CARRIER FREQUENCY OFFSET AND SYMBOL TIME OFFSET ESTIMATION TECHNIQUE ON OFDM SYSTEM SYMBOL

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TEKNIK ANGGARAN OFSET FREKUENSI PEMBAWA DAN KESAN SIMBOL OFSET MASA KE ATAS SIMBOL SISTEM OFDM

GHASSAN MUSLIM HASSAN AL-SADDI

TESIS YANG DIKEMUKAKAN UNTUK MEMPEROLEHI
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DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

17 April 2019

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ABSTRACT

System synchronization is crucial in all wireless communication systems, especially in orthogonal frequency division multiplexing (OFDM). An OFDM technique is a multi-carrier system that provides high quality and high data rate wireless communication services. In an OFDM technique, the receivers do not know the end or the beginning of the OFDM symbols; therefore, this situation is very important for receiving a signal without errors. The performance of an OFDM technique is degraded by the carrier frequency offset (CFO) and the symbol timing offset (STO). Therefore, the purpose of this study is to improve synchronization performance for data transmission by considering the related factors. Hence, four objectives were chosen to achieve this. The first objective was to investigate the performance evaluation for OFDM synchronization in the time domain using the cyclic prefix (CP) estimation and standard training sequence (TS) in the time domain for CFO and STO. The second and third objectives for CFO and STO respectively, were to design and implement time synchronization. The time synchronization based on the proposed TS method which employs two equally sized sliding windows that are equal to the size of a CP. With a size of the CP is equal to ¼ size of fast Fourier transform (FFT), and to expand the range of CFO estimation from CFO ≤ |0.5| to CFO ≤ |2|. Finally, the forth is with the development of time synchronization using a combination of CP and TS as an adaptive combination system. This method shows improvement in the range of tracking for estimation. It depends on the signal to noise ratio (SNR) value especially when equal to 18dB (which has been verified in a practical way). The performance of the proposed method is evaluated by conducting a set of simulation experiments using MATLAB, including bit error rate (BER) and mean square error (MSE). Objective evaluation was used to assess the achieved synchronization transmission, robustness under high noise and high values of STO and CFO, and prediction of the starting symbols. Validation was applied by comparison between the proposed and previous methods by comparison, which added more confidence to the work. The proposed training sequence method for STO can reduce the errors by half if compared to the standard training sequence as well as reduce the errors with different rates when compared with cyclic prefix. For example, if STO=10 and SNR=15dB then the error is $TS_{proposed}$=0.0041, $TS_{standard}$=0.0149, $CP_{difference}$=0.0090, and $CP_{correlation}$=0.0082. Also for CFO, it keeps the fixed percentage of errors Despite the increase of CFO value which reaches to +2 or decreases to -2. For example, if CFO=0.51 and SNR=15dB then the error is $TS_{proposed}$=0.0002, CP=0.9784, Moose=0.4998, and Classen=0.3199. The proposed method that tested on practical image, text, and speech applications signified that method has notable enhancement in the data transmission synchronization with an acceptable.

ABSTRAK

Sinkronisasi sistem adalah terpenting dalam semua sistem komunikasi wayarles, terutamanya dalam pemultipleksan pembahagian frekuensi ortogonal (OFDM). Teknik OFDM adalah sistem pelbagai-pembawa yang menyediakan perkhidmatan komunikasi wayarles berkualiti tinggi dan kadar data tinggi. Dalam teknik OFDM, penerima tidak mengetahui akhir atau permulaan simbol-simbol OFDM, oleh itu, keadaan ini sangat penting untuk menerima isyarat tanpa kesilapan. Prestasi sesuatu teknik OFDM ternyahgred oleh ofset frekuensi pembawa (CFO) dan ofset masa simbol (STO). Oleh itu, tujuan kajian ini adalah untuk meningkatkan prestasi sinkronisasi untuk penghantaran data dengan mempertimbangkan faktor-faktor yang berkaitan. Dalam kajian ini, empat objektif telah ditempatkan untuk mencapai matlamat tersebut. Objektif pertama adalah untuk meningkatkan penilaian prestasi pengesahan sinkronisasi masa menggunakan anggaran awalan siklik (CP) dan urutan latihan standard (TS) dalam domain masa untuk CFO dan STO. Objektif kedua dan ketiga adalah untuk mereka bentuk dan melaksanakan sinkronisasi masa berdasarkan kaedah cadangan TS yang menggunakan dua tingkap gelongsor bersaiz sama yang sama dengan saiz sesuatu CP, manakala saiz CP itu adalah sama dengan ¼ saiz jelmaan Fourier pantas (FFT), dan untuk memperluaskan julat anggaran CFO dari CFO $\leq |0.5|$ kepada CFO $\leq |2|$. Akhir sekali, dengan perkembangan sinkronisasi masa menggunakan gabungan CP dan TS sebagai sistem gabungan adaptasi, kaedah ini menunjukkan peningkatan dalam julat penjejakan untuk anggaran, yang bergantung pada nilai nisbah isyarat ke hingar (SNR) terutama sekali apabila sama dengan 18dB (yang telah disahkan dengan cara praktikal). Prestasi kaedah yang dicadangkan dinilai dengan melakukan satu set eksperimen simulasi menggunakan MATLAB, termasuk kadar ralat bit (BER) dan ralat min kuasa dua (MSE). Penilaian objektif telah digunakan untuk menilai penghantaran sinkronisasi yang dicapai, keteguhan di dalam keadaan hingar yang tinggi dan nilai-nilai STO & CFO yang tinggi, dan ramalan simbol permulaan. Pengesahan digunakan dengan kerja-kerja yang berkaitan untuk menambah keyakinan terhadap kajian, dengan perbandingan antara kaedah yang dicadangkan dan yang sebelumnya. Hasil ini menandakan bahawa kaedah yang dicadangkan telah meningkatkan sinkronisasi penghantaran data dengan kadar yang boleh diterima dan telah diuji pada aplikasi imej praktikal, teks, dan pertuturan.

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ADC	Analog to Digital Converter
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BW	Bandwidth
CAZAC	Constant Amplitude Zero Autocorrelation Waveform
CCDF	Complementary Cumulative Distributive Function
CF	Carrier Frequency
CFO	Carrier Frequency Offset
COFDM	Coded Orthogonal Frequency Division Multiplexing
CP	Cyclic Prefix
CR	Cognitive Radio
CS	Complementary Sequence
dB	Decibel
DA	Data Aided
DAB	Digital Audio Broadcasting
DAC	Digital to Analog Converter
DCS	Data Conjugte Scheme
DF	Decision Feedback
DS	Doppler Shift
DSRM	Design Science Research Methodology
DVB	Digital Video Broadcasting
DWHT	Double Walsh Hadamard Transform
EDT	Equivalent Discrete Time
EGC	Equal Gain Combining
EKF	Extended Kalman Filtering
FCFO	Fractional Carrier Frequency Offset
F_{CRX}	Carrier Frequency of the Receiver

F_{CTX}	Carrier Frequency of the Transmitter
FD	Frequency domain
FDMA	Frequency Division Multiple Access
FDQ	Frequency Domain Equalization
FEC	Forward Error Correction
FFT	Fast Fourier Transform
F-OFDM	Flash Orthogonal Frequency Division Multiplexing
FPGA	Field Programmable Gate Array
GS	Gold Sequence
HPA	High Power Amplifier
ICFI	Integer Carrier Frequency Offset
ICI	Inter Carrier Interference
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
KS	Kasami Sequence
LFSR	Linear Feedback Shift Register
LRF	Linear Power Amplifiers
LS	Least Squares
LTE	Long Term Evolution
MATLAB	Matrix Laboratory
MB-OFDM	Multiband Orthogonal Frequency Division Multiplex
MBWA	Mobile Broadband Wireless Access
MIMO	Multiple Inputs Multiple Output
MLE	Maximum Likelihood Estimation
MMSE	Minimum Mean Sequre Error
MRC	Maximal Ratio Combining
MSE	Mean Square Error
NDA	Non Data Aided
OFDM	Orthogonal Frequency Division Multiplexing

OFDMA	Orthogonal Frequency Division Multiplexing Access
P/S	Parallel to Serial
PAPR	Peak to Average Power Ratio
PB	Preamble Based
PI	Peak Insertion
PN	Psedo Noise
PR	Phase Rotation
PS	Pulse Shaping
PSK	Phase Shift Keying
PT	Pilot Tone
QAM	Quadrature Amplitude Modulation
RCW	Real Constant Weighted
RS	Reed Solomon
SC	Self Cancellation
$S_{(C)}$	Choi Algorithm
$S_{(MB)}$	Minn and Bhargava Algorithm
$S_{(P)}$	Park Algorithm
$S_{(R)}$	Ren Algorithm
$S_{(SC)}$	Schmidl and COX Algorithm
$S_{(SS)}$	Shi Serpedin Algorithm
$S_{(W)}$	Wang Algorithm
$S_{(Z)}$	Zhou Algorithm
$S_{(ZX)}$	Zhang and Xuan Algorithm
S/P	Serial to Parallel
S-SW	Sub-Sliding Window
SNR	Signal to Noise Ration
SP	Signal Processing
STO	Symbol Timing Offset
TD	Time domain

TDMA	Time Division Multiple Access
TDW	Time Domain Windowing
TDZCE	Time Domain Zadoff-Chu Estimation
TkM	Tracking Mode
TnM	Training Mode
TS	Training Sequence
UWB	Ultra Wideband
VOFDM	Vector Orthogonal Frequency Division Multiplexing
WCT	Weighted Conjugate Transformation
WHT	Walsh Hadamard Transform
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WOFDM	Wideband Orthogonal Frequency Division Multiplexing
WRN	Wireless Relay Networks
ZC	Zadoff Chu
ZF	Zero Forcing

CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is one of the wideband wireless digital communication methods. OFDM is a multi-carrier modulation transmission technique, in which the available spectrum is divided into many subcarriers. Each one of the subcarriers is modulated by using a low rate data stream. OFDM uses the spectrum efficiently by spacing the channels much closer together with ORTHOGONALITY between these subcarriers (Joshi 2013).

The main advantage of OFDM (with multi carriers) over single carrier method is the simplicity of equalizer design of the receiver, which deals with the common multipath fading channels in wireless communication systems. The multipath fading causes frequency selective distortion in the signal transmission and increases inter symbol interference (ISI). These adverse impacts need to be mitigated by an equalizer that is more complex as the system bandwidth increases. For OFDM systems, every subcarrier is seen as a narrow band with a low rate signal. With the insertion and removal of guard intervals (guard band), equalization method in the OFDM can be performed by using a single tap equalizer on each subcarrier. This single tap equalizer is much simpler than that used in the single carrier systems (the single carrier system had only one carrier for all the transmitted data, so, it needs a complex equalizer to prevent the interference).

OFDM technology has become the core technology of the next generation mobile communication system because of the high bandwidth efficiency, the strong ability to resist inter carrier interference (ICI) and anti-channel interference. However, the OFDM system is very sensitive to synchronization errors because the OFDM method is a multicarrier modulation system (Thakur & Khare 2012).

OFDM is a reliable technology for high speed data transmission by virtue of its spectral efficiency and robustness to multi path fading. These advantages can be achieved with efficient synchronization in both time domain and frequency domain (Rana & Setia 2015).

The technology of OFDM can be summarized as follows: OFDM is a digital multi-carrier modulation method that expands the idea of subcarrier modulation by using multiple subcarriers on the same single channel. Instead of transmitting a set of stream data in high data rate through a single carrier, OFDM enables the use of a large number of most spaced orthogonal subcarriers transferred in parallel. Every subcarrier had been modulated with one of the traditional digital modulation technique such as quadrature amplitude modulation (QAM), phase shift keying (PSK) etc. This modulation technique had been done at a low symbol rate. However, the collection of several subcarriers supports data rates as the same as the traditional single carrier modulation techniques within the corresponding bandwidths (Rumney 2013).

OFDM is found to have total immunity to multi path delay spread because of providing reflection time less than the guard period used in the OFDM signal. Figure 1.1 shows the block diagram of a typical OFDM transceiver (transmitter and receiver). The transmitter section converts binary data to be transmitted into a mapping of subcarrier amplitude and phase after converting the input binary data from serial to parallel (S/P) and modulate this data by using phase shift keying (PSK) or quadrature amplitude modulation (QAM). This spectral representation of the data will be transformed from the frequency domain (FD) to the time domain (TD) using an inverse fast Fourier transform (IFFT). The cyclic prefix (CP) (guard band) is then added to help in synchronization process. After that, the transformation of the data from parallel to serial (P/S) is followed by the digital to analogue conversion (DAC).

The channel will be mixing the incoming data signal with additive white Gaussian noise (AWGN). At the receiver side, the operations here are the reverse of the operations on the transmitter side. Before the fast Fourier transforms (FFT), there are analogue to digital conversion (ADC), serial to parallel (S/P), and CP removal. FFT analyses the signal in the frequency domain. The amplitude and phase of the subcarriers are then picked out and converted back to the digital data.

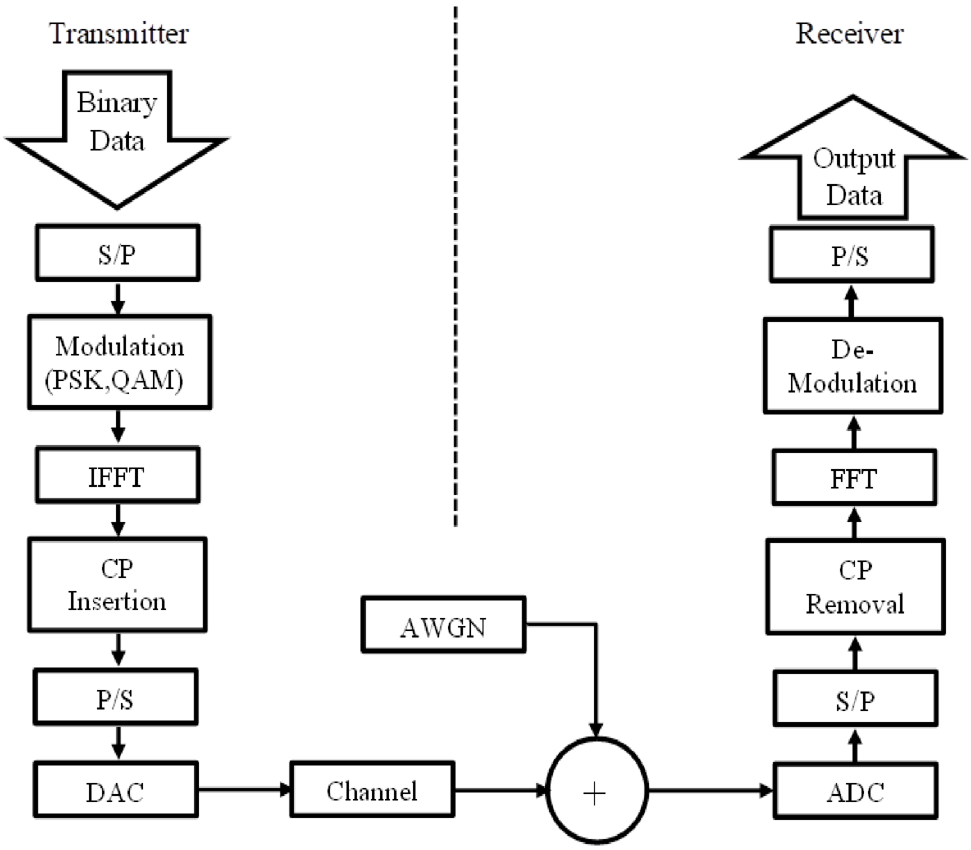


Figure 1.1 OFDM transceiver blocks

1.2 PROBLEM STATEMENT

OFDM is a largely adopted multi-carrier modulation technique in recent broadband wireless communication standards for its ability to cope with severe channels. OFDM systems are however very sensitive to synchronization errors that effect on the orthogonality between subcarriers and resulting in performance degradation. The synchronization problem can lead to two other problems which are carrier frequency offset (CFO) and symbol time offset (STO) (Gul et al. 2015; Salido et al. 2014; Wang 2014; Asran et al. 2015).

Frequency offset will effect on the orthogonality between subcarriers which can cause inter carrier interference (ICI), and time offset will lead to the inter symbol interference (ISI). To guarantee the fast and accurate data transmission, the ICI and ISI caused by the transmission have to be reduced as much as possible (Gul et al. 2015; Salido et al. 2014, Cho et al. 2010; Nasir et al. 2010).

The CFO is a frequency error that occurs in the OFDM system. CFO happens due to the differences between the receiver oscillator and transmitter oscillator, instabilities of an oscillator or by the Doppler shift (DS) of the channels of mobile (Paramita et al. 2014; Benzarti et al. 2015; Cho et al. 2010). There are two types of CFO which are fractional carrier frequency offset (FCFO) that leads to ICI, and integer carrier frequency offset (ICFO) that causes a phase change of symbol number (Liu et al. 2014; Pham et al. 2014).

Another problem is STO. The received symbols will affect the frequency domain and time domain by STO samples. The effect of STO may differ according to the estimated location of the starting point of the OFDM symbol (Kaur & Sappal 2012; Aziz et al. 2012)

Therefore, the interest of this study is that the above issues represented by the tradeoff between the estimation factors can be solved by proposing the training sequence method to both STO and CFO for enhancing the synchronization of OFDM signal. The details of the proposed methods are discussed in chapter three, and the results are presented in chapter four.

1.3 RESEARCH OBJECTIVES

The main objective of this research is to retain the synchronization between transmitter and receiver. This can be done by preventing STO and CFO effects in the transmitted signal to halt degrading the OFDM symbol (synchronization enhancement). Since STO and CFO lead to ISI and ICI respectively, the sub objectives of the research can be as follows:

1- To design and implement a time synchronization method based on the proposed training sequence (TS) method in STO and to expand the estimation range of CFO

2- To propose a novel estimation method by merging cyclic prefix (CP) method and training sequence (TS) method in carrier frequency offset (CFO) estimation which depends on the signal to noise ratio (SNR) and the error value.

3- To implement a real applications such as image, text, and speech by applying the proposed OFDM synchronization techniques.

4- To evaluate the performance of OFDM synchronization in the time domain using the cyclic prefix (CP) estimation including autocorrelation and square difference methods and standard training sequence (TS) in the time domain for STO and CFO.

1.4 RESEARCH SCOPE

In general, the research work is based on using the proposed TS technique for STO, proposed TS technique for CFO, and merging TS method with a CP method to get a transmission of data with the best synchronization with few errors resulting from ICI and ISI in which to increase estimation range for the received symbols. The main focus is on an adaptive preamble which is used to estimate the beginning of the received symbol by using two equal sliding windows so that the data loss will be minimal. This is where the methods must be used to reduce these errors. This mechanism will be validated using both autocorrelation and mean square difference methods. Additionally, it can be used with a number of subcarriers lead to prevent or reduced the percentage of ISI and ICI.

Research scope of this thesis is indicated as in Figure 1.2. This thesis focuses on the OFDM synchronization based on the proposed TS technique used for STO and CFO, and in merging of CP with TS which is handled with the CFO.

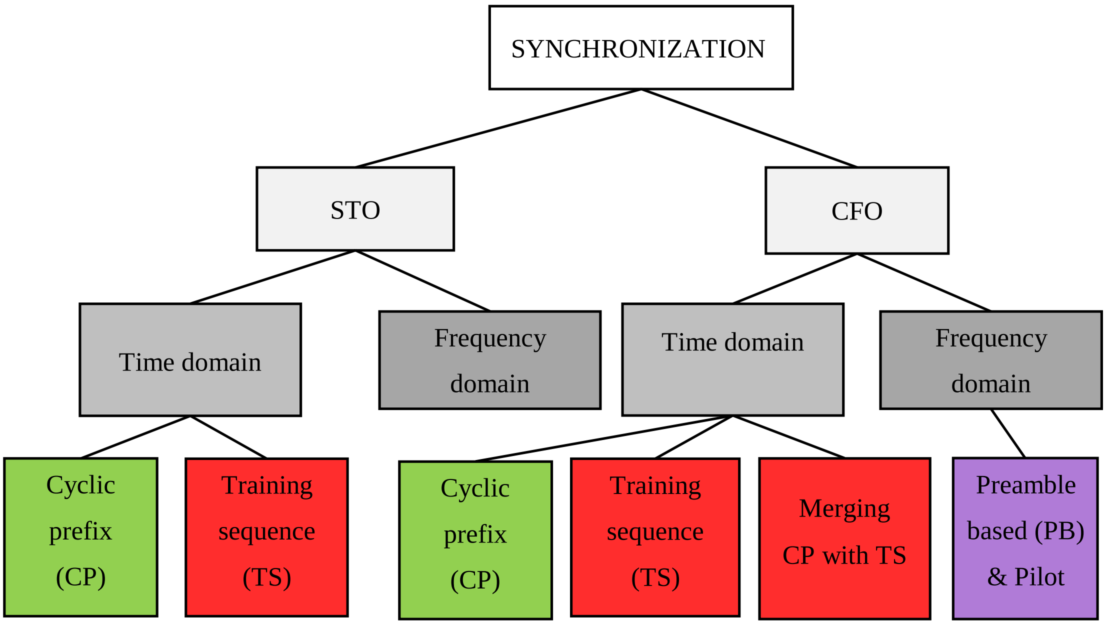


Figure 1.2 Classification of the synchronization

The green box means that the technique is done for validation and verification with the previous works, including the CP method in STO and CFO in time domain by using autocorrelation and mean square difference techniques. While the red box means that the TS method is done as a proposed method in STO and CFO as well as a method from merging a CP method with the TS method in CFO through time domain. The purple box means the symbol preamble based (PB) and pilot tone based (PT) techniques in the frequency domain of CFO used by Moose and Classen & Myer respectively, which are used for comparison with the proposed method.

The simulation was done using MATLAB ver. R2014a. The use of MATLAB is suitable because there are many functions available especially in the transmission signal, and this is discussed in chapter three.

The structure of this thesis can be summarized as in Figure 1.3;

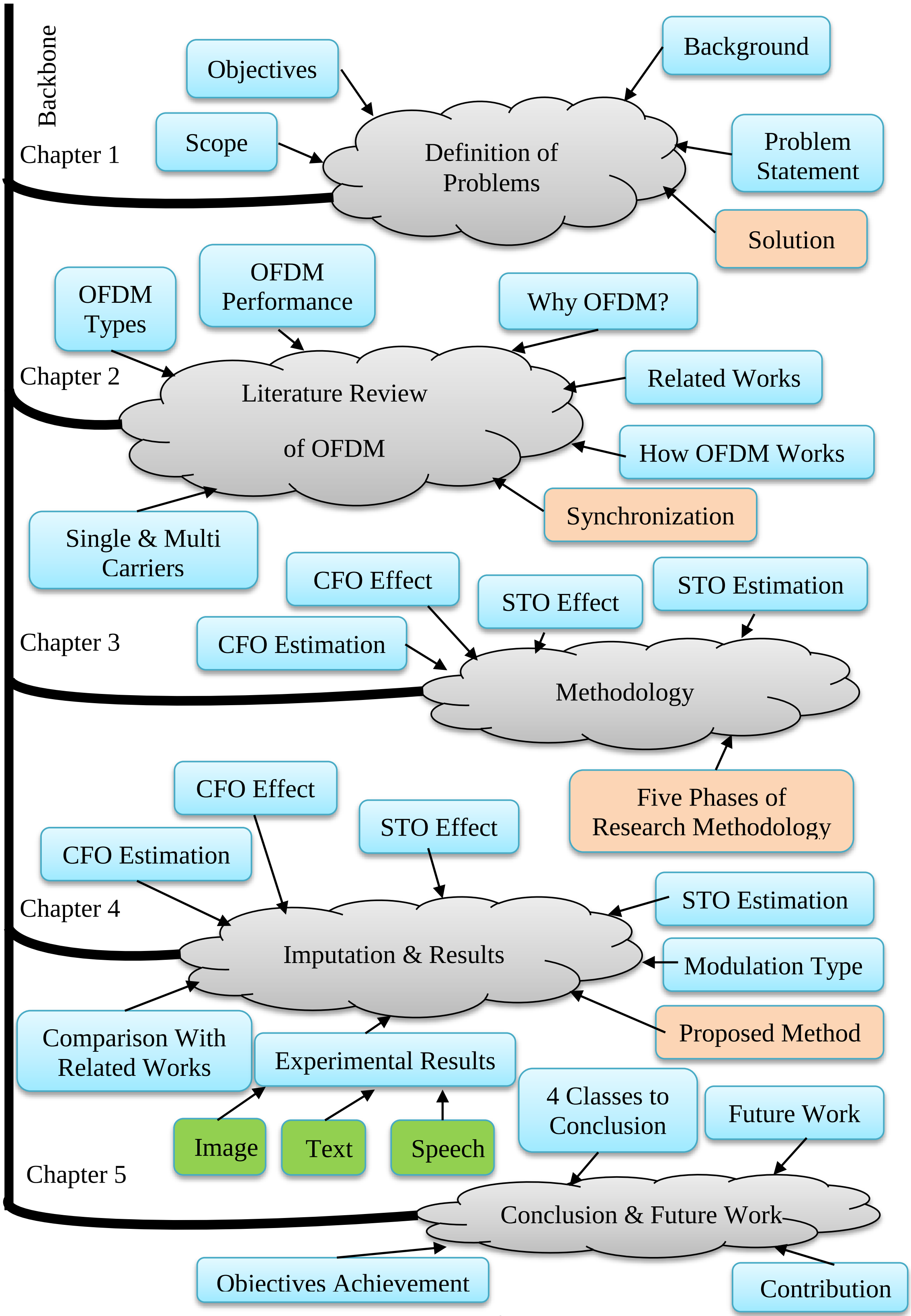


Figure 1.3 Structure of the thesis

1.5 ORGANISATION OF THE THESIS

The thesis can be organized as follows: This chapter (chapter I) introduces the information of this research study in general to cover research background, the problem statement, list of the research objectives, and the research scope.

Chapter II presents a methodical literature review of the orthogonal frequency division multiplexing (OFDM) system as well as its advantages and disadvantages. It also presents the single carrier and multi carrier types of the OFDM with their differences between them. The whole OFDM system is shown in this chapter with the design issues and how it works. The variants of OFDM were addressed. Main performance, which includes bit error rate (BER), mean square error (MSE), and signal to noise ratio (SNR) was also illustrated. Some obstructions of the OFDM were listed with their solutions. The synchronization which is the heart of this thesis was shown with the effectiveness of symbol time offset (STO) and carrier frequency offset (CFO) (effects and estimation). Correlation is one of the techniques used to find the similarity between the signal with its phase shift (delay of the signal). Finally, the related works are at the end of this chapter.

Chapter III includes research methods especially with regard to estimation methods for implementing the STO and CFO in the time domain by using the cyclic prefix method (CP) and training sequence method (TS). The algorithms of STO and CFO were listed. The research methodology were divided into five phases as appeared in this chapter. MATLAB is the simulation program used in this work, and the specification of the MATLAB with advantages and disadvantages are listed in this chapter. Finally, this chapter consists of the experimental applications of OFDM.

Chapter IV deals with the implementation and the results (after applied the simulation program) including STO and CFO effects and estimation, chosen modulation type, comparison and investigated with related works. Many results of the proposed method, the experimental results on how to apply the proposed method on real data including images, text, and speech are shown.

Chapter V concludes the thesis by characterizing how the research objectives were accomplished, giving an overview of the contributions of this study and making some conclusions and suggestions for future research. Also, this chapter deals with the limitations of the study.

CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) system and its related parameters are discussed in this chapter. The orthogonality of the OFDM technology is the most important part of the multi-carrier transmission. The drawback and the advantage of the OFDM system, the most related topic in the synchronization, and the recent methods used in synchronization are described in this chapter. Additionally, a short explanation of the OFDM obstructions which includes the peak to average power ratio (PAPR), inter carrier interference (ICI), and inter symbol interference (ISI) are explained.

2.2 ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM)

This section is dedicated to OFDM concepts and benefits. It is necessary to give details of such technology in order to understand the idea of OFDM and how it works.

2.2.1 What is OFDM?

OFDM was invented by Chang 1966 (Chide et al. 2013; Li 2014). In recent times, OFDM gives attention to people because of its abilities to withstand multi path fading and noise occurred during communication with data transmission. The technology of OFDM is considered one of the essential technologies of 4G (Nee & Prasad 2000). It is a technology for improving the multi-carrier modulation (Nee & Prasad 2000). The OFDM main concept technology is “In the frequency domain, the certain channel which is dedicated to the transmission process is split into several orthogonal sub channels. Each of these sub channels is modulated by using one subcarrier through a method of modulation methods, and then the transportation of the data by using these subcarriers is done in the parallel". The effect of the channel time delay of the OFDM systems is increased due to the symbol duration in each subcarrier. Therefore, the duration growth of the symbol on each subcarrier can reduce the action of channel time delay to OFDM systems (Li 2014).

In the frequency domain, in order to ensure the subcarriers' orthogonality, the CP or guard interval is placed in between the subcarriers. The interference between the symbols of the OFDM is eliminated, through inserting CP (Dai & Wang 2014; Mehra & Cheema 2015). This insertion between the symbols of OFDM, which involves the last portion of the symbol in OFDM is copied and put at the beginning of each symbol as shown in Figure 2.1. The orthogonality between the subcarrier is kept when there is a time dispersive channel, with a condition that the length of CP is larger than the dispersion time of the channel (Asran et al. 2015).

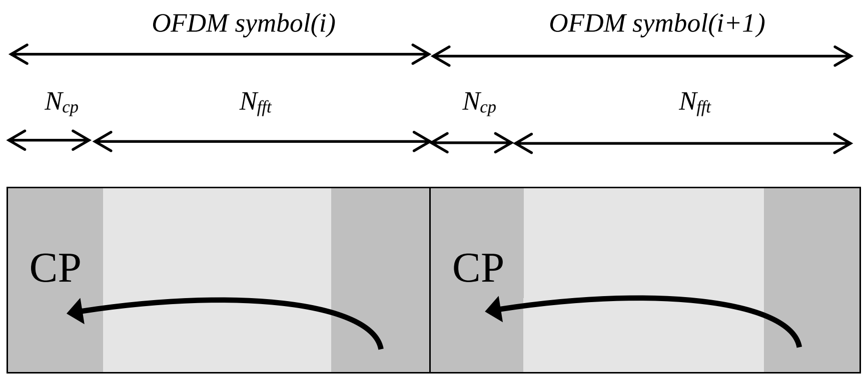


Figure 2.1 CP Insertion into the beginning of each OFDM symbol

Insertion of the CP at the beginning of each OFDM symbol has many advantages which can be summarized as follows (Sankar 2008; Shah et al. 2010);

- The addition of the cyclic prefix adds the robustness of multipath propagation of the OFDM signal.
- If required, the retransmitted data can be used (as a CP is duplicated in the last portion of the symbol).
- The cyclic prefix (guard interval) eliminates the effect of inter symbol interference (ISI).

While the disadvantages of the CP insertion are;

- Because the cyclic prefix retransmits part of the original data which is transmitted previously, it takes from the capacity of the system, and therefore decreases the data rate.

- Cause power loss due to the transmission power loss to send the redundant symbols.

The orthogonality between the OFDM subcarriers eliminates the chance for the presence of the inter carrier interference (ICI) and inter symbol interference (ISI). However, the system of the OFDM is comparatively sensitive to the offset of frequency and time. Furthermore, the systems of OFDM are extremely sensitive to the errors of timing synchronization more than any systems that have a single carrier. In the received signal, due to the offset of the frequency and offset of the time that leads to ICI and ISI respectively, the orthogonality between the OFDM subcarriers will destroy. Therefore, to achieve a better performance in the OFDM system, an exact frequency and time synchronization are crucial (Dai & Wang 2014). The wide use of the OFDM in various systems due to its capacity and ability to overcome the effect of the multipath fading, and soaring spectral efficiency such as digital video / audio broadcasting (DVB / DAB) (Asran et al. 2015). This property belongs to data transmitted in the OFDM system as a parallel set stream at a low data rate over narrowband subcarriers in the orthogonality way (100 Hz – 50 KHz) (Asran et al. 2015). By using inverse fast Fourier transform (IFFT) which is to convert the data stream from frequency domain to time domain, the transmission of the OFDM can be generated at the transmitter side, while the data is received by using fast Fourier transform (FFT) that converts the data from time domain to frequency domain at the receiver. By using a huge number of subcarriers, the OFDM system can offer a soaring data rate (Asran et al. 2015). Another important feature in the OFDM system is the synchronization between the receiver and transmitter which affects the performance of the system. Nevertheless, any synchronization loss between the receiver and transmitter leads to a phase shift in the frequency and time in the receiver. Therefore, ICI and ISI happen and, the system performance is degraded when the synchronization is lost (Asran et al. 2015).

2.2.2 Why Need OFDM?

OFDM avoids most of the difficulties such as inter symbol interference (ISI) with both time division multiple access (TDMA) and frequency division multiple access (FDMA). OFDM divides the available bandwidth which is dedicated to the transmission process to several thin sub band channels. The carriers for every channel are prepared orthogonal to one another, permitting them to be spaced very near together (Albogame & Elleithy 2014).

The meaning of orthogonality between the subcarriers is that each subcarrier has cycles of integer number over a period of the symbol, and there is no overlap between these subcarriers. Therefore, each subcarrier in the system has a full spectrum in the center frequency which is related to the other carriers. It is assumed that there is no interference and intersection between the subcarriers, letting them diverge as near as theoretically possible. This beats the dilemma of overhead subcarrier spacing which is needed in FDMA. Each subcarrier in the signal of the OFDM has a constricting bandwidth (BW); (i.e. 1 kHz), this leads to the low data rate of resulting symbol, and bandwidth saving as shown in Figure 2.2 (Albogame & Elleithy 2014).

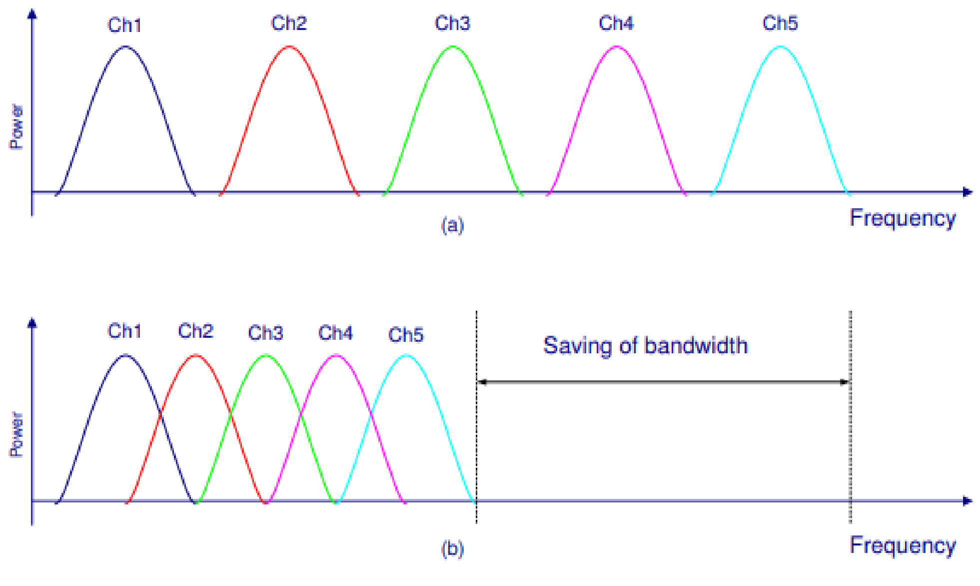
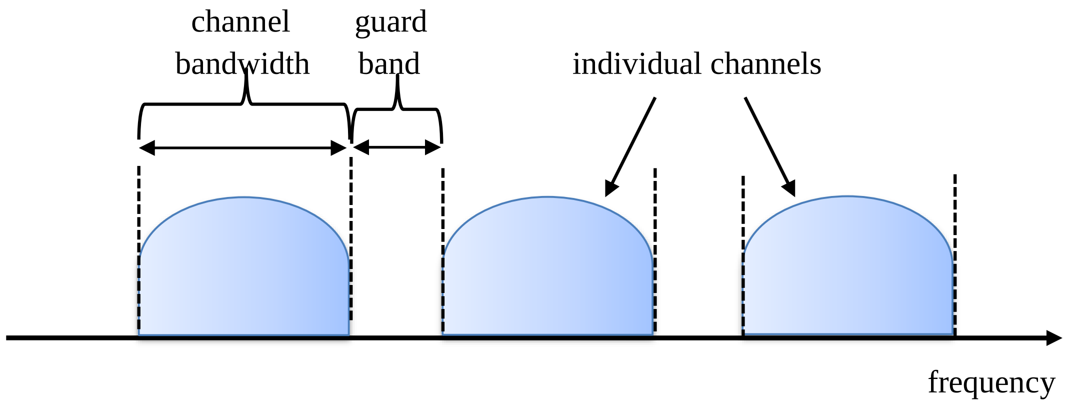


Figure 2.2 Orthogonality between subcarriers in OFDM system (Albogame & Elleithy 2014)

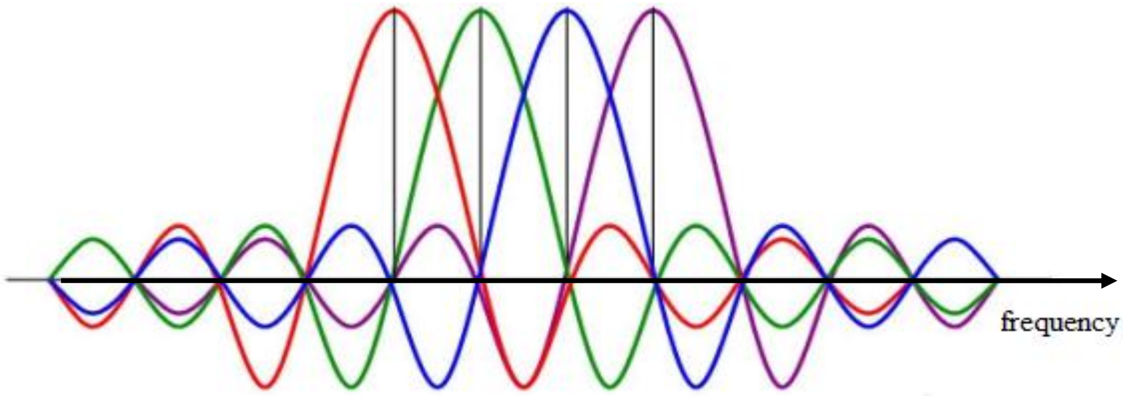
2.2.3 How OFDM Works?

The main idea came after the development of the communication system and the increasing demand for the need for speed of data transfer in each transmitting process, and this was an idea of the frequency division multiplexing (FDM). This technique is to divide the channel to sub channels and divide the carrier to subcarriers. The data will send more than two different signals on the same given band at the same time, and this helps to solve several problems in which the whole band can previously be used to send one signal, then another signal, and so on. This caused several problems, especially in the sending television signal where the image had been sent and then the sound, which results in the picture was preceded by the sound often means there is a delay between these two signals (Cheers 2015).

By using FDM, the band and the information are divided into frames. This means if the band is divided into parts, the information is also divided into parts, and then send each part one after the other (sequentially). Nevertheless, the FDM technique had several problems, such that; a part of the band is left on the two sides of each carrier to prevent the interference in the subcarrier themselves, so this reduces the efficiency of the technique because a large part of the band is lost without taking an advantage of it and this is so-called “a guard band” as shown in Figure 2.3.(a). Due to different carriers, a lot of demodulators must be used (Rayal 2010).



(a)



(b)

Figure 2.3 Guard band (a) existing in FDM technique, (b) no guard band in OFDM (Rayal 2010)

Therefore, this problem must be overcome by finding some solutions. It is found that the subcarriers were as far as possible when they are orthogonal. The intersection between the subcarrier was allowed without overlap (they were orthogonal if their multiplication of integration equals zero). It is so-called OFDM, in which speedy data rate by using the whole band and reduced to demodulator by using FFT/IFFT (Khan et al. 2012; Chide et al. 2013).

Figure 2.4 shows how OFDM works. There is one requirement in the system of the OFDM transceiver, which has to be linear. If there is nonlinearity somewhere in the transmitted signal that leads to interference among the carriers. Therefore the unwanted signals were introduced (comes from radio transmission) to increase the occupied bandwidth and lead to interference between the adjacent channels. After that, it producing damage and interference the orthogonality in the transmitted signal and increase the usage of the spectrum (Anon 6).

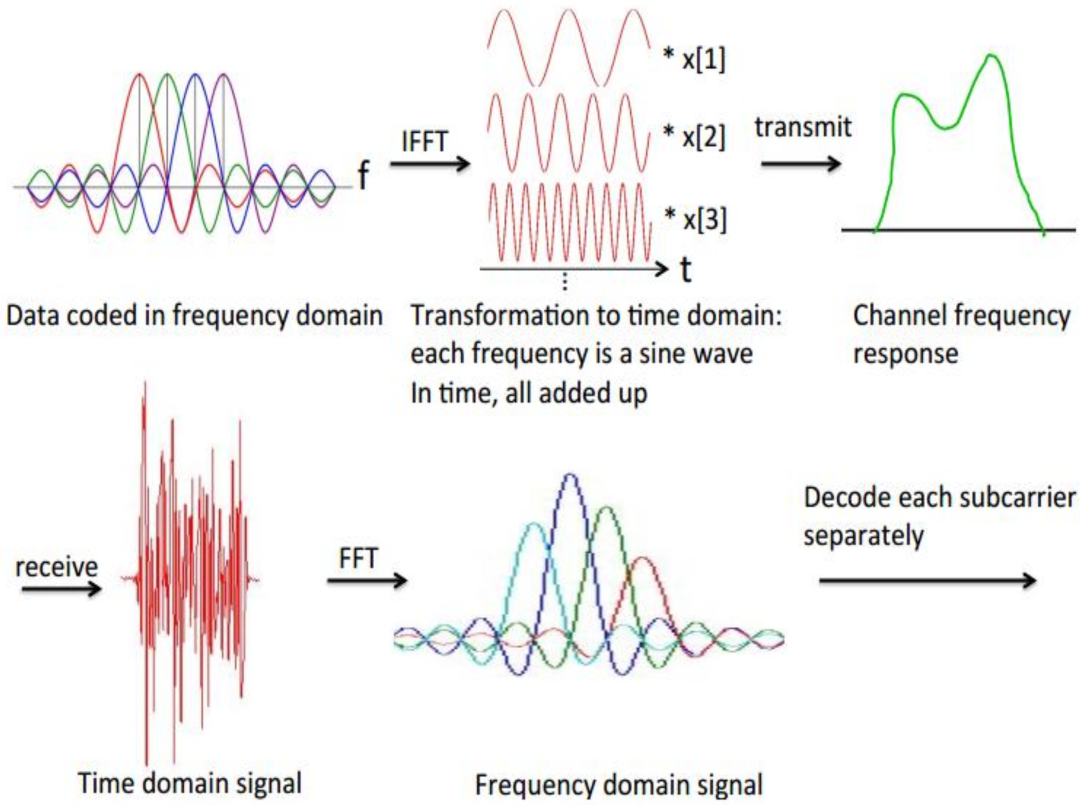


Figure 2.4 Work of the OFDM (Mawari & Zohdy 2017)

2.2.4 Work Scenario Of OFDM

In each transmission process of the OFDM system, there are *N* subcarriers (*N* can be any value from 16, 32, 64, …, 1024, 2048,… and it depends on the system which is in use). The following example was taken with a sequence of bits using for transmission and using only 4 subcarriers (for simplicity) (Cho et al. 2010; Madhumita 2016; Leopedrini 2014; Anon 6);

1, 1, - 1, - 1, 1, 1, 1, - 1, 1, - 1, - 1, - 1, - 1, 1, - 1, - 1, - 1, 1, 1 , - 1, - 1, - 1, 1, 1

which appears in Figure 2.5

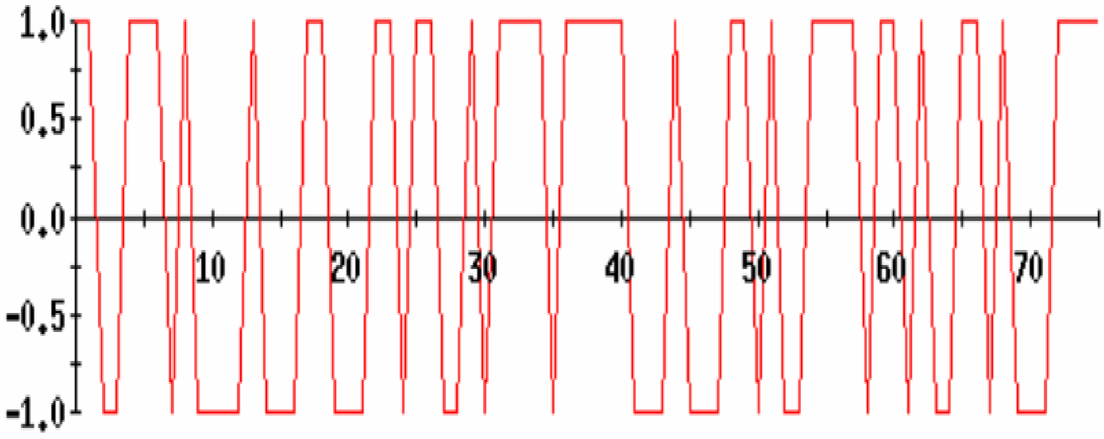


Figure 2.5 An example stream of data bits used for OFDM transmission by using 4 subcarriers (Madhumita 2016)

By using serial to parallel conversion (S/P), the stream of bits which appear in one line was converted to four parallel sets (if using 4 subcarriers, S1, S2, S3, and S4) in the frequency domain as shown in Table 2.1;

Table 2.1 Data from serial to parallel

	S1	**S2**	**S3**	**S4**
Symbol 1	1	1	- 1	- 1
Symbol 2	1	1	1	- 1
Symbol 3	1	- 1	- 1	- 1
Symbol 4	- 1	1	- 1	- 1
Symbol 5	- 1	1	1	- 1
Symbol 6	- 1	- 1	1	1

Each subcarrier has one bit from each symbol. For example, subcarrier 1 (S1) has a set of values of 1, 1, 1, - 1, - 1, and - 1 as shown in Figure 2.6. While subcarrier 2 (S2) has a set value of 1 1, 1, - 1, 1, 1, and - 1 as shown in Figure 2.7. For subcarrier 3 (S3) has a set value of – 1, 1, - 1, - 1, 1, and 1 as shown in Figure 2.8. Finally, subcarrier 4 (S4) has a set value of – 1, - 1, - 1, - 1, - 1, and 1 which is shown in Figure 2.9.

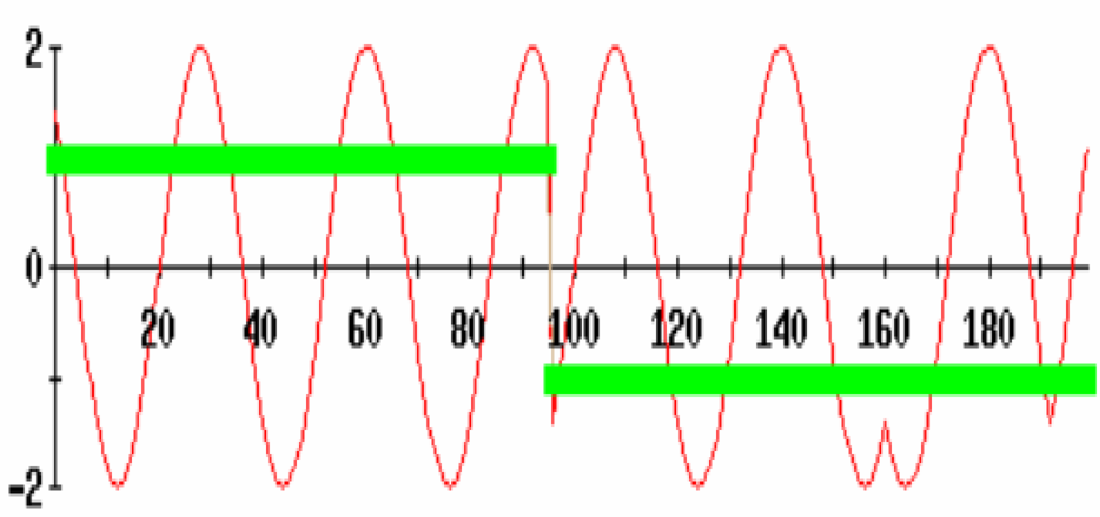


Figure 2.6 Subcarrier 1 [S1 in Table 2.1] (Madhumita 2016)

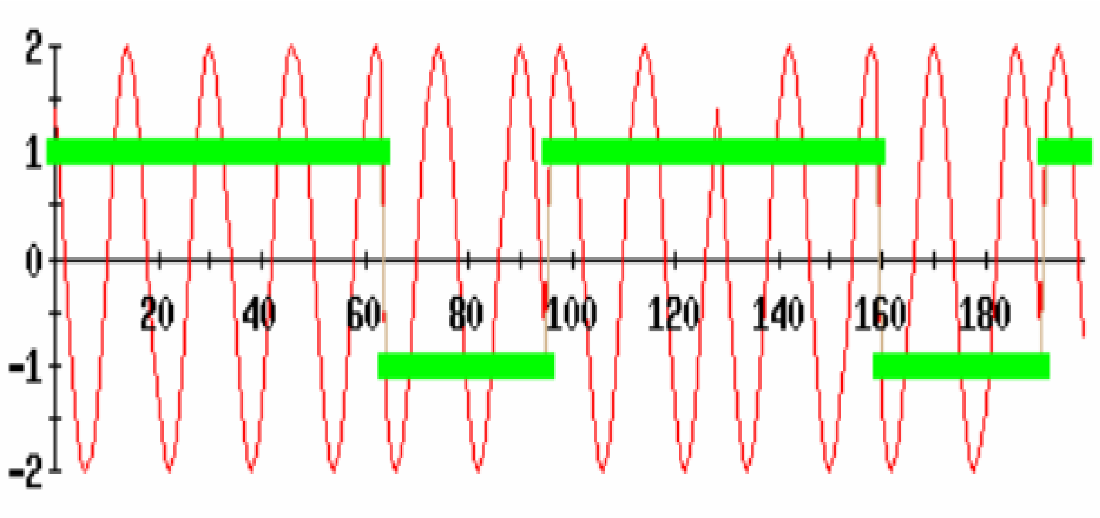


Figure 2.7 Subcarrier 2 [S2 in Table 2.1] (Madhumita 2016)

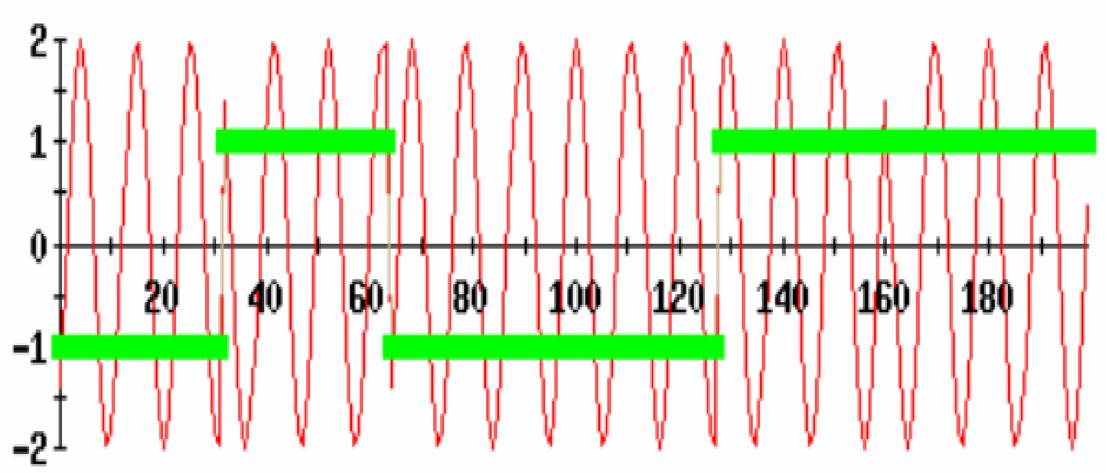


Figure 2.8 Subcarrier 3 [S3 in Table 2.1] (Madhumita 2016)

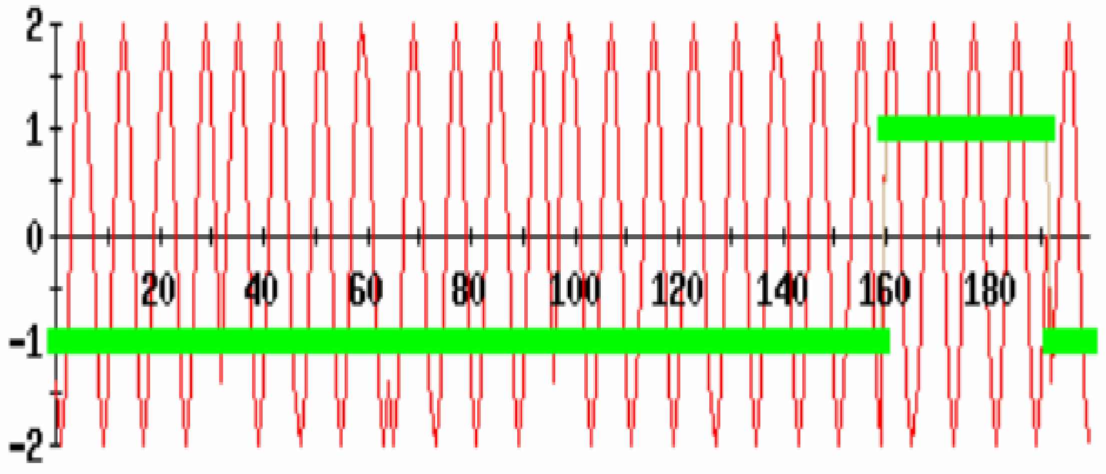


Figure 2.9 Subcarrier 4 [S4 in Table 2.1] (Madhumita 2016)

After that, by using 16 QAM as a type of modulation that is applied using 4 independent carriers. Taking the stream of bits, distributed them, each subcarrier takes one bit (for 4 subcarriers) at a time as shown in Figure 2.10.

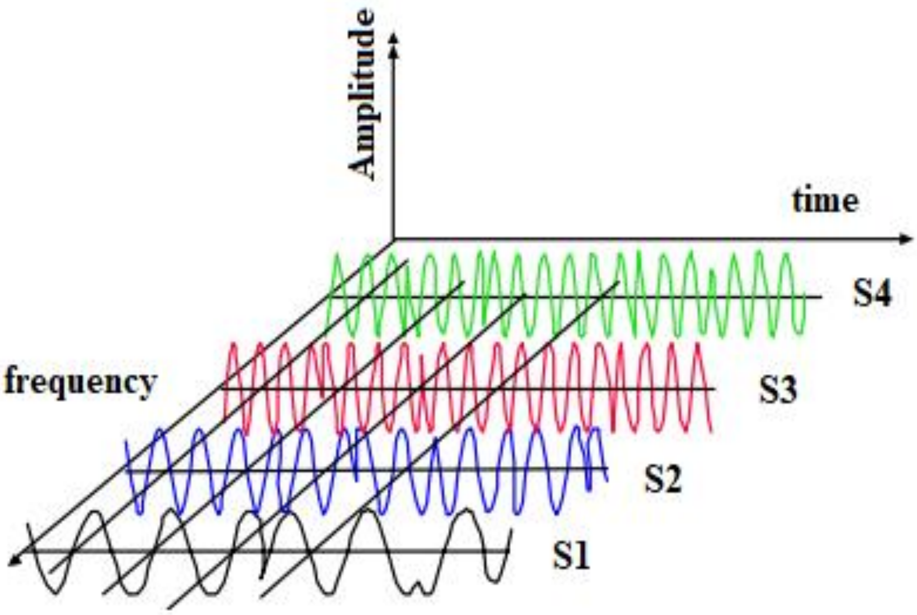


Figure 2.10 Signal of OFDM in frequency and time domain (Madhumita 2016)

Conversion from the frequency domain to the time domain by using IFFT, and adding those four subcarriers to get the form of the data appeared in Table 2.2, and Figure 2.11.

Table 2.2 Data of the signal in time domain

S1	S2	S3	S4
0	2 – 2j	0	2 + 2j
2	0 – 2j	2	0 + 2j
- 2	2	2	2
- 2	0 – 2j	- 2	0 + 2j
0	- 2 – 2j	0	- 2 + 2j
0	- 2 + 2j	0	- 2 – 2j

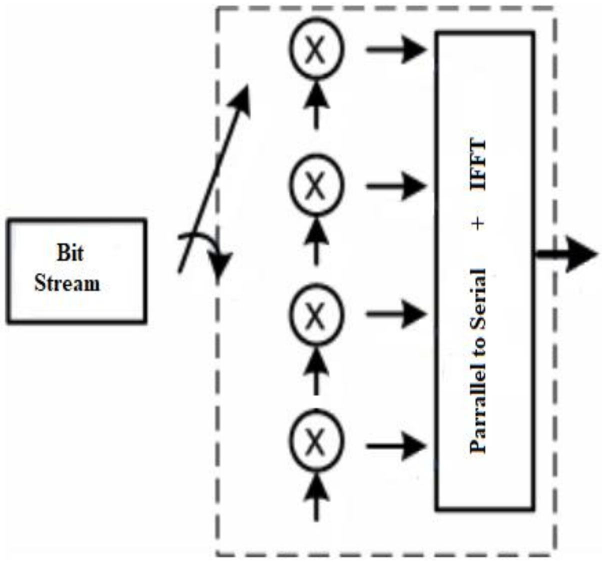


Figure 2.11 Creation of OFDM signal after IFFT (Madhumita 2016)

Figure 2.12 shows the final OFDM signal which is being sent. The guard band (cyclic prefix) play an important part in the data transmission. It was added to each symbol of the OFDM to protect each symbol from ISI as shown in Figure 2.13. The CP (guard period) which is added at the beginning of each symbol is the better, and efficient method for a multipath problem of the transmitted signal as shown in Figure 2.14.

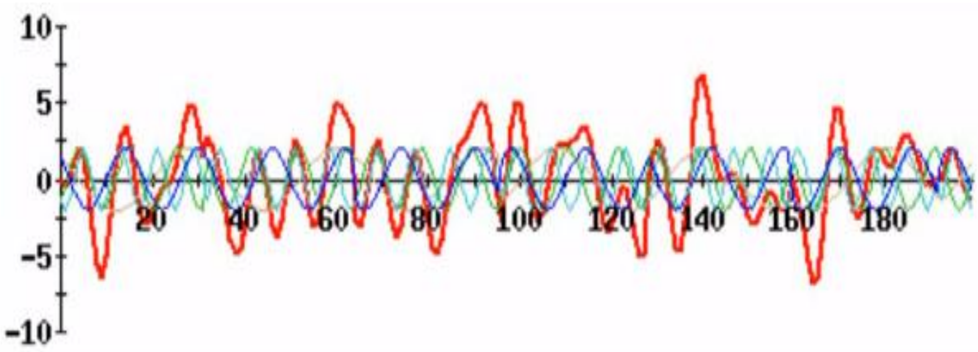


Figure 2.12 Generated OFDM signal prepared for transmission (Madhumita 2016)

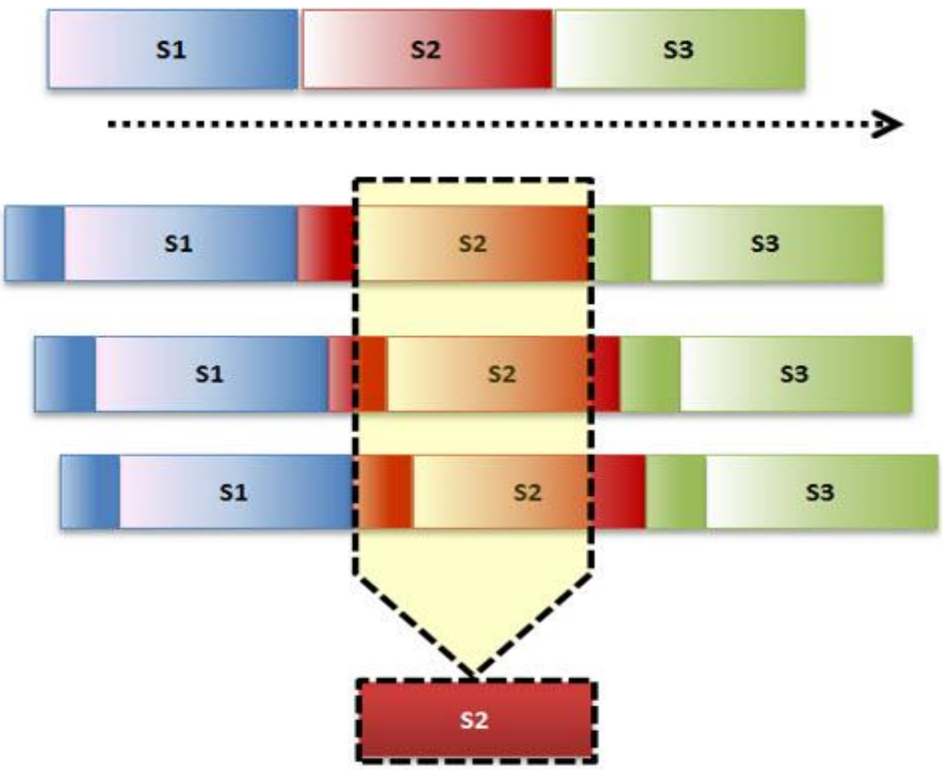


Figure 2.13 Cyclic prefix added to each symbol (Leopedrini 2014)

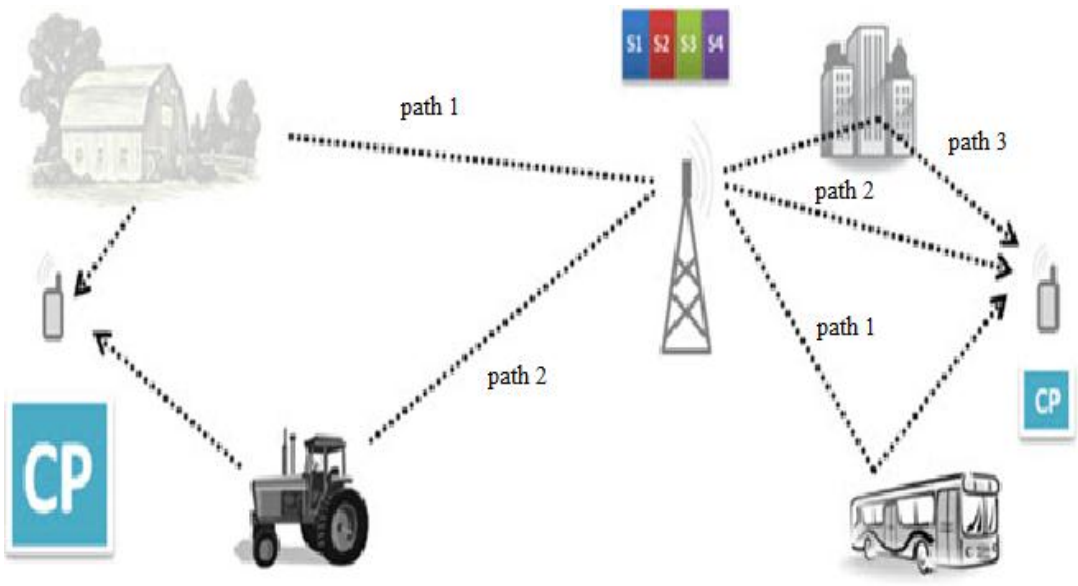


Figure 2.14 Cyclic prefix with multipath of the OFDM signal (Leopedrini 2014)

Then, parallel to serial (P/S) conversion was used to convert the OFDM signal to serial mode and become ready for transmitting, which made the transmitted data like this,

“ 0, 2 – 2j, 0, 2 + 2j, 2, 0 – 2j, 2, 0 + 2j, - 2, 2, 2, 2, - 2, 0 – 2j, - 2, 0 + 2j, 0, - 2 – 2j, 0, - 2 + 2j, 0, - 2 + 2j, 0, - 2 – 2j ”.

In the receiver, all the previous operation was repeated inversely to get the originally transmitted data.

2.3 SINGLE CARRIER AND MULTI CARRIER

When a single carrier on the radio frequency is used to transmit the information, it means this transmission is done using only one carrier. Therefore, the bits of the information are held by only one single carrier. Transmission of multi carrier uses several carrier signals with different frequencies. Bits of the information will be distributed on these multi carriers. The whole sub-channels are dedicated to one data source. In case of OFDM transmission, the transmitter uses IFFT to achieve these several subcarrier signals, which have different frequencies (each subcarrier has its own frequency). It uses a very near spaced multiple carriers over the band. Each one of these carriers holds data bits ready for the modulation process. Therefore, the data rate of OFDM transports is higher when compared to the single carrier system which is shown in Figure 2.15 (Anon 1; Liu 2017). Figure 2.16(a) shows a block diagram structure of the single carrier system, while Figure 2.16(b) shows a block diagram of the multi carrier system,

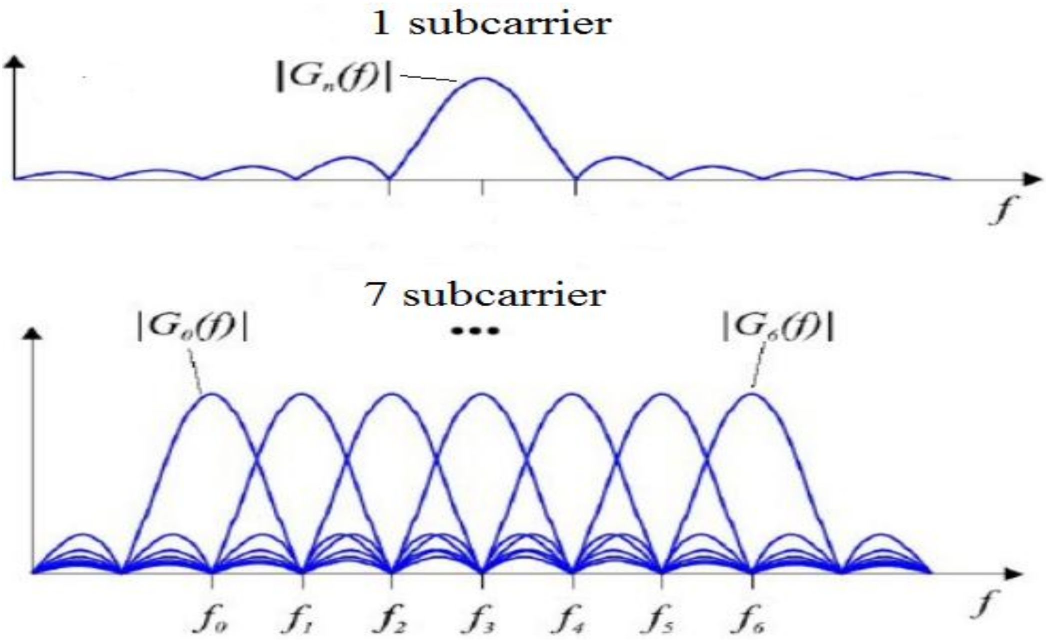


Figure 2.15 Single and multi-carrier OFDM system (Anon 2008)

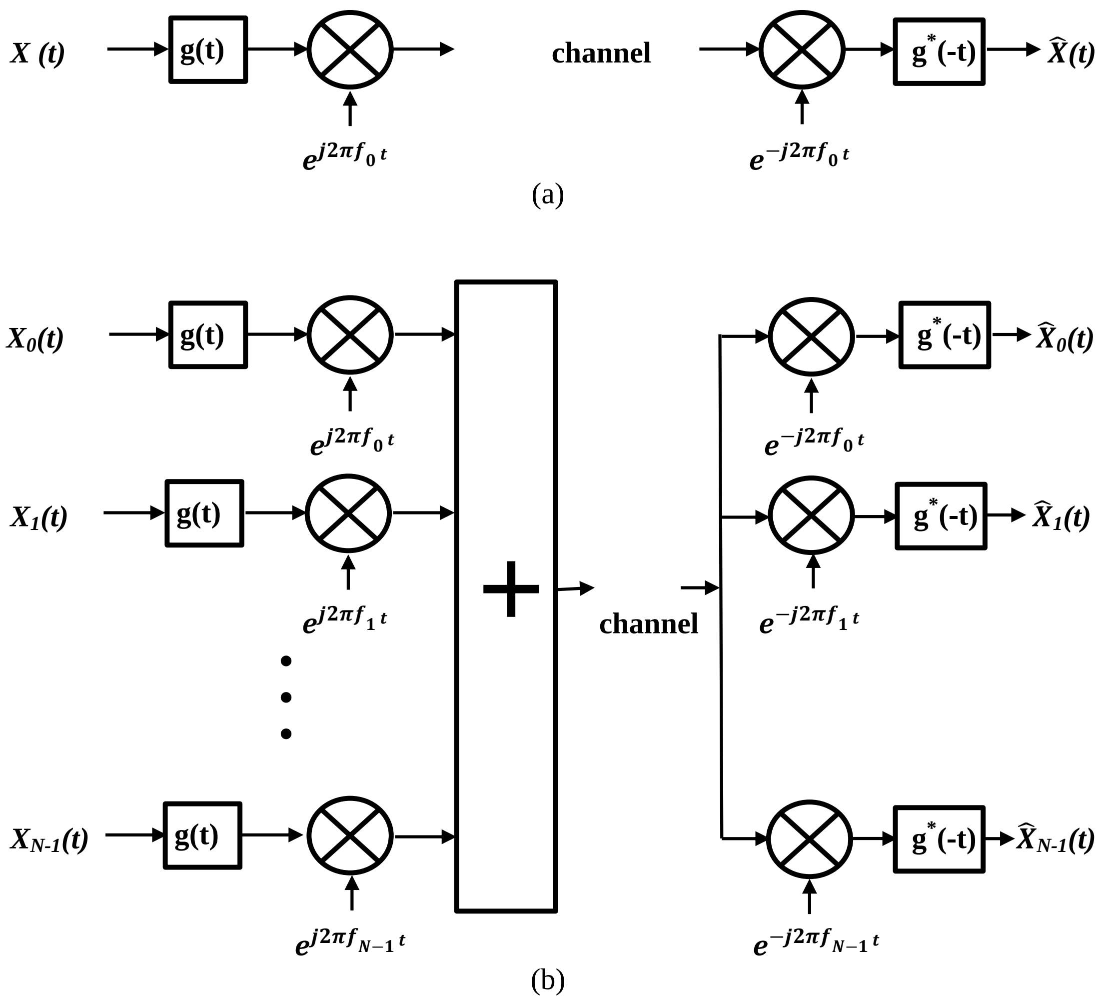


Figure 2.16 Structure of carrier system (a) single carrier (b) multi carrier

2.4 ADVANTAGES AND DISADVANTAGES OF THE OFDM SYSTEM

There are many advantages of the OFDM for provide many wireless systems especially in high data rate, it can be used in such a wide wireless communication application area. On the other side, there are some disadvantages of the OFDM system which must be taken into account when OFDM transmission takes place. Some of the OFDM advantages which are: by allowing overlap feature, the use of the spectrum made efficiently; through using CP, the ISI can be eliminated. Also, OFDM is less susceptible to sample timing offsets than the system of a single carrier. Table 2.3 summarized these advantages and disadvantages (Anon 2; Banupriya & Thilagavathi 2016; Marchetti et al. 2009);

Table 2.3 Advantages and disadvantages of OFDM

Advantages	Disadvantages
1)The spectral efficiency is high when compared with other modulation techniques of double sideband.	1)Due to the noise which is similar to amplitude, which has a huge dynamic range, the signal of the OFDM needs to use linear power amplifiers (LRF) with a great PAPR. This will lead to higher battery consumption (nonlinear power amplifiers are more efficient than LRF)
2)By using techniques of IFFT / FFT and using a technique for modulate and demodulate the signal, OFDM will be computationally effective.	2)When compared with the systems of single carrier and the leakage of the IFFT / FFT techniques, it is the carrier frequency offset sensitive.
3)By using a cyclic prefix (CP), ISI is removed or is reduced to a minimum case.	3)The total spectral efficiency is dropping when cyclic prefix (CP) was used.
4)By using interleaving and sufficient channel coding, the lost symbol is recovered as a result of the channel frequency selectivity.	4)Sentient to the Doppler shift.
5)The equalization of the channel is simple if compare with systems of single carrier which uses the technique of adaptive equalization.	5)Sentient to the problem of frequency synchronization.
6)Decoding of maximum likelihood can be possible to use with sensible complexity.	
7)Very easy conformation with channel conditions without any complexity.	
8)Less sensitivity to the errors of time synchronization.	
9)When the channel is divided into many sub channels with narrow band flat fading, makes the OFDM signal unaffected by frequency selective fading when compared with a system of a single carrier.	
10)If compare with systems of the single carrier, it is a smaller amount of sensitivity to the sample timing offsets.	
11)Offers excellent guard against impulsive unwanted noise and sub channels interference.	
12)In the frequency domain, the signal of OFDM can be scalable from the lower bandwidths to the higher bandwidths.	

2.5 VARIANTS OF OFDM

OFDM has several variants listed as the following (Chide et al. 2013; Gurve et al. 2014; Anon 2011)

i. Coded orthogonal frequency division multiplexing (COFDM)

In such a type of OFDM variants, the coding of error correction is incorporated in the signal. It offers a real advantage in the existence of a narrow band isolated signal. The systems of OFDM are capable to obtain excellent performance on channels of frequency selective because of the joint advantages of coding and multi carrier modulation as shown in Figure 2.17.

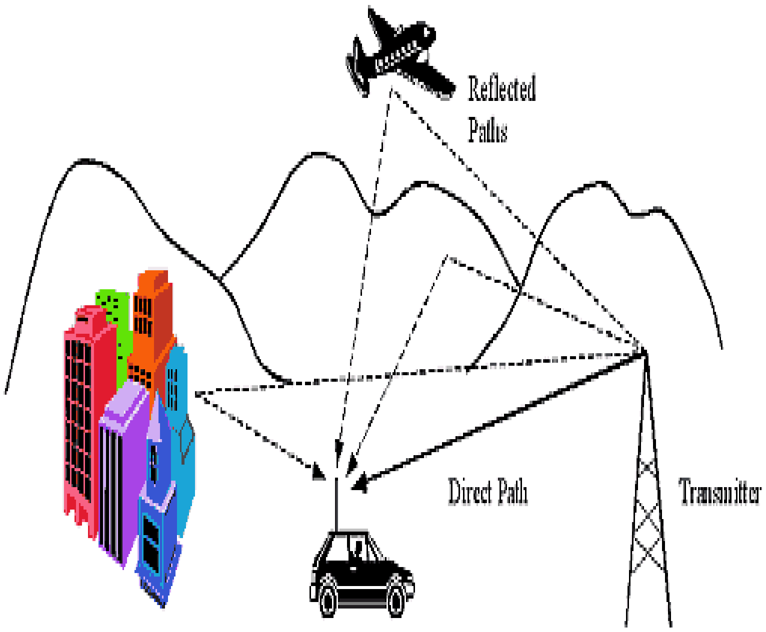


Figure 2.17 Coded orthogonal frequency division multiplexing (Anon 2011)

ii. Orthogonal frequency division multiple access (OFDMA)

A system which offers a capability of multiple access used in applications like the telecommunications of cellular phone using an OFDM system to spread signals within a spectrum band. It is considered a multi user type when the OFDM system is used. OFDMA use further carriers (such as 2048 or 4096 of FFT / IFFT) which are then divided to the subcarriers. Due to the nature of orthogonal, the OFDMA does not need control of the power and can exploit the maximum availability of power in downlink transmission. The best important benefits of the OFDMA are scalable. In the structure of the subcarrier of the OFDMA, its ability supports a wide range of bandwidth as shown in Figure 2.18.

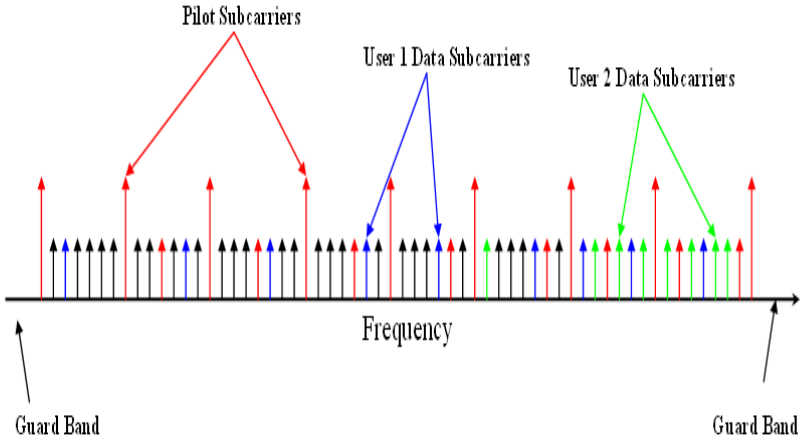


Figure 2.18 Orthogonal frequency division multiple access (Anon 2011)

iii. Flash orthogonal frequency division multiplexing (F-OFDM)

It is a low response time access with the seamless handoff. The F-OFDM is developed by Flarion and it is a form of fast advance OFDM (Chide et al. 2013; Gurve et al. 2014). The spread signal within a certain spectrum band uses fast hopping and multiple tones. F-OFDM is a technology for fast wireless broadband which provides a wireless link to offices, homes, PCs, and mobile. It supports a high data rate with losses of delay and very low packet. F-OFDM operates in licensed spectrum, with low frequencies such as 450 MHz, 700 MHz, 800 MHz and thus attaining an area for larger coverage by using a single base station. This technology has the ability to work on interfering signals. If the speed of the traveling users is 250 km/h (Chide et al. 2013; Gurve et al. 2014), then they can upload their data on speed equal to 500 Kbit/s and download the data on 1.5 Mbit/s as shown in Figure 2.19.

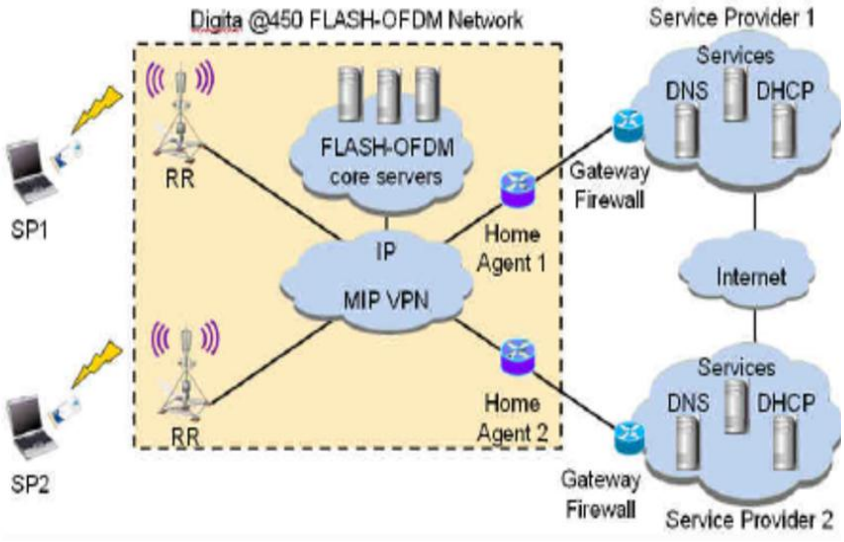


Figure 2.19 Flash-OFDM architecture (Anon 2011)

iv. Vector orthogonal frequency division multiplexing (VOFDM)

This technique was developed by CISCO system. The multipath, interference, and tolerance of the wireless system to noise are significantly increased, when spatial diversity is used. It increases high reliability internet, subscriber encasement for high speed, access of the virtual private network, and services of extensive telephony. VOFDM is a join between OFDM (used for exploiting frequency and time diversity) with the processing of spatial (used for spatial diversity explosion), which gives greatest advantages. By using VOFDM, the next functions can be implemented in two categories, the first is the delay of spread tolerance and the data rate are programmable, while the second is the use of the optimal method (Anon 2011), as shown in Figure 2.20.

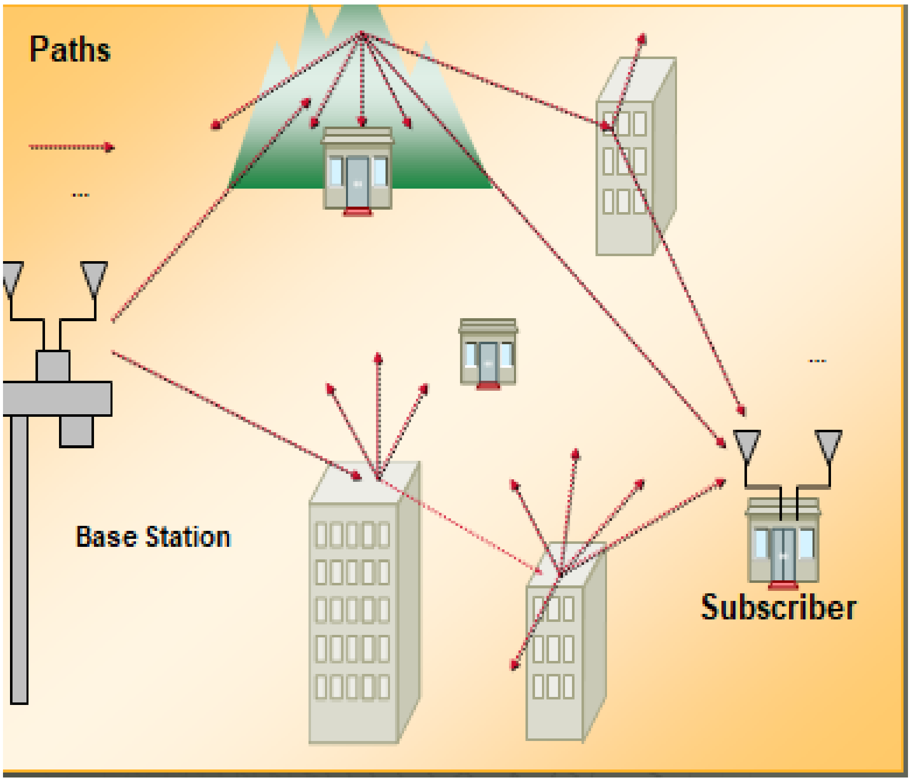


Figure 2.20 Vector orthogonal frequency division multiplexing (Anon 2011)

v. Wideband orthogonal frequency division multiplexing (WOFDM)

While the spacing is sufficiently large between the channels, any errors in frequency between the receiver and the transmitter have no effect on the system's performance. It is mainly appropriate for the Wi-Fi systems. WOFDM allows a number of independent channels to work with the same band. WOFDM has ideal performance versus multipath, best efficiency of the power of the amplifier in the transmitter, fewer sensitive for carrier offset, and more protected against fading.

Table 2.4 shows the summary of the OFDM variants,

Table 2.4 Variants of OFDM

COFDM	OFDMA	FOFDM	VOFDM	WOFDM
* Coded OFDM Digital * Audio Broadcasting (DAB) * Digital Video	* Developed by Iospan Wireless * Uses multiple antennas to transmit and receive radio	* Fast hopped OFDM * Wide band spread spectrum technology * Avoids the	* Vector OFDM * Developed by CISCO *Increases subscriber coverage	* Wideband OFDM *Invented by Wi-LAN * Large spacing between carriers

to be continued...

…continuation

Broadcasting (DVB-T) * Offers real benefit in the presence of isolated narrow-band interfering signals	signals * Spatial multiplexing	compromises inherent in other mobile data systems * Capability to work around interfering signals	* Lowers the cost of provisioning and deploying infrastructure * Employs both frequency and spatial diversity * Creates a robust processing technique for multi-path fading and narrow band interference	* Advantages: - Optimal performance against Multipath - Less sensitive to carrier offset -Optimal power efficiency of the transmitter amplifier - More immune against fading

2.6 OFDM SYSTEM STEPS

The processing of the OFDM signal passes through several stages beginning of its entry into the transmitting side until it reaches the final stage at the receiving side. The general procedures of an OFDM system can be summarized as listed below (Tarokh 2009),

- **i.** Choosing the type of modulation such as type of PSK or QAM.
- **ii.** Choosing the number of FFT such as 16, 32, 64, and 128.
- **iii.** Choosing the type of estimation.
- **iv.** Data initialization.
- **v.** Choosing the range of signal to noise ratio (SNR).

Transmitter stage

- **i.** Convert data file to binary. This data may be random or real data (could be image, speech, or text).
- **ii.** Convert the input binary data from serial to parallel (S/P).
- **iii.** Apply the chosen type of modulation.
- **iv.** Apply the range value of SNR.

v. Convert the data signal from the frequency domain to the time domain by using an IFFT operation.

vi. CP insertion.

vii. Convert from parallel to serial (P/S).

viii. Signal ready to transmit

Channel stage

i. Add AWGN

ii. Calculate data power.

iii. Add noise to the channel.

Receiver stage

i. Convert from serial to parallel (S/P).

ii. Remove CP.

iii. Convert the data from the time domain to the frequency domain by using FFT operation.

iv. Channel estimation.

v. Apply demodulation.

vi. Convert from parallel to serial (P/S).

vii. Recover the original data.

2.7 SYSTEM OF THE OFDM

Figure 2.21 shows the block diagram of a typical OFDM transceiver (transmitter and receiver) with all stages (Rao et al. 2013; Joshi, 2013). At the end of the transmitter stage, the data will become ready to transmit after doing all the procedures of the OFDM system. These data were mapped to subcarrier amplitude and phase after the stages of the transmitter. These stages consists of converting the data from a serial to a parallel (S/P) and doing modulation by using one type of PSK or QAM. Then, the transform of this spectral representation of the data from the frequency domain (FD) to the time domain (TD) using IFFT is achieved. Next, CP is added to the data to help with synchronization. Then, the data is transformed from parallel to serial (P/S), followed by a DAC. The output signal is ready to transmit and take the form like the output of the Equation 2.1 (Rao et al. 2013);

$$x(n) = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} X(m) \, . \, e^{\frac{j2\pi nm}{N}} \qquad (2.1)$$

where *x(n)* is the OFDM signal, *X(m)* is modulated symbol in the frequency domain for the m^{th} subcarrier whereas $0 \leq m \leq N - 1$, *n* is a time domain sample index, and *N* denotes the number of subcarriers.

Through the channel, the incoming signal (transmitted data) was mixed with AWGN. While in the receiver stage, the reverse operations are done. The incoming signal passes through ADC then converts from serial to parallel (S/P) consequently. The CP is removed from the signal; the signal is transformed from time domain to frequency domain by using FFT; the amplitude and phase of the subcarriers are picked out and converted back to digital data (to the end of receiver stage) that is similar to the output of the Equation 2.2, (Rao et al. 2013);

$$Y(m) = \sum_{n=0}^{N-1} \left[y(n) \, . \, e^{\frac{j2\pi n\varepsilon}{N}} + w(n) \right] \qquad (2.2)$$

where, $Y(m)$ is the output of FFT stage, $w(n)$ is AWGN, $y(n)$ the received signal after passing through the AWGN channel affected by frequency offset, ε the normalized frequency offset (given by $\Delta f\ N\ T_s$, where Δf is the frequency difference of local oscillator between the transmitter and receiver, and T_s is the symbol period).

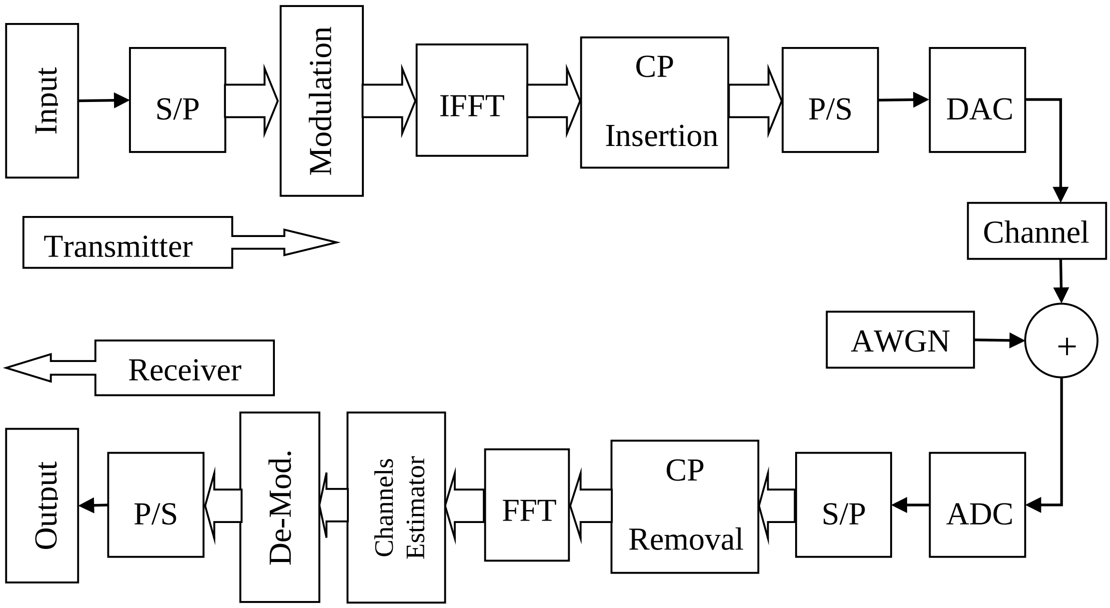


Figure 2.21 OFDM generation and reception block diagram

2.7.1 Design Issues of the OFDM System

The design of the system always requests comprehensive and complete consideration and understanding of critical factors. The basic philosophy of OFDM is to reduce the data rate in the subcarriers that leads to increasing the duration of the symbol. Therefore, the multipath is removed effectively (Marchetti et al. 2009). This leads to a challenging problem when the value of the CP is high which improved the results (eliminates ISI). This increases the energy loss as a result of CP insertion. Therefore, there is a need for reasonable design to get a trade-off (Mesfin 2007; Marchetti et al. 2009; Suksompong 2007; Suksompong 2010).

b. Design Requirements of the OFDM System

The four requirement factors that the OFDM systems depend on (Marchetti et al. 2009) are,

- **The bandwidth availability**: Bandwidth is always a rare resource. Therefore, the main design of the OFDM system must be careful about the bandwidth availability for each operation. The length of the bandwidth plays the main role to determine the subcarriers number, because, as a great bandwidth, there is an easy way to fit a huge number of subcarriers with an acceptable guard space.

- **Bit data rate requirement**: The complete system must be able to provide the required data rate by the users.

- **Acceptable delay spread:** It is user environment dependent. Practical measurements illustrate that the indoor environment has a maximum delay spread at most with a limited hundred of a nanosecond (ns). While the outdoor environment reaches to 10 microseconds (μs) (Marchetti et al. 2009). Therefore, the length of the CP must be specified and determined according to the acceptable delay spread.

- **The value of the Doppler:** The vehicle at high speed gets a high effect of the Doppler shift, and the walkers get a minimal effect of the Doppler shift. These two scenarios which affect the OFDM system should be taken into consideration and develop a strategy to deal with this effect.

c. Parameter Design of the OFDM System

The design of the OFDM depends on some parameters which play the main role in the OFDM system and make the transmission smoothly without any synchronization's error. These parameters are illustrated as the following, (Lehne & Bohagen 2008; Marchetti et al. 2009; Suksompong 2010);

- **Number of subcarriers:** Data rate with respect to each subcarrier reduced when the number of subcarriers increased and vice versa. Through the delay multipath phenomenon which happens in time, it makes decreasing in a comparative amount of the dispersion as shown in Figure 2.22. The best number of subcarriers depends on the some factors such as noise, interference, and ratio of the signal. Based on the signal to noise ratio and the amount of the interference, the subcarriers which are used to transmit the signal of data must be closely determined. All subcarriers are used when the interference is small to maximize the capacity of the channel. Besides, fewer numbers of subcarriers should be used when the interference level increases to mitigate the interference (Rim 2012).

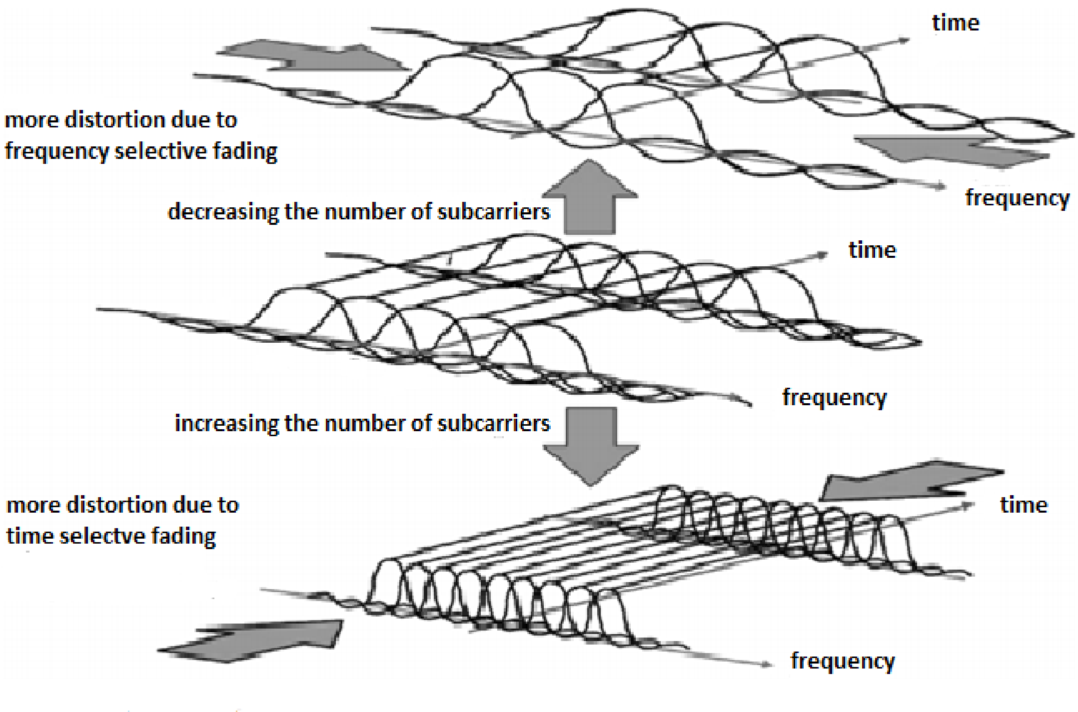


Figure 2.22 Spacing design of the subcarrier in OFDM system (Lehne & Bohagen 2008)

- **CP interval (guard band) with symbol duration:** There always should be a better ratio between the length of the CP and the duration of the symbol. Therefore, the multipath must be determined, and there is no significant amount of energy lost as a result of CP as shown in Figure 2.23. With the reasonable amount, the symbol length must be larger enough than the guard duration to reduce the SNR loss. Due to the larger time symbol, it leads to more subcarriers fitted within the time of the symbol. The signal processing increases when the subcarriers increase in the receiver side and the transmitter side. Therefore, the complexity and the cost also increase.

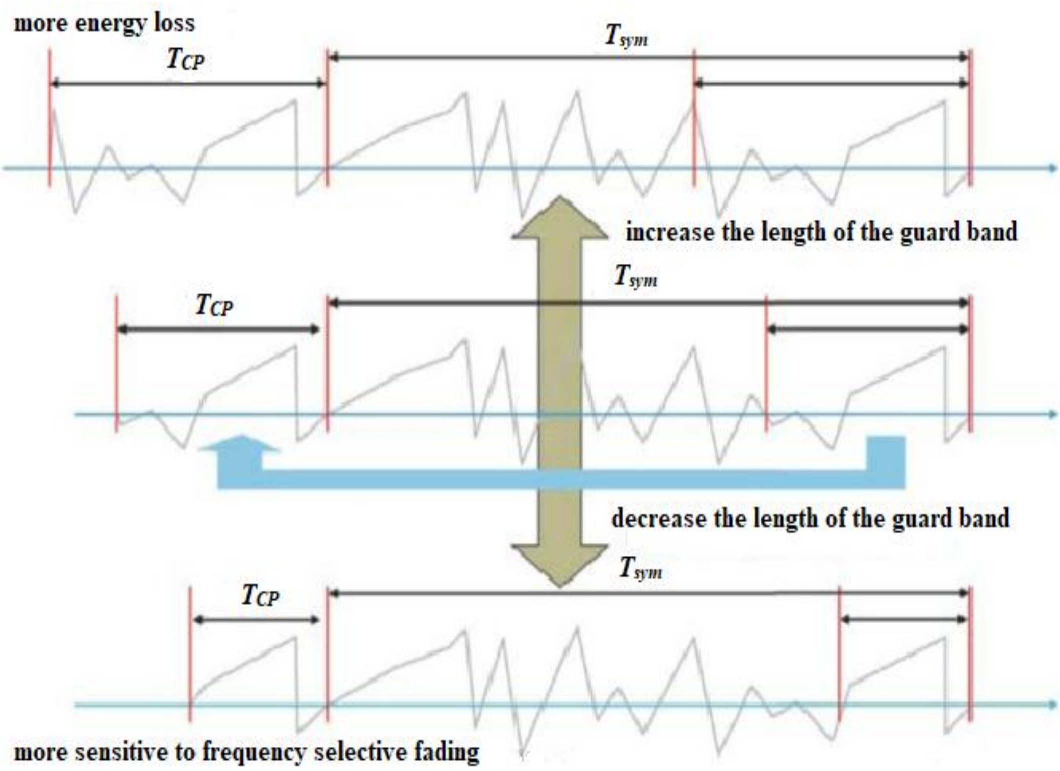


Figure 2.23 Design of CP duration in OFDM system (Marchetti et al. 2009)

- **Subcarrier spacing:** When the synchronization is achieved, the subcarrier spacing must be kept at the level. This mainly depends on the number of the required subcarrier and available bandwidth.

- **Modulation type**: Modulation type have an important factor used in wireless communication which is used in the OFDM system. By using different modulation type (any type of PSK or QAM), we can get different performances. The complexity computation may vary by the type of modulation.

- **Forward error correction (FEC) coding:** The chosen type of FEC plays an effective role. The channel becomes robust to all the random errors when there is an appropriate choice of the FEC coding.

2.8 OBSTRUCTIONS OF THE OFDM

There are many types of obstructions in the OFDM transmission signal, which are;

2.8.1 Inter Carrier Interference (ICI)

The major weakness in the system of OFDM is inter carrier interference. It is an error of carrier frequency offset in local oscillator frequency which occurs between received and transmitted signal. Another reason of ICI is the Doppler shift in the receiver as a result of motion between the receiver and transmitter. This leads to loss of the orthogonality between the subcarriers, and the orthogonality spectrum is destroyed. Finally, the signal is received with interference and systems' performance degrades. There are many techniques used for ICI cancellation such as equalization of the frequency domain, windowing of time domain, Maximum Likelihood estimation (MLE), self-cancellation, and pulse shaping (Gupta et al. 2015).

To mitigate the OFDM signal from ICI, the guard space of CP is filled to preserve the orthogonality between subcarriers on the situation that the copies of multiple delayed come within receiver due to the propagation of multi-path. At the transmitter, if the guard space filled with 0's, then the numerous copies arrived at the receiver will have the non-orthogonal form, and in some case, they correlated to each other producing ICI (Klose 2013; Sharma et al. 2017).

There are many techniques used for ICI reduction, which are illustrated in Figure 2.24 (Rao et al. 2013; Chaudhary & Arora 2015; Himja & Kumar 2015)

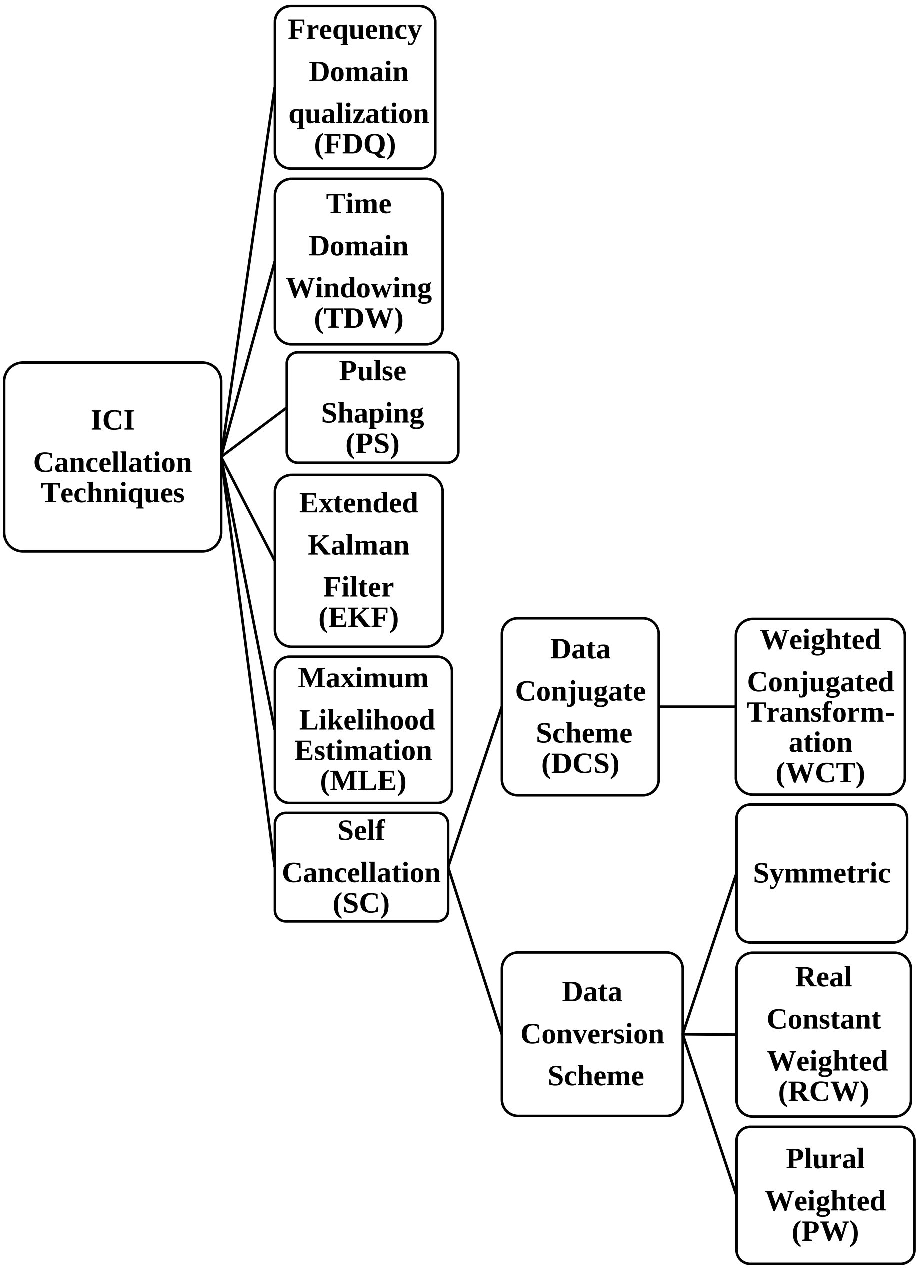


Figure 2.24 Techniques for ICI cancellation

In (Rao et al. 2013), different techniques of ICI cancellation were studied such as pulse shaping, time domain windowing, frequency domain equalization, and ICI self-cancellation.

The several ICI self-cancellations were studied and reviewed by (Chaudhary & Arora 2015). The complete comparison of these techniques is described in this research paper. The technique has two main benefits when compared with other techniques for ICI cancellation. First, it is less complex when compared with other correlation and estimation techniques. Second is to combat the effect of frequency offset even when the frequency offset is low. Therefore, there is no need for channel estimation to decrease ICI. From the simulation results, it appears that the technique of Weighted Conjugate Transformation (WCT) is the best one of all conventional ICI reduction techniques.

Many reduction techniques for ICI have been discussed in (Himaja & Kumar 2015), such as frequency domain equalization, time domain windowing, extended Kalman filtering (EKF), Maximum likelihood estimation (MLE), and self-cancellation technique.

2.8.2 Inter Symbol Interference (ISI)

At the receiver and as a result of multipath propagation, several copies of the transmitted data waveform arrive at various time instants. If there is no CP (guard space or guard band) between successive symbols of the OFDM, then the transmitted symbols may overlap with successive symbols at the receiver, which gives rise to inter symbol interference. In time domain and by inserting CP between successive symbols of OFDM, the domain mitigates this effect.

There are many techniques used for ISI reduction, which are illustrated in Figure 2.25 (Wong & lok 2000; Klose 2013).

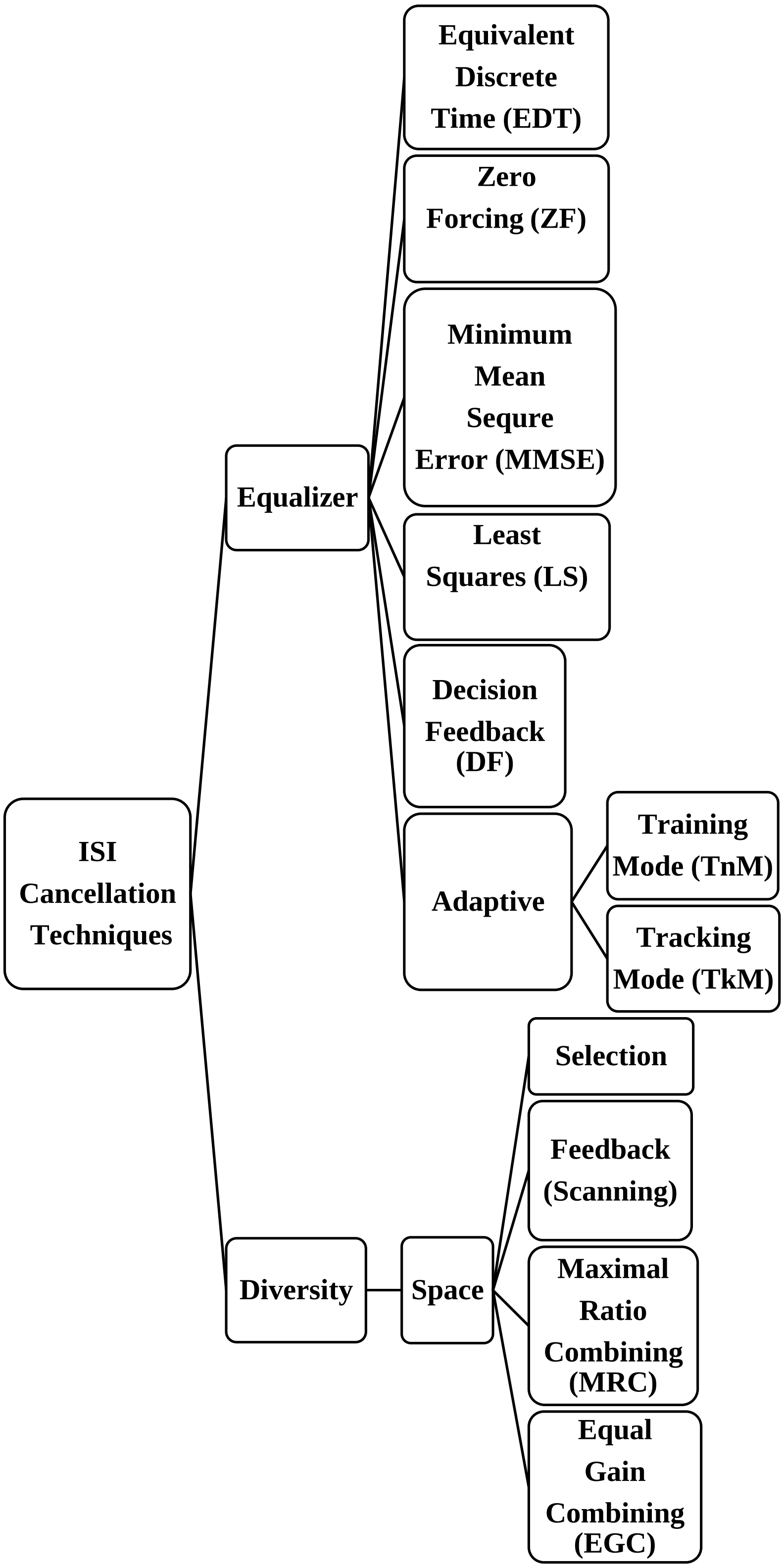


Figure 2.25 Techniques for ISI cancellation

Moreover, to overcome this problem, a guard space is inserted between successive symbols of the OFDM in the time domain. In the maximum channel, if the spread delay is less than the guard space, then all copies of the multi-path arrive within this guard space, which keeping the successive OFDM symbols has no effect. 0's may fill this guard space to overcome the ISI (Klose 2013).

2.9 SYNCHRONISATION IN OFDM

The synchronization is an essential task for any digital communication system. Without accurate synchronization algorithms, it is impossible to recover the transmitted data (Thakur & Khare 2012). Therefore, synchronization is an important factor which must be solved. It must be used as an efficient method of synchronization to get a better performance. Because the OFDM system is a multi-carrier modulation system, the system is very sensitive to its synchronization errors. The advantages of OFDM can be achieved only with efficient synchronization in time and frequency domain (Rana & Setia 2015). However, OFDM system is relatively sensitive to time and frequency offset.

There are two serious challenges of synchronization which frequently experienced by the system of OFDM; symbol time synchronization and frequency synchronization.

In order to guarantee the orthogonality of subcarrier, the guard interval or CP are inserted among the sub-carrier. Through inserting guard interval or CP, the interference among the OFDM symbols is eliminated (Dai & Wang 2014). Plus, the OFDM system is highly sensitive to an error caused by carrier frequency, which tends to destroy the orthogonality among carriers and significantly degrade system performance.

OFDM system is useful when orthogonality is preserved. As long as the subcarriers are orthogonal, the spectrum for each carrier has a null at the center frequency of the other carriers within the system. This results in the absence of interference among carriers, which in turn, allows them to be spread out as close as theoretically possible. Two kinds of deformation related to the carrier signal exists

(Kayalvizhi et al. 2015); the CFO and the STO. Compared with single-carrier systems, the sensitivity errors to timing and carrier offset is greater in OFDM systems.

The synchronization is considered as a major problem in OFDM systems (Rao et al. 2013). Sometimes the synchronization requires an inclusive processing with extremely effective systems, and some type of synchronization methods in the receiver are applied to the transmitted data (Kaur et al. 2012). Therefore, OFDM needs some parameters to overcome this problem, such as cyclic prefix (CP), carrier frequency (CF), frame detection (FD), and so on (Schmidl & Cox 1997; Kaur et al. 2012).

In (Sharma & Gupta 2014), the term immunity to impulse interference, high spectral density, robustness to channel fading, multipath, and much lower computational complexity are discussed. All parameters are compared using additive white Gaussian noise and Rayleigh fading channel by changing the phase of several subcarriers using QPSK in OFDM modulation.

(Punchihewa, et al., 2011) presented a blind parameter estimation algorithm for OFDM signal which is considered additive Gaussian noise, the time-dispersive channel, and other parameters of OFDM synchronization. This algorithm was proposed by extracting some OFDM parameters which are required for blind demodulation. The indication of simulation results shows that the algorithm proposed by the authors achieves well, even with low SNR in a fading channel. The proposed algorithm plays an important part in cognitive radios.

2.9.1 The Effects of STO and CFO Factors

The fundamental functions which are needed in the modulation and demodulation techniques of OFDM systems are IFFT and FFT in transmitter and receiver, respectively. There is a need to exact sample of the OFDM symbol duration of the transmitted signal to discover the starting point of the OFDM symbol, in which the exact samples are obtained (Li 2014). In the OFDM system, the STO may be caused by phase distortion, and also by ISI (Li 2014).

The CFO refers to the difference between the transmitter and the receiver carrier frequencies. The baseband signal which is received under the presence of STO (δ) and the CFO (ε) is expressed as

$$y_l[n] = IDFT\{y_l[k]\} = IDFT\{H_l[k].X_l[k] + Z_l[k]\}$$

$$= \frac{1}{N} \sum_{k=0}^{N-1} H_l[k] \, . \; X_l[k] \, . \, e^{j2\pi(k+\delta).(n+\varepsilon)/N} + Z_l[n] \qquad (2.3)$$

where; $Z_l[n] = IDFT\{ Z_l[k] \}$, δ normalized STO, ε normalized CFO, and $Y_l[k]$ the l^{th} received symbol at the k^{th} subcarrier (Benzarti et al. 2015).

(Li et al. 2016) showed that the CFO is the significant problem in the front end of the OFDM system, especially when using lesser precision ADC. They analyzed three algorithms for CFO estimation in OFDM system with quantization at low precision.

A different technique of PAPR with the OFDM system which is used in wireless communication is mentioned by the authors in (Barakabitze & Ali 2015). Another focus had been done also to the behaviors of the OFDM with CFO techniques. They also provided many wireless communication standards and a number of applications in which OFDM was used.

In (Sheu & Huang 2009) a new detection technique for symbol timing which is robust to the CFO was proposed for OFDM system in time domain synchronization. The sliding correlation technique was computed from the received signal and the sequence of differential pseudo noise (PN).

The STO effects are studied in (Aziz et al. 2012) and correspondingly different protective techniques in time and frequency domain are used in the receiver to overcome it. These techniques are compared by using simulations in MATLAB.

The authors in (Nasraoui1 et al. 2013) applied a proposed effective technique which deals with timing synchronization in the OFDM system for standards of IEEE

802.11 a/g. Two different techniques were taken into account: a brute force with the single stage in which it carries difference correlation exclusively, and a technique of two stages to reduce complexity, including fine and coarse stages.

While the authors in (Silva et al. 2013) did a proportional study of long and short preambles. The proposed long preamble which is based on a sequence of CAZAC, uses the sequence of Golay Rudin Shapiro. The improved structure of CAZAC and structure of weighted CAZAC were combined sequences to make preamble ready for synchronization and the possibility to join these two structures to get a better estimation response for frequency and timing offset.

Authors in (Dai & Wang 2014), proposed an enhanced algorithm of the timing synchronization that implements the training sequence, and the estimation function of the timing synchronization which improved for the algorithm.

Studies about the reason for CFO creation and the CFO effects on the OFDM performances were done by the authors in (Mohseni & Matin 2012; Mohseni & Matin 2013). The major algorithm of the CFO estimation and their techniques were reviewed, and an algorithm used for estimation and reparations of the CFO effect was proposed.

The STO is considered as a delay in the carrier frequency offset and the channel impulse response (Farzamnia et al. 2017). This give an increase to a shift in the frequency domain as a result of a difference between local oscillators of the transmitter and receiver. The STO was shown as an ISI and phase rotation (PR). The CFO causes damage of orthogonality between subcarriers. Consequently, signals transmitted on each carrier become independent from one another. The CFO is exemplified as inter-channel interference (ICI) and phase rotation (Sklar 2001).

Authors in (Ouarzazi et al. 2013) proposed a transmission system based on OFDM technique and channel estimation to enhance the pilot assisted channel estimation performance without data rate loss. A frequency diversity-based solution was proposed. By using the same number of the pilot symbols, the overall system performance was better for the higher mobility speed.

a. Effect Of The STO

As long as the FFT function takes place in the receiver, the careful samples of the transmitted signal are required for the duration of OFDM symbol (Kaur et al. 2012) in order to take the *N* point FFT at the receiver. Next, the aim is to see the effects of the STO by considering the received signal in the frequency domain and by taking the FFT of the time domain received samples $X_l = [n + \delta]_{n=0}^{N-1}$, given by (Benzarti et al. 2015)

$$Y_l[k] = \frac{1}{N} \sum_{n=0}^{N-1} x_l \, [n + \delta] \, . \, e^{-j2\pi k/N}$$

$$= x_l[k] e^{j2\pi k\delta/N} \qquad (2.4)$$

The effect of STO depends on the beginning point of estimation for OFDM symbol. Figure 2.26 illustrates the four different states of STO estimation, which are: accurate (state 1), small earlier (state 2), more earlier (state 3), and a little later (state 4), (Li 2014; Aziz et al. 2012).

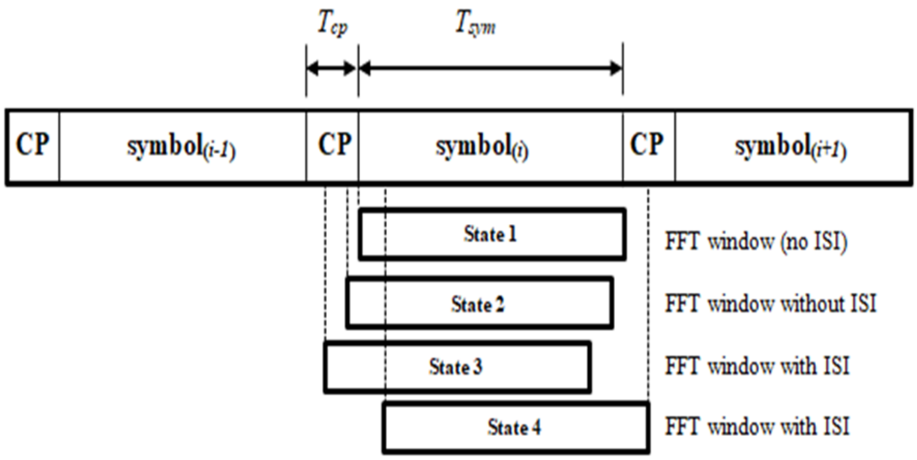


Figure 2.26 Four different states for estimation of beginning symbol point of the STO

- State 1: This state is when the estimation is begun exactly when the OFDM symbol begins. In this case, the orthogonality of subcarrier will be preserved, and the symbol of OFDM can be totally recovered with no interference.

- State 2: This is a state that the OFDM symbol begins to estimate before the precise point. In this situation, the symbol *i* is not overlapped with the preceding *i - 1* symbol and not suffering any ISI. It means that the orthogonality among subcarrier frequency components can be completely protected.

- State 3: This is a state that the OFDM symbol is beginning to be estimated too early before the perfect point. Thus the orthogonality between components of subcarriers is destroyed through the ISI (coming from prior symbol), as a result of this, ICI happens.

- State 4: This is a state that the OFDM symbol is beginning to be estimated later than the perfect point, and the timing of the symbol is a small later than the perfect point. Therefore, the content of the signal is part of the *i* OFDM symbol and a part of *i* + 1 symbol. It leads to destroying the orthogonality; also, there is ISI in the received signal.

b. Effect of the CFO

The main sources of the CFO (Benzarti et al. 2015; Kayalvizhi et al. 2015) are as the following:

- The frequency phase shift between the receiver and transmitter: The signal after modulation is centered on a frequency δf instead of being centered at (0 MHz), as a result of the phase difference between the frequency of the receiver and transmitter. The CFO is shown in Figure 2.27, since $\delta f = |F_{CRX} - F_{CTX}|$, where F_{CRX} is the carrier frequency of the receiver, and F_{CTX} is the carrier frequency of the transmitter.

- Doppler Effect: The carrier frequency at the receiver (F_{CRX}) can differ due to the Doppler Effect in the status of mobile receivers. Doppler Effect is the additional source of CFO.

- The sampling frequency difference: Another source of the CFO is the gap between the sampling frequencies between the destination and the data source.

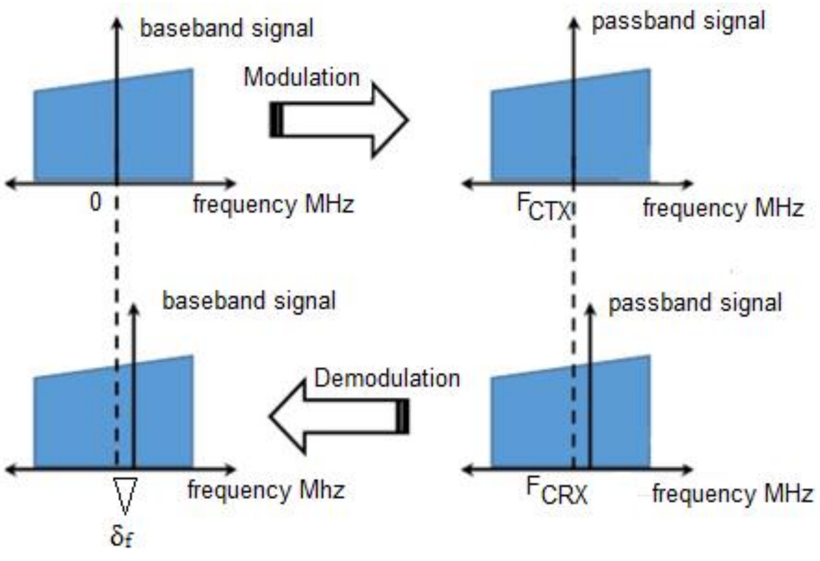


Figure 2.27 Effect of CFO (Benzarti et al. 2015)

The subcarriers are sampled at their peak. This can happen only when there is no frequency offset observed. Nevertheless, if a frequency offset occurs, the sampling is done at the offset point, which is not the peak point. This reduces the anticipated subcarriers' amplitude, which can then increase the ICI from the neighboring subcarriers. The impact of the CFO is illustrated in Figure 2.28.

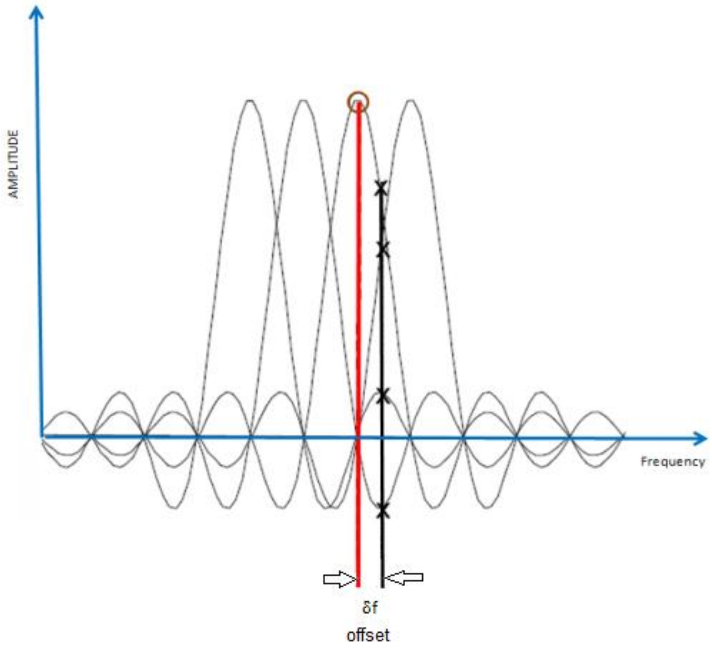


Figure 2.28 Frequency offset of the receiving signal (Kayalvizhi et al. 2015)

The Doppler frequency shift f_d causes the CFO. Here, f'_c and f_c are the receiver and transmitter carrier frequencies, respectively, while f_{offset} is the difference between them, ($f_{offset} = f_c - f'_c$). The normalized CFO, referred as ε, is a ratio of the CFO to subcarrier spacing Δf, which is given by (Benzarti et al. 2015)

$$\varepsilon = \frac{f_{offset}}{\Delta f} \qquad (2.5)$$

From Equation 2.3, the received signal in the time-domain is expressed as (Cho et al. 2010)

$$y_l[n] = \frac{1}{N} \sum_{k=0}^{N-1} H_l[k] \, . \, X_l[k] \, . \, e^{j2\pi(k+\varepsilon)\,n/N} + Z_l[n] \qquad (2.6)$$

Before demodulation of the OFDM signal, synchronization of pre-FFT achieves CFO estimation. The pre-FFT method offers minimal computing power and quick synchronization. The synchronization of the pre - FFT can be categorized into data aided (DA) and non-data aided (NDA) (Rajeswaran & Nair 2016). The method of DA takes advantage of the recognized sequence of the TS of the OFDM signal, which is inserted at the beginning of every packet of OFDM signal and then used to estimate CFO fraction (Yadav & Bera 2015). In another way, the disadvantage of DA reduces the efficiency of transmission as a reason for TS insertion at the same time.

The method of NDA takes advantage of the similarities between the part of CP and the part of matching data belongs to the symbol of the OFDM, which is used to estimate the CFO fractional (Yadav & Bera 2015; Gupta & Jain 2015; Anon 2014; Rao et al. 2013). This is done by taking the square difference or correlating the part of CP with the equivalent part of OFDM symbol, which is used to estimate the frequency and timing offsets.

DA gives better results and varied estimation range of CFO if it is compared with the NDA method. The range of estimation used for CFO in DA method is ± 2 while in NDA method is ± 0.5 (Yadav & Bera 2015; Gupta & Jain 2015; Anon 2014; Rao et al. 2013; Joshi 2013).

The remaining part of pre-FFT frequency synchronization is usually achieved by post-FFT to estimate the residual integer CFO. By using the correlation between receiving pilot subcarriers with a shifted form of the recognized pilot subcarriers, the integer CFO is estimated (Classen & Meyr 1994). When some type of estimation techniques (in the receiver) are used, it helps to clarify distortion in the sending symbols, so the estimation of the CFO is necessary. Table 2.5 shows the synchronization of this area that can be classified into the following;

Table 2.5 Types of synchronization with depend on Pre FFT and Post FFT

Synchronization		
Time domain (Pre FFT)		**Frequency domain (Post FFT)**
Estimation before demodulation		**Estimation after demodulation**
Non-data-aided (NDA)	**Data-aided (DA)**	
* Use CP correlation * Estimate fractional CFO * Does not waste bandwidth *Does not reduce transmission speed * Does not require additional data *High efficiency of data transmission * Estimation ranges too small * Not suitable for acquisition	* Use TS or pilot symbols for estimation * Estimate fractional CFO * High estimation accuracy * Fast synchronization speed * Low computation complexity * Decreases the efficiency of data transmission * Loses the bandwidth * Reduce data transmission speed.	* Estimate remaining integer CFO * Expand the range of estimation CFO able to several integers of subcarriers

A new structure for frequency and time synchronization (data-aided) has been proposed by the authors in (Nasraoui et al. 2011), which is based on the preamble with a single symbol. By adding CP with suitable length, the preamble was extended. This structure was enough for a scheme of synchronization with two-stage, which is named a reduced complexity coarse synchronization stage.

2.9.2 The Standard Timing Synchronization Estimator Algorithms

According to data aided and non-data aided which described perversely, the fine timing synchronization algorithms are introduced. These algorithms are based on the training sequence (TS). The goal for time synchronization is to discover the start of the OFDM symbol and the estimation of the time offset.

There are four types of training sequences. The first type uses Pseudo noise (PN). Synchronization based on the training sequence mostly uses PN (Schmidl & Cox 1997; Ren et al. 2007; Lin & Huan 2007; Gui et al. 2008) because it is a simple sequence. PN sequence uses a linear feedback shift register (LFSR). The second type consists of two sequences having m samples (using two PN sequence) that are the same length. By using an XOR method, a new sequence is generated which called Gold sequence. The third type of training sequence having constant amplitude with less strain on power amplifier used for transmission which is called constant amplitude autocorrelation sequence (CAZAC) (Wu et al. 2009; Pelinkovic 2013; Joshi 2013; Silva et al. 2013). At nonzero lags, the CAZAC sequence has zero autocorrelation and provides signal ORTHOGONALITY in time. While the fourth type of the training sequence is a Zadoff Chu sequence. This sequence is used in LTE for an uplink reference signal (Gul et al. 2015; Kaushal et al. 2018; Zivkovic & Mathar 2014).

Following are the different types of timing offset algorithms which are described briefly (Asran et al. 2015; Chen & Yang 2012; Gupta & Jain 2015; Dai & Wang 2014; Wu & Abu Rgheff 2007; Romeo 2008; Joshi 2013) .

i. Schmidl and Cox (SC) algorithm (Schmidl & Cox 1997)

Two identical segments for training sequence are used and located at the beginning of each OFDM symbol. These segments have a length of $N/2$, and take the following form,

$$S_{(SC)} = [\, A, A]$$

Where N is the number of samples in each OFDM symbol (size of FFT) and A represents the samples in each segment part. The SC algorithm uses PN sequence on an even number of the subcarrier and putting zeros on the odd subcarriers.

ii. Minn and Bhargava (MB) algorithm (Minn et al. 2003)

For OFDM training sequence, MB proposed an algorithm that has four segments, and the length of each is $N/4$ as the following pattern

$$S_{(MB)} = [\, A, A, -A, -A]$$

The MB algorithm uses PN sequence which is identical for the first two parts and has a negative version for the last two parts.