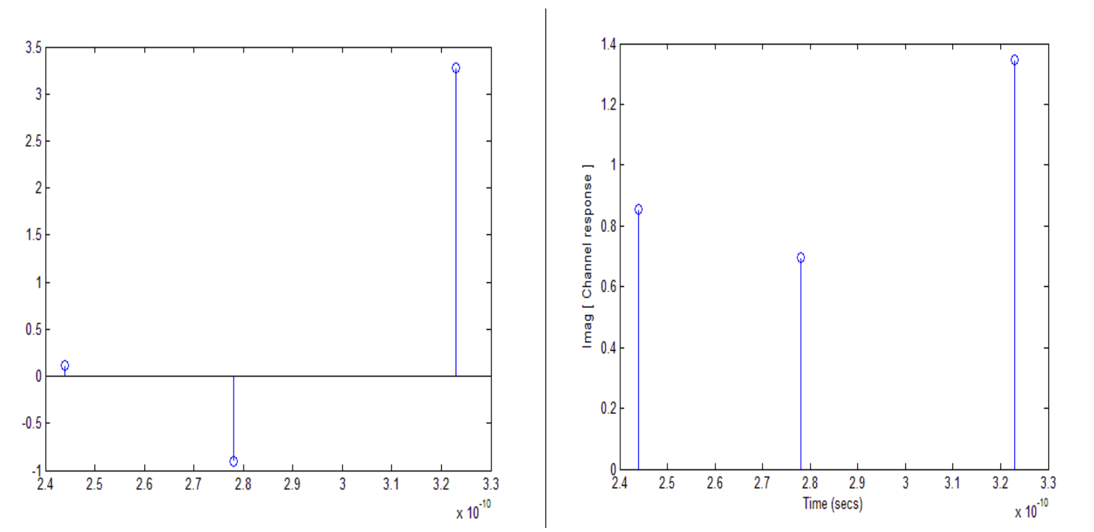


(f) Modulus of channel transfer function | H(f) $|^2$ with $\tau_n = 64$ ns, $\tau_0 = 15$ ns.

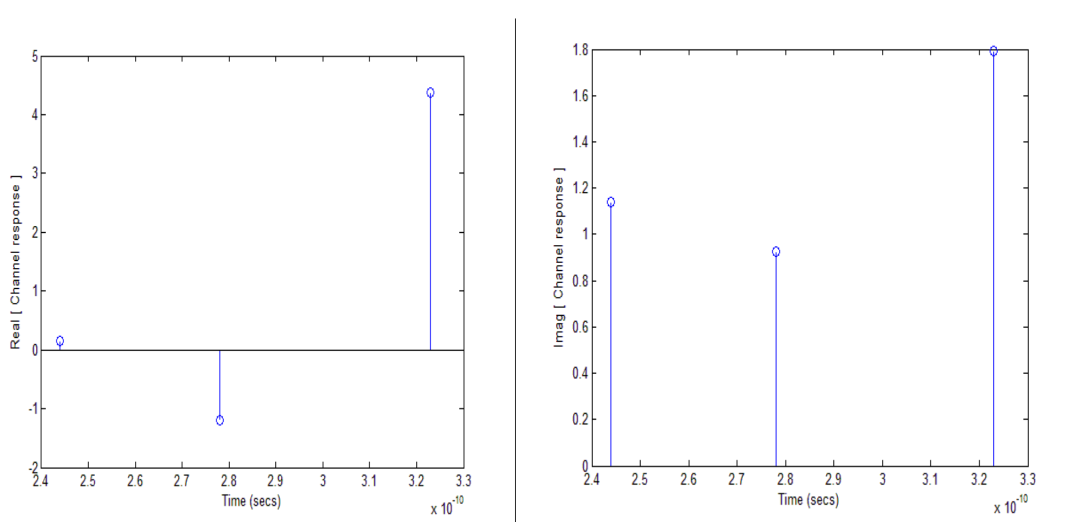
Figure 4.11: Modulus of UWB channel transfer function $|H(f)|^2$ for different scenarios.

As τ_n increases, the multipath effect decreases and the channel transfer function tends to resemble the transfer function of an ideal channel. Note that the value of affects the position and the number of the peaks in the transfer function.

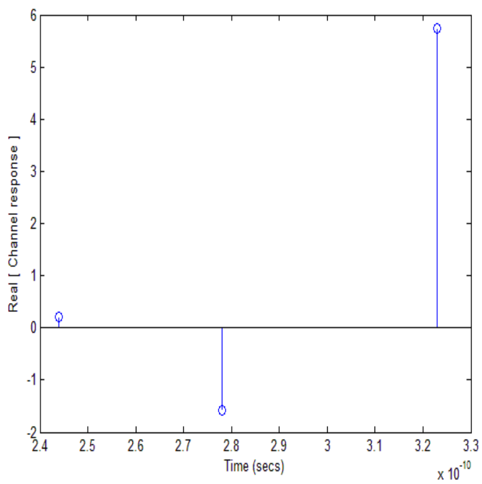
For high τ_o, there is a high and narrow peak, while the peak widens and lowers when τ_o decreases. Gain varies with according to an exponential law; when τ_o decreases, α_n decreases rapidly, leading to a flatter transfer function.



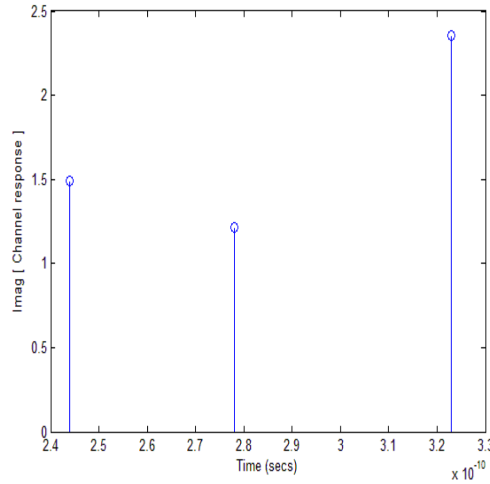
(a) Band 1 Channel Impulse Response – Real part. (b) Band 1 Channel Impulse Response – Imag part.



(c) Band 1 Channel Impulse Response – Real part. (d) Band 1 Channel Impulse Response – Imag part.



(e) Band 1 Channel Impulse Response – Real part.



(f) Band 1 Channel Impulse Response – Imag part.

Figure 4.12: Channel impulse response of 3 bands for a channel scenario with τ_n = 2 ns, τ_0 = 15 ns and N=10.

Chapter 5

Experiments and Results

5.1 EXPERIMENTAL SETUP FOR BER PERFORMANCE IN AN AWGN CHANNEL

The goal of this experiment is to evaluate the BER performance of the system when UWB signal is passed through an AWGN channel. Each noise component w(n) is a complex Gaussian RV with a variance of 0.01 / 0.1 and it is added to every symbol transmitted. A simple equalizer has been designed to cancel the channel impairments by equalizing the output using the channel estimate. We observe that as signal power increases, BER decreases.

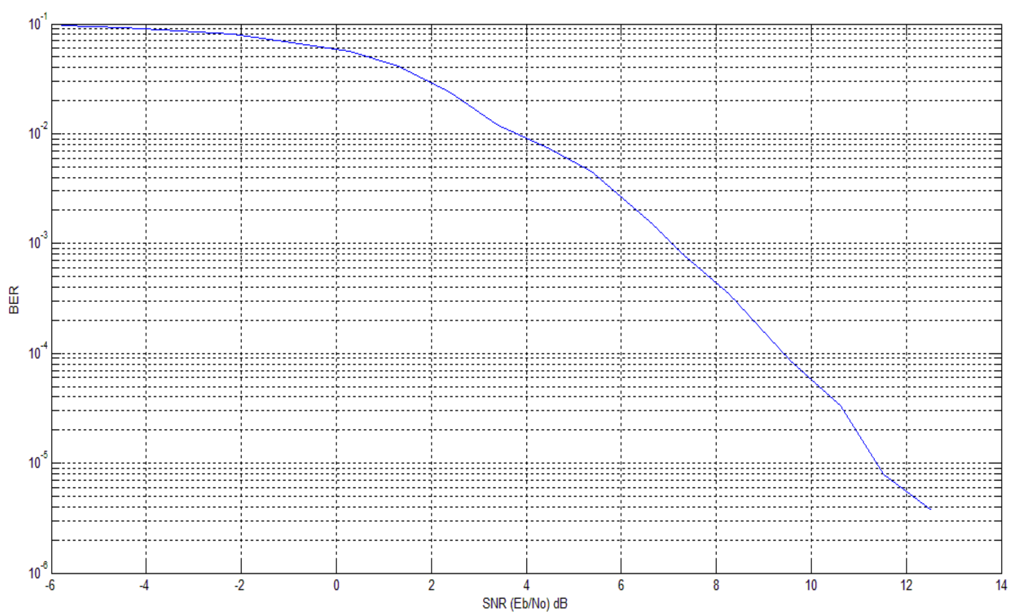


Figure 5.1: BER curve showing the performance in an AWGN channel with noise variance N_0=0.01.

5.2 EXPERIMENTAL SETUP FOR A SYSTEM WITH / WITHOUT DIVERSITY

The goal of this experiment is to evaluate the BER performance of the system using symbol diversity and multicarrier diversity and compare the results to see any improvement. We have evaluated the SNR-BER curve for six different channel scenarios based on the values of $\boldsymbol{\tau}_n$, $\boldsymbol{\tau}_0$ and N (Number of multipath components).

To evaluate the performance improvement, experiments were performed by sending the data on more than one band and on more than one subcarrier in an OFDM symbol.

1. **No diversity scheme** where we just perform equalization to remove the channel effects such as dispersion, ISI etc.
2. **Multiband Diversity scheme** where we transmit an OFDM symbol on different frequencies and make use of multiple copies of the same signal to improve the BER performance.
3. **Multicarrier Diversity scheme** where we transmit the same data on different subcarriers orthogonal to each other in an OFDM symbol and improve the BER performance.
4. **Multicarrier Diversity scheme knowing the channel information** where we improve the performance by knowing the periodicity of the channel transfer function and sending the data on different subcarriers sensibly.

Multicarrier Diversity

When we send an OFDM symbol on a band, data is actually sent on 100 parallel subcarriers with a spacing of 3.9 MHz. In multicarrier diversity, we send the same data on two different subcarriers i.e. the same data on subcarrier 1 and subcarrier 50 and make use of diversity to improve the BER performance. For example, we consider a channel transfer function with $\boldsymbol{\tau}_n$= 1 sample

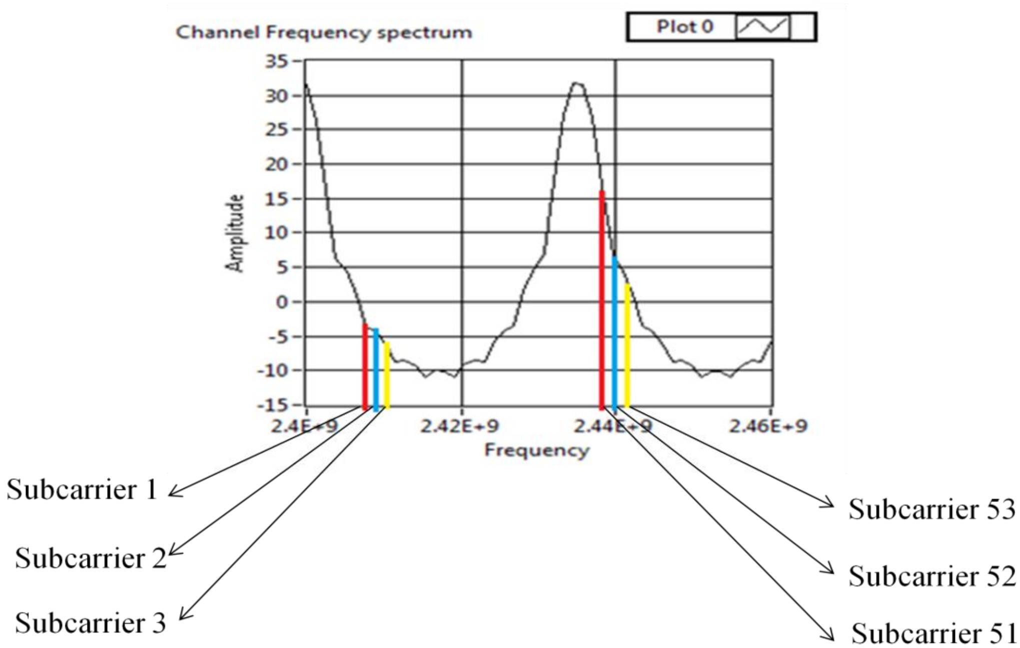


Figure 5.2: Channel Frequency spectrum showing the frequencies on which same data is sent not knowing the channel information in advance.

The diagram shows that we send the same data on subcarrier frequencies marked in red, blue and yellow and combine their outputs at the receiver to improve the performance. Since we have the channel estimate for each band *i.e* an estimate for each subcarrier within a band, we can combine the outputs of the subcarriers with the same data by

$$\hat{r}_i = r_{k,i}\tilde{h}_{k,i} + r_{k,i+50}\tilde{h}_{k,i+50} \tag{5.1}$$

Where,

$r_{k,i}$ is the i^{th} subcarrier of the k^{th} OFDM symbol

$\tilde{h}_{k,i}$ is the complex conjugate of the channel estimate of the i^{th} subcarrier frequency in that band.

$r_{k,i+50}$ is the $i+50^{th}$ subcarrier of the k^{th} OFDM symbol

$\hat{r}_i$ is the combined output of the same data sent on 2 different subcarriers.

Multicarrier diversity with prior channel information

As a special case, we can improve the performance by sending data on specific subcarriers sensibly if we know the channel information in advance. In this case, we send the same data on two different subcarriers – subcarrier frequency experiencing a good fade and a subcarrier frequency experiencing less fade. We consider the same channel transfer function with $\boldsymbol{\tau}_n$= 1 sample.

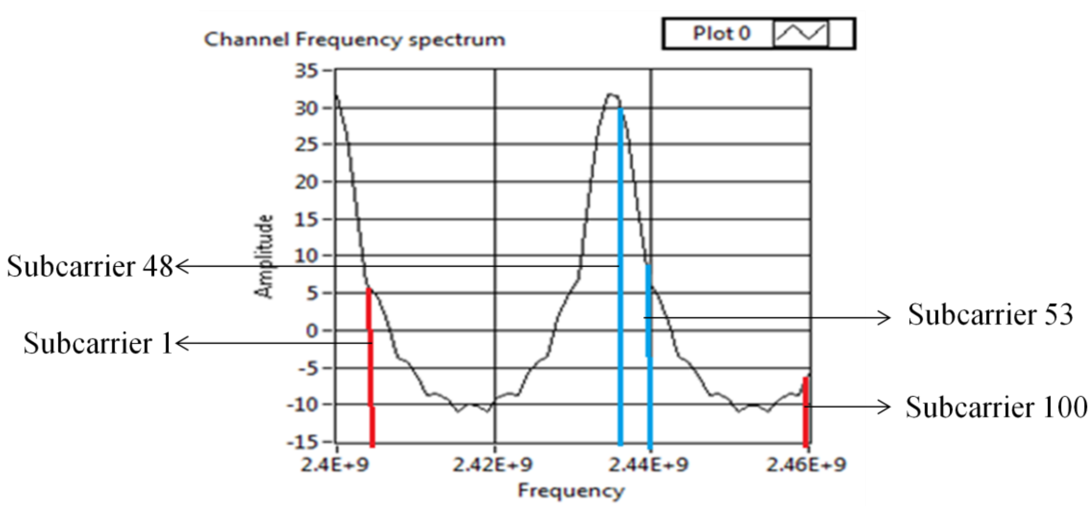
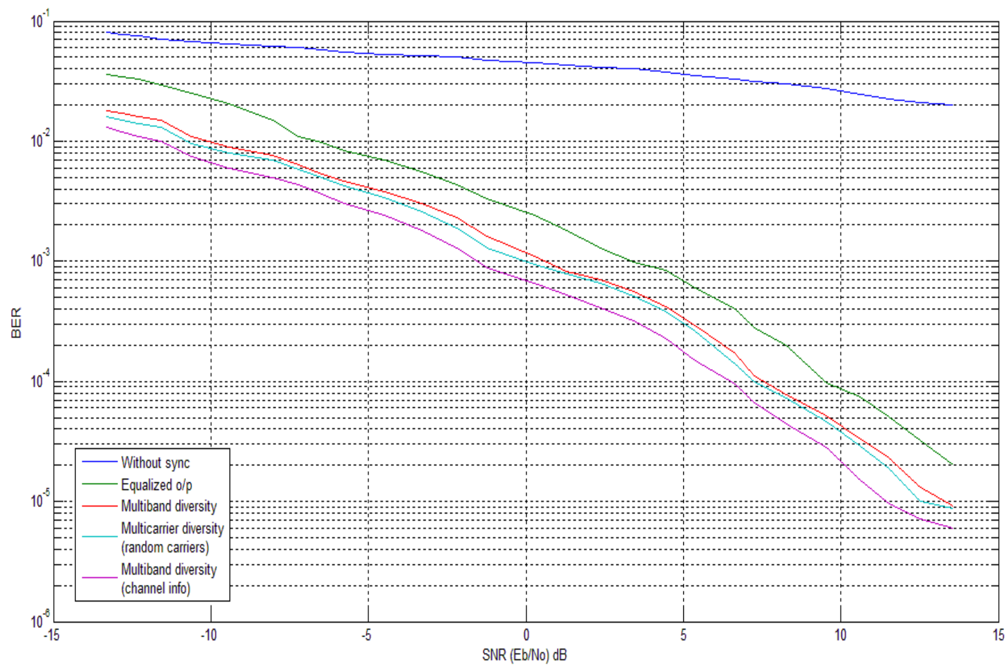


Figure 5.3: Channel Frequency spectrum showing the frequencies on which same data is sent knowing the channel information in advance.

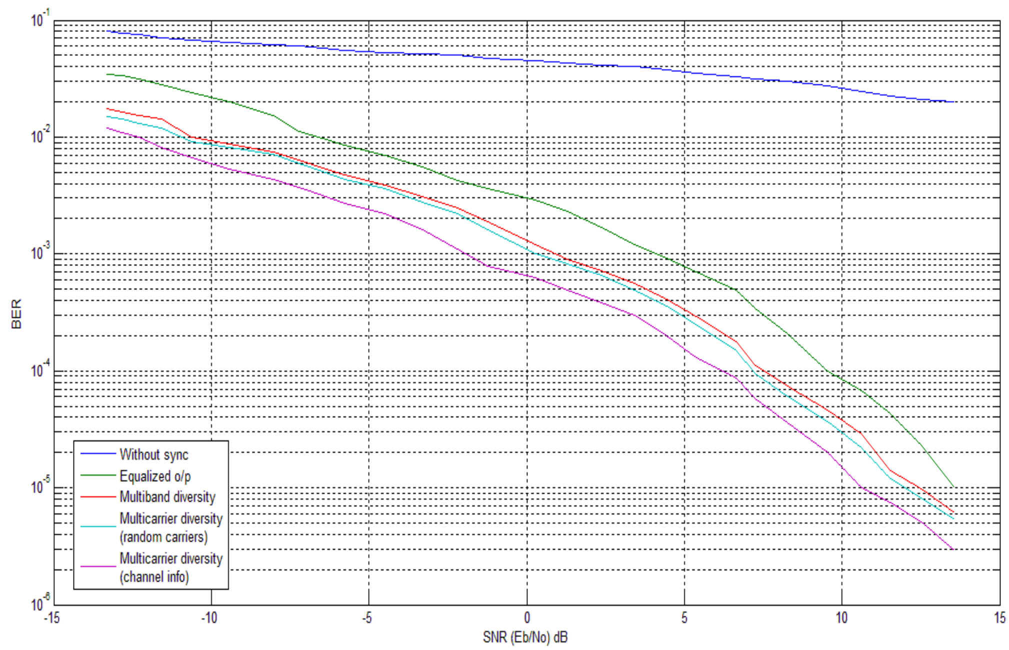
The diagram shows that we send the same data on subcarrier frequencies marked in red and blue and combine their outputs at the receiver to improve the performance. When an OFDM symbol is sent on this band (2.41GHz ~ 2.46GHz), we see that the first subcarrier frequency has less fade and the last subcarrier frequency has more fade. By knowing this channel information, we send the same data on subcarrier 1 and subcarrier 100 sensibly to make full use of multicarrier diversity.

We evaluate the BER performance of the system by performing multiband diversity and multicarrier diversity and see its influence in the following set of diagrams.

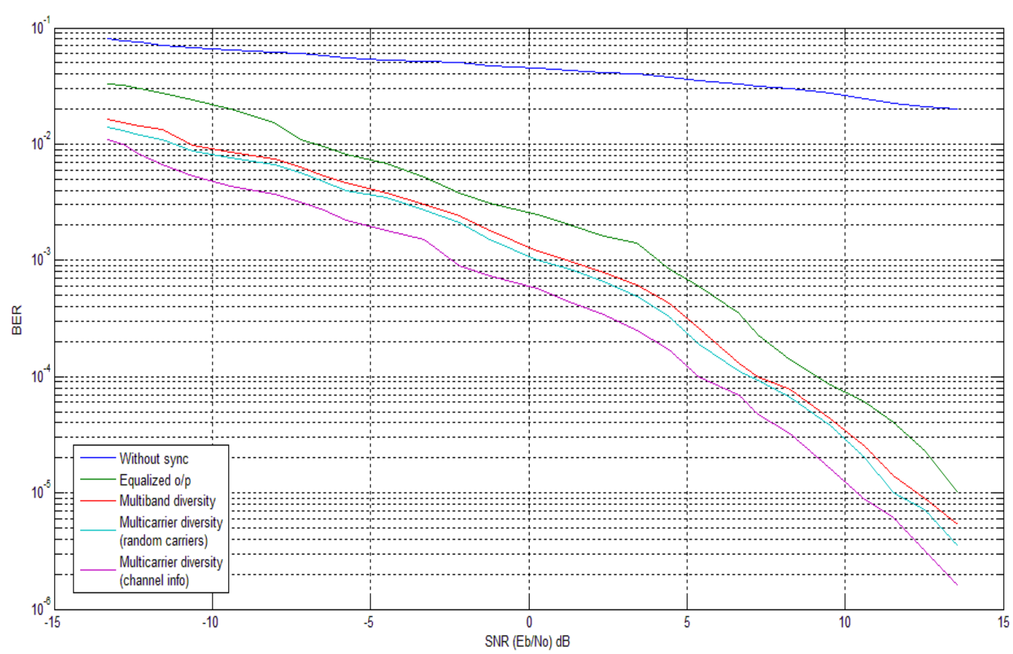


(a) BER curves showing the performance in a UWB channel with $\boldsymbol{\Delta\tau}_n$ = 6 ns, $\boldsymbol{\tau}_0$ = 15 ns, Number of Channel taps = 1

The results show that BER improves by using diversity mechanism. Since we have a tapped delay line channel model with equally-spaced taps ($\boldsymbol{\tau}_n$) and an exponential transfer function, subcarrier frequencies in every OFDM symbol will experience similar fading for constant $\boldsymbol{\tau}_o$ and N.

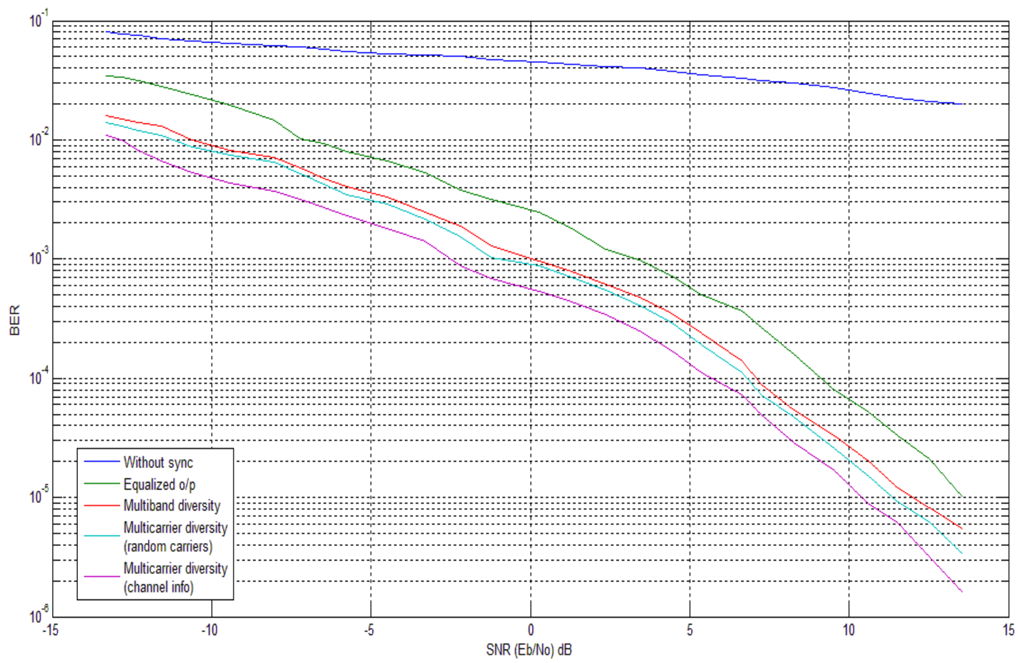


(b) BER curves showing the performance in a UWB channel with $\boldsymbol{\Delta\tau}_n$ = 6 ns, $\boldsymbol{\tau}_0$ = 15 ns, Number of Channel taps = 4

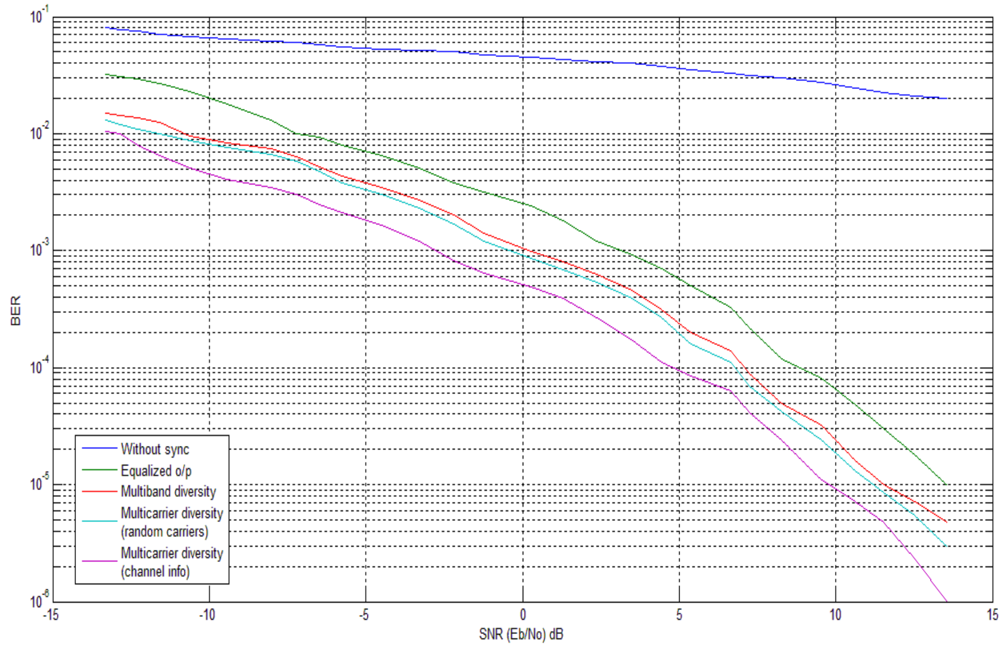


(c) BER curves showing the performance in a UWB channel with $\boldsymbol{\Delta\tau}_n$ = 6 ns, $\boldsymbol{\tau}_0$ = 15 ns, Number of taps = 7

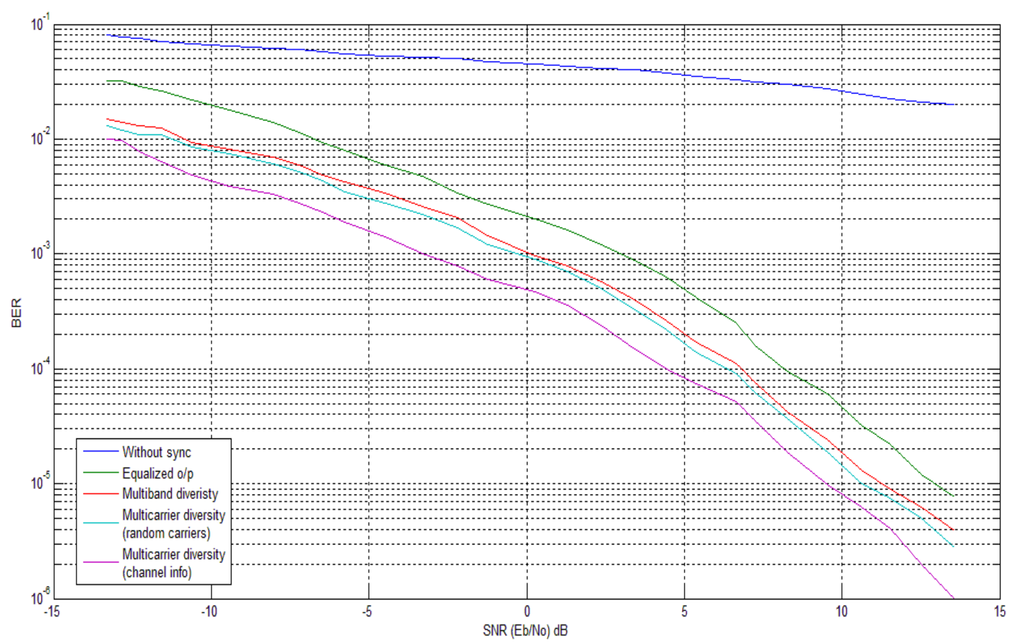
Multicarrier diversity shows a marginal increase in performance over diversity as the chance of sending the data on two frequencies with different fades is high. BER performance is the best when we perform multicarrier diversity knowing the channel information in advance. As the delay between the multipath components is increased ($\boldsymbol{\Delta\tau}_n$ = 12 ns), the overall BER performance of the system improves for both multiband diversity and multicarrier diversity compared to the previous scenario ($\boldsymbol{\Delta\tau}_n$ = 6 ns) considered.



(d) BER curves showing the performance in a UWB channel with $\boldsymbol{\Delta\tau}_n$ = 6 ns, $\boldsymbol{\tau}_0$ = 15 ns, Number of Channel taps = 1



(e) BER curves showing the performance in a UWB channel with $\boldsymbol{\Delta\tau}_n$ = 12 ns, $\boldsymbol{\tau}_0$ = 15 ns, Number of Channel taps = 4

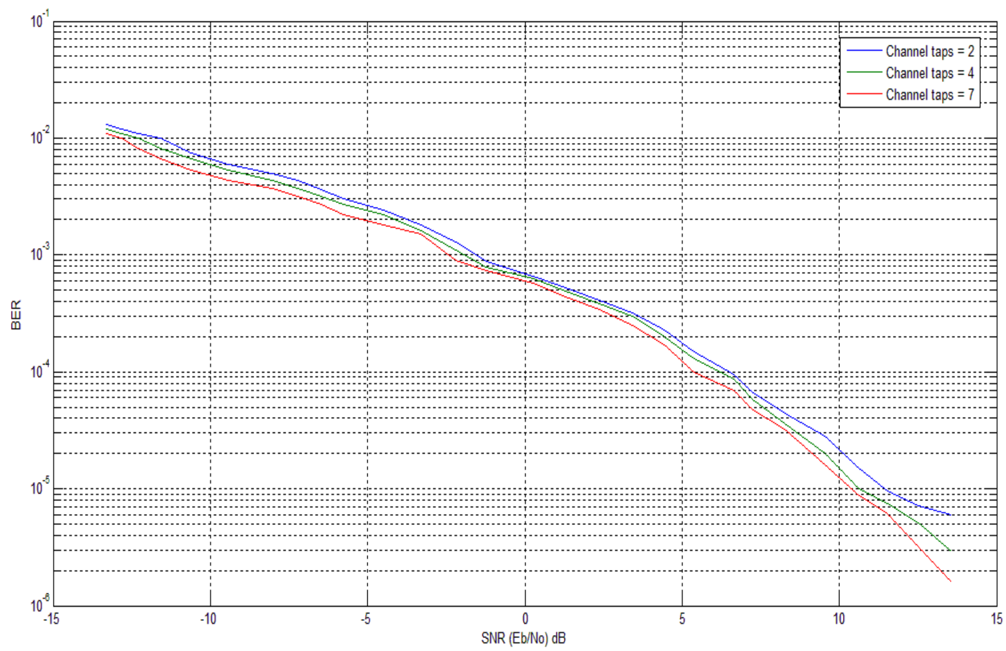


(f) BER curves showing the performance in a UWB channel with $\boldsymbol{\Delta\tau}_n$ = 12 ns, $\boldsymbol{\tau}_0$ = 15 ns, Number of Channel taps = 7

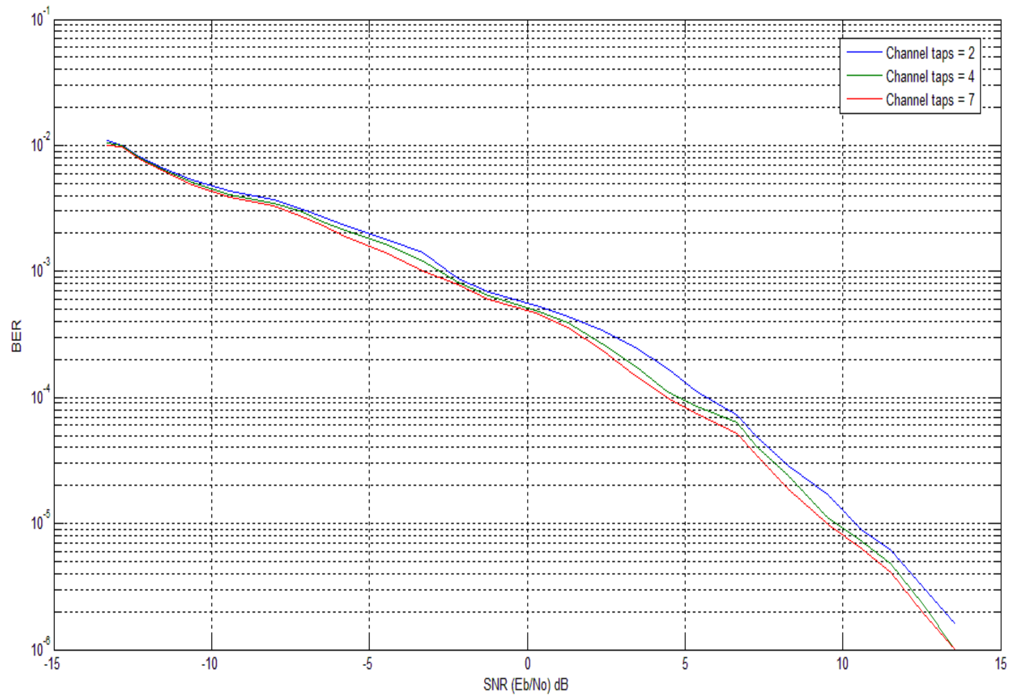
Figure 5.4: BER curves showing the performance in a UWB channel using an equalizer, symbol diversity and multicarrier diversity

5.3 EFFECT OF MULTIPATH COMPONENTS (N):

Experiments were performed to see the influence of multipath components on the BER keeping τ_n and τ_o constant. For the same delay between any 2 consecutive multipath copies (τ_n=3 samples), BER improves marginally when the number of channel taps increases for diversity and multicarrier diversity. Increase in the number of channel taps increases the number of multipath copies of the same signal. The more the number of copies, better is the BER performance. In this experiment, we compare the BER results of the system with no diversity, diversity and multicarrier diversity for different number of multipath components (N).



(a) BER curve showing the performance in a UWB channel with $\Delta\tau_n$ = 6 ns and τ_0 = 15 ns

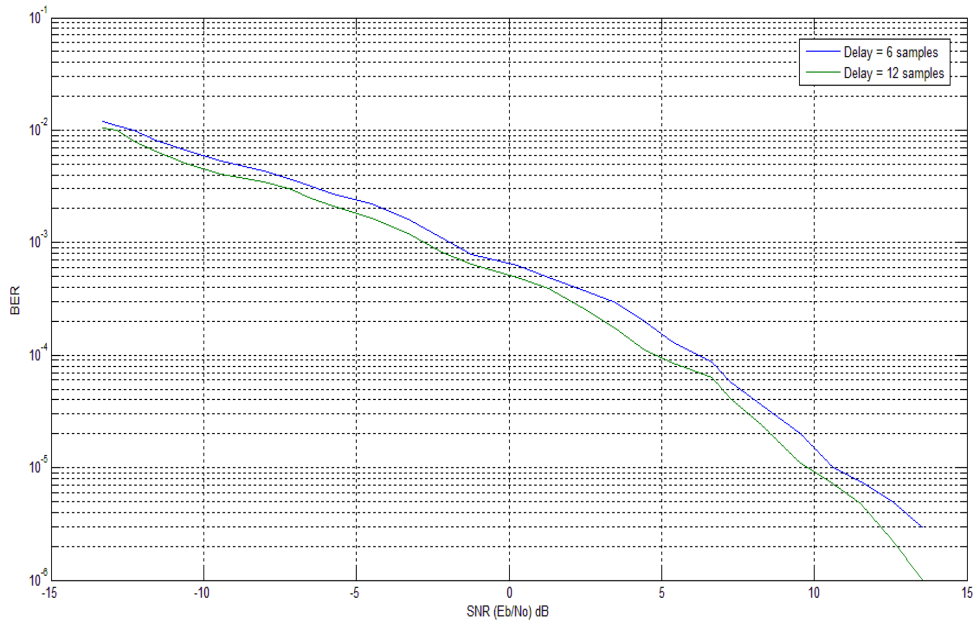


(b) BER curve showing the performance in a UWB channel with $\Delta\tau_n$ = 12 ns and τ_0 = 15 ns

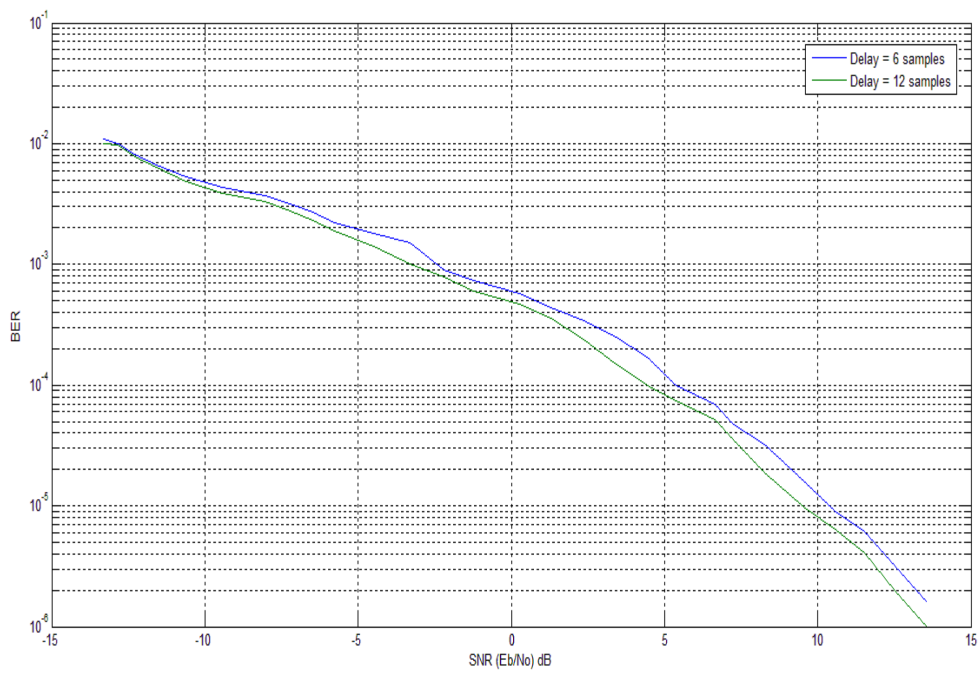
Figure 5.5: BER curves showing the performance in a UWB channel for different values of N

5.4 EFFECT OF τ_n:

Experiments were performed to see the influence of delay between multipath components on the BER keeping N and τ_o constant. As the delay between the multipath components τ_n increases, the channel transfer function becomes more flat with less fade and the BER performance improves. Increase in τ_n decreases the multipath effect decreases and BER also decreases for the same SNR. In this experiment, we compare the BER performance for a system with no diversity/ diversity / multicarrier diversity for different values of τ_n.



(a) BER curve showing the performance in a UWB channel with τ_0 = 15 ns and N=4



(b) BER curve showing the performance in a UWB channel with τ_0 = 15 ns and N=7

Figure 5.6: BER curves showing the performance in a UWB channel for different values of N

Chapter 6

Conclusion and Future Direction

6.1. Conclusion

The thesis explores the design and implementation of a MB-OFDM UWB system on a LabVIEW platform and evaluates its performance by passing the UWB signal through different channel scenarios controlled by few variables. Every OFDM symbol is transmitted on one of those 3 bands depending on the Time Frequency Code (TFC). A low complexity synchronization method was implemented keeping in mind the low power requirement and affordability of UWB devices. A parallel autocorrelator structure performs TFC identification, symbol timing and carrier frequency offset correction together making the synchronization very simple. There was scope for improving the performance by sending the same data on multiple bands or multiple subcarriers within an OFDM symbol to exploit diversity at the receiver. Experiments were conducted to study the relative increase in performance of the system using symbol diversity, multicarrier diversity without knowing channel information and multicarrier diversity knowing channel information in advance. The results show that symbol diversity performance is better than a system with no diversity scheme and multicarrier diversity is better than symbol diversity. BER performance is the best when multicarrier diversity is performed knowing the channel information in advance.

6.2. Future Work

- PAPR REDUCTION

OFDM signal exhibits a high Peak-to-Average Power Ratio (PAPR) and a high PAPR necessitates the Power Amplifier to be linear within a wide dynamic range. PAPR reduction techniques like Tone Reservation and Selective Mapping could be studied.

- MULTIPLE-ACCESS SCHEMES FOR SEVERAL USERS

This system can be extended to TDMA OFDM and OFDMA system for multiple users and its performance could be studied

- DYNAMIC MODULATION TECHNIQUES

The idea of adaptive modulation is to employ high-order modulation schemes at subcarriers with high SNR, and vice versa. With adaptive modulation, the performance of an OFDM system can be greatly enhanced.

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