ABSTRACT

PERFORMANCE EVALUATION OF FIXED AND VARIABLE ZERO PADDING LENGTH IN ULTRA-WIDEBAND RECEIVER DESIGN USING MB-OFDM BASED ON ECMA-368 STANDARD

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Traditional OFDM systems use cyclic prefix (CP) in front of an OFDM symbol to maintain orthogonality. Ultra-wideband (UWB) systems use multiband OFDM approach in implementing applications of Wireless Personal Area Network (WPAN). Federal Communications Commission (FCC) put some regulations on UWB to co-exist with other narrowband and spread spectrum users. MB-OFDM follows OFDM modulation scheme where CP is used but CP introduces a structure into the transmitter due to which the ripples are produced in power spectral density (PSD). Because of these ripples, power back-off is required at the receiver which is as large as 1.5 dB. As an alternative to CP, zero padding (ZP) is used where a flat PSD is obtained which requires zero power back-off. Circular convolution in CP is a natural phenomenon, but for ZP, overlap and add method (OLA) is used to ensure circular convolution.

The ZP length used for OLA method is fixed and equal to 32 samples according to ECMA-368. If timing synchronization estimation errors occur, fixed ZP length may cause intersymbol interference (ISI). So, a variable ZP length is required to avoid ISI depending upon the current band. Hence, a multiband timing synchronization algorithm is proposed to achieve variable ZP length based on current band for OLA method. This method benefits large delay spread channels. Improvement in SNR is achieved at particular bit error rate (BER) for large delay spread channels.

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BY

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CHAPTER 1: INTRODUCTION

Now-a-days, wireless communications and internet services are affecting our everyday life in a considerable amount. Moreover, the thirst for wireless communications is increasing heavily and the wireless communication systems that are based on voice have been already released. High-speed voice communication has become the main goal of present generations. Hence, in order to meet such high data rates, many technologies and systems have been developed such as Bluetooth, WIMAX, Wi-Fi, OFDMA, ultra-wideband, LTE, etc. Due to this development, third generation (3G) and fourth generation (4G) came into existence. Code division multiple access (CDMA) and orthogonal frequency division multiplexing (OFDM) are the base for 3G and 4G wireless communication systems.

WIMAX is a broadband access technology which provides low data rates across a large area. It has no facility of one-to-one connection and faces problems while transmitting signals through walls or buildings. Because of this, there comes a need for a technology which distributes the broadband signals across a short communication range such as inside home or office. When it comes to Wi-Fi, it operates within a range of some access point (AP) and, due to its availability in a spectrum which is very tight, noise is produced. Moreover it requires much power consumption due to which its applications are limited. Even Bluetooth also operates as in the same frequency range of Wi-Fi. Though the consumption of power is low compared to Wi-Fi, the data rates are increased up to 2 megabits per second (Mbps), but presently, people are looking for higher data rates than this. So, even applications of Bluetooth are limited.

There comes the Ultra-wideband technology offering high data rates upto 480 Mbps across a short communication range less than 10m. With such high data rates, downloading movies or copying photos from digital camera can be done quickly in minutes.

Ultra-wideband (UWB) is a rising and wanted technology now-a-days because of its unique applications and is attracted everywhere. UWB is one of the Wireless Personal Area Network (WPAN) standards. It belongs to IEEE standard 802.15TG3a which is of very high-data-rate WPAN. MB-OFDM is the better approach in implementing UWB systems.

There are many advantages of MB-OFDM UWB system as it's benefited by OFDM modulation scheme. The main drawback is timing synchronization error which can introduce severe distortion in MB-OFDM UWB system resulting in intersymbol interference (ISI).

CHAPTER 2: OFDM SYSTEM

Orthogonal frequency division multiplexing is the basis for fourth-generation (4G) technologies. The long-term evolution (LTE) is the most dominant 4G cellular standard. OFDM can support high data rates in excess of 100 Mbps which is crucial in broadband wireless communication systems. Wireless LAN standards are also based on OFDM modulation scheme. Consider the scenario for communications that existed previously before OFDM such as single-carrier system (SCS) and multicarrier modulation (MCM) system.

2.1 Single-Carrier System

In single-carrier system, the information bits are traditionally modulated onto to a single unique carrier of a certain higher frequency. Amplitude, phase or frequency can be changed in order to modulate a carrier signal depending on message signal, i.e., information bits.

$$\mathrm{C(t) = Asin(\omega t + \theta)} \tag{2.1}$$

where A is amplitude, ω is frequency and θ is phase of carrier signal.

Consider a bandwidth 'B' is available for communication. The whole bandwidth B is occupied by the single carrier. Hence, one symbol is transmitted every T seconds, T=symbol rate=1/B sec. S(t) is the transmitted signal. The block diagram which shows the functioning of single-carrier system is shown in Figure 1.

$$\mathrm{S(t) = X(k), \quad where\ kT \leq t \leq (k+1)T} \tag{2.2}$$

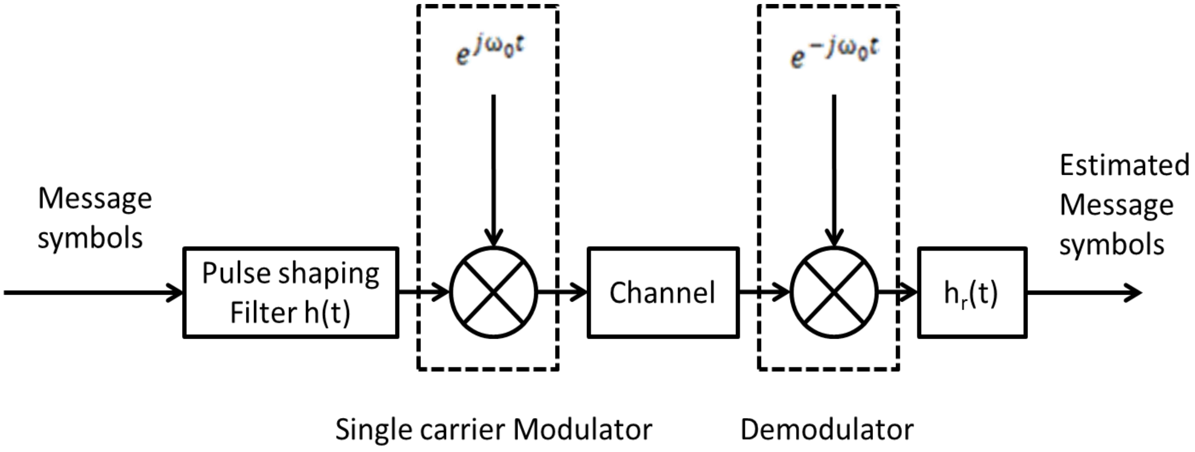


Figure 1: Block diagram of single-carrier system.

A single modulator and demodulator are required to implement single-carrier system. The symbol duration to transmit a bit becomes lesser when need for bandwidth increases which makes single-carrier system to lose information easily. Because of this information loss, symbol recovery at the receiver becomes difficult. Moreover, increasing the bandwidth increases the chance of interference with other sources. Hence, single-carrier system is prone to intersymbol interference (ISI), which is a frequency-selective fading case.

2.2 Multicarrier System (MCM)

In multicarrier system, instead of taking a single-carrier, multiple subcarriers are taken with a spacing of B/N [1]. Here, bandwidth is decomposed into multiple sub-bands. Each subcarrier represents a sub-band. Hence, each subcarrier has a smaller bandwidth when compared to single-carrier system. In MCM, the serial data is divided into several parallel data with the help of a multiplexer where each parallel stream modulates a subcarrier accordingly. The bandwidth B which is available for communication is divided into N subcarriers where each subcarrier has a bandwidth equal to B/N. The value of N is a power of 2 typically such as 256, 512, 1024, 2048. Consider an example of a system which has a bandwidth B=1024 KHz and N=256, then the bandwidth of each sub band or subcarrier is 1024/256=4 KHz. The ith subcarrier center frequency is given by

$$f_i = \frac{iB}{N}, \qquad \text{where} -\frac{N}{2} + 1 \leq i \leq \frac{N}{2} \tag{2.3}$$

2.2.1 Multicarrier Transmission

The data symbols that are to be transmitted are converted from serial form to parallel. Each parallel stream modulates a subcarrier as shown in Figure 2. Let $0 \leq i \leq N - 1$; symbol Xi is the data to be transmitted on ith subcarrier. The modulated signal on this subcarrier is considered as Si(t) which is given by the following equation.

$$S_i(t) = X_i e^{j2\pi fit} = X_i e^{j2\pi i\frac{B}{N}t} \tag{2.4}$$

$$S(t) = \sum_{i=0}^{N-1} S_i(t) = \sum_{i=0}^{N-1} X_i e^{j2\pi i\frac{B}{N}t} \tag{2.5}$$

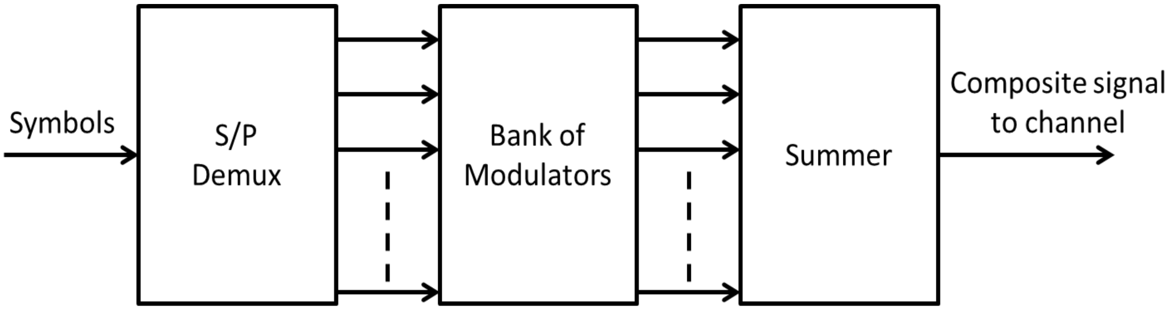


Figure 2: Block diagram of multicarrier transmitter.

N data symbols, X_i modulates N subcarriers of composite symbol of MCM. This MCM composite symbol transmits N data symbols for every N/B seconds. Hence the transmission time of subcarrier increases to N/B when compared to single-carrier transmission time 1/B. The overall symbol rate remains the same for MCM system as it consists of N data. Comparison of symbol time of single-carrier and multicarrier transmitter is shown in Figure 3.

$$\text{symbol rate} = \frac{\mathrm{N}}{\mathrm{N}/\mathrm{B}} = \mathrm{B} = \text{symbol rate of single} - \text{carrier system}$$

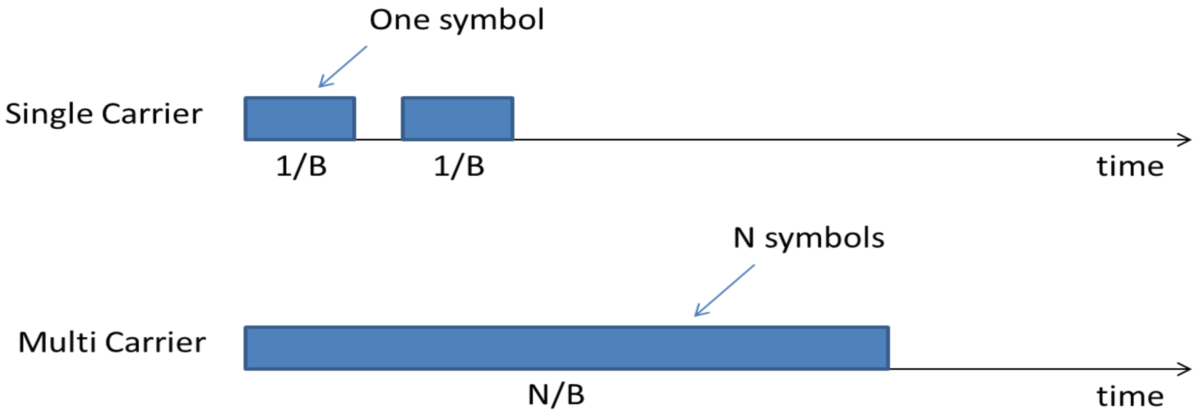


Figure 3: Symbol time comparison of single-carrier and multicarrier transmitter.

2.2.2 Multicarrier Detection

At the receiver end, in order to recover data related to N subcarriers one needs to demodulate accordingly with each subcarrier. Multicarrier receiver block diagram is shown in Figure 4. Consider the received composite signal as y(t); y(t) is sent through a repeater in order to create N number of copies of received signals. These copies then pass through a bank of demodulators or co-relators where demodulation is done using the conjugate of subcarriers. X_i $(0 \leq \mathrm{i} \leq \mathrm{N}-1)$ is the output recovered at the receiver.

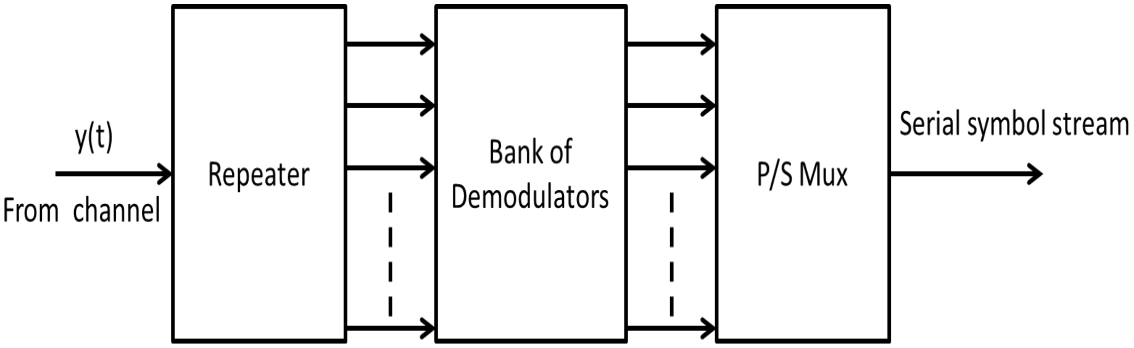


Figure 4: Block diagram of multicarrier receiver.

Demodulating the received signal with lth subcarrier in order to recover data symbol X_l is shown in equations 2.6 and 2.7

$$y(t) = S(t) \tag{2.6}$$

$$X_l = \frac{B}{N}\int_0^{\frac{N}{B}} y(t)\, e^{-j2\pi flt} dt$$

$$= \frac{B}{N}\int_0^{\frac{N}{B}} \sum X_i e^{j2\pi i\frac{B}{N}t}\, e^{-j2\pi fit} dt$$

$$= \frac{B}{N}\sum_k \int_0^{\frac{N}{B}} X_i\, e^{j2\pi kfot},\ \text{where } k = i - l, f_0 = \frac{B}{N} \tag{2.7}$$

$$= \begin{cases} 0 & \text{if } i \neq l \\ X_l & \text{if } i = l \end{cases}$$

Except lth subcarrier, all the other subcarriers are orthogonal. Hence X_l can be easily recovered as all the other subcarriers become zero. To recover symbols corresponding to N subcarriers, coherently demodulate with the conjugates of subcarriers respectively. Rectangular window of time associated with detection of this multicarrier signal is N/B, i.e., the time period of integration, which is the time taken to transmit an MCM composite symbol. This scheme is the basis for OFDM. The advantage of MCM system is to remove ISI when compared to single-carrier system. As known, the coherence bandwidth B_c should be of the range 200 to 300KHz.

As bandwidth of each subcarrier is less than coherence bandwidth, the channel becomes flat fading and no ISI is seen.

2.3 Frequency Division Multiplexing System

In frequency division multiplexing system for separating the channels the guard intervals are introduced and filtering is done to reduce interference as shown in Figure 5. Band-pass filters are required to separate and extract information at the receiver. But the usage of guard interval or bands reduces the spectrum efficiency. Also the realization of filter banks is complex.

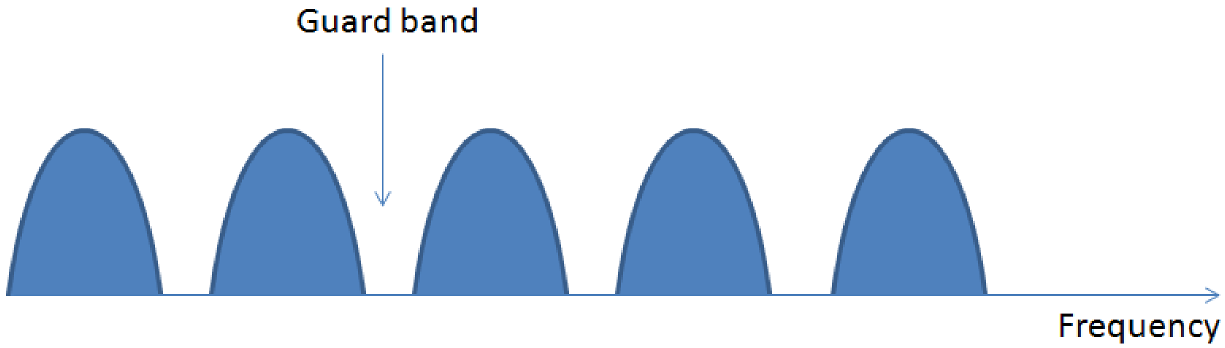


Figure 5: Spectrum of frequency division multiplexing system

This problem is eliminated in orthogonal frequency division multiplexing system by making the subcarriers orthogonal. This increases the spectral efficiency of the system as no guard bands are required and transmission system capacity also increases.

2.4 Orthogonal Frequency Division Multiplexing System (OFDM)

Multicarrier transmission is the basic idea behind OFDM, where a single data stream is transmitted over a large number of subcarriers. OFDM is a key broadband wireless technology which supports data rate in excess of 100 MBPS. It is a combination of modulation and multiplexing. It consists of N orthogonal subcarriers which increase the spectral efficiency as the spectrum of OFDM overlaps. The subcarriers are made orthogonal by keeping carrier spacing at multiple of 1/NT (OFDM symbol time). Thus, carrier interference gets reduced. As can be seen from the Figure 6, the maximum of one subcarrier coincides with the zero of adjacent subcarriers.

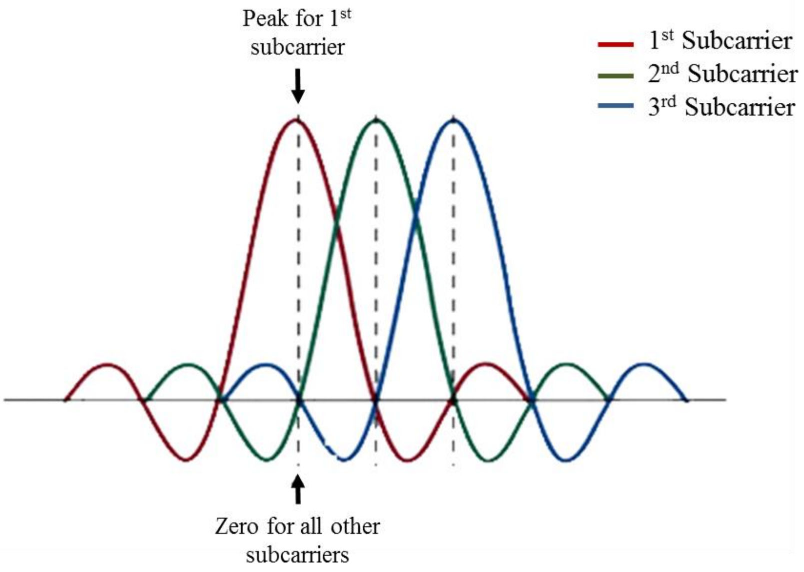


Figure 6: Spectrum of OFDM system.

It is a challenge to implement one correlator and decorrelator which results in difficulty in implementing N number of modulators and demodulators. Large number of hardware components is required. Hence, the practical reliability of MCM system is low. There was a key advancement made by Weinstein and Ebert [2] in data transmission by using discrete Fourier transform (DFT) for frequency division multiplexing.

Consider composite MCM transmit signal S(t) which is band limited to 'B' sampled at nyquist rate where $t = UT_s = U/B$:

$$S(t) = \sum X_i e^{j2\pi i \frac{B}{N} t}, \quad \text{where} -\frac{N}{2} + 1 \leq i \leq \frac{N}{2} \qquad (2.8)$$

$$\mathrm{S}(\mathrm{UT_s}) = \mathrm{x}(\mathrm{u}) = \sum \mathrm{X_i} e^{j2\pi i \frac{BU}{NB}} \tag{2.9}$$

$$\mathrm{x}(\mathrm{u}) = \sum \mathrm{X_i} e^{j2\pi i \frac{U}{N}} \tag{2.10}$$

The obtained result is the inverse discrete Fourier transform (IDFT) of data symbols X_i. Thus, this result says that there is no need for modulators and demodulators. All that is needed are sample signals which are information symbols. DFT and IDFT can be replaced by FFT and IFFT for faster implementation as the number of calculations is decreased and the speed of functioning is increased. The composite MCM transmit signal can therefore be simply generated by using IFFT operation. This enhances the practical reliability of MCM system. OFDM is considered as the generation of signal. To recover the original data symbols at the receiver, FFT operation is used.

2.4.1 OFDM Transmitter

Using BPSK, QPSK or M-QAM, the information or message symbols are generated and those are converted from serial to ‘N’ parallel streams. Then IFFT operation is implemented to make ensure each subcarrier gets the ease of modulation with message or information symbols. The set of modulated subcarriers comprise of an OFDM symbol. Hence, each OFDM symbol consists of N original message symbols. Parallel to serial conversion is done and finally cyclic prefix is added in order to resist against multipath propagation. OFDM transmitter block diagram is shown in Figure 7.

$$\mathrm{x_n} = \sum_{k=0}^{N-1} \mathrm{X_k} e^{\frac{-j2\pi kn}{N}}, \qquad 0 \le n \le N-1 \tag{2.11}$$

Where x_n is OFDM symbol, X_k are the message symbols.

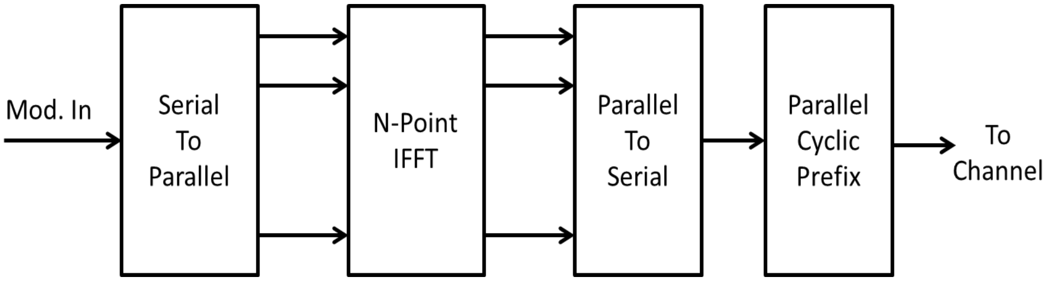


Figure 7: Block diagram of OFDM transmitter.

2.4.2 OFDM Receiver

The incoming OFDM symbols from channel get processed in order to remove the cyclic prefix. Then serial to parallel conversion is done and instead of complicated demodulation process, a simple N point FFT operation block is used. Original message symbols are recovered and converted into a serial stream. OFDM receiver block diagram is shown in Figure 8.

$$X_k = \sum_{n=0}^{N-1} x_n e^{\frac{-j2\pi kn}{N}}, \ 0 \leq k \leq N-1 \qquad (2.12)$$

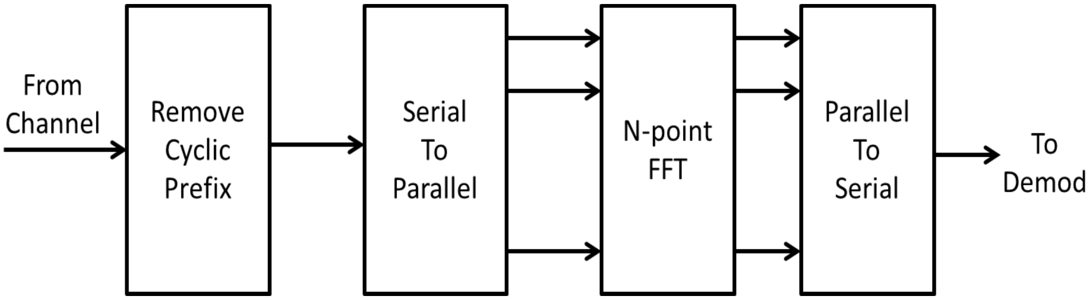


Figure 8: Block diagram of OFDM receiver.

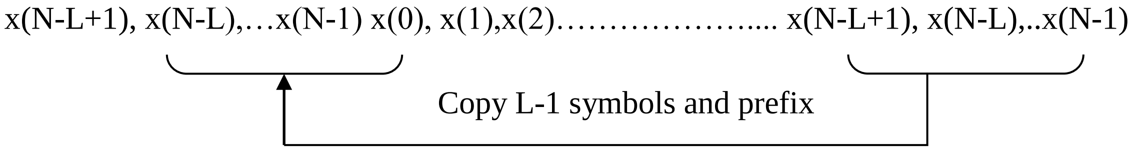
2.5 Cyclic Prefix

The OFDM scheme is not ready to use until cyclic prefix is added. In an OFDM system, cyclic prefix is used in order to maintain orthogonality among subcarriers even in multipath channel. The composite transmitted symbol or the OFDM symbol {x(0), x(1),…..x(N-1)} corresponds to the IFFT of X(0), X(1),…..X(N-1) transmitted at rate B.

Consider $\tilde{x}(0), \tilde{x}(1), \dots\dots \tilde{x}(N-1)$ as input symbols of previous OFDM symbol and $x(0), x(1), \dots\dots x(N-1)$ as input symbols of current OFDM symbols. Consider frequency-selective channel which can be modeled as multipath channel or FIR filter h(0), h(1),……..h(L-1) with L taps. The head part of the received signals of current OFDM symbol block are affected by ISI from previous OFDM block as shown in Figure 9.

Figure 9: Intersymbol interference due to multipath fading.

There is interference from previous OFDM symbol as the initial samples are affected by ISI. To eradicate this situation, cyclic prefix is implemented by taking the last ‘L’ data symbols from the current OFDM symbol and prefixing it at the head part.



The received symbols y(0), y(1),…..y(N-1) are free from ISI after applying cyclic prefix.

$$y(0) = h(0)x(0) + h(1)x(N-1) + h(2)x(N-2) + \dots\dots h(L-1)x(N-L+1)$$

$$y(1) = h(0)x(1) + h(1)x(0) + h(2)x(N-1) + \dots\dots\dots h(L-1)x(N-L+2)$$

$$\vdots$$

$$\mathrm{y(N-1) = h(0)x(N-1) + h(1)x(N-2) + \ldots\ldots.\ldots...\ldots h(L-1)x(N-L)}$$

So by prefixing last part of current OFDM symbol, ISI is removed from previous OFDM symbol. As ‘x’ is shifted circularly, the nature of convolution here is circular.

$$\mathrm{[y(0)y(1)\ldots\ldots y(N-1)] = [h(0)\ h(1)\ldots..h(L-1)] \circledast [x(0)x(1)\ldots\ldots x(N-1)]}$$

$$\mathrm{y = h \circledast x} \qquad (2.13)$$

$$\mathrm{Y(k) = H(k).X(k)} \qquad (2.14)$$

where Y(k) is received symbol across k^{th} subcarrier, H(k) is channel coefficient corresponding to k^{th} subcarrier and X(k) are modulated information symbols(QAM, PSK, BPSK etc.) loaded onto k^{th} subcarrier. The output is therefore channel multiplied by symbol coefficient. Hence, the frequency-selective channel is converted into a group of narrowband flat fading channels with one channel across each subcarrier as shown in Figure 10.

$$\mathrm{H(0)H(1)\ldots.H(N-1) = N\ pt\ FFT\ of\ [h(0)\ h(1)\ldots..h(L-1)]}$$

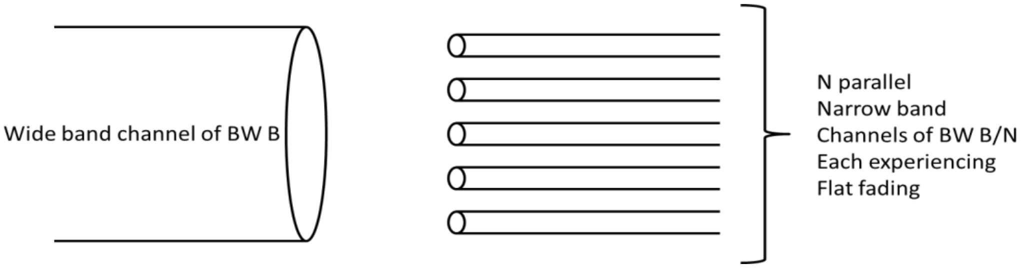


Figure 10: Frequency-selective channel converted to set of parallel flat fading channels.

A simple detection scheme can now be used for X(k) using zero forcing (ZF), minimum mean squared error equalizer (MMSE) or matched filter. The length of cyclic prefix should be greater than delay spread of channel on order to remove ISI. Since, the symbol is repeated there is low transmitter efficiency.

$$\text{Loss in efficiency} = \frac{L-1}{N+L-1} \tag{2.15}$$

Hence, as N (the length of FFT window) increases, the loss in spectral efficiency becomes closer to zero and only a smaller fraction is affected by ISI. But if there is an increase in N, then the decoding delay of the system increases. Hence, there is a tradeoff for increasing N vs decoding delay. Intuitive framework to understand CP is that in order to overcome multipath fading, the length of cyclic prefix must be more than the delay spread of the channel.

$$N_{CP} \times T_S \geq T_d \tag{2.16}$$

$$N_{CP} \geq B \times \frac{1}{2B_C}$$

$$\text{For efficiency} \qquad N \gg N_{CP} \gg \frac{B}{2B_C}$$

$$\therefore\ B_C \gg \frac{B}{N} \tag{2.17}$$

where N_{CP} = number of symbols used in cyclic prefix, T_S = symbol time, T_d = delay spread of channel, B_C = coherence BW, B is BW of system and B/N is BW of each subcarrier. Thus, the bandwidth of each subcarrier is less than the coherence BW and hence the designed OFDM system converts a frequency-selective fading channel into a group of parallel narrowband flat fading channels.

2.6 Applications of OFDM

So far, the OFDM system is used in many wireless communication standards as shown below:

- IEEE 802.15.3a Ultra-wideband (UWB) Wireless PAN

- IEEE 802.11a/g/ n (Wi-Fi) Wireless LANs
- IEEE 802.16d/e (WiMAX), WiBro, and HiperMAN, Wireless MANs
- IEEE 802.20 Mobile Broadband Wireless Access (MBWA)
- DVB (Digital Video Broadcast), DAB (Digital Audio Broadcast) systems
- Downlink of 3GPP UMTS, 3GPP LTE (long-term evolution), and 4G communication systems.

2.7 Advantages of OFDM

- Spectrum utilization is done efficiently as orthogonal subcarriers are overlapping.
- Addition of cyclic prefix converts a frequency-selective channel into a group of parallel narrowband flat fading subchannels.
- Also, addition of cyclic prefix results in reduction of intersymbol interference.
- Equalization of channel for an OFDM system becomes simpler than for a single-carrier system.

2.8 Disadvantages of OFDM

- Carrier frequency offset can introduce severe distortion in OFDM system resulting in loss of orthogonality among subcarriers.
- Timing synchronization estimation errors which cause intersymbol interference in OFDM system.

CHAPTER 3: ULTRA-WIDEBAND TECHNOLOGY

3.1 Wireless Personal Area Network (WPAN)

Ultra-wideband (UWB) technology is one of the Wireless Personal Area Network (WPAN) standards (Figure 11).

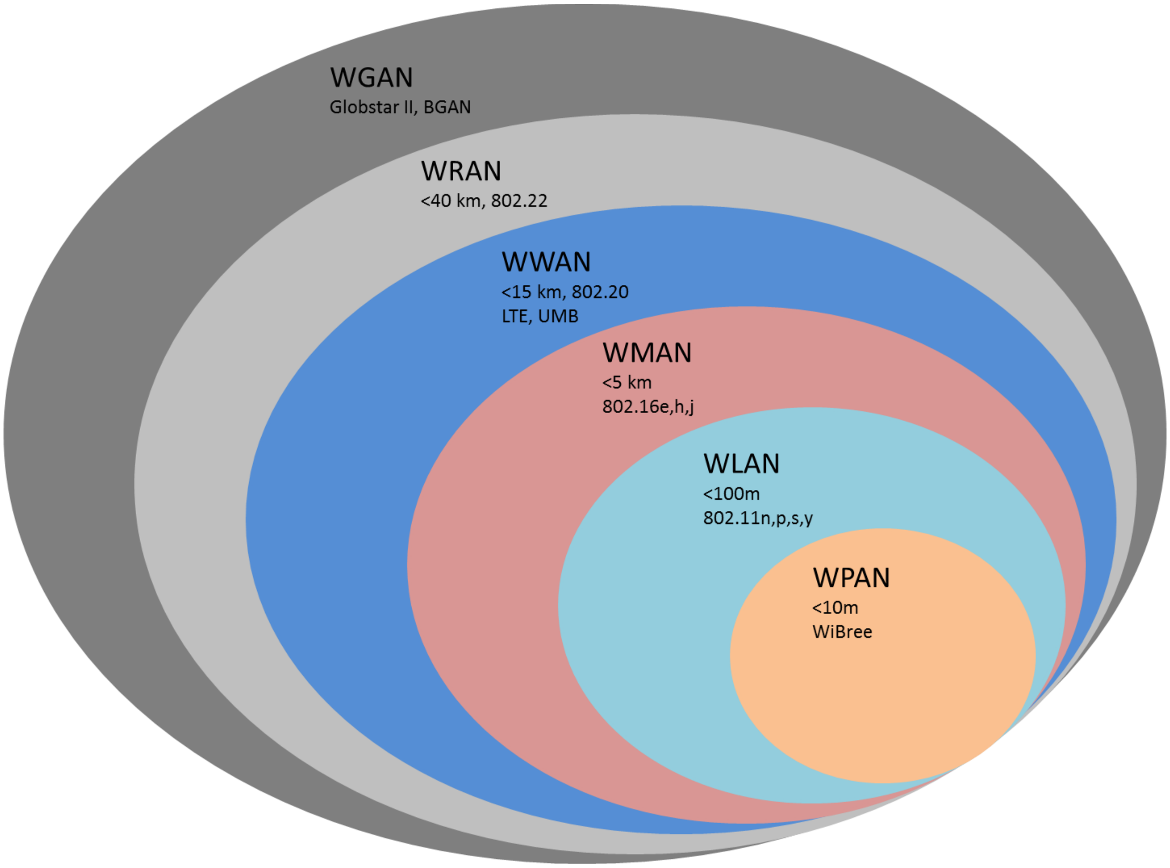


Figure 11: Six layered complementary wireless communication technologies [3]

Wireless Personal Area Network (WPAN) is a low-range wireless personal (or rather, person-centric) area network in which the devices are connected through wireless around an individual workspace. WPAN with its technology can communicate within short range (about 10 meters). WPAN can also be defined as personal operating space (POS), which simply is the area in the near vicinity of a device or individual. Bluetooth is one of the short-range wireless technologies that was used as the basis for a new standard, IEEE 802.15.

WPAN covers only a few dozen meters, so WPAN is generally used to link peripheral devices like printers, cell phones, office or home appliances or two computers in a room with no use of wire as illustrated in Figure 12. Figure 13 shows the emblems of different wireless standards of personal area network.

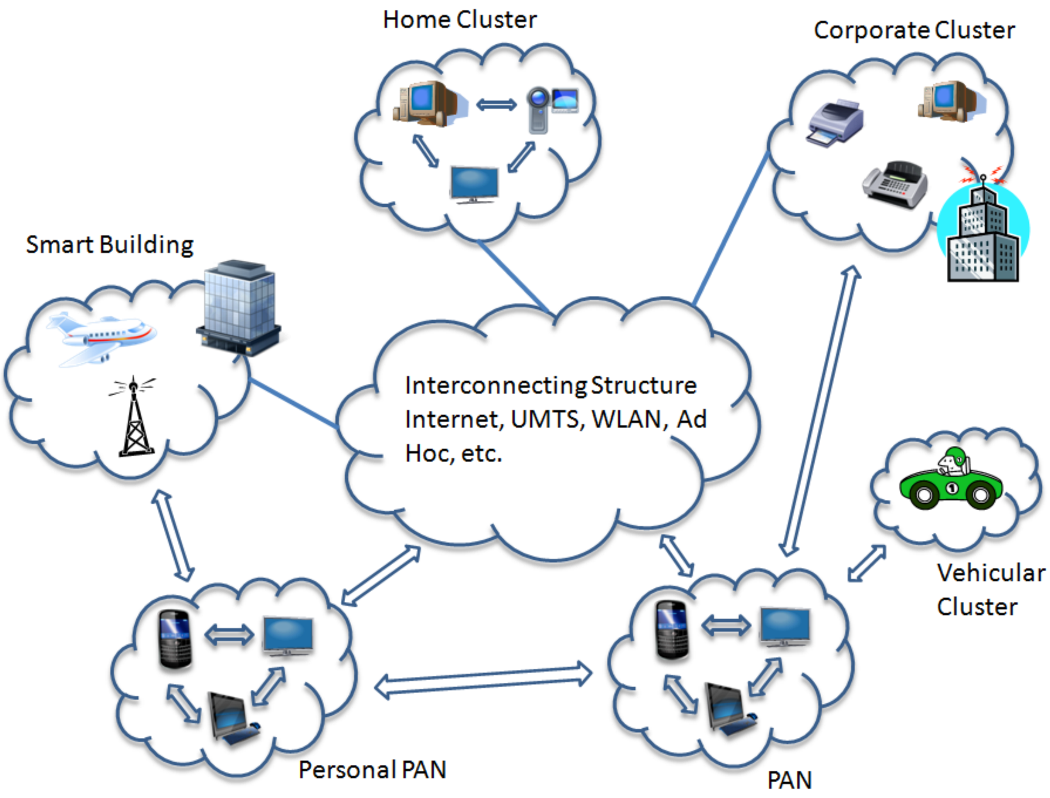


Figure 12: Concept of Wireless Personal Area Network [3]

Figure 13: Various WPAN standards [3]

Bluetooth is the main WPAN technology. Bluetooth was launched by Ericsson in 1994, which offers a maximum throughput of 1 Mbps over a maximum range of about thirty meters. Bluetooth is very energy efficient so that makes it well suited for its use in small devices. Bluetooth is also known as IEEE 802.15.1.

HomeRF can cover a range of about 50 to 19 meters without an amplifier and it has a maximum throughput of 10Mbps.

ZigBee can cover a range of about 100 meters and can reach transfer speeds of up to 250Kbps. ZigBee operates on 16 channels on a frequency band of 2.4 GHz. ZigBee is also known as IEEE 802.15.4. ZigBee is used for connecting devices at low cost with less energy consumption. This makes ZigBee directly installed into small electronic devices like toys and stereos.

UWB has high data rates from 53.3 Mbps to 480 Mbps over a short range of few dozen meters. It belongs to IEEE standard 802.15TG3a. UWB is thus, an enabling technology for WPANs (Figure 14).

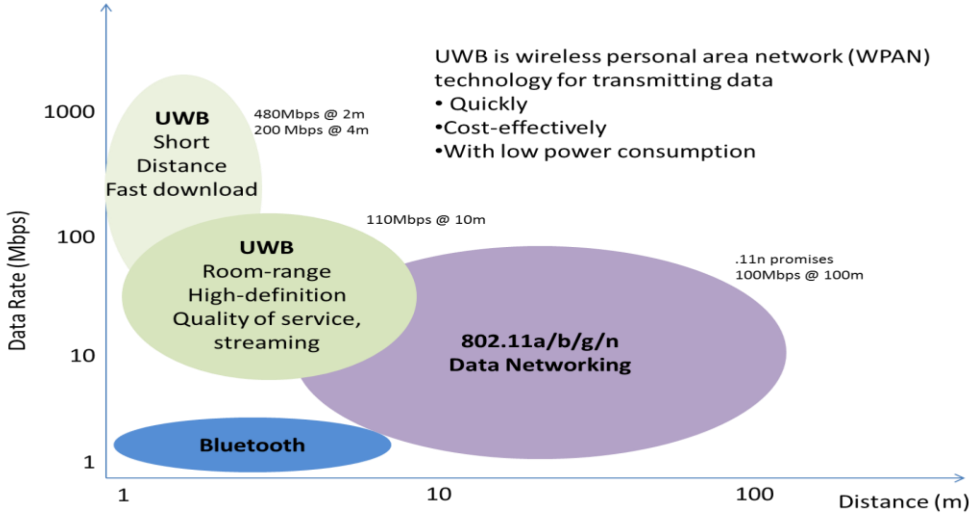


Figure 14: Position of UWB in WPAN [3]

3.2 Ultra-wideband (UWB)

Ultra-wideband technology is a radio technology. The impulse modulation of ultra-wideband signals are shown in Figure 15. It shows the time domain and frequency domain behavior of modulated signals for ultra-wideband and narrowband communication.

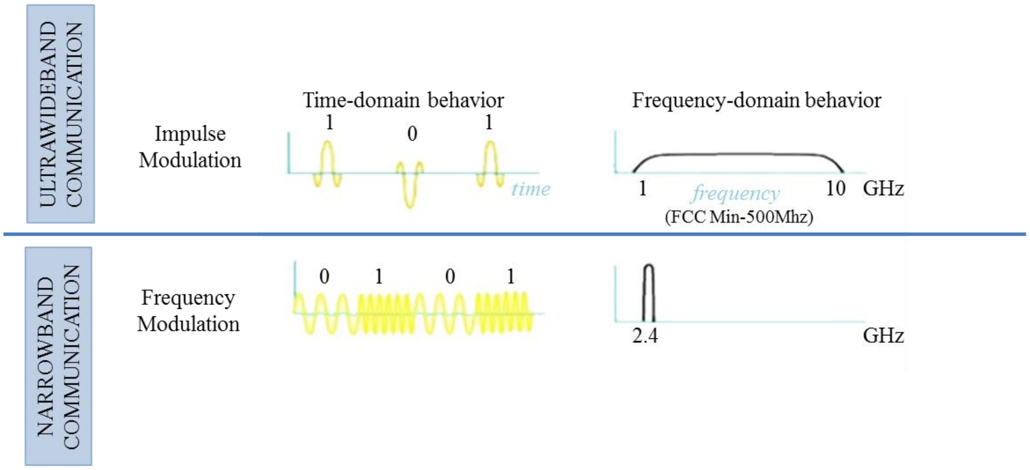


Figure 15: Behavior of Ultra-wideband and narrowband communications in time and frequency domains.

3.3 Overlay of UWB According to FCC

In previous days, ultra-wideband was used only for military purposes. Later in 2002, the Federal Communication Commission (FCC) introduced regulations and the use of UWB for commercial purposes is allowed with restrictions on power.

As per FCC, UWB is a radio technology which offers high bandwidth greater than 500 MHz across a less accessible range less than 10m with 10 dB power levels. This can be explained by the Shannon’s channel capacity equation as follows:

$$\mathbf{C = W. \log_2(1+(S/N))}$$

where C = channel capacity

W = channel bandwidth

S/N = signal power to noise ratio

Here, in order to gain more channel capacity (i.e., bit rate), instead of increasing the signal power to noise ratio which is logarithmically related to channel capacity, it is easier to increase the bandwidth which is linearly related to channel capacity. UWB is a broadband spectrum which has more data rates but the communication range is low as there are some restrictions on power levels for UWB by FCC. As per the Figure 16, the UWB has a wide spectrum which ranges from 3.1 GHz to 10 GHz i.e., 7.5 GHz.

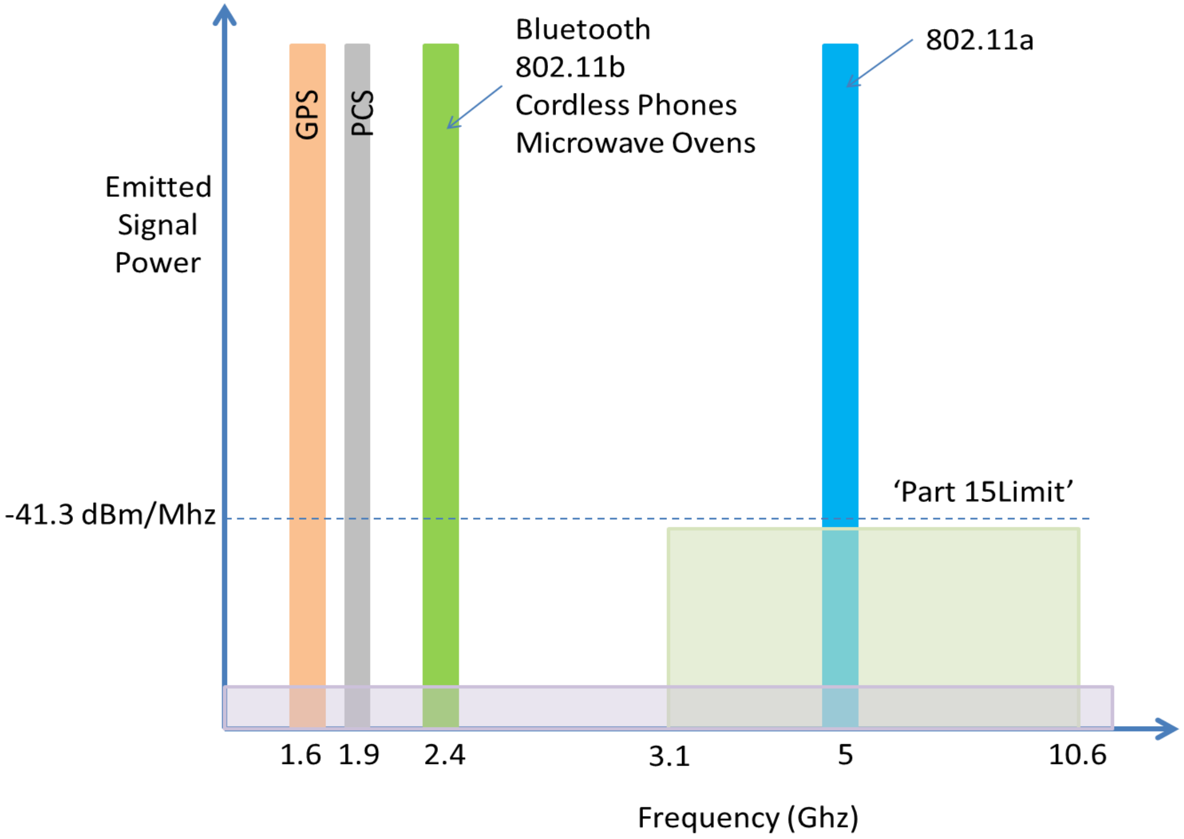


Figure 16: Overlay of UWB according to FCC [3]

According to FCC, the restrictions on UWB limit it to a short-range communication and high data rates are possible. UWB is not particularly defined as some fixed technology; any technology or system which consists of 20% of its central frequency or bandwidth greater than 500 MHz can be called UWB. Figure 16 shows that the UWB lies along with other narrowband and spread-spectrum users without interfering because of the power spectral density regulation set by FCC not to be greater than -41.3 dBm/MHz.

3.4 Advantages of Ultra-wideband Technology

Because of the benefits of ultra-wideband, it has many advantages in applications for wireless communications as well as radar communications.

1) Huge free spectrum of 7.5 GHz

Because of availability of such wide spectrum, people are attracted to this technology which has numerous applications in real life and usage of such wide spectrum increases the spectral efficiency.

2) Co-existence with other narrowband and spread spectrums

Because of the regulations set by FCC on power spectral density (PSD) spectrum of UWB as -41.3 dBm/MHz, it is able to co-exist with other narrowband and spread-spectrum users.

3) Power consumption is very low

The power consumption is very low for UWB because of the OFDM modulation scheme used and the zero padded suffixes.

4) High data rates possible

With UWB, high data rates ranging from 53 Mbps to 480 Mbps can be achieved across a communication range of 2 m to 15 m.

5) UWB is very resistant to multipath propagation

The OFDM modulation scheme benefits UWB with its features such as spectral efficiency and resistance to multipath fading. Hence, UWB becomes robust to multipath propagation because of OFDM modulation scheme.

3.5 Applications of Ultra-wideband Technology

There are many applications of UWB in wireless communications as well as radar communications. The commercial applications of UWB in wireless communications and radar communications are as follows:

1) Wireless home networking

2) Wireless Universal Serial Bus (USB)

3) Wireless mouse

4) Wireless speakers

5) Wireless keyboard

6) Wireless sensors

7) Wireless Personal Area Network (WPAN) applications

8) Transferring data at high rates

9) Vehicular radar airbag

10) Handheld walkie-talkie

Figure 17 depicts the applications of ultra-wideband technology.

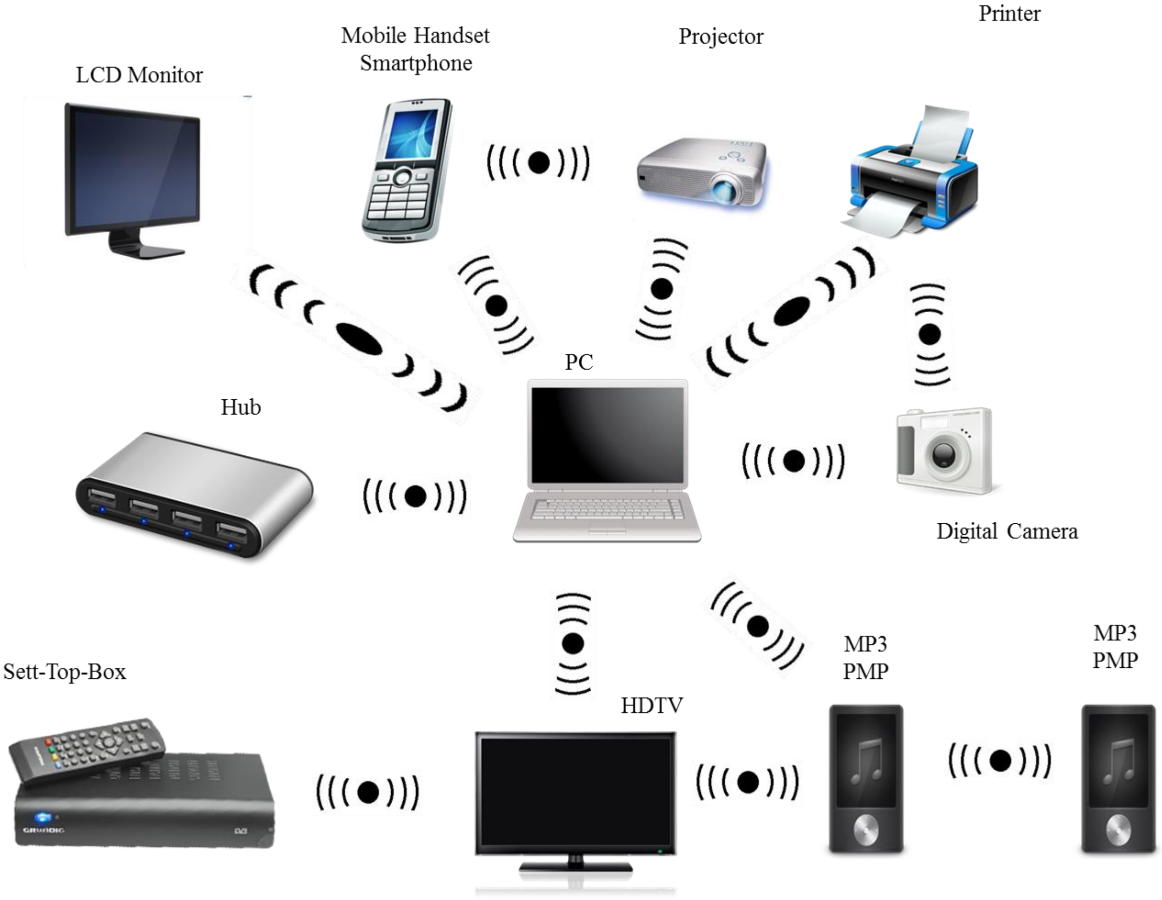


Figure 17: Applications of UWB: Home networking and wireless USB [3]

3.6 Challenges for Ultra-wideband Technology

Though UWB has many advantages, there are some factors that are to be considered for the successful growth of this technology in the present world. The factors that are to be considered are narrowband interference (NBI), timing synchronization estimation techniques, multiple access interference (MAI), UWB channel modeling, design of transmitter and receiver accordingly and finding the channel delay and spread coefficients. Thus, there are many challenges in designing UWB system effectively. The challenges in designing of UWB system are listed as follows:

1) Restrictions on PSD of UWB, which question the existence of UWB along with other narrowband and spread-spectrum users.

2) Usage of such high bandwidth of 7.5 GHz.

3) Designing of low-noise amplifiers, analog to digital converter (ADC), digital to analog converter (DAC), etc.

4) UWB channel modelling in various noise environments.

5) Achievement of low power levels.

3.7 Generation of UWB Signals

Usually there are two approaches to generate UWB signals. They are as follows:

1) Single-band UWB (impulse UWB or direct spectrum UWB)

2) Multiband OFDM UWB (MB-OFDM UWB)

3.8 Direct-Spectrum UWB

Single-band UWB systems use short time-domain pulses of the order of 500 ps to 2 ns to occupy the wide spectrum. The information is then transmitted by modulating these time-domain pulses either in time or in frequency. Generation of this transmitted signal using analog circuitry is simple. But such an extreme wide spectrum makes the design of analog and mixed signal circuitry such as analog to digital converter (ADC), digital to analog converter (DAC), etc., an uphill task. Moreover, high frequency makes power consumption to shoot up and hence makes this approach less attractive.

Another challenge of this approach is it requires a large number of fingers in RAKE receiver in order to capture sufficient energy in a dense multipath scenario, making the baseband design quite complex. Hence, we go for the other approach.

CHAPTER 4: MULTI BAND OFDM UWB (MB-OFDM UWB)

Usage of such huge spectrum poses a challenge to the UWB system designers. Hence, this approach is described as follows:

The huge spectrum of 7.5 GHz is divided into several sub-bands. As per regulations of FCC, each sub-band consists of a bandwidth greater than 500 MHz and then the signals are transmitted in time domain pulses across these sub-bands. This method is known as Pulsed multiband technique. Pulsed multiband technique removes the problem of high power consumption by taking time-domain pulses of order 2 nanoseconds to 4 nanoseconds. This technique makes use of some modulation techniques such as pulse position modulation (PPM) and binary phase shift keying (BPSK) in order to modulate the transmitted time domain pulses.

This method reaps many benefits as the information is simulated across different sub-bands which results in low power levels, cost and complexity of designing a system. This increases the benefits of spectral effectiveness of the system. Moreover, the time for a band to be in a given state is 4 nanoseconds to 8 nanoseconds and this causes an issue in having the multipath energy. Especially this affects the non-line of sight (NLOS) path which has the time to be in a given state less than the delay spread of the channel, which is 40 nanoseconds to 70 nanoseconds. One can overcome this problem if a number of radio frequency (RF) chains are used, but this usage increases complexity, power consumed and cost of design. These are the disadvantages of pulsed multiband technique.

One can overcome these disadvantages by employing a modulation technique which is very good enough to have the multipath energy and use the longer time domain symbol. Here comes the multiband orthogonal frequency division multiplexing (MB-OFDM) method which is very useful in implementing the UWB systems. It follows the OFDM modulation scheme which benefits the MB-OFDM method with its features such as spectrum effectiveness, resistance against multipath propagation, narrow band interference (NBI) reduction and usage of equalizer is less complicated.

Because of this OFDM modulation technique, MB-OFDM is able to have multipath energy with the help of a single RF chain. Hence, MB-OFDM have all the benefits of OFDM due to which the design cost, consumption of power, and complications are reduced.

Thus, MB-OFDM is considered as the best method in implementing UWB systems when compared to pulsed multiband technique and code division multiple access (CDMA). ECMA-368 is one of the international standards which use MB-OFDM approach.

4.1 Band Planning for MB-OFDM System Following ECMA-368 Standard

In MB-OFDM approach, the huge spectrum of 7.5 GHz (from 3.1 GHz to 10.6 GHz) is divided into 14 non-overlapping and consecutive sub-bands, each sub band having a bandwidth of 528 MHz,. These 14 sub-bands are further grouped into five non-overlapping and consecutive band groups where the first four band groups consists of three bands and the last band group consists of two bands only. Currently, usage of the first band group, i.e., first three bands, is implemented for simplicity. This MB-OFDM scheme can be explained by Figure 18.

Transmission of signals in UWB system is done by OFDM modulation technique. Though MB-OFDM is very similar to OFDM modulation scheme, MB-OFDM has some unique features which make the implementation of UWB system much more effective and less complicated. Considerable differences between OFDM and MB-OFDM are as follows:

1) Time frequency interleaving scheme, which hops OFDM symbols across three consecutive and non-overlapping bands and which results in following:

Total average power transmitted, $P_{t,\ \mathrm{Total}} = P_{t,\ \mathrm{sub\ band}} * N$

$P_{t,\ \mathrm{sub\ band}}$ = Average power transmitted per sub band

N - Number of sub-bands

Here, the operated bandwidth remains very small, i.e., 528 MHz

2) The complexity of designing ADC, DAC, etc., is reduced by selecting a constellation size. As, MB-OFDM uses QPSK the UWB system is less complicated.

3) The spacing between the subcarriers is more in MB-OFDM due to which the timing synchronization estimation errors are reduced.

4) In order to maximize the power transmitted, MB-OFDM uses a zero-padded suffix instead of cyclic prefix.

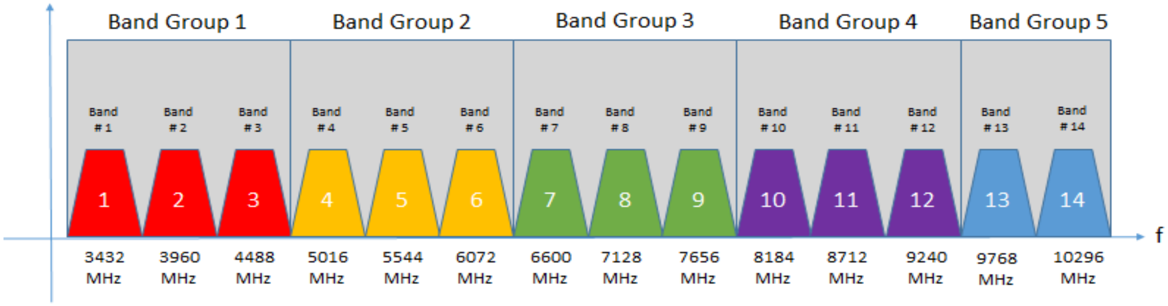


Figure 18: Band planning for MB-OFDM.

Thus, the resultant transmitted symbols are made to be over the first three bands, i.e., within first band group in a time frequency interleaving (TFI) method. Here, the OFDM signal hops over three bands across time. Figure 19 depicts the example of TFI method used in MB-OFDM approach. The length of OFDM symbol is 312.5 ns, cyclic prefix (CP) or zero pad (ZP) suffix length is 60.6 ns and guard interval length is 9.5 ns. The guard interval is used for convenience to move from one band to another.

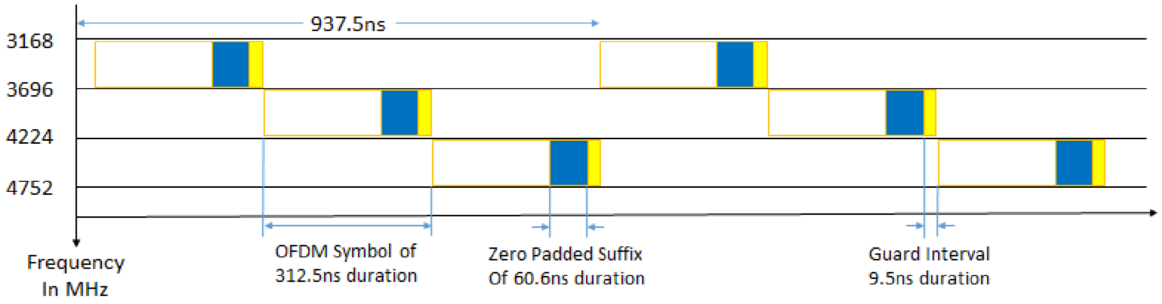


Figure 19: Example of time frequency interleaving for MB-OFDM system.

For simplicity, we consider implementing UWB system only for band Group #1, i.e., Band #1, Band #2 and Band #3.

Band width of each band = 528 MHz

1/band width = 1/528 MHz = 1.89 ns ~ 2 ns

OFDM symbol duration = 312.5 ns

No of samples in each symbol = 312.5 ns * 528 MHz = 165 samples

FFT window duration = 242.4 ns

FFT window length = 242.4 ns *528 MHz = 128

Zero padding length = 60.6 ns * 528 MHz = 32

Guard interval length = 9.5 ns * 528 MHz = 5

Hence, the OFDM symbol here is 165 samples.

4.2 Cyclic Prefix-Based OFDM System

Cyclic prefix (CP) is to increase the length of OFDM symbol in order to reduce the intersymbol interference (ISI) by taking a few samples from the last part of the OFDM symbol and adding them to the initial part of OFDM symbol. The OFDM symbol size is increased for making it essentially look like something with symbol time that is much larger than the delay spread of the channel. This is the basic idea behind ISI. If delay spread is much smaller than the symbol time , then the ISI can be neglected. Instead of transmitting the symbol directly, a small portion of symbol is taken and that portion is repeated as a prefix to actual OFDM symbol. Instead of taking samples from previous OFDM symbol, some of the last samples of OFDM symbols are taken cyclically and these samples are prefixed to the current OFDM symbol. Thus, by removing the impact of ISI on current OFDM symbol, OFDM system experiences flat fading characteristics with addition of cyclic prefix (Figure 20).

Addition of cyclic prefix to OFDM symbol creates a structure in transmitter due to which ripples are produced in power spectral density (PSD). This increases the power required at the receiver to increase. So, as an alternative, zero padding is used instead of cyclic prefix.

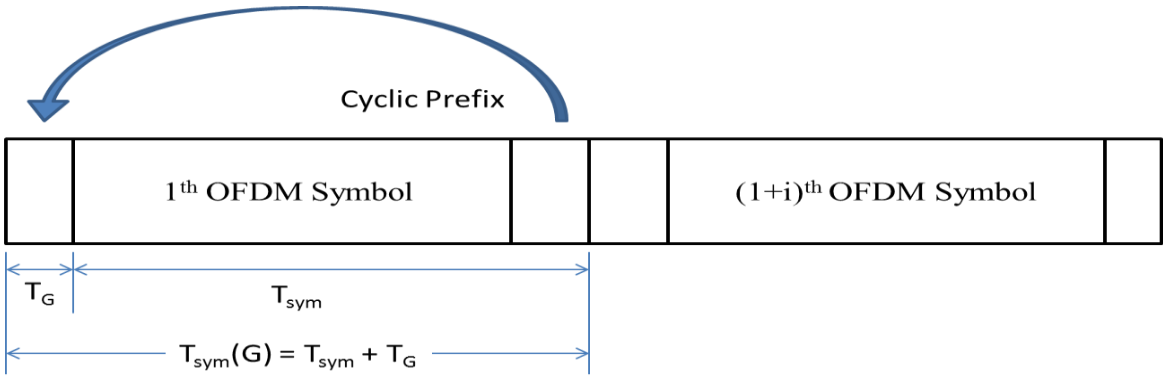


Figure 20: OFDM symbols with cyclic prefix [4]

4.3 Zero Padding-Based OFDM System

Initially, a buffer is created with zeroes, then it is added to the OFDM symbol to get zero-padded OFDM symbol. The real length of zero-padded OFDM symbol is less when compared to the length of CP because zero padding is full of zeroes.

OFDM symbol is used in front of an OFDM symbol in order to maintain orthogonality between sub-carriers, but the addition of CP introduces a structure in transmitter due to which ripples are produced in power spectral density (PSD) which makes power required to increase to as much as 1.5 dB

Hence, instead of cyclic prefix, Zero padding is used in MB-OFDM approach (Figure 21). Zero padding usage in OFDM results in a zero ripples power spectral density which makes power required zero at the receiver. This increases the transmitted power to a higher range.

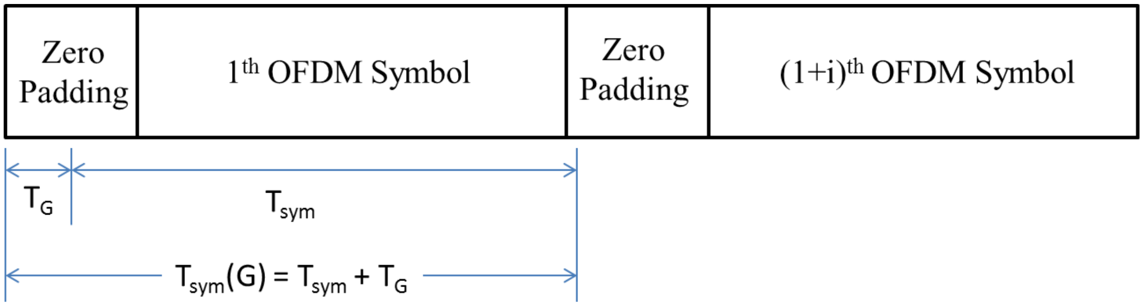


Figure 21: OFDM symbol with zero padding [4]

4.4 Overlap and Add Method

For a CP-based system, the circular convolution is natural because of the cyclic prefix addition. Circular convolution provides the flexibility to maintain orthogonality between sub-carriers. But for a ZP-based system, circular convolution is not natural as OFDM generally produces a linear convolution. Hence, in order to regain circular convolution when ZP is used, overlap and add method is used.

Frequency domain samples → IFFT → 128 time domain samples + N_{ZPS} → OFDM symbol

Overlap add operation:

$$\mathbf{r_{n,OLA}} = \begin{cases} \mathbf{r_n + r_{n+NFFT}}\ \mathbf{, for\ n=0,1,2,.......\ N_{OLA} - 1} \\ \mathbf{r_n}\ \mathbf{, otherwise} \end{cases}$$

r_n = received signal

N_{FFT} = 128 time domain samples

N_{OLA} = zero padding length (ZP_LEN) = 32 (according to ECMA-368)

It effectively means that we need to add main OFDM symbol with another OFDM symbol whose first few symbols are the zeroes. Initially, a buffer with all zeroes is created which is overwritten with the zero-padded values. Then the main OFDM symbol and this buffer are added. In this way, the circular convolution is achieved. In OLA technique, zero padding length is fixed which is the same as the channel length.

CHAPTER 5: TIMING SYNCHRONIZATION ESTIMATION ERROR

5.1 UWB Channel Models

In UWB, four channel-models Channel Model1 (CM1), Channel Model2 (CM2), Channel Model3 (CM3) and Channel Model4 (CM4) are proposed depending on the mean delay spread of channel. Here, CM1 corresponds to a small delay spread channel and delay spread increases as we go towards CM4. CM1 is a line of sight (LOS) Path while the other channel models are non-line of sight (NLOS) paths. The mean delay spread differs significantly across bands which happens due to manifestation of the channel differs significantly based on band of operation [5]. Hence, accordingly the mean delay of different channel models is considered as follows:

CM1 - 4 samples (LOS)

CM2 - 4 samples (NLOS)

CM3 - 8 samples (NLOS)

CM4 - 10 samples (NLOS)

Previously, it was proven that there exists an overlap add length (ZP_LEN) for which the receiver works optimally[6]. Because consider for CM1, if delay spread of the channel is four samples and we take ZP_LEN as fixed, i.e., 32 samples (according to ECMA-368), then we will pick up pure noise samples during overlap add process which affects BER severely. Hence, the channel length is estimated previously by estimating the magnitude squared of channel impulse response and filtering it with a moving average in order to obtain the channel impulse response length, and a variable ZP_LEN is used during overlap add process. This type of method adds advantage to only a small delay spread channel and any small estimation error of the start of FFT window reduces the advantages and causes intersymbol interference (ISI).

5.2 Timing Synchronization Estimation Error

Timing synchronization estimation error is defined as the error in detecting the true start point of the FFT window or an error in detection of an OFDM symbol. Overlap and add method requires a small estimation error to work efficiently, which is difficult to achieve. This concept of timing synchronization estimation was neglected previously, which is considered as the key motivational factor for this work. FFT window is spread across because of the multipath propagation in UWB receiver. So, the FFT window start point detection affects the OLA process as well as the function of UWB system. Thus, ZP-based system is more sensitive to timing synchronization estimation errors when compared to CP-based system as overlap add method requires small estimation error of start of an OFDM symbol.

5.3 Multiband Timing Synchronization Algorithm

Suppose, if estimation error is negative, i.e., the system becomes non-causal as the equalizer do not consider the non-causal component as a multipath component, we need to make the system causal by making the error positive. If zero padding length is fixed, it causes intersymbol interactions with the OFDM symbol. Hence, a variable zero padding length is required for OLA process. The mean delay significantly differs across bands due to the manifestation of channel differs significantly based on the band of operation [5]. So, there is need to achieve the variable ZP_LEN based on the current band of operation. Hence, In order to make the system causal and to avoid intersymbol interference (ISI), a multiband timing synchronization algorithm is implemented.

Multiband timing synchronization algorithm is defined for implementing the FFT window shift to avoid intersymbol interference (ISI). It consists of two parts:

1) Algorithm #1 is used to make the system causal (Figure 22).

2) Algorithm #2 is used to implement the key idea that FFT window is shifted (Figure 23) [6].

If FFT window is shifted, hence, bound to start FFT from that point (which is deemed to be optimal for FFT), in that case one does not want to enter to the next OFDM symbol to avoid ISI (Figure 24). So you need to shorten ZP length. Algorithm #1 is followed by Algorithm #2.

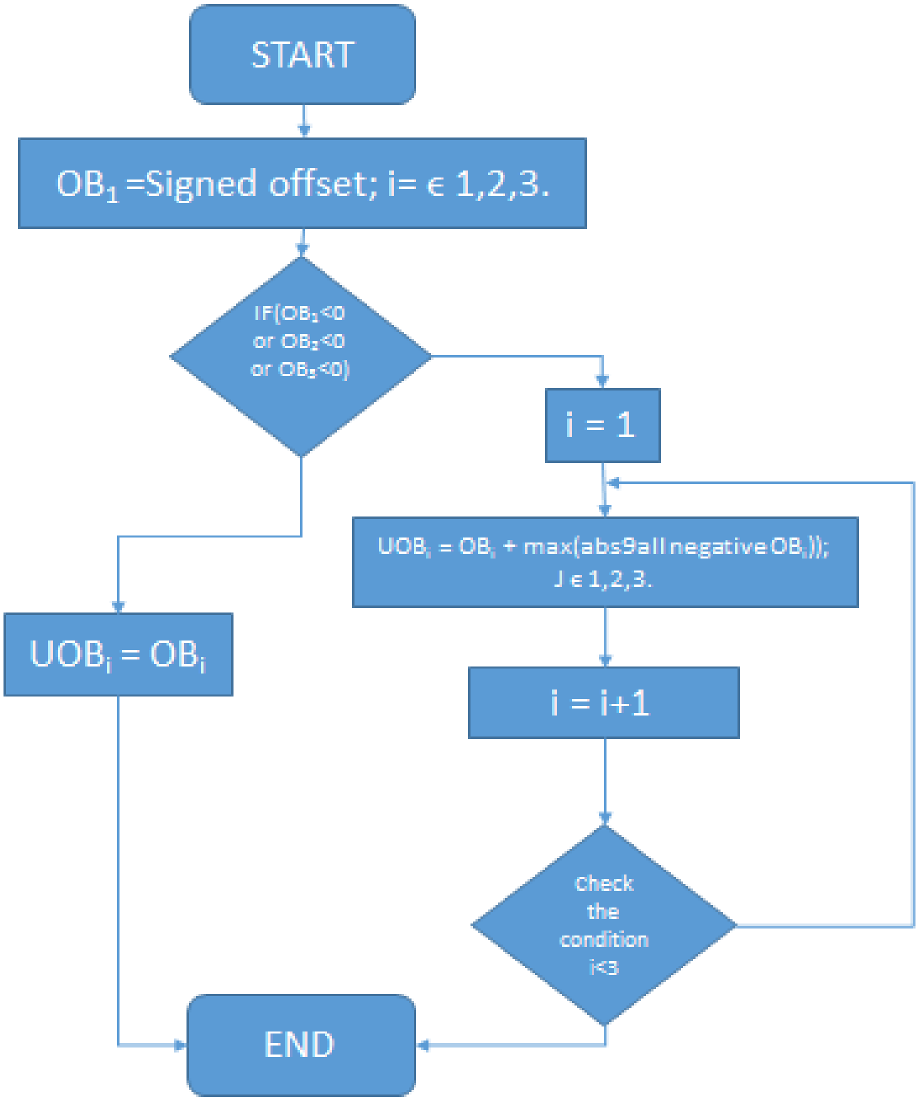


Figure 22: Algorithm # 1

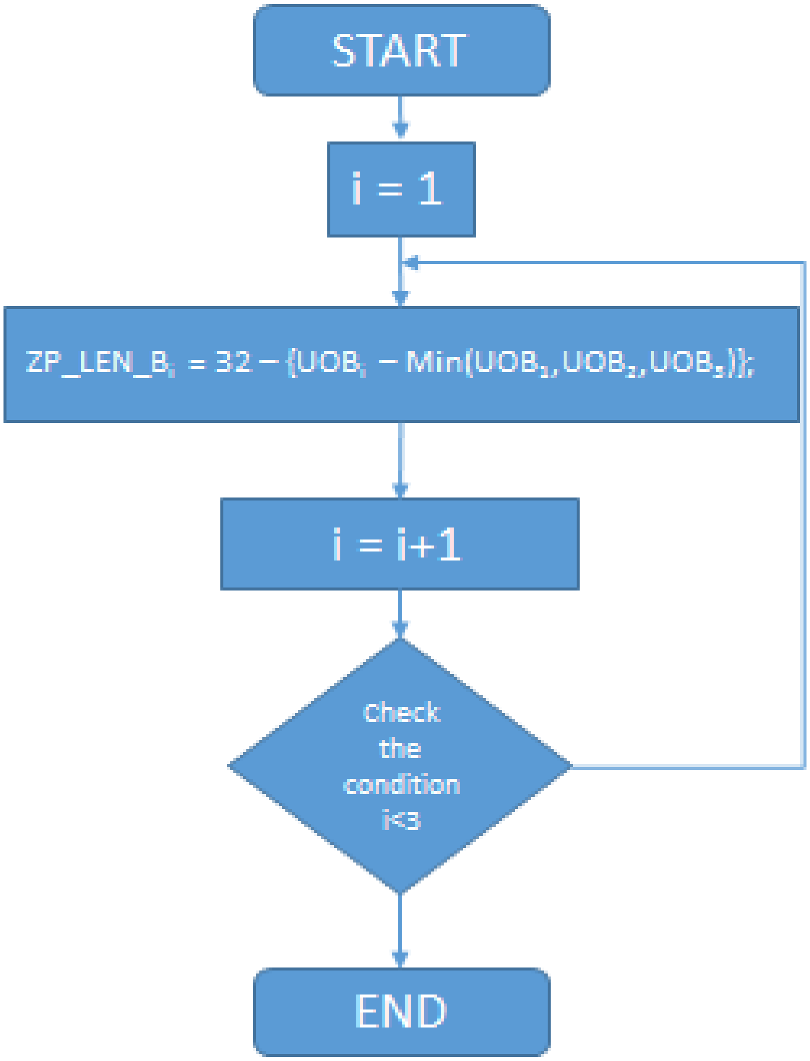


Figure 23: Algorithm # 2

Algorithm #1 is supportive to make sure Algorithm #2 can be implemented. Multiband timing synchronization algorithm can be used for a single-band or dual-band transmission process. The UWB system stops to be dependent on band for a single band and ZP_LEN becomes 32 samples, i.e., fixed.

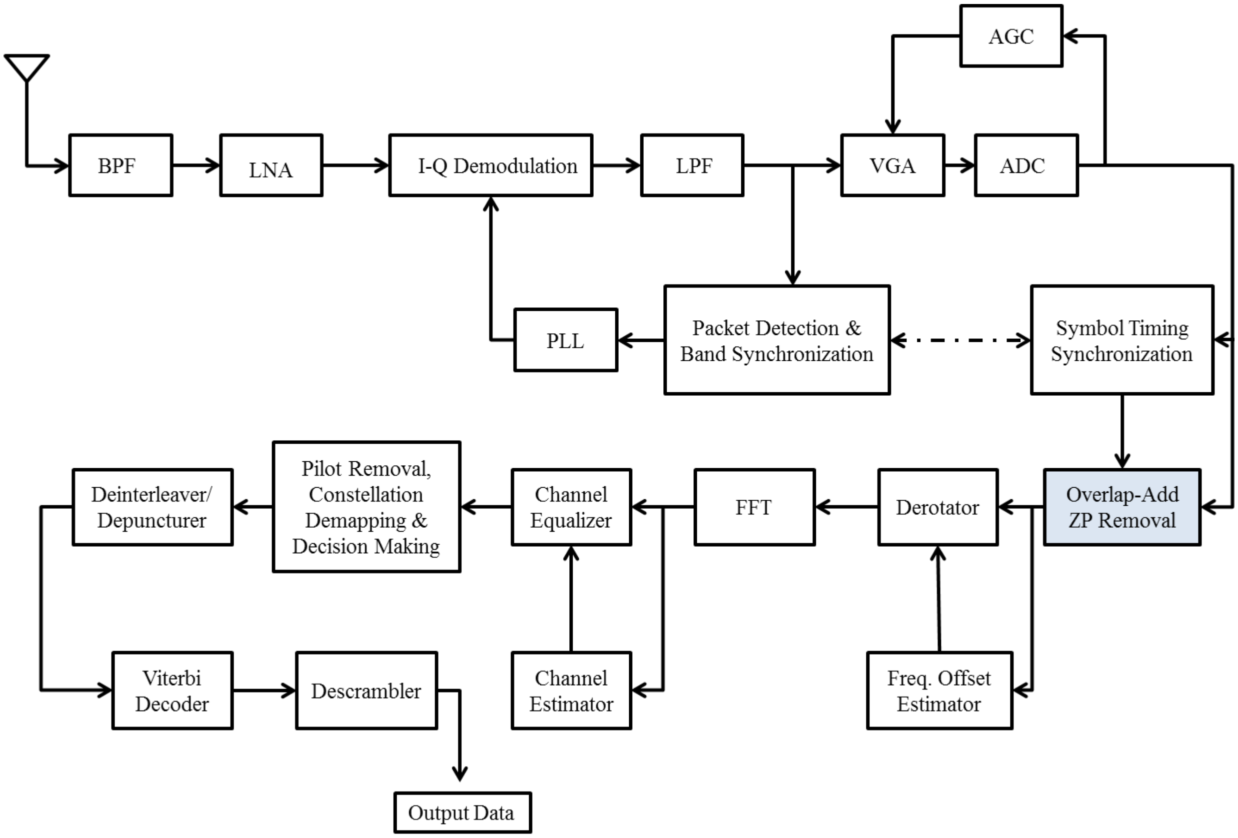
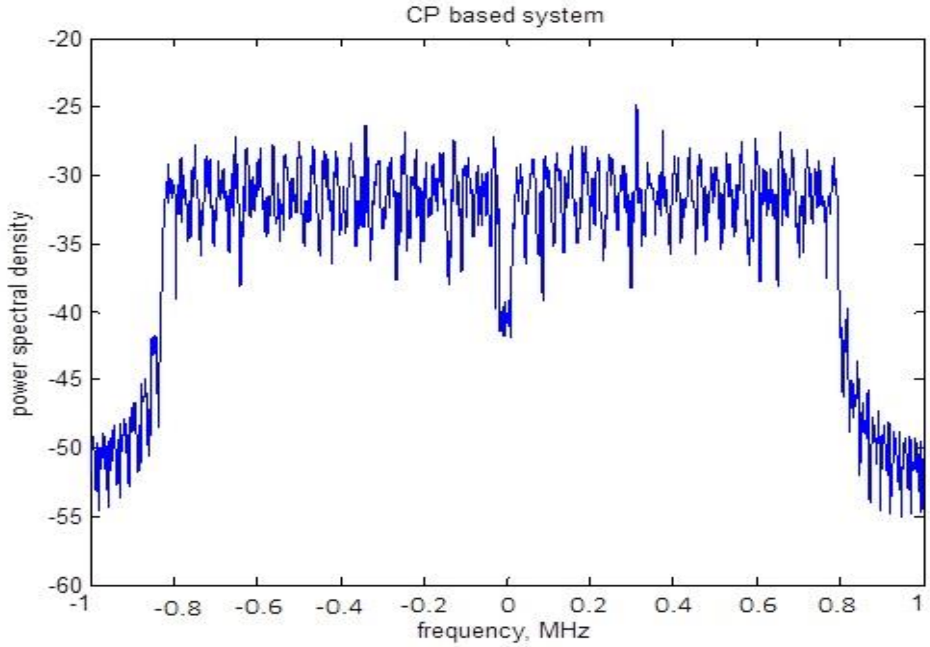
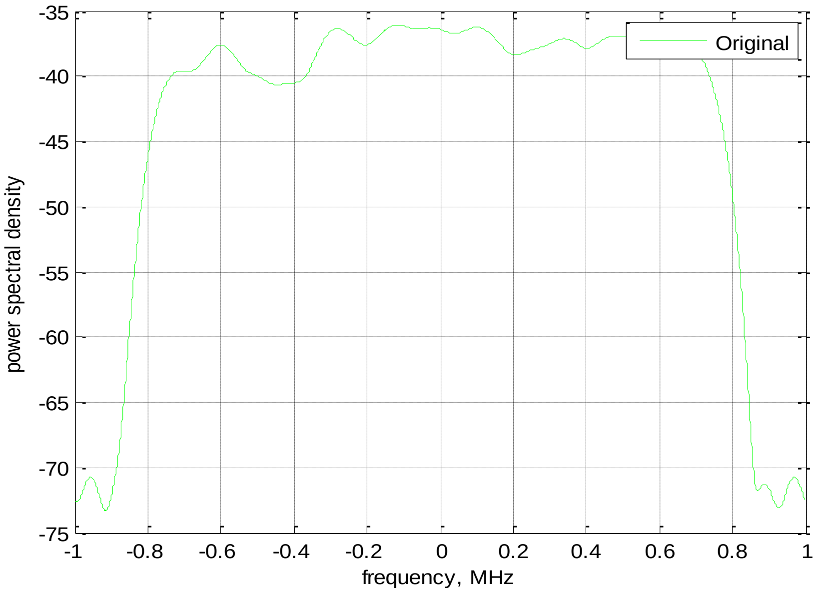


Figure 24: Typical MB-OFDM based receiver architecture

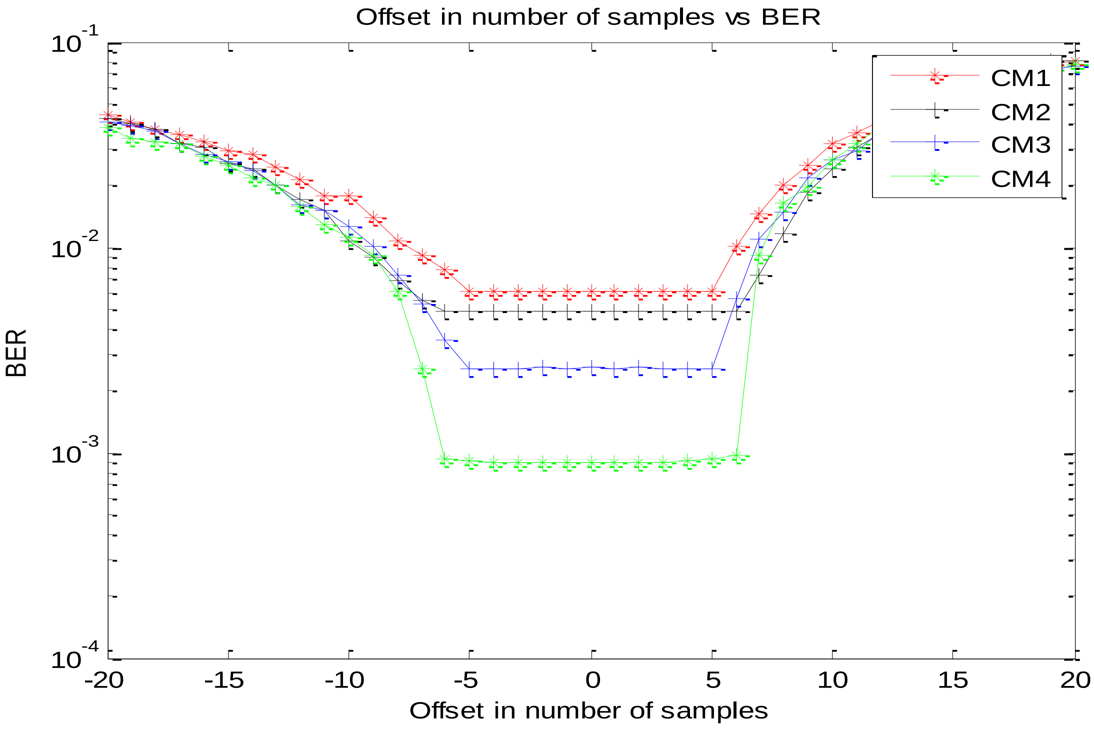
CHAPTER 6: RESULTS

1) CP-based system vs ZP-based system

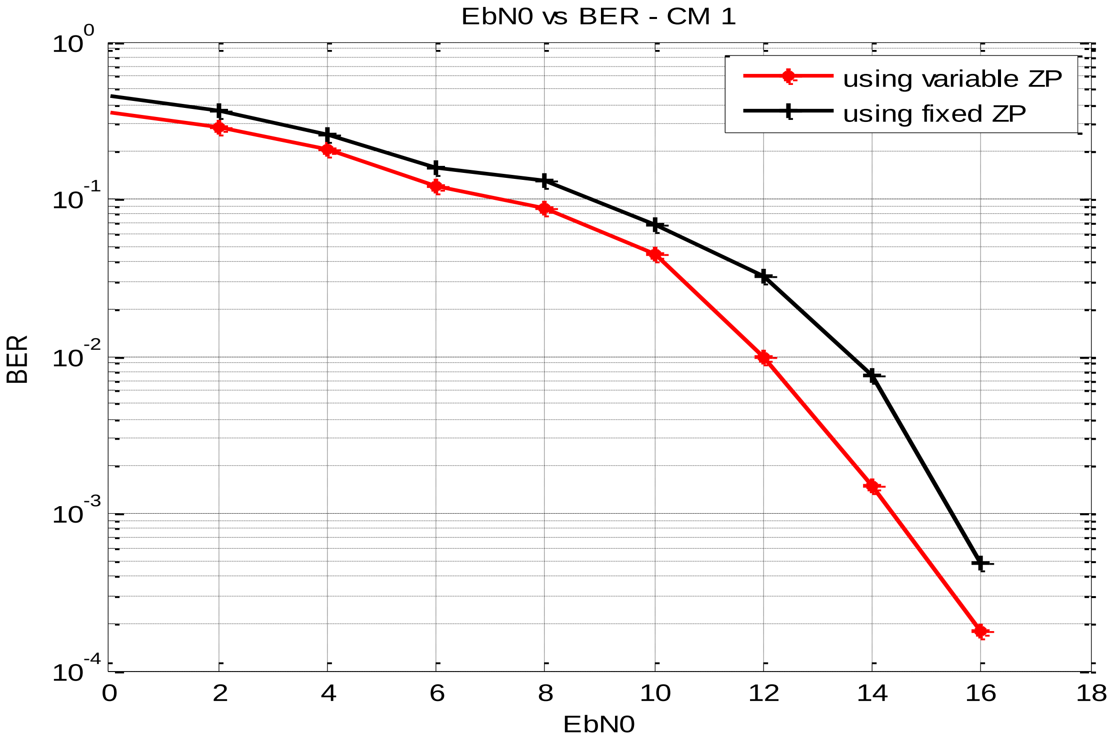


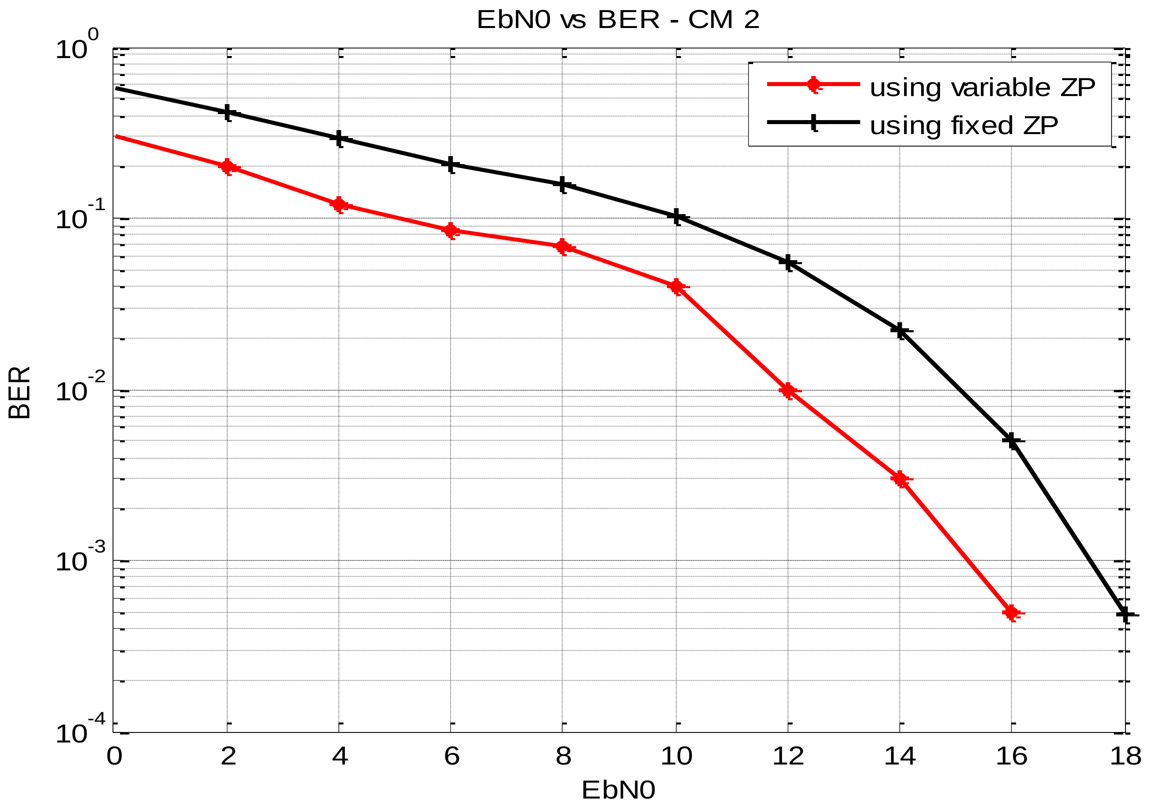


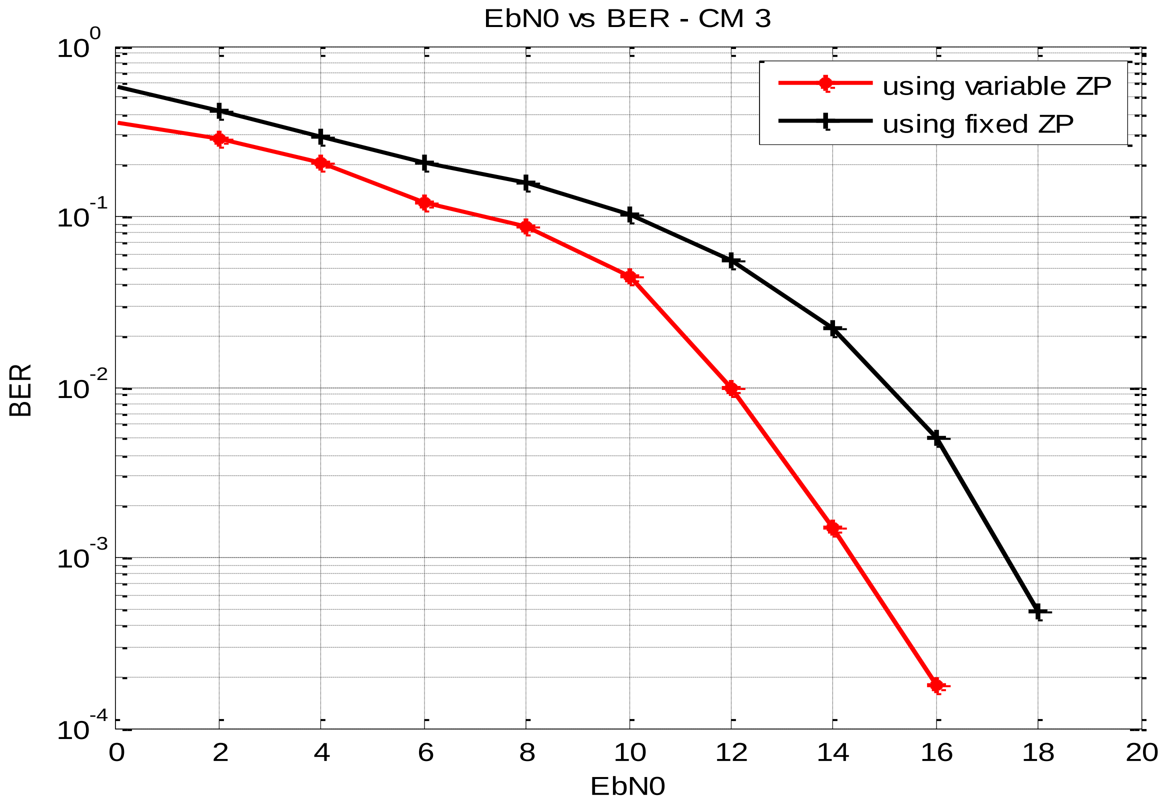
2) Offset sensitivity of multiband OFDM system

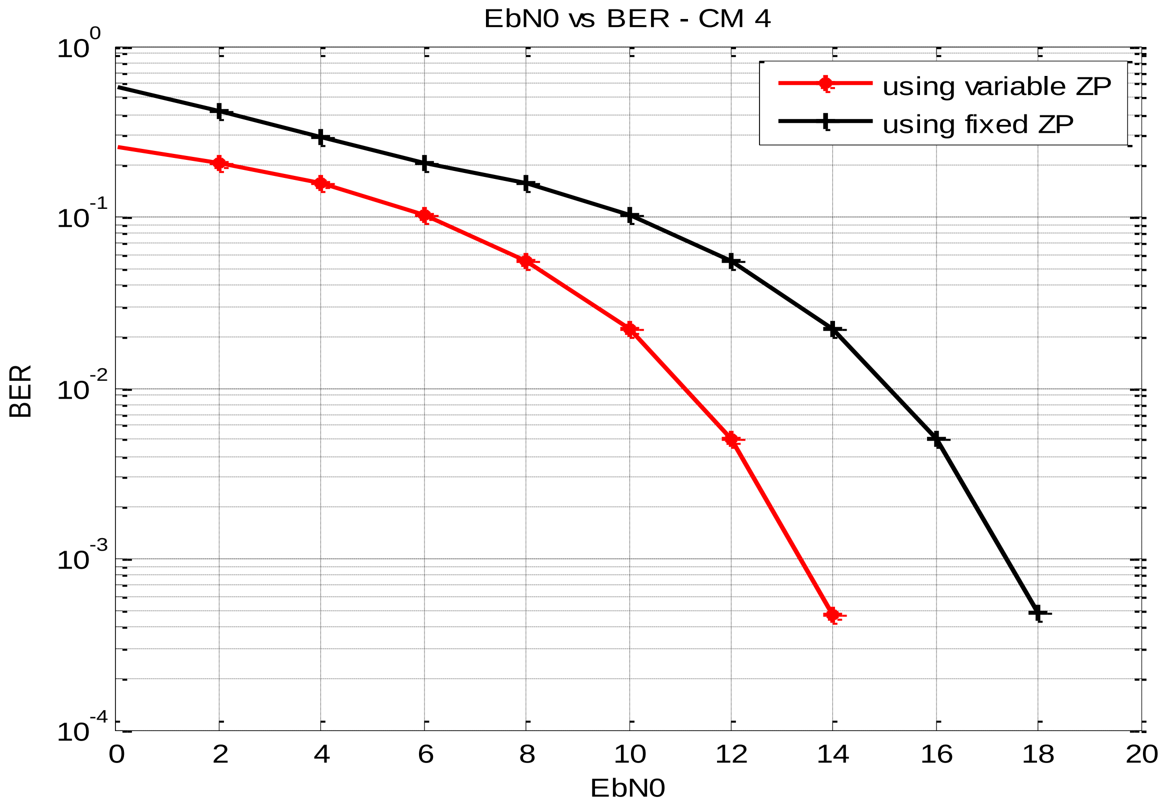


3) Comparison of fixed and variable zero padding length




EbN0 vs BER - CM 2
BER
EbN0
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
12
14
16
18
using variable ZP
using fixed ZP


EbN0 vs BER - CM 3
BER
EbN0
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
12
14
16
18
20
using variable ZP
using fixed ZP



6.1 Channel Coefficients for Different Channels

Absolute values of Channel Coefficients

Channel Model 1: Line of sight path (4 samples)

Channel Coefficients: 0.4193 0.5213 0.3298 0.4023

Channel Model 2: Non-Line of sight path (4 samples)

Channel Coefficients: 0.55 0.623 0.419 0.3219

Channel Model 3: Non-Line of Sight path (8 samples)

Channel Coefficients: 0.5300 0.3759 0.5186 0.2693 0.3121 0.3130 0.3670 0.3306

Channel Model 4: Non-Line of sight path (10 samples)

Channel Coefficients: 0.611 0.4356 0.7191 0.2190 0.321 0.518 0.613 0.4879 0.2169 0.483

Here, the channel coefficients are kept constant for each OFDM symbol.

CHAPTER 7: CONCLUSION

- Power spectral density of CP-based system and ZP-based system is compared.
- Sensitivity of multiband OFDM system to intersymbol interference is observed.
- SNR vs. BER of MB-OFDM UWB system with fixed and variable ZP_len are compared for each channel.
- The main advantage of this system is that it is not so sensitive to timing synchronization error, and in spite of any error, it tries to minimize intersymbol interference from the next OFDM symbol.
- Recently, Apple Company proposed to use ultra-wideband technology in order to create their own spectrum for transmitting signals [7].

These are final results after removing the noise. At particular bit error rate, an improvement in S/N is achieved: 10^{-2} BER is achieved at 11 dB in CM4. When compared to other channels, there is an improvement of 1 dB for CM4. Thus, multiband timing synchronization algorithm is beneficial for large delay spread channels.

7.1 Future Work

Instead of using a fixed offset, you can find offset by implementing a timing synchronization estimation error block using different techniques as mentioned below.

Timing offset can be estimated blindly or with the help of pilot symbols and training symbols. The synchronization methods which use the preamble to estimate timing offset are known to be pilot aided. Because of the effects of channel condition, the blind methods are much more complicated than the pilot-aided methods. So, pilot-aided methods are most commonly used.

The symbol timing estimator uses both cyclic prefix along with the information available in the form of pilot bits to estimate the channel by finding the maximum likelihood estimator over additive white Gaussian noise (AWGN) channel. This yields in better results when compared to estimation results without pilot bits [8].

In order to reduce the variations in estimating synchronization offset, a special preamble sequence is designed. Along with this preamble sequence, path gains of the channel are used to estimate the timing offset [9].

As known, the Schmidl's estimation method results in a plateau for timing metric which causes variations in estimating the offset. Hence, in order to reduce this variation in estimating the offset, a method is proposed where a preamble sequence is designed [10]. The simple timing offset estimation technique is to modify the Schmidl and Cox's method [11] where a training sequence is generated. Using this training sequence, the length of timing metric is removed and the system functioning is encouraged [12].

And moreover we can try implementing MB-OFDM UWB system by combining both channel length estimation and the concept of FFT window shifting quite a bit.

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