CHAPTER 3: MIMO OFDM

In this chapter a detailed explanation about the OFDM system its evaluation and this chapter helps to understand the fundamentals behind OFDM system and why channel estimation is very relevant in the context of OFDM systems. This chapter also provides a brief understanding about MIMO techniques. This chapter lays the fundamentals for further understanding of OFDM channel estimation approaches.

Orthogonal Frequency Division Multiplexing (OFDM) is a multi carrier transmission system, where a high data rate serial data is converted into a number of parallel data streams; In FDM entire signal frequency band is divided into ‘N’ non overlapping frequency sub channel [94]. Every sub channel is modulated with a different carrier and then the N sub channels are multiplexed with frequency. It is good to evade spectral overlap of channels to suppress inter channel interference (ICI). However, this results an inefficient use of the available frequency spectrum. Due to the bandwidth inefficiency, the number of ideas proposed, in which the parallel data is used and in Frequency Division Multiplexing (FDM) the overlapping sub channels carrying a signal rate ‘r’ is separated w apart in frequency to eliminate the use of ultra speed equalization and to fight with impulsive noise and multi path distortion, as well as the efficient use of the available bandwidth.
Figure 3.1: Conventional non-overlapping multicarrier technique

The figure depicts the traditional non overlapping multicarrier method. In a single carrier system, the entire link is failed due to the single fade where as in multi carrier system only a few percentage of the sub carrier is affected. The term orthogonal shows the exact mathematical correlation between the frequencies of the carriers in the system. In a general FDM system, the filters are used for providing space between carriers and demodulators are used to receive the signals. In those receivers, guard bands are used between the different carriers and these results low spectrum efficiency in the frequency domain [94].

Figure 3.2: Illustration of multicarrier modulation with overlapping
The above figure shows by utilizing the overlapping multi carrier modulation technique, very nearly half of bandwidth is saved. To perceive the overlapping multi carrier technique, the crosstalk is present in between sub carriers. However to lessen the cross talk between those subcarriers, orthogonality is maintained between the various modulated carriers. One of the main intentions to employ OFDM is to enlarge the carrier strength against frequency selective fading and narrow band intervention. Flat fading arises when ever the bandwidths of the subcarriers are small compared to the coherence bandwidth of the channel, which requires simple equalization. This infers that the time period of the sub streams are made long when compared with the delay spread of the time dispersive radio channel. The idea of OFDM orthogonality of the sub carriers has recently been applied broadly in wireless channel schemes because of its high information rate transmission ability with high bandwidth efficiency and lustiness to multipath delay.

It is achievable to organize the carriers in an OFDM signal the side bands of specific subcarriers overlap and the received signals are without adjacent carrier interface then these carriers are strictly orthogonal. The receiver behave as a bank of demodulators, converting each carriers to DC, to recover the raw data all the resulting signals are integrated over a symbol period, assuming that the other carriers all minimize the frequencies that, in the time domain, have a total number of cycles in the symbol period T, this results the integration process have zero contribution from all the remaining carriers. Thus, whenever the carrier spacing is several number of 1/T, results the carriers are orthogonal to each other. Much of the research work is done on the high efficient multi carrier transmission system depends on ‘orthogonal frequency’ carriers.
In parallel transmission system, both the modulator and demodulator used DFT. At the receiver the DFT is employed and it calculates the correlation values of each subcarrier with the centre of frequency. At that point the transmitted information is recollecting without any crosstalk. Furthermore, utilizing the DFT based multicarrier technique; by using base band processing we can achieve Frequency Division Multiple Access not by band pass filtering. Also, to exclude the banks of sub carrier oscillators and FDM is utilized by coherent demodulators, entire digital implementations could be worked around unique purpose network implementations performing the Fast Fourier Transform (FFT), which is an efficient application of the DFT. Recent developments in very large scale integration (VLSI) technology make rapid, huge size FFT chips commercially affordable. Utilizing this strategy, both transmitter and receiver are executed utilizing efficient FFT techniques. By introducing cyclic prefix (CP) inter symbol interference (ISI) is eliminated in OFDM, which is accomplished by extending an OFDM symbol with some part of its head or tail [94].

Besides ISI, any loss of orthogonality in sub channel of an OFDM block results inter carrier interference (ICI) is identified the limitation of the performance of OFDM systems. The error floor made by ISI and ICI makes challenges for the achievements of OFDM based High Definition Television (HDTV). Trellis coding and aerial diversity plans can extremely lower the error floors are caused by ICI. The single frequency network (SFN) having a very long delay represents the possibility of time interval of the ISI which crosses the length of the guard interval. Those ISI can be called as residual ISI and can be pulverizing, even in little sums. To reduce the residual ISI by increasing the length of the guard interval, results low spectrum efficiency. It has been recently
practiced in wireless local area network for high information rate communication. With these points of interest, OFDM is used by many wireless standards such as Digital Video Broadcasting (DVB), Digital Audio Broadcasting (DAB) and Wireless Metropolitan Area Network (WMAN) [95].

The OFDM transmission plan has the following benefits: by using an equalizer, implementation complexity is reduced than that of the single carrier system. In moderately slow time varying channels, by adjusting the information rate per sub carrier as a result to increase the capacity is indicated by the signal to noise ratio (SNR) of that specific sub carrier. OFDM is solid against narrow band interference, because such interference influences only a few percentages of sub carriers. Single frequency networks (SFN) are possible using OFDM, which is particularly alluring for broadcasting applications. Then again, OFDM also has a few disadvantages compared with single carrier modulation. OFDM is more touchy to frequency offset and phase noise. OFDM has comparatively large peak to average power ratio (PAPR), which has a tendency to lessen the power efficiency of the radio frequency (RF) amplifier. Depends on various requirements OFDM parameters are chosen [26].

Usually, bandwidth, bit rate and delay spread are the three main requirements in any communication system. The guard time is directly dictated by the delay spread. Usually the guard time is set above twice to four times the mean squared root delay spread. The type of coding and Quadrature Amplitude Modulation (QAM) determines this value. Quadrature Phase Shift Keying (QPSK) is more stable to ICI and ISI than higher order QAM (like 64- QAM). Such interference is reduced by using heavier coding [96] & [97]. By considering the large symbol duration when compared to guard time, the
SNR loss is minimized. It can’t be randomly extensive, however, because large symbol period means more sub carriers with a little spacing, a huge usage complexity, and more affectability to phase noise and frequency offset, and also an enlarged peak to average power ratio (PAPR). Hence, in practical design to make the symbol time period not less than five times the guard time, which signifies a 1 dB SNR loss on account of the guard time [98]. After the guard time and symbol duration are fixed, as the required 3 dB bandwidth is divided by the time of sub carrier spacing directly follows the number of sub carriers, which is less than the guard time and inverse of the symbol duration. Alternatively, the required bit rate per sub carrier defines the number of sub carriers. The modulation type, coding rate and symbol rate determine the bit rate per sub carrier. One of the prime reasons to utilize OFDM is it’s accessibility to manage extensive delay spread with a reasonable usage complexity. In a single carrier system, the usage complexity is ruled by equalization, which is important when the delay spread is bigger than around 10 percentage of the symbol duration. In OFDM, the complexity of an OFDM system is basically determined by the FFT, which is utilized to demodulate the different sub carriers and an equalizer is redundant in OFDM [99] [100].

3.1 MATHEMATICAL DESCRIPTION OF OFDM SYSTEMS:

The pilot based channel estimation of the OFDM system is depicted in the Figure 3.3, in the “signal mapper” the binary data is first arranged and mapped according to the type of modulation. Pilots are inserted either with in specific period to all sub carriers or uniformly in which the data sequence [96]. The block diagram of the base band OFDM system model is shown in Figure 3.3.
Figure 3.3: A baseband OFDM System

To transform the data sequence of length $N\{X(k)\}$ into time domain signal $\{x(n)\}$ by using IDFT with the following equation:

$$
\begin{align*}
    x(n) &= \text{IDFT} \sum_{k=0}^{N-1} X(k) e^{j2\pi kn/N} \\
    n &= 0, 1, 2, \ldots, N-1
\end{align*}
$$

Where $N$ is the DFT length.

Following IDFT block, guard time insertion block, is used to prevent inter symbol interference, which is taken to be larger than the expected delay spread [97]. In order to eliminate ICI guard time adds the cyclically extended part of OFDM symbol, the resultant OFDM symbol is given below:

$$
\begin{align*}
    x_f(n) &= \begin{cases} 
        x(n + N_g), & n = -N_g, -N_g + 1, \ldots, -1 \\
        x(n), & n = 0, 1, \ldots, N - 1
    \end{cases}
\end{align*}
$$

where $N_g$ is the guard interval length.

On the assumption of base band system model, after following D/A converter, this signal will be sent from the transmitter. The transmitted signal will pass through the time
varying frequency selective fading channel with additive white noise. The received signal is represented by Eq.3.3.

\[ y_f = x_f \otimes h \otimes w \]  \hspace{1cm} 3.3

Where, w(n) is additive white Gaussian noise and h(n) is the channel impulse response [96], which can be represented by Eq. 3.4.

\[ h = \sum_{i=0}^{r-1} h_i e^{j \frac{2\pi}{N} f_{Di} T_n} \delta(n - \tau_i) \hspace{0.5cm} 0 \leq n \leq N - 1 \] \hspace{1cm} 3.4

where \( r \) is the total number of propagation paths, \( h_i \) is the complex impulse response of the \( i^{th} \) path, \( f_{Di} \) is the \( i^{th} \) path Doppler frequency shift, \( \lambda \) is delay spread index, \( T \) is the sample period and \( \tau_i \) is the \( i^{th} \) path delay normalized by the sampling time.

At the receiver, guard time is removed, after passing to discrete domain through A/D :

\[ y = y_f + N_g \hspace{1cm} n = 0,1,\cdots N - 1 \] \hspace{1cm} 3.5

Then \( y(n) \) is sent to DFT block for the following operation:

\[ Y = DFT \left\{ \frac{1}{N} \sum_{n=0}^{N-1} y e^{-j \frac{2\pi kn}{N}} \right\} \hspace{0.5cm} k = 0,1,2,\ldots N - 1 \] \hspace{1cm} 3.6

Assuming there is no ISI, [99] shows the relation of the resulting \( Y(k) \) to \( H(k)\text{=}DFT\{h(n)\} \), \( I(k) \) that is ICI because of Doppler frequency and \( W(k)\text{=}DFT\{w(n)\} \), with the following equation:

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The pilot signals are extracted, after the DFT block, and the channel is estimated $H_e(k)$ for the sub-channels is obtained in channel estimation block. Then estimated the transmitted data is given by:

$$X_e = \frac{Y}{H_e} \quad k = 0,1, \cdots N-1$$

Finally the binary information data is obtained in “signal demapper” block.

### 3.2 An Overview of MIMO Technology:

MIMO is a technology for wireless communications that uses multiple antennas for both transmitter and receiver, by using this technology to transfer much data at the same time [107]. MIMO is one of smart antenna technology like MISO and SIMO. Smart antennas utilize spatial diversity scheme, inserts additional antennas to good use. Assuming that there are more antennas than spatial streams, the surplus antennas can add diversity of receiver and raise the range.

**MISO:** Multi Input Single Output

**SIMO:** Single Input Multi Output

**MIMO Basics:**

The utilization of multiple antennas, MIMO technology is capable to significantly increase the capacity of the channel. By raising the number of transmit and receive
antennas it is achievable to proportionally increase the throughput of the channel with each pair of antennas are combined to the system [108].

In recent years, MIMO technology is one of the most valuable wireless techniques to be engaged. One of the basic ideas following MIMO wireless systems space time signal processing in which time is complemented with the spatial dimension inherent in the use of multiple spatially distributed antennas i.e, the utilize of multiple antennas spotted at different points. These additional paths are used to contribute additional lustiness to the radio link by increasing the signal to noise ratio.

The two important formats for MIMO are listed below

1. Spatial multiplexing: This format of MIMO is used to contribute additional data capacity by using different paths to transmit surplus traffic, i.e, improving the data throughput ability.

2. Spatial diversity: Spatial diversity used in this limited sense generally refers to transmit and receive diversity. These two formats are utilized to provide increments in the SNR and they are described by increasing the reliability of the system with respect to the distinct forms of fading [109] – [115].

Advantages of MIMO technology:

i. To achieve high data throughput in limited bandwidth channels in order to overcome the adverse effects of multipath fading, multiple antenna configurations are used.

ii. Better data rates, range and reliability.
3.3 EVOLUTION OF OFDM WIRELESS STANDARDS:

In 1998, to select OFDM as the base for a advanced physical layer standard development to current 802.11 MAC standard is decided by the IEEE 802.11 standardization [101-103]. The advanced standard targeted a range from 6 up to 54 Mbps of data rates in the 5 GHz band.

The main parameters of the draft OFDM standard are listed in Table 3.1. A main parameter, the choice of other parameters which are heavily influenced is the guard interval of 800 ns. Depending on the coding rate and modulation used this guard interval gives robustness to mean-squared root delay spreads up to several hundreds of nanoseconds. In effect, this process that the modulation is suitable to be used in any private environment, including big factory buildings. It can further be used in outside environments; in this case directional antennas may be used to reduce the delay spread to a satisfactory amount and to boost the range.

In order to restrict the corresponding amount of power and time used on the guard time to 1 dB, 4 μs are preferred to the symbol duration. The subcarrier spacing is chosen to be 312.5 kHz is determined by the symbol duration, which is the reciprocal of the symbol duration less the guard time. By using variable modulation types from BPSK to 64-QAM, the uncoded data rates of 12 to 72 Mbps can be achieved by using 48 data subcarriers. Forward error correction is used across the sub carrier, in order to adjust for subcarriers in far fades, with variable coding rates from 6 up to 54 Mbps. Convolution codes having the generator polynomials (133,171) with the industry standard rate 1/2,
constraint length 7 code is used. By perforation the 1/2 code rate, higher coding rates of 2/3 and 3/4 are obtained.

Table 3.1: Main Parameters of the OFDM standard for WLAN [101]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate</td>
<td>6, 9, 12, 18, 24, 36, 48, 54 Mbit/s</td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK, QPSK, 16-QAM, 64-QAM</td>
</tr>
<tr>
<td>Coding rate</td>
<td>1/2, 2/3, ¾</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>52</td>
</tr>
<tr>
<td>Number of pilots</td>
<td>4</td>
</tr>
<tr>
<td>OFDM symbol duration</td>
<td>4 µs</td>
</tr>
<tr>
<td>Guard interval</td>
<td>800 ns</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>312.5 kHz</td>
</tr>
<tr>
<td>-3 dB Bandwidth</td>
<td>16.56 MHz</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>20 MHz</td>
</tr>
</tbody>
</table>

One of the major elements of LTE is the utilization of OFDM. The utilization of OFDM is a essential choice for LTE. While the fundamental concepts of OFDM are used, it has essentially been custom-made to fit the accurate requirements for LTE. Even
though the use of multiple carrier each one carrying the same low data rate. OFDM is very strong to interference, that’s why it was chosen as the signal carrier format. Various forms of broadcasting standards utilizing OFDM having a considerable level of experience has gained in recent years, used along with Wi-Fi and Wi-MAX. For carrying high data rates OFDM modulation format is very suitable - one of the major requirements for LTE [104].

Besides this, both FDD and TDD formats are using OFDM. This becomes an extra benefit. One of the important parameters associated with the utilization of OFDM inside LTE is the superior of bandwidth. A variety of decisions are influenced by the available bandwidth along with the number of carriers that can be contained in the OFDM signal and following this influences elements containing the symbol length et cetera. A number of channel bandwidths are defined by LTE. Definitely better the bandwidth, the better the channel capacity.

The channel bandwidths that have been chosen for LTE are [104]:

1. 1.4 MHz
2. 3 MHz
3. 5 MHz
4. 10 MHz
5. 15 MHz
6. 20 MHz
Besides this the spacing between subcarriers is 15 kHz, i.e. the subcarriers of LTE are spaced 15 kHz aside from each other. For maintaining orthogonality a symbol rate of 1 / 15 kHz gives 66.7 μs. Every subcarrier is capable to carry information at a maximum rate of 15 ksps (kilo symbols per second). This contributes a 20 MHz bandwidth system a raw symbol rate of 18 Msp. In order this is capable to support a raw data rate of 108 Mbps as every symbol using 64QAM is able to perform six bits.

Mainly OFDM is used as a modulation format within LTE because of its resilience to spread and multipath delays; it is one of the main reasons. On the other hand adding resilience to the system is still necessary to implement designs. To overcome the inter-symbol interference (ISI) it helps that result from this. To prevent ISI by inserting a guard time section into the timing at the starting point of each data symbol, where the areas ISI is expected. It is possible to duplicate a portion from the extreme of the symbol to the starting point. This is referred to as the cyclic prefix, CP. At the optimum point the receiver can then sample the waveform and evade any inter-symbol interference produced by reflections that are slowed by times up to the portion of the cyclic prefix, CP.

The cyclic prefix (CP) length is important. To cancel out the multipath reflection delay spread, the length of the CP is enough long. Otherwise, it will decrease the data throughput capacity. For LTE, 4.69 μs has been chosen as the standard length of the cyclic prefix. Up to 1.4 km it can enables the system to hold path variations. In LTE the symbol length set to 66.7 μs. For OFDM systems, the length of symbol is defined by the fact that the symbol length is identical to the inverse of the carrier spacing, in that case
orthogonality is accomplished. The symbol length of 66.7 µs, it comes from the carrier spacing of 15 kHz [105].

Including a maximum number of 2048 different sub-carriers of the OFDM signal having a spacing of 15 kHz used in LTE. Even though it is necessary for the mobiles to have capacity to be capable to receive entire 2048 sub-carriers, not all essential to be transmitted by the base station which only wants to be capable to support the transmission of 72 sub-carriers. So all the mobiles are can communicate to any base station.

Three types of modulation orders are used in the OFDM signal is chosen for the LTE signal [105]:

1. \textit{QPSK} (= \textit{4QAM}) 2 bits per symbol
2. \textit{16QAM} 4 bits per symbol
3. \textit{64QAM} 6 bits per symbol

Depending upon the dominant conditions the precise LTE modulation format is chosen. The lower order modulation (QPSK), does not require a specific large signal to noise ratio but are incapable to send the data rapidly. Higher order modulation formats are used, where there is a adequate signal to noise ratios.

In the downlink, the subcarriers are divided into resource blocks. This allows the system to be able to separate the data over standard number of subcarriers. Resource block consists of 12 subcarriers, unconcerned to the complete LTE signal bandwidth
They also contain single slot in the time frame. This aid that various LTE signal bandwidths will posses various numbers of resource blocks.

3.4 OFDM ADVANTAGES & DISADVANTAGES:

OFDM advantages:

Many high data rate wireless systems used OFDM because it provides many advantages.

- **Immunity to selective fading:** One of the major advantages of OFDM is that is more impervious to frequency selective fading compared to single carrier systems because it splits the overall channel into different narrowband signals that are concerned individually as flat fading channels.

- **Resilience to interference:** The channel bandwidth may be limited due to the appearance of interference. This aid that none of the data is lost.

- **Spectrum efficiency:** Using sub-carrier overlapping technique, an important advantage of OFDM is that it causes the efficient utilization of the available spectrum.

- **Resilient to ISI:** Another benefit of OFDM is that it is perfect resilient to inter-symbol interference (ISI) and inter-frame interference. This result each sub channel is free from the low data rate.

- **Resilient to narrow-band effects:** It is possible to recover symbols lost because of the frequency selectivity of the channel and narrow band interference of the channel by using adequate channel coding and interleaving. None of the data is lost.
• **Simpler channel equalisation:** CDMA systems suffer with complexity of the channel equalisation because it was applied across the entire channel. OFDM has an advantage is that it utilizes multiple sub-channels, this results; the channel equalization comes much simpler.

**OFDM disadvantages:**

While OFDM has been broadly used, there are still a few drawbacks to its use, they are

• **High peak to average power ratio:** An OFDM signal suffering with a noise similar to amplitude variation with nearly large dynamic range, in other words peak signal to average power ratio (PAPR). The amplifiers are need to be linear and contains the large amplitude variations which effects the efficiency of RF amplifier and these aspects mean the amplifier cannot reach with high efficiency level.

• **Sensitive to carrier offset and drift:** Another drawback of OFDM is that it is touchy to drift and carrier frequency offset. Single carrier systems are less touchy.

**3.5 OFDM VARIANTS:**

In technical literature, there are several other variations of OFDM for which the labels are shown. All these variants follow the basic format of OFDM, but have additional attributes:
- **COFDM**: Coded orthogonal frequency division multiplexing. In Coded OFDM the error control coding and OFDM modulation process combined together. One important step is done in Coded OFDM is spacing bits and code the bits before to the IFFT.

- **Flash OFDM**: Fast Low latency Accesses with Seamless Handoff. Flarion developed this variant of OFDM. It entirely based on IP. Flash OFDM is the basis of the IEEE standard 802.20

- **OFDMA**: Orthogonal frequency division multiple access. OFDMA provides a multiple accesses capability for cellular tele communications.

- **VOFDM**: Vector OFDM, Cisco systems developed this VOFDM. In VOFDM. In VOFDM, OFDM and spatial processing combined together. To exploit the time and frequency diversity by using OFDM in the new combined technology.

- **WOFDM**: Wideband OFDM. WOFDM over helms problems with multipath by transmitting symbols; the unfortunate channel effects can then be decreased through an easy separation by the channel frequency response. It also contains a spreading forward error correction code, like Reed solmon.

All of these forms of OFDM use the same fundamental concept of utilizing close spaced orthogonal carriers each one transmitting low data rate signals. To obtain the complete signal during the demodulation, the phase and the data is then combined. In the wireless market, orthogonal frequency division multiplexing (OFDM) has gained a significant place. In today’s communication arena the combination of huge data capacity, high spectral efficiency, also it is endurance to interference is ideal for high data rate applications.