Analysis of LTE Radio Frame by eliminating Cyclic Prefix in OFDM and comparison of QAM and Offset-QAM
Acknowledgement

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Spectral efficiency is the key factor for the development of future Wireless communications. Orthogonal Frequency Division Multiple Access (OFDMA) is the multiple access technology used at the physical layer of latest wireless communication technologies. Anything on the improvement or overcoming the disadvantage of the present system will be considered for the future wireless systems. Long Term Evolution (LTE) is one of the 4th generation wireless communications and it is taken as the reference system in this thesis.

The main concern of this thesis is to analyze the LTE radio frame. We designed and simulated the OFDM system with cyclic prefix, its Bit Error Rate (BER) is verified by changing the Signal to Noise Ratio (SNR) value and we investigated the OFDM system by eliminating the cyclic prefix. By eliminating cyclic prefix bandwidth efficiency is achieved, though using cyclic prefix in OFDM has more advantages. Filter banks are used to compensate the advantages of cyclic prefix when it is removed. Introducing Offset in QAM results in less distortion and amplitude fluctuations. We designed, simulated and compared the QAM digital modulation with Offset-QAM digital modulation its BER vs. SNR are verified using simulations on MATLAB.
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LTE-INTRODUCTION

1. INTRODUCTION

The Long Term Evolution of UMTS has been introduced by the 3GPP and it is in the release 8 documents. It has new Physical layer concepts and protocol architecture for UMTS. From the Ericsson analysis, by the year of 2016, there will be about 5 billion mobile broadband subscribers and these are supported by HSPA and LTE networks in majority.

In the year of 1981, there was a big commercial growth in the mobile communication system that was known as ‘First Generation Systems’. The first analog mobile communication systems were introduced in the Nordic countries by the NMT (used in parts of Europe) and at the same time in the North America by analog AMPS. There were number of independently developed systems worldwide, other analog systems in the world are TACS (used in parts of Europe) and J-TACS (used in Japan and Hong Kong).

The Second Generation Systems developed with the advent of digital communications. Global roaming was first introduced in this system, increase in the data rate, capacity and the consistency of the quality of the systems attracted the mobile communication subscribers. The second generation systems like GSM was originally the solution for voice traffic while the data capability was added later. 2G based CDMA developed by Qualcomm was the biggest competition for GSM. GPRS introduced in GSM, carried Packet data over cellular systems. This system was referred to as 2.5G.

In Europe, RACE initiated the first phase of research towards 3G and UMTS had been named as 3G in Europe. WCDMA was selected as the technology for UMTS in the paired spectrum (FDD) and TD-CDMA for the unpaired spectrum (TDD).

3GPP is the standards-developing body of GSM, it is a partnership project formed by the standard bodies of ETSI, ARIB, TTC, CCSA and ATIS. 3GPP2 was also developed in parallel and this standard body is for CDMA-2000 which is a 3G technology and it is developed from 2G-CDMA which is of IS-95 standards.
HSPA is the ‘Third Generation System’ which has boosted data usage incredibly. Almost 90 percent of the global mobile subscribers are served by 3GPP technologies-GSM/GPRS/EDGE and WCDMA/HSPA. 3GPP LTE is built on the large base of 3GPP technologies.

First Generation Analog system was based on Frequency Division Multiple Access. GSM/GPRS/EDGE was based on Time and Frequency Division Multiple Access (TDMA/FDMA). IS-95, CDMA-2000/UMTS family of W-CDMA/HSPA was based on Code Division Multiple Access. UMTS-LTE uses OFDMA, which is the latest multiple access technology used in the mobile radio standards[1][2][3].

1.1 LTE Standardization

During the first workshop of 3GPP which was held on November 2004, 3GPP started their study on LTE working. In December 2004, 3GPP TSG approved to study the LTE. They came up with the requirements and targets issues of LTE. These were settled and approved on June 2005[4].

1.2 Requirements and targets for LTE

LTE technology has superior performance when compared to the existing 3GPP standards which is based on HSPA networks. This superior performance enables the users of LTE to have high data rates, high capacity, interactive TV, advanced games, mobile video blogging and more services[5][6].

- Increased spectral efficiency more than two to four times of HSPA release 6.
- Increased user data rates.
- Efficient usage of spectrum, frequency flexibility.
- Simplified Network architecture.
- High-level of security and seamless mobility.
- Optimized power consumption for the mobile terminal.
- Reduced delays, enables round trip time<10ms.
1.3 Summary of the key performance requirement targets for LTE

**Downlink Requirements:**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak transmission rate</td>
<td>&gt;100 Mbps</td>
</tr>
<tr>
<td>Peak spectral efficiency</td>
<td>&gt;5 bps/Hz</td>
</tr>
<tr>
<td>Average cell spectral efficiency</td>
<td>&gt;1.6-2.1 bps/Hz/cell</td>
</tr>
<tr>
<td>Cell edge spectral efficiency</td>
<td>&gt;0.04-0.06 bps/Hz/user</td>
</tr>
<tr>
<td>Broadcast spectral efficiency</td>
<td>&gt;1 bps/Hz</td>
</tr>
</tbody>
</table>

**Uplink Requirements:**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak transmission rate</td>
<td>&gt;50 Mbps</td>
</tr>
<tr>
<td>Peak spectral efficiency</td>
<td>&gt;2.5 bps/Hz</td>
</tr>
<tr>
<td>Average cell spectral efficiency</td>
<td>&gt;0.66-1.0 bps/Hz/cell</td>
</tr>
<tr>
<td>Cell edge spectral efficiency</td>
<td>&gt;0.02-0.03 bps/Hz/user</td>
</tr>
</tbody>
</table>

**System Requirements:**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>User plane latency (two wave radio delay)</td>
<td>&lt;10 ms</td>
</tr>
<tr>
<td>Connection set-up latency</td>
<td>&lt;100 ms</td>
</tr>
<tr>
<td>Operating Bandwidth</td>
<td>1.4-2.0 MHz</td>
</tr>
</tbody>
</table>

**LTE Release 8 parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>UL</th>
<th>DFTS-OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access Method</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DL OFDM</td>
</tr>
<tr>
<td>DL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td></td>
<td>1.4,3,5,10,15 &amp; 20 MHz</td>
</tr>
<tr>
<td>Minimum TTI</td>
<td></td>
<td>1ms</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td></td>
<td>15KHz</td>
</tr>
<tr>
<td>Cyclic Prefix</td>
<td>Short</td>
<td>4.7μs</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>Modulation types</td>
<td>QPSK, 16QAM, 64 QAM</td>
<td></td>
</tr>
</tbody>
</table>
| Spatial Multiplexing | Single layer for UL per UE  
Up to 4 layers for DL per UE  
MU-MIMO supported for UL & DL |

1.4 LTE Network Architecture

LTE Architecture is divided into three main domains. Their domains are responsible for transporting IP traffic. The three important domains are UE, EUTRAN and EPC. This architecture provides IP connectivity to the subscribers as shown in Figure 1.1.

![LTE Network Architecture](image)

*Figure 1.1 LTE Network Architecture.*

1.4.1 User Equipment:

In this architecture, UMTS mobile device is called UE and this is provided with LTE modem service. UE comprises with SIM, ME and TE. In LTE SIM it is in the form of UICC. In ME it has LTE specific protocols and the TE is supported by software drivers, operating system and
applications. The entire features are integrated into the device which may be into the form of LTE Laptop or PC card [1].

1.4.2 Functions of EUTRAN:


**Data Compression**: IP Header Compression using PDCP.

**Data Protection**: The data is protected when it is across the air, eNodeB performs encryption of radio link.

**Routing**: It forwards the Control plane signaling to the correct MME and User Plane traffic to the S-GW.

1.4.3 Evolved Packet Core

EPC consists of MME, S-GW and PDN-GW.

**Functions of MME**:

- NAS signaling and security
- Services for tracking and paging
- Gateway Selection
- Handover and Roaming
- Authentication

**Functions of Serving-Gateway**:

- Mobility Anchor
- Data Buffering
- Packet Routing
- Lawful Interception

**Functions of Packet Data Network-Gateway**
Packet Filtering and screening
- Accounting
- IP address allocation
- Lawful Interception

1.5 LTE Protocol Structure

IP Packets are passed through these protocols, the structure has PDCP, RLC, MAC and PHY.

In the Physical layer, OFDMA is employed for the downlink transmission and SC-FDMA for the uplink transmission. The data that has to be transmitted from the physical layer is turbo coded, carrier modulation is done through one of the following digital modulations QPSK, 16QAM, and 64QAM and then it is OFDM modulated. Antenna mapping is also done at the Physical layer. Two types of cyclic Prefix are supported, mostly OFDM use a normal cyclic prefix of 4.7µs duration and in some cases extended cyclic prefix are employed which is of 16.7µs duration. In
this thesis, short cyclic prefix is taken as reference. The data from the LTE Physical layer is organized into LTE Radio frames[7][8].

1.6 LTE generic frame structure

LTE supports both TDD and FDD. In TDD, communication is carried out in one frequency but the time employed for transmitting and receiving data is different. In FDD, two frequencies are used, transmitting and receiving data are done using different frequency. In this thesis, LTE FDD frame is considered [9][10].

![LTE Frame Structure Diagram](image)

**Figure 1.3 LTE frame structure**

LTE frame structure is of 10ms in duration. These frames are divided into 10 sub frames, each sub-frame is of 1ms in duration. Each sub-frame is further divided into two slots, each slot is of 0.5ms in duration. Each slot consists either of 7 OFDM symbols or 6 OFDM symbols depends upon the type of cyclic prefix employed which is normal or extended Cyclic prefix.

In the Table 1.1, LTE parameters are discussed mainly for the number of resource block allocated in each channel bandwidth.
<table>
<thead>
<tr>
<th>Channel Bandwidth (MHz)</th>
<th>1.4</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcarrier Bandwidth (KHz)</td>
<td></td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical resource block (KHz)</td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of Resource block</td>
<td>6</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 1.1: Relation for LTE bandwidth and its resource block**

Basic unit of the resource is the Physical Resource Block. PRB is either in the form of 12 subcarrier * 7 symbols (Short CP) or 12 subcarrier * 6 symbols (Long CP). In this thesis we are considering frame with short cyclic prefix. The following Figure 1.4 describes how physical resource blocks are arranged in accordance with channel bandwidth in one slot time duration.

![LTE slot structure](image)

**Figure 1.4 LTE slot structure**
1.7 Problem Description

As mentioned earlier LTE radio frame is of length 10ms, it has sub frame of length 1ms and each sub frame has two slots and each slot is of length 0.5ms. The following Figure 1.5 explains the LTE radio frame with OFDM+CP symbols [11].

![LTE Frame structure OFDM + CP](image)

**Figure 1.5 LTE frame structure OFDM +CP**

There are 14 OFDM symbols in one LTE sub frame of each subcarrier. The Table 1.2 below summarizes the main physical layer LTE parameters. In frequency domain, depending on the channel bandwidth, the number of subcarriers varies from 128 to 2048. For example in 5 MHz channel bandwidth there are 512 subcarriers.

Considering 20 MHz bandwidth of LTE parameters. Sample rate is 30.72MHz in the time domain, $T_s$ is expressed as $1/30720000$. The LTE radio frame in length is 10ms.
(T_{Frame}=307200T_s). In each frame there are equally divided 10 sub frame. The LTE sub frame in length is 1ms (T_{subframe}=30720T_s). There are two slots in each sub frame, LTE slot length is 0.5ms (T_{slot}=15360T_s).

OFDM symbol duration is 1/subcarrier spacing (1/15000=66.7\mu s). LTE OFDM symbol duration is 66.7\mu s (T_{symbol}\text{ time}=2048T_s). The first cyclic prefix duration in one slot is 5.21 \mu s(T_{cp}=160T_s), then the next each 6 cyclic prefix duration are 4.7 \mu s (T_{cp}=144T_s). The first cyclic prefix in the slot is different because to make the overall slot length equally which can be divisible by 15360[12].

<table>
<thead>
<tr>
<th>CHANNEL BANDWIDTH (MHz)</th>
<th>1.4</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO OF RESOURCE BLOCK</td>
<td>6</td>
<td>15</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>SUB- CARRIER SPACING</td>
<td>15Khz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO OF CARRIERS</td>
<td>72</td>
<td>180</td>
<td>300</td>
<td>600</td>
<td>900</td>
<td>1200</td>
</tr>
<tr>
<td>IFFT LENGTH</td>
<td>128</td>
<td>256</td>
<td>512</td>
<td>1024</td>
<td>1536</td>
<td>2048</td>
</tr>
<tr>
<td>SAMPLE RATE(Mhz)</td>
<td>1.92</td>
<td>3.84</td>
<td>7.68</td>
<td>15.36</td>
<td>23.04</td>
<td>30.72</td>
</tr>
<tr>
<td>SAMPLE PER SLOT</td>
<td>960</td>
<td>1920</td>
<td>3040</td>
<td>7680</td>
<td>11520</td>
<td>15360</td>
</tr>
<tr>
<td>OFDM SYMBOL TIME</td>
<td>667\mu s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP LENGTH \mu sec</td>
<td>4.69\mu s for 6 OFDM symbols and 5.21\mu s for the first OFDM symbol</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 2.2: Tabulation of LTE Parameters*
Figure 1.6 LTE Sub frame structure.

From the above Figure 1.6, it is noted that the sum of all cyclic prefix used in one sub frame will give the length of 66.7µs or 2048 sample which is equal to one OFDM symbol length.

In eliminating cyclic prefix, there can be a transmission of 15 OFDM symbol in one radio sub frame length of single subcarrier. The following Figure 1.7 shows 15 OFDM symbols in one sub frame by eliminating cyclic prefix.

Figure 1.7 LTE frame structure without CP.

In OFDM+CP transmission, 14 OFDM symbols are transmitted in 15 KHz subcarrier of 1 ms duration. In one resource block which means in 180 KHz, there are 168 OFDM symbol
transmitted in 1 ms. The bit rate depends on the carrier modulation used. BPSK modulation (1bit/symbol), QPSK modulation (2bits/symbol), 16 QAM modulation(4 bits/symbol) etc and offset is used in modulation to improve bit error rate and amplitude fluctuations are reduced.

![Diagram for OFDM with CP and without CP.](image)

**Figure 1.8 Diagram for OFDM with CP and without CP.**

We investigated that, by eliminating CP in OFDM, 15 OFDM symbols can be transmitted in 15 KHz subcarrier of 1 ms duration. In one resource block 180 OFDM symbols can be transmitted in 180 KHz channel bandwidth of 1 ms duration. The bandwidth is effectively used and the data rates can be improved as shown in Figure 1.8.

**1.8 Purpose of the thesis**

The main purpose of the thesis is to design and simulate OFDM+CP signal, its Bit Error Rate is verified by varying its Signal to Noise Ratio. We investigated the OFDM without CP model (Filter Bank Multicarrier) and prepared a technical report on FBMC transceiver structure and how to compensate the advantages of cyclic prefix by eliminating it. In addition to this, we designed, simulated and compared the QAM digital modulation with Offset-QAM digital modulation, its BER vs SNR is verified and compared.
1.9 Thesis Outline

The structure of the thesis is organized as follows, in Chapter 2 we discuss the detailed view of the OFDM+CP transmitter and receiver structure. In Chapter 3 we describe Digital modulation techniques in detail. In Chapter 4 FBMC/OQAM transciever structure is described in detail. In Chapter 5, we provide the simulation works which was carried on MATLAB. Finally in Chapter 6 conclusions are made and the future work is outlined.
2. Digital Modulation

2.1 Introduction:

Digital Modulation is a process that impresses a digital symbol onto a signal suitable for transmission. For short distance modulation ‘baseband modulation’ is the most generally used. Baseband modulation is often called ‘Line Coding’.

Several baseband modulation forms are shown below. The first one is the Non-Return to Zero level modulation which represents a symbol 1 by a positive and a symbol 0 by a negative square pulse with a period T. The Second one is the unipolar return to zero modulation in which symbol 1 is with a positive pulse of T/2 and nothing for symbol 0. Both are shown in the Figure 2.1.

![Figure 2.1 a) Signal for Non-Return to zero b) Unipolar return to zero.](image)

The third one is the bi-phase level where a waveform consisting of a positive first-half T pulse and a negative second-half T pulse for 1 and a reversed waveform for 0 as shown in the Figure 2.2.
For long distance and wireless transmissions, band pass modulation is used. It is also called carrier modulation. A sequence of digital symbols is used to alter the parameters of a high-frequency sinusoidal signal called the carrier. The three basic parameters of a sinusoidal signal are the Amplitude, Frequency and Phase. The Amplitude modulation, Frequency modulation and Phase modulation are the three basic modulation methods in pass band modulation. The below Figure 2.3 shows the three binary carrier modulations.

**Figure 2.3 Binary Carrier Modulation**

they are also called Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK) and Phase Shift Keying (PSK). Based on these three schemes variety of modulation schemes can be derived from their combinations. For example by combining two binary PSK signals with orthogonal
carriers a new scheme called Quadrature phase shift keying (QPSK) can be generated. Similarly by modulating amplitude and phase we can obtain a scheme called Quadrature Amplitude Modulation (QAM). We shall look into the details in the following below sections.

2.2 I and Q channels:

Before discussing the modulation concepts, let us go through one of the main characteristics by which modulation is defined the In-Phase and Quadrature components. Let us take a simple example to define these parameters. Consider a signal in a vector form. Let us say in both Rectangular form and polar form as shown below in the Figure 2.4

![Figure 2.4 (a) I and Q projections, (b) polar form.](image)

Take a look at the rectangular form. Here $D_{11}$ is the projection of the signal on the x-axis and we call it as In-Phase (I) projection of the signal, where as you see $D_{12}$ is the projection of the same signal on the y-axis as shown in the Figure 2.4(a). It’s called the Quadrature (Q) projection of the signal. The coefficients of $D_{11}$ and $D_{12}$ represent the amplitudes of the I and Q signals respectively. When we plot these amplitudes on the X and Y axis we get the signal vector. The angle with which the signal vector makes with the X-axis is considered as the phase of the signal and the magnitude is given by $M=\sqrt{I^2 + Q^2}$, and the Phase $\Phi = \tan^{-1}(I/Q)$. 
2.3 Amplitude Shift Keying:

When it comes to bandwidth efficiency, PSK is more efficient compared to FSK and ASK. But still ASK and FSK are simple and hence used in communicative systems. The simplest form of ASK is when it operates as a switch. The presence of a carrier wave is indicated as a binary one and its absence as to indicate a binary zero. This type of modulation is called on-off keying. The example for OOK is given below in Figure 2.6[13].

![Figure 2. 5 Baseband information sequence](image)

Amplitude Shift Keying can be mathematically represented as,

\[
\text{ASK}(t) = s(t)\sin(2\pi ft).
\]  

(2.3.1)
2.4 Frequency Shift Keying:

In this Frequency Shift keying generally two signals with two different frequencies are used to identify the binary 1 and 0 respectively. Mathematically it can be written as below,

\[ s_1(t) = A \cos(2\pi f_1 t + \Phi_1) \quad kT \leq t \leq (k + 1)T, \text{ for } f_1, \quad \text{(2.4.1)} \]

\[ s_2(t) = A \cos(2\pi f_2 t + \Phi_2) \quad kT \leq t \leq (k + 1)T, \text{ for } f_2, \quad \text{(2.4.2)} \]

In the above equations 2.4.1 and 2.4.2, \( \Phi_1 \) and \( \Phi_2 \) are phases initially of the two signals at \( t=0 \) respectively. And \( T \) is the time period or here the bit period. These two signals are not coherent, as \( \Phi_1 \) and \( \Phi_2 \) are never the same in general. This form of shift keying is called noncoherent or discontinuous FSK.

The second type of FSK is called the Coherent or Continuous FSK. Here the two signals have the same phase \( \Phi \) at different frequencies \( f_1 \) and \( f_2 \), which are synchronized.

The signals are delivered in a fashion that for binary 1, \( s_1 \) will be pass and for binary 0 \( s_2 \) will be passed. For coherent demodulation the frequencies of the signals are chosen that the two signals are orthogonal to each other, so we have,

\[ \int_{kT}^{(k+1)T} s_1(t)s_2(t)dt = 0. \quad \text{(2.4.3)} \]

Figure 2.6 Binary ASK (OOK) signal.
The above Figure 2.7 shows the FSK for two different frequencies $F_1$ for binary 1 and $F_2$ for binary 0 signals [13].

2.5 Phase Shift Keying

The most widely used scheme in wireless communication is Phase Shift Keying. The basic approach in this shift keying is changing the phase and sending the information. For example in the below Figure 2.8, we shift the phase of the sinusoid by 180 degrees to indicate the binary 0. In this case phase shift represents the change in the state of information.
Mathematically we can represent Phase Shift Keying as below,

\[
\text{PSK} (t) = \sin(2\pi ft) \text{ for bit } 1,
\]

\[
\text{PSK} (t) = \sin(2\pi ft + \pi) \text{ for bit } 0.
\]

PSK unlike ASK and FSK has various modulations, below we will discuss about two modulations which are relevant to this thesis they are BPSK and QPSK[14].

2.5.1 BPSK: Binary Phase Shift Keying

In this modulation as discussed above we use only one sinusoid as the basis function. This is a one dimensional signal with two values binary 0 and binary 1. Each symbol is signaled by a change in the phase of the signal. In BPSK two packets are defined of the cosine wave, one with 180 degree phase and the other with a zero phase. The BPSK signal totally lies on the X-Axis, it has no y-axis projection.

For clear understanding let us construct a simple BPSK carrier. Let the bit sequence be 1110 0001 1111 1000. In this context, we need 16 symbols as each BPSK symbol stands for one bit. Hence we defined s1 is binary zero and s2 as binary 1. Now if we map according to the above sequence the mapping would be as shown in Figure 2.9.

![Figure 2.9 BPSK mapping for 1110 0001 1111 1000](image-url)
The above Figure 2.9 is at a carrier frequency of 1Hz which is not realistic. In reality the frequency is far higher and we can observe that the signal covers a lot of cycles in each transition [14].

2.5.2 QPSK: Quadrature Phase Shift Keying

The number of basis functions define the dimensionality of modulation. This makes QPSK two dimensional. It’s called so because it uses two independent signals to create the symbols. The signals used are the sine and cosine. The most often used scheme is the QPSK as it does not suffer from BER degradation on top of that the bandwidth efficiency is increased.

The QPSK signal is nothing but the extension of the above discussed PSK. Mathematically we can write the modulated signal as given below[13],

\[ s(t) = B_c Q_s(t) \cos \left( 2\pi f_c t + \frac{2\pi I}{M} \right), \]  

(2.5.2.1)

where \( Q_s \) is the pulse shaping function. The phase changing part is in **bold**. We can use \( M \) quantized levels of \( 2\pi \), to create variety of PSK modulation. ‘I’ varies from 1 to \( M \) values. When the value of \( M \) is 2 it is BPSK, 4 makes it as QPSK, and so on. The below Figure 2.10 shows some modulations and their constellations for better understanding.

![Figure 2. 10](image.png)

**Figure 2. 10** a) BPSK b) QPSK c) QPSK d) PSK

Let us consider a square pulse with an amplitude \( A_1 \) and time period \( T_1 \), The power is calculated as shown below in the equations,
This is the equation of the pulse which is equal to $Q_s$ as we discussed earlier. Now substituting $Q_s$ value in the equation 2.5.2.1 and substituting $T$ for $T_1$ we have,

$$s_1(t) = B_c \sqrt{\frac{2}{T}} \cos(2\pi f_c t + \frac{2\pi l}{M}).$$ \hspace{1cm} (2.5.2.4)

Now setting the Carrier Amplitude as $\sqrt{E_s}$ the equations becomes a general MPSK signal as shown below:

$$s_1(t) = \sqrt{\frac{2E_s}{T}} \cos \left(2\pi f_c t + \frac{2\pi l}{M}\right).$$ \hspace{1cm} (2.5.2.5)

we can observe that there are phase shifts at $90^0$ and $180^0$, whereas in BPSK the phase shift is only for $180^0$.

Expanding the equation 2.5.2.5 as shown below,

$$s_1(t) = \sqrt{\frac{2E_s}{T}} \cos \left(2\pi f_c t + \frac{2\pi l}{M} + \frac{\pi}{4}\right),$$

$$= \sqrt{\frac{2E_s}{T}} \left[\cos(2\pi f_c t) \cos \left(\frac{2\pi l}{M} + \frac{\pi}{4}\right) - \sin(2\pi f_c t) \sin \left(\frac{2\pi l}{M} + \frac{\pi}{4}\right)\right],$$ \hspace{1cm} (2.5.2.6)

an initial phase shift of $45^0$ is introduced which does not alter the modulation in any way.

Recollecting the I and Q channels we discussed above we write them here as,

$$S_1 = \cos w_c t, \quad S_2 = \sin w_c t.$$

Now the scaled version which fit into the equation above is given as,

$$I = \sqrt{(2E_s/T)} \cos(2\pi f_c t), \quad \text{and} \quad (2.5.2.7)$$

$$Q = \sqrt{(2E_s/T)} \cos(2\pi f_c t), \quad (2.5.2.8)$$
the above I and Q are indeed orthogonal as we just multiplied them with constants. Multiplying these two equations by the angular part as in the above equation 2.5.2.6 and substitute in the $S_i(t)$ function, we get the following function as shown below,

$$s(t) = \sqrt{\frac{2E_s}{T}} \cos(\theta(t)) \cos(2\pi f_c t) - \sqrt{\frac{2E_s}{T}} \sin(\theta(t)) \sin(2\pi f_c t).$$

(2.5.2.9)

This is the Quadrature form of the modulation. The two signals are indeed orthogonal, the bold part is the amplitude of the I and Q channels. The values of them are same on both the X and Y axis which is equal to $\sqrt{E_s}$. So a combination of two Quadrature signals formed the phase modulated signal.

QPSK has 4 symbols, each symbols stands for two bits, In general we start by $45^\circ$ and increment $90^\circ$ each time for the next symbol, the I and Q values are computer by keeping the carrier frequency $f_c = 0$.

2.6 QAM modulation

QAM modulation is the modulation technique which is widely used for OFDM transmission for modulating data signals into a carrier. QAM is a method of sending a two separate channel of information through one channel which is further shifted to form the sine and cosine wave. These outputs are algebraically summed up along with I and Q phase to form a constellation mapping for QAM. QAM is widely used for digital broadcasting where these would carry higher data rates.

In 16 QAM modulation there would be exactly 4 I values and 4 Q values which would create around 16 possible combinations. These values can transition from any state to other within the symbol time. Each constellation mapping would have 4 bits to it in which 2 would be for I phase and 2 would be for Q phase. The symbol rate is $\frac{1}{4}$ th of the bit rate. Let us take an example of $M=16$ where each 4 bits would represent a signal and all these symbols can be plotted in a square
shape constellation rather than a circle one. This is because the QAM achieves higher constellation due to that data error are reduced. This will allow QAM to transfer more signals through its carrier. Higher the modulation higher the no of bits sent. QAM modulation helps out to achieve good spectral efficiency compared to all modulation.

In a M-QAM we are not only varying the phase as shown for QPSK but we are varying the Amplitude along with the phase such that it result in reduced data error rate. A variety of QAM modulation is used 4,16,32,64 QAM. Higher the modulation higher the no of bits sent through it. The diagram for the QAM constellation with M=16 with 4 I phase and 4 Q phase values are shown below in fig 2.11

![QAM Constellation Diagram](image)

**Figure 2.11 (a) 64 QAM (b) 16 QAM**

### 2.7 OQAM Modulation:

The Offset QAM has a minor but very important change when compared to QAM modulation. The change is the reason for the names ‘Offset’ QAM. In the OFFSET QAM the Q channel discussed in the previous sections is shifted by a half a symbol rate. The introduction of this shift is for a more “constant envelope” more than the conventional QAM.
Figure 2. 12 Shows the shift in the Q-Channel

The above Figure 2.12 clearly shows us how the Q channel is shifted by half the symbol rate. Unlike QAM the I and Q channels of OQAM do not undergo transition at the same time. This means that transitions now are never more than 90°, this gives us the constant envelope, which we desire.

For example let us consider a situation in QAM for a change in either the I or Q component brings a change of 90°, but consider the situation where I and Q both change, the phase shift should be ideally 180° and theoretically or ideally the phase jump should be instantaneous, but practically it’s not the case, instead produces a shifting in the non-zero time and cause the envelope to approach to reach zero (due to filtering effect). This is shown in the below Figure 2.13.

OQAM having this offset a constant envelope can be achieved as the phase shift is occurred every 90° only but not 180°. By introducing half-symbol delays between in-phase and quadrature components that alternate for even and odd channels, crosstalk is moved to even samples while the transmitted complex symbols are recovered without crosstalk from the odd samples [14].
Offset QAM was proposed for spectral efficiency in optical communications. Multi-carrier Offset-QAM has the potential to allow for symbol-rate spacing at high-speeds with low implementation complexity.
3. Orthogonal Frequency Divisional Multiplexing (OFDM)

3.1. Introduction of OFDM

This chapter deals with OFDM for wireless system. The basic principle behind the working of OFDM is that higher data streams are divided into lower data streams and simultaneously they are sending it through a subcarrier. The main concept of OFDM is its orthogonality. Most of the carriers are of sine or cosine. Due to that the area under carrier wave for sine or cosine is zero for one period.

In OFDM the serial data streams which are to be sent through the serial to parallel block is first encoded and then modulated to give a constellation mapping. OFDM does not need any filters to separate the sub bands since orthogonality is maintained across subcarriers.

3.2 Functional diagram of OFDM

![OFDM block structure](image)

Figure 3.1 OFDM block structure

3.3 Mapping and De-mapping

Many modulation techniques can be used for OFDM simulation. Higher the modulations lower the symbol error rate. Hence usually higher end modulation technique is used in OFDM widely. Techniques such as BPSK, QPSK and QAM are most commonly used in common.
QAM is the most important modulation technique in the OFDM generation and we use QAM for the simulation in our project. As the signal can be divided into real and imaginary values which would be helpful in constellation mapping with respect to PAM[15].

3.4 Serial to parallel conversion

The bit stream symbols which are passed through QAM modulation is sent through the serial to parallel block where the modulated bits would be arranged in a way, such that it would feed as an input to the IFFT block.

3.5 Inverse Fast Fourier transform /Fast Fourier transform:

In the OFDM system the modulation and demodulation part is widely carried out by FFT/IFFT. The mathematical operations of IFFT/FFT are mainly used to convert the signals from time domain to frequency domain vice versa.

OFDM systems are both incorporated with the help of Fast Fourier Transform and Inverse Fast Fourier Transform which are the equivalents of IDFT/DFT and they are mathematically proved to be the efficient and easiest way to implement. In an OFDM system the complex valued data generated from the 16 QAM modulations are said to be in a frequency domain. These complex valued data’s are given as input to the IFFT block and we would get the output of modulated multiplexed signals which are in time domain as shown in Figure 3.2.

IFFT gets N samples of complex valued data with time period T. These modulated signals are N orthogonal sinusoids where each N values would have different frequency values. The final output of the IFFT block would be the summation of all these N samples into a single OFDM symbol. The length of the OFDM symbol is NT where T is the input symbol period of IFFT.
These OFDM symbol generated would be send through a channel and at the receiver side FFT block would be placed. The FFT would get time domain signals as input and would convert it to frequency domain signals as shown in the Figure 3.3. The output from the FFT block is nothing but the input data’s given to the IFFT block. These data’s can be used for constellation mapping which would actually form a 16QAM [17][16].
3.6 Cyclic prefix Addition/Cyclic prefix removal

Cyclic prefix is an extension of the OFDM signal by copying the last samples of an OFDM symbol. Let $A_g$ denote the length of cyclic prefix and $A_{sub}$ denote the length of OFDM symbol. The extended OFDM symbol would now have duration $A_{sym} = A_g + A_{sub}$. Let the Figure 3.4 describe the two signal with cyclic prefix added to it,

![Figure 3.4 A single cyclic prefix frame](image)

Figure 3. 4 A single cyclic prefix frame

![Figure 3.5 cyclic prefix structure](image)

Figure 3. 5 cyclic prefix structure
Guard intervals, longer than the maximum delay of multipath channel allows maintaining orthogonality between the signals. Orthogonality between the subcarriers is not due to the frequency domain separation but it is also due the frequency domain structure of each row. If the length of CP is longer than the maximum delay in multipath channel ISI will not occur. In order to prevent that, guard interval is introduced in the next symbol such that it helps to reduce ISI. ISI and ICI leads to loss of orthogonality between the symbols. Each single delayed carrier is attached with CP to maintain orthogonality between the symbols, as the orthogonality is maintained. For the first OFDM signal that will arrive with the a delay of $t_0$,

$$
\frac{1}{T_{sub}} \int_0^{T_{sub}} e^{j2\pi f_k (t - t_0)} e^{-j2\pi f_i (t - t_0)} dt = 0, k \neq i.
$$

(3.6.1)

For the second signal that will arrive with the a delay of $t_0 + t_s$,

$$
\frac{1}{T_{sub}} \int_0^{T_{sub}} e^{j2\pi f_k (t - t_0)} e^{-j2\pi f_i (t - t_0 - T_s)} dt = 0, k \neq i.
$$

(3.6.2)

If the CP (cyclic prefix) is kept short than the maximum delay for the multipath channel. Due to this delay in cyclic prefix the tail part of the $A_{sym}$ affects the head part of the next symbols for FFT which ultimately results in ISI which can be clearly visualized through the diagram Figure 3.6.
Figure 3. 6 ISI effect on a multipath channel with cyclic prefix shorter than the maximum delay

STO might also occur due to that, head of the OFDM symbol will interface with FFT start point. Main disadvantage of cyclic prefix is that signal power used to create a cyclic prefix leads to power loss since it is not used to its full extent. Loss in bandwidth too occurs due to the power loss where OFDM symbol rate is reduced without a reduction in overall signal bandwidth. ISI and ICI can also occur even if the cyclic prefix is longer than the maximum delay in multipath channel.
If the FFT start point is before the start point of the lagged symbol ISI would occur. If it’s FFT start point is behind the symbol beginning point ISI and ICI both might occur.

If the cyclic prefix length is set exactly with the maximum delay of the channel and the FFT window start point is set within its interval (without any ISI and ICI) UN affected by its previous symbol. The OFDM receiver takes the FFT of the received samples to yield, such that

\[
G_t(k) = \sum_{N=0}^{N-1} y_t(n) e^{j2\pi Kn/N},
\]

\[
= \sum_{N=0}^{N-1}\left(\sum_{m=0}^{\infty} h_t[m]x_t[n-m] + z_t[n]\right)e^{j2\pi Kn/N},
\]

\[
= \sum_{N=0}^{N-1}\left(\sum_{m=0}^{\infty} h_t[m]\left(\sum_{i=0}^{N-1} F_t(i)e^{j2\pi Kn/N}\right)\right) + z_t[k],
\]

\[
= \frac{1}{N}\sum_{N=0}^{N-1}\left\{\left(\sum_{m=0}^{\infty} h_t[m]e^{j2\pi Kn/N}\right)F_t[i]\sum_{n=0}^{\infty} e^{j2\pi (K-1)n/N}\right\} e^{-j2\pi Kn/N} + z_t[k],
\]

\[
= H_t[k]F_t[k] + Z_t[k],
\]  

(3.6.3)
where $F_i[k], G_i[k], h_i[k], I_i[k]$ these are $k^{th}$ subcarrier frequency components of $l^{th}$ transmission symbol, received symbol, channel frequency response. The equation 4.20 simply specifies that the product of input message symbol with channel frequency response in frequency domain $[k] = H_i[k]*F_i[k]$ under no noise conditions and when cyclic prefix is added to it. Note that $Y[k]$ not equal to $H_i[k]F_i[k]$ without cyclic prefix addition. DFT of $y_i[k]$ not equal to DFT of $F_i[k]*DFT h_i[k]$ when $(G[k]=F_i[k]*h_i[k])$ where * for convolution operation. As we have, $G_i[k] = H_i[k] F_i[k]$ when $G_i[k] = F_i[k] \circ h_i[k]$ where $\circ$ denotes the circular convolution. Transmit samples circularly convolve with channel samples when cyclic prefix is added to the samples at the transmitter side [16][17][18].

3.7 Digital to analog conversion

The output of the cyclic insertion block is fed to a digital to analog converter at the rate of $f_s$. A basic representation of the equivalent complex transmitted signal is given by

$$x(t) = \sum_{n=0}^{N-1} D_n e^{j \frac{2\pi n}{N} f_s t}, \text{ for } -\frac{k_1}{f_s} < t < \frac{N+k_2}{f_s},$$

(3.7.1)

where $D_n$, represents the $n^{th}$ data symbol transmitted on the $n^{th}$ subcarrier, $k_1$ is length of cyclic prefix, $k_2$ is length of cyclic postfix and $T = N+k_1+k_2f_s$ is the OFDM symbol duration[16].

3.8 ADVANTAGES OF OFDM

3.8.1 SPECTRAL EFFICIENCY

In a FDM each channel is placed with 25% guard band gap so that it could prevent interface with each other when it is transmitted and the bandwidth of that is 2/symbol rate period.

In the OFDM channels signals overlap with each other and because due to this the symbol rate when compared, are twice better than FDM. Because of this factor the OFDM has a double the spectral efficiency compared to the FDM.
OFDM channel still requires guard band between the channels as these channels would have no overlap of subcarrier over lapping each other. Hence the symbol rate of the subcarriers when added with all subcarriers for an individual channel would be greater than the normal FDI which results in no ISI (Inter Symbol Interface) between the channels.

3.8.2 Reduced Inter Symbol Interface

In single carrier systems there is often ISI due to multipath propagation. When a wave is send through a propagation model over a huge distance the received signal which would have passed through multipath propagation would have ISI and signal reflection overlay to each other in very little amplitudes. These reflections remain as a challenge as they interfere with the subsequent symbol passed along the direct path. These reflections are cut down considerably by the pulse shaping filter which reduces the starting and ending part of the symbol period. But at higher rates these problem become more complex as these reflections would cover most of the symbol period which would ultimately result in ISI.

These OFDM systems overcome this problem by having a long symbol period compared to the one which would have low symbol period. Smaller symbol rate results in smaller reflections which would be very less compared to the symbol period. These smaller reflections can be further removed with the help of guard band which ultimately results in reduced ISI.
4. Filter bank multicarrier (FBMC)

4.1 Introduction:

One of the main disadvantages of the OFDM system is loss of spectral efficiency due to the addition of cyclic prefix. In this Chapter we focus on FBMC+OQAM i.e. Filter Bank Multicarrier based on Offset–QAM. FBMC+OQAM compensate the use of cyclic prefix in OFDM system which improves the spectral efficiency and power efficiency during the transmission.

OFDM is very similar to Transmultiplexer. It consists of synthesis filter bank and analysis filter bank. In this prototype filter, rectangular pulse is used. It results in poor frequency response because of rectangular window for prototype filter.

In [19], they proposed a Trans multiplexer with non-rectangular windows and nyquist pulse shaping is used, their cascade of synthesis filter bank and analysis filter bank should meet nyquist criterion. Ideal bandwidth efficiency is achieved by using nyquist criterion. The below Figure 4.1 shows the OFDM functional diagram along with the proposed FBMC modification in it.

![Figure 4.1 Block diagram of OFDM and proposed FBMC](image-url)
**FBMC with OQAM:** OFDM and FBMC Multicarrier systems are both based on FFT computation. The major difference is Cyclic prefix is added after FFT in OFDM system. In FBMC, Polyphase Network (PPN) which is set of digital filters is added after FFT computation (Synthesis Filter Bank at the transmitter and Analysis Filter Bank at the receiver). As a result, during the data transmission signal streaming is different in each system. To achieve maximum efficiency filter banks are combined with Offset-QAM[19][20].

**Role of FBMC with OQAM:** In FBMC, Offset QAM has been used instead of conventional QAM. As a result of this, orthogonality between sub-carrier is maintained, there is no requirement of guard time and the information flows continuously. The advantage of the cyclic prefix can be compensated by using the nyquist pulse shaping before transmitting the OFDM signal which mitigates the effect of Inter Symbol Interference (ISI). In this chapter we are going to deal with the polyphase networks. Analysis filter bank and Synthesis filter bank are the most fundamental concepts of Multirate filter bank [19][20][21].

![Diagram for OQAM +FBMC sub channel signal mode](image)

**Figure 4.2 Diagram for OQAM +FBMC sub channel signal mode**

### 4.2 Decimator

The decimator is defined from the equation below,

\[ g_d(n) = f(M_n), \quad (4.2.1) \]
which implies that every \( M^{th} \) signal of the \( f(n) \) is retained. This can be demonstrated with the help of \( M=3 \). The samples shown by decimator are shown below in Figure 4.3,

\[
\begin{align*}
g_n(0) &= f(0), \quad g_n(1) = f(3), \quad g_n(2) = f(6).
\end{align*}
\]

\[ f(n) \quad \text{DECIMATOR} \quad g_x(n) \]

\[ g_x(n) \]

\[ f(-3) \quad f(0) \quad f(3) \quad f(6) \quad f(9) \]

\[ -3 \quad -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \]

\[ \begin{array}{c}
-3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 \\
\end{array} \]

\[ \begin{array}{c}
g_x(n) \\
\end{array} \]

\[ \begin{array}{c}
f(-3) \quad f(0) \quad f(3) \quad f(6) \quad f(9) \\
-3 -2 -1 0 1 2 3 \\
\end{array} \]

\[ \text{Figure 4.3 Decimator input and output signals with } N=3 \]

This decimator is also called as down sampler which results in loss of information. But in natural it is limited with the help of using correct bandwidth to it[22].

\subsection*{4.3 Decimationfilter}

Consider the equation for the decimation filter in \( z \) domain,

\[
g_n(z) = \frac{1}{M} \sum_{l=0}^{M-1} f \left( z^{\frac{1}{M}} \ast W^l \right), \quad (4.3.1)
\]

it is important to understand these above equation in frequency variable \( w \). By substituting \( z=j^{ew} \) in the above equation we get as shown below,
where $W = e^{-j2\pi/M}$, for the decimator the output for $g_n(e^{jw})$ will be the addition of all $M$ terms. The zero term would be $f(e^{jwM})$ and the first term would be $f\left(e^{j\frac{2\pi}{M}}\right)$, this term is nothing but the stretched version of $f(e^{jwM})$ which is stretched by $2\pi$. Hence these stretched version usually overlap with each other which would result in aliasing and it can be viewed in the Figure 4.4 below where $M=3[22]$.

\[
g_n(e^{jw}) = \frac{1}{M} \sum_{l=0}^{M-1} f\left(e^{j\frac{(w-2\pi l)}{M}}\right),
\]

\[\text{(4.3.2)}\]

\[\text{Figure 4.4 Input and output of the decimator } N=3.\]

In this equation (4.3.2) the stretched version of $f$ overlaps with each other signals which lie simultaneously as shown in the Figure 4.4. Hence the original signal $f(n)$ could not be recovered from the decimated version $g_n(n)$. The overlapping of the signals with each other is called aliasing. If the original signal is band limited to a certain region without overlapping signal
aliasing can be avoided. This would result in recovering the original \( f(n) \) signals from the decimated versions.

The original signal \( f(n) \) need to be a low pass band limited signal in order to recover from \( M \) folded decimated versions. Let us consider the band pass signal with the Fourier transform \( \frac{2\pi}{N} \). If the signal fig 4.5(a) is decimated one then the stretched version will not overlap with the extended version. The decimated version of fig 4.3(b) would be free from aliasing since \( W_0 = K\pi/M \). When the pass band region is quite near to the non-zero part of the signal in a band pass filter the ordinal signal \( f(n) \) can be recovered from \( f(M_0) \).

![Image of band pass signal with total bandwidth \( \frac{2\pi}{m} \)](a)

![Image of band pass signal with total bandwidth \( \frac{2\pi}{m} \)](b)

*Figure 4.5 band pass signal with total bandwidth \( \frac{2\pi}{m} \) (a) the real signal and (b) complex signal.*

Given a signal \( f(n) \) which is a primary signal it is passed through \( S(z) \) band limiting filter through which there will be no aliasing between the signals when it is sent in to decimator. This block diagram is shown in the Figure 4.6. The band limiting filter \( S(z) \) is called as a decimation filter. The decimation filter can be a low pass, high pass or a band pass filter as shown in the Figure 4.6[22].
4.4 Analysis filter bank

In this system there are M decimation filters with f(n) input. The value of N>M when it is used for communications. The value of N<M when it is used for adaptive filtering and signal processing. This whole system which comprises of all these blocks is called as analysis filter bank. As shown in the fig 4.7[22].
These analysis filter bank can be also represented in polyphase identity format as shown below such that,

\[ s_m(z) = \sum_{k=0}^{N-1} Z^K c_m z^n, \]  

Expressing the bank of M filters in a matrix column format,

\[
\begin{bmatrix}
s_0(z) \\
s_1(z) \\
\vdots \\
s_{M-1}(z)
\end{bmatrix} = t(z^w) 
\begin{bmatrix}
1 \\
z \\
\vdots \\
z^{(N-1)}
\end{bmatrix}.
\]

The above matrix equation is said to be the polyphase representation of the analysis filter bank. This can be represented as shown in the Figure 4.8[22].
The first noble identity is applied to the polyphase filter and hence the f(n) is first blocked by type 1 polyphase components $f_k$ and after that the output is sent to the filter $S(z)$. The block diagram to represent the use of first noble identity is given below in fig 4.9[22].
Figure 4.9 modified polyphase filter with its first noble identity.

4.5 Expander

The M fold expander is shown in the Figure 4.10 and this expander would act as an up sampler. The expander is shown in time domain by its input output equation,

\[ g_e(n) = \{ f \left( \frac{n}{M} \right) \text{ where } n = \text{Multiple of } M. \]  

(4.5.1)

This expander insert only the zeros in between the f (n) values symmetrically such that there is no loss of information due to its expanding and the block which does this is called as the
expander. As shown in Figure 4.10[22].

\[ f(n) \rightarrow \text{EXPANDER} \rightarrow g_e(n) \]

\[ \text{TRANSMITTER} \]

\[ f(n) \]

\[ g_e(n) \]

\[ f(-1) \quad f(0) \quad f(1) \quad f(2) \quad f(3) \]

\[ -3 \quad -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \]

\[ \text{Figure 4.10 N fold expander with input } f(n) \text{ and output } g_e(n) \text{ signals.} \]

4.6 Interpolation filter

In z domain the input and output relation can be expressed in the equation below which is,

\[ g_e(z) = f(z^M), \]

we understand this above variable in terms of frequency variable \( w \) by substituting \( z = e^{jw} \) in the above equation,

\[ g_e(e^{jw}) = f(e^{jwM}), \]  \hspace{1cm} (4.6.1)

And hence for the expander the \( g_e(e^{jw}) \) can be obtained by reducing the \( f(e^{jw}) \). By factor of M. The reduced factor M must be in terms of period \( 2\pi \)[22].
Figure 4.11 Discrete interpolation filter along with its operation in frequency domain

The interpolation filter which acts as a discrete time domain filter is normally used at the output of the expander. This combination of the interpolation filter along with an expander is called as an interpolator. Expander does nothing but introduces zero valued samples between the input samples. The work of the interpolation filter is to sum an average value from the input values and replace it with the zero valued samples. Let us take the interpolation filter in the frequency domain where the output of the interpolation filter is nothing but the reduced copies of the original input[22].

The interpolation filter retains one of the reduced original outputs. Thus the interpolator output of $f(e^{j\omega})$ is nothing but the reduced version of $g_\varepsilon(e^{j\omega})$ with images removed. Consider the interpolation filter shown below in the Figure 4.12. The zero valued samples produced by the
expander enter into the interpolation filter and results in wasted computation which results in higher rate. In order to overcome this we use the below mentioned filter in its type 1 composition,

\[ R(z) = \sum_{k=0}^{M-1} z^{-k} A_k z^m, \]  

(4.6.2)

Then the whole system can be redrawn as shown below in Figure 4.13.

By using the second noble identity the whole block diagram can be simplified more from the previous one. This simplification of the block diagram leads to no zeroed values entering the filter\(A(z)\). This would result in low rate computations. The output of \(g(n)\) is the interleaved version of \(A(z)\)[22].

Figure 4.12 Interpolation filter polyphase representation
Figure 4.13 Simplification of polyphase filter with respect to second noble identity

4.7 Synthesis filter bank

In this system there are $M$ interpolation filters with $d(n)$ input. The value of $N>M$ when it is used for communications. The value of $N<M$ when it is used for adaptive filtering and signal processing. This whole system which comprises of all these blocks is called as synthesis filter bank. As this combines the signals $d(n)$ into an output $g(n)$. The polyphase version of the synthesis filter bank is formed in order to implement it more efficiently[22].
The above matrix equation is said to be the polyphone representation of the synthesis filter bank. This can be represented as shown in the Figure 4.14.

Figure 4. 14 Synthesis filter bank

Figure 4. 15 Polyphone version of synthesis filter bank.
\( R(z) = \sum_{k=0}^{M-1} z^{-k} A_k z^m \), which is the representation of Synthesis Filter Bank,

\[
\begin{bmatrix}
R_0(Z) & R_1(Z) & \ldots & R_{M-1}(Z)
\end{bmatrix} = \begin{bmatrix} 1 \quad z^{-1} \quad \ldots \quad z^{-(N-1)} \end{bmatrix} Az^N,
\]  

(4.7.1)

The above equation is said to be polyphase representation of the synthesis filter bank. The second noble identity is applied to the polyphase filter and it can be redrawn as shown below in Figure 4.16 which is called polyphase implementation of the synthesis filter bank[22].

\[ \quad \]

4.8 The nyquist property

The sine input responses satisfies the property
$$r(Mn) = \delta(n) \text{(Nyquist M property)}$$

In this region it has regular zero crossing at nonzero multiples of M[22], and moreover $h(0)=1$. A filter which satisfies this property is called as a nyquist filter. The nyquist property in the nyquist filter would make sure that the original input signal $f(n)$ is retained from the interpolation or the decimation filter without any damage to the original input signals.

Thus the M solo version of the signal $f(n)$ returns the original signal $g(n)$.

**Proof**

The fact that the nyquist condition can be verified is through setting $n=1M$ and rewriting the equation we obtain,

$$g(lM) = \sum_{k=-\infty}^{\infty} f(k) g(lM - kM) = \sum_{k=-\infty}^{\infty} x f(k) e(l-k), \quad (4.8.1)$$

where $e(n) = i(Mn)$, we have proved that the sequence $g(nM)$ is equal to the convolution($f * e$)($n$). So It tends to have $g(nM)=f(n)$ for all the inputs of $f(n)$ if and only if the nyquist criteria is fulfilled. There is n number of methods for the design of nyquist filter which satisfies the nyquist property exactly and the simple approach is to do with the help of window approach Black Man, Hanning or Kaiser Window are used in the making og the nyquist filters[22].
5. Simulation and Results

5.1 Empirical Observation

In this chapter we present the result which we performed using the MATLAB. We had simulated OQAM and QAM separately along with OFDM+CP. We here check the BER vs SNR for each and every model simulated here. We shall investigate the following cases here,

QAM model,

OQAM model,

OFDM with CP model.

5.2 QAM model

In this section we simulate QAM model and we would verify the Bit Error Rate vs Signal Noise Ratio curve then we would compare the results with OQAM.
5.2.1 Results of QAM model

Simulation results of the following are plotted below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of signal constellation</td>
<td>4</td>
</tr>
<tr>
<td>No of random bits to process</td>
<td>30000</td>
</tr>
<tr>
<td>Type of modulation</td>
<td>QAM</td>
</tr>
<tr>
<td>Oversampling rate</td>
<td>2</td>
</tr>
</tbody>
</table>

- Random bits are generated for the QAM modulation.
- Bit to symbol mapping of the modulated data.
- QAM modulation performed on the modulated data.
- Constellation mapping of the modulated data.
- QAM modulated data output is sent through the AWGN.
- The received signal with the AWGN is removed and demodulated using QAM demodulation.
- QAM demodulated data symbol to bit mapping.
- BER is verified by varying the signal noise ratio.

*Figure 5. Random generated bits of QAM*
Figure 5.2 Scatter plot for QAM

Figure 5.3 Modulated random symbols of QAM
In this section we simulate OQAM model and we would verify the bit error rate vs signal noise ratio curve. Then we would compare the results with QAM BER value.

**Figure 5.4 BER vs SNR for QAM**

### 5.3 OQAM model

In this section we simulate OQAM model and we would verify the bit error rate vs signal noise ratio curve. Then we would compare the results with QAM BER value.
5.3.1 Result of OQAM model

The outputs of OQAM and its simulation results using Matlab are shown below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of signal constellation</td>
<td>4</td>
</tr>
<tr>
<td>No of random bits to process</td>
<td>15000</td>
</tr>
<tr>
<td>Symbol rate</td>
<td>256200</td>
</tr>
<tr>
<td>Oversampling rate</td>
<td>2</td>
</tr>
</tbody>
</table>

- Random bits are generated for the OQAM modulation.
- Bit to symbol mapping of the modulated data.
- OQAM modulation performed on the modulated data.
- Constellation mapping of the modulated data.
- OQAM modulated data output is sent through the AWGN.
- The received signal with the AWGN is removed and demodulated using OQAM demodulation.
- OQAM demodulated data symbol to bit mapping.
- BER is verified by varying the signal noise ratio.

![Figure 5.5 Random generated bits of OQAM](image)

*Figure 5.5 Random generated bits of OQAM*
Figure 5. 6 Modulated bits of OQAM

Figure 5. 7 BER vs SNR for OQAM
5.4 OFDM model

In this section we investigate the complete OFDM model with cyclic prefix added to it and we would verify the bit error rate (BER) vs signal noise ratio (SNR) curve.

5.4.1 Result of OFDM model

OFDM modulation and demodulation are simulated using the Matlab. Random data are first generated and then it is modulated using QAM and cyclic prefix added to it. This addition of cyclic prefix to the original OFDM symbol increases the OFDM signal size. Cyclic prefix helps in overcoming problems caused by ICI and ISI. This whole signal along with cyclic prefix is sent through the OFDM and received signal along with cyclic prefix is removed and the signals are demodulated to receive the original signal.

Simulation parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of carriers</td>
<td>64</td>
</tr>
<tr>
<td>Coding used</td>
<td>Convolutional coding</td>
</tr>
<tr>
<td>Single frame bits</td>
<td>96</td>
</tr>
<tr>
<td>Total no of frames</td>
<td>100</td>
</tr>
<tr>
<td>Modulation</td>
<td>16 QAM</td>
</tr>
<tr>
<td>No of pilots</td>
<td>4</td>
</tr>
<tr>
<td>Cyclic extension</td>
<td>25% (16)</td>
</tr>
</tbody>
</table>

- Setting no of carriers to 64 along with 25% of the cyclic prefix in which there would be 48 data carrier, 4 pilot signals and a null carrier.
- Generate random bits for all carriers.
- Convolutional encoding data which is generated from the random signals.
- Interleaving coded data.
- Binary to decimal conversion of interleaved data.
- QAM modulation performed on the interleaved data.
- Modulated carrier is sent through the IFFT block after that an addition of 25% of cyclic prefix is added to it the signal and it is carried.
- The OFDM signal with the cyclic prefix is fed into the AWGN channel.
- The cyclic prefix extension from the original signal is removed.
- FFT operation is applied to the received signal and the signal is demodulated and the results are obtained.
The bit error rate is varied by varying the signal noise ratio.

Figure 5. Random generated bits of OFDM + CP.
Figure 5. 9 Scatter plot for OFDM + CP

Figure 5. 10 Modulated symbols for OFDM + CP
6. Conclusion

In this thesis, we did a fair study on LTE network architecture and protocol structure. We analyzed the LTE-TDD radio frame and studied how data are organized in LTE radio frames from LTE Physical layer. OFDM symbols are used inside the radio frames with cyclic prefix. We studied the working principle of OFDM and investigated the use of cyclic prefix. Then we extended our study on Digital carrier modulation techniques. Mainly focused on Quadrature amplitude Modulation and Offset-Quadrature Amplitude Modulation.

Cyclic Prefix has a big role in the OFDM structure but at the same time redundancy of CP results in the loss of bandwidth efficiency. We studied and prepared a technical report on Filter Bank Multicarrier (FBMC) which is useful to eliminate cyclic prefix in OFDM and at the same time to compensate the advantages of cyclic prefix in OFDM.
We designed and simulated the OFDM with Cyclic Prefix transceiver structure, its Bit Error Rate is verified by changing the Signal to Noise Ratio. We designed, simulated and compared the Offset-QAM with QAM, its BER vs. SNR was verified. Our simulation results showed Offset-QAM modulation is better than normal QAM modulation.

7. Future work:

The vital part of this thesis is to analyze LTE radio frame by eliminating the cyclic prefix in OFDM structure. Our future work is to design, simulate and implement the FBMC structure in LTE radio frame. Implementation work can be investigated and compared with OFDM+CP structure.
References


[4] 3GPP TR25.913 “Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)”.


[19] Krishna Arya, Dr. C. Vijaykumar “Elimination of Cyclic Prefix of OFDM systems using filter bank based multicarrier systems,”.


<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
</tr>
<tr>
<td>AMPS</td>
<td>Advanced Mobile Phone System</td>
</tr>
<tr>
<td>ASK</td>
<td>Amplitude Shift Keying</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>EDGE</td>
<td>Enhanced Data rates for GSM Evolution</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
</tr>
<tr>
<td>EUTRAN</td>
<td>Evolved Universal Terrestrial Radio Access Network</td>
</tr>
<tr>
<td>FBMC</td>
<td>Filter Bank Multicarrier</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency Shift Keying</td>
</tr>
<tr>
<td>GPRS</td>
<td>General packet radio service</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>HSPA</td>
<td>High Speed Packet Access</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse Fast Fourier Transform</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MME</td>
<td>Mobility Management Entity</td>
</tr>
<tr>
<td>NAS</td>
<td>Non-Access Stratum</td>
</tr>
<tr>
<td>NMT</td>
<td>Nordic Mobile Telephony</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>OOK</td>
<td>On Off Keying</td>
</tr>
<tr>
<td>OQAM</td>
<td>Offset Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>OQPSK</td>
<td>Offset Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>PAM</td>
<td>Pulse Amplitude modulation</td>
</tr>
<tr>
<td>PDCP</td>
<td>Packet Data Convergence Protocol</td>
</tr>
<tr>
<td>PDN-GW</td>
<td>Packet Data Network-Gateway</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical layer</td>
</tr>
<tr>
<td>PRB</td>
<td>Physical Resource Block</td>
</tr>
<tr>
<td>PSK</td>
<td>Phase Shift Keying</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RACE</td>
<td>Research &amp; Development of Advanced Communication in Europe</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>STO</td>
<td>Symbol Timing Offset</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>S-GW</td>
<td>Serving-Gateway</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>TACS</td>
<td>Total Access Communication System</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TSG</td>
<td>Technical Specification Group</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
</tr>
<tr>
<td>UTRAN</td>
<td>Universal Terrestrial Radio Access Network</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband- Code Division Multiple Access</td>
</tr>
</tbody>
</table>