# PERFORMANCE EVALUATION OF SFBC-OFDM SYSTEM USING ZERO-FORCING DETECTION SCHEME UNDER MOBILE ENVIRONMENT

Thesis submitted towards the partial fulfilment of requirement for the award of degree of

**MASTER OF ENGINEERING**

**IN**

**WIRELESS COMMUNICATION**

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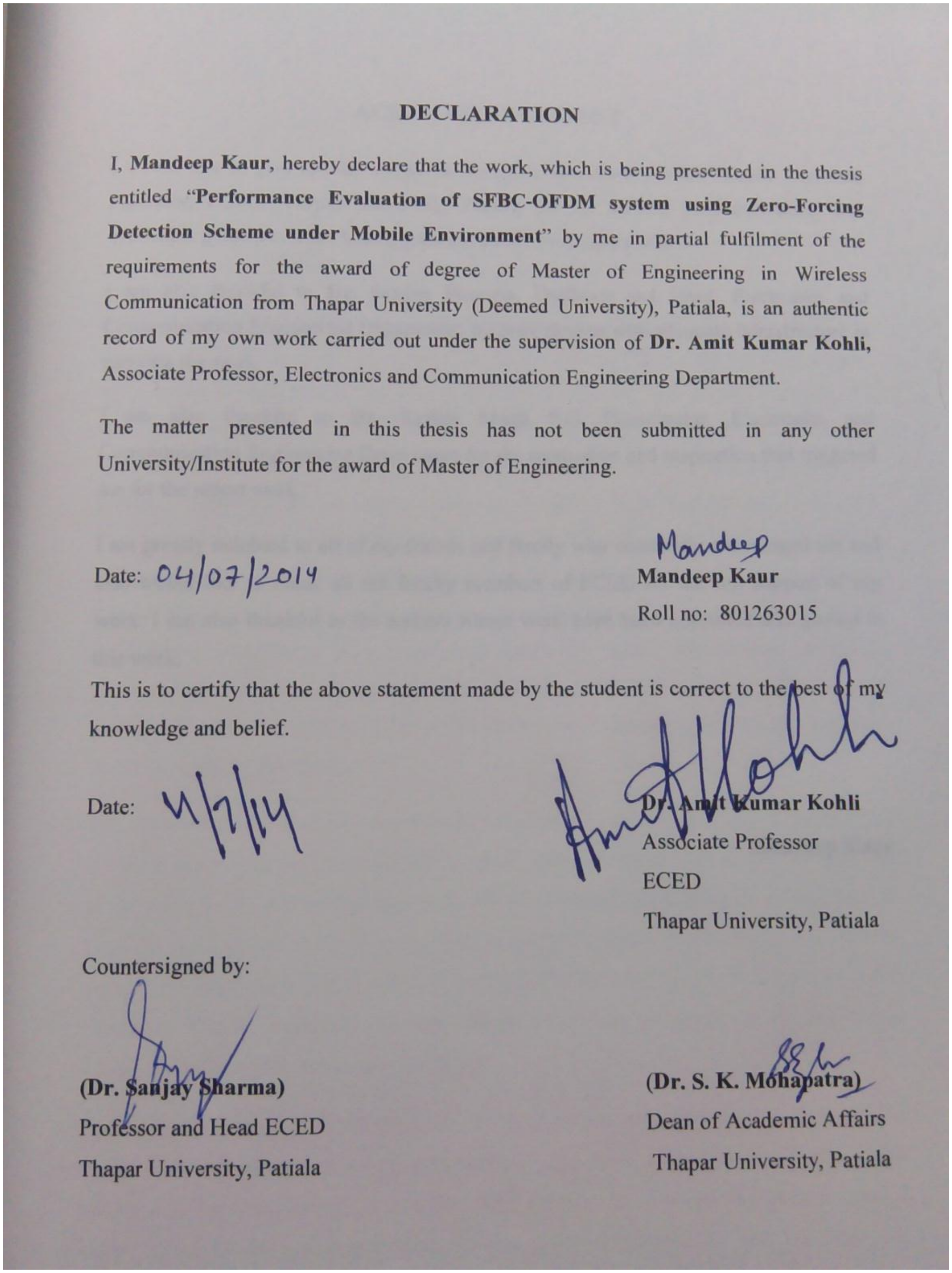
**(Established under the section 3 of UGC Act, 1956)**

**PATIALA – 147004, INDIA**

**JULY-2014**



# DECLARATION

I, **Mandeep Kaur**, hereby declare that the work, which is being presented in the thesis entitled "**Performance Evaluation of SFBC-OFDM system using Zero-Forcing Detection Scheme under Mobile Environment**" by me in partial fulfilment of the requirements for the award of degree of Master of Engineering in Wireless Communication from Thapar University (Deemed University), Patiala, is an authentic record of my own work carried out under the supervision of **Dr. Amit Kumar Kohli,** Associate Professor, Electronics and Communication Engineering Department.

The matter presented in this thesis has not been submitted in any other University/Institute for the award of Master of Engineering.

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# ACKNOWLEDGEMENT

I would like to give special thanks to my guide **Dr. Amit Kumar Kohli**, Associate Professor, ECED, Thapar University, Patiala, for his advice, kind assistance, and invaluable guidance. It has been a great honour to work under him.

I am also thankful to **Dr. Sanjay Sharma**, Professor and Head, Electronics and Communication Engineering Department, for providing us with adequate infrastructure in carrying the work.

I am also thankful to **Dr. Kulbir Singh** P.G. Coordinator, Electronics and Communication Engineering Department for the motivation and inspiration that triggered me for the report work.

I am greatly indebted to all of my friends and family who constantly encouraged me and also would like to thank all the faculty members of ECED for the full support of my work. I am also thankful to the authors whose work have been consulted and quoted in this work.

**Mandeep Kaur**

# ABSTRACT

Fading is an important issue when communication has to be done via wireless channel in mobile environment. Since the behaviour of the multipath wireless channel is such that the amplitude and power of the received signal is random, therefore Rayleigh fading model is used to model the characteristics of the channel.

The other important technique which is widely used nowadays is Orthogonal Frequency Division Multiplexing (OFDM), which reduces the effect of frequency selective channel by dividing the data stream that is to be transmitted into multiple parallel channels and the channel is thus divided into number of parallel narrowband sub channels such that each sub channel has lower data rate. Thus, OFDM converts the frequency selective fading to approximate flat fading. However, OFDM is more popular due to its easy implementation using Discrete Fourier Transform (DFT). Moreover, OFDM is bandwidth efficient because parallel subcarriers are orthogonal to each other and thus no interference occurs. However, there are many other issues such as Inter-Block interference (IBI) and Inter-carrier interference (ICI) which may affect the system performance in mobile environment. By using cyclic prefix (CP), the IBI can be eliminated completely but to remove ICI, channel estimation has to be performed accurately which further increases the complexity of the receiver.

The other most important strategy used by wireless communication systems is known as Multiple Input Multiple Output (MIMO) which enhances the quality as well as data rate of the system. By transmitting data over MIMO channels, maximization of data rate or diversity has been ensured. So, space-time or space-frequency block coding is used with OFDM systems which further helps in getting better bit error rate performance over the frequency selective channels. Further, the data rate can be improved by employing MIMO with the above mentioned technique.

In this thesis, we have made an effort to study space-frequency block-coded OFDM under frequency selective fading environment. We have presented a scheme, which employs a low complexity zero-forcing (ZF) receiver in wireless fast fading channel where channel response is not same for the adjacent subcarriers. The bit error rate performance of low complexity receiver has been compared to the classical ZF receiver and the matched filter (MF) receiver, which shows that the low complexity receiver outperforms the MF receiver in fast fading mobile environment and performs well against classical ZF receiver. Moreover, application of the low complexity receiver reduces the computational complexity nearly to half when compared to ZF receiver, as it eliminates the use of pseudo-inversion method of channel matrix for the higher spatial diversity schemes.

**Keywords:** Space-Frequency Block Coding (SFBC), Inter carrier interference (ICI), Inter block interference (IBI), frequency selectivity, Zero-Forcing (ZF), Matched Filter (MF).

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| BER | Bit Error Rate |
| BPSK | Binary Phase Shift Keying |
| CFR | Channel Frequency Response |
| CP | Cyclic Prefix |
| DFT | Discrete Fourier Transform |
| FDE | Frequency Domain Equalization |
| FFT | Fast Fourier Transform |
| FIR | Finite Impulse Response |
| GI | Guard Interval |
| IBI | Inter Block Interference |
| ICI | Inter Carrier Interference |
| IDFT | Inverse Discrete Fourier Transform |
| IEEE | Institute of Electrical and Electronics Engineers |
| IFFT | inverse fast Fourier transform |
| ISI | Inter Symbol Interference |
| LAN | Local Area Network |
| LOS | Line Of Sight |
| LMS | Least Mean Square |
| LS | Least Square |
| MF | Matched Filter |
| MIMO | Multi Input Multi Output |
| ML | Maximum Likelihood |
| MMSE | Minimum Mean Squared Error |
| MRRC | Maximum Ratio Receive Combining |
| OC | Orthogonal Code |
| OFDM | Orthogonal Frequency Division Multiplexing |
| PAPR | Peak to Average Power Ratio |
| PDF | Probability Density Function |
| PSK | Phase Shift Keying |

| | |
|---|---|
| QAM | Quadrature Amplitude Modulation |
| QO-STFBC | Quasi-Orthogonal Space- Time Block Coding |
| QPSK | Quadrature Phase Shift Keying |
| RF | Radio Frequency |
| RMS | Root Mean Square |
| Rx | Reciever |
| SC | Single Carrier |
| SER | Symbol Error Rate |
| SF | Space Frequency |
| SFBC | Space Frequency Block Code |
| SNR | Signal to Noise Ratio |
| ST | Space Time |
| STBC | Space Time Block Code |
| STC | Space Time Code |
| STTC | Space Time Trellis Codes |
| Tx | Transmitter |
| Wi-MAX | Worldwide Interoperability for Microwave Access |
| ZF | Zero-Forcing |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction to Wireless Communication System

Wireless communication system needs a very high quality of service for different multimedia services with high data rate. This goal has to be achieved with limited spectrum available which is a very challenging in this wireless environment. There are numerous challenges that are faced in the design of wireless communication system such as network conditions or user locations or traffic patterns that change continuously; security and privacy issues of network in existing systems; wireless channels are difficult to model than wired channels and also they have limited capacity. So, it is quite difficult to predict the wireless channel as it is random in nature. Therefore, signal experience random fluctuations and reaches at the destination along many different paths, thus called multipath. These paths may happen due to scattering, reflection, and diffraction as described below:

- **Scattering:** When a wave propagates through a medium which is a rough surface such as foliage, street signs, this phenomenon happens.
- **Reflection:** When a wave strikes an object while travelling and that object has greater dimension compared to the wavelength of the transmitting wave, this is called reflection.
- **Diffraction:** This occurs when path between transmitter and receiver is blocked by surface having sharp edges.

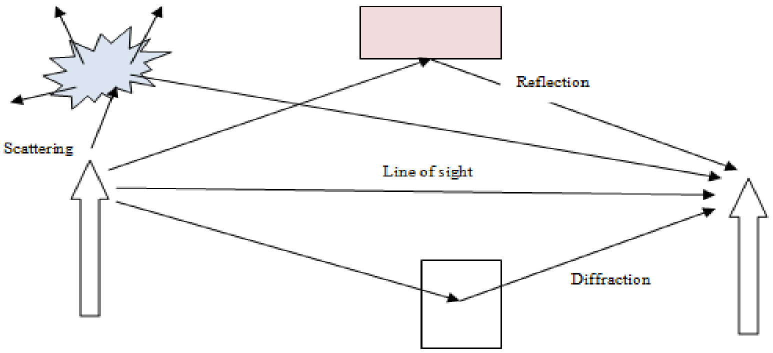

Fig. 1.1. Different paths in a wireless communication system

Multipath fading and interferences affects the wireless channel very easily. If in case the mobile unit is moving in the multipath field, the motion adds the Doppler's shift which broadens the spectrum of the signal. Antenna diversity is a technique which is widely used to lessen the effects of multipath fading [1]. Moreover, multiple input multiple output (MIMO) with orthogonal frequency division multiplexing (OFDM) has been adopted for present and future wireless broadband communication standards such as LTE or WiMax [2-3].

There are many methods which are proposed with time to overcome various limitations caused by the wireless environment such as by using different modulation techniques, equalization techniques and spread spectrum techniques. However for broadband and mobile applications, wireless communication channels are generally time varying or frequency selective.

The traditional methods such as allowing deep fades by increasing the power were used to mitigate the effects of fading, but this led to higher power consumption than the actual required power consumption because the transmission has to be done for multiple times. So, transmit diversity could be a better option which not only mitigate inter-carrier interference (ICI) but also provides robustness to deep fades. This increases the complexity of the receiver [4].

Channel diversity now days have become more successful scheme to overcome the effects of the signal fading. In this case, several independent copies of the signal of the interest are transmitted over independently fading channels which have to be received by the receiver. Thus the probability that the entire signal components will fade simultaneously reduces considerably. To obtain the several replicas of the signal, several different techniques have been adopted and proposed with time:

**Time Diversity:** In time diversity, transmission of information is done repeatedly at time spacing that exceed the coherence time of the channel, where the coherence time is defined as the minimum time separation between independent channel fades.

**Frequency Diversity:** In Frequency diversity, transmission of information is done on more than one carrier frequency with a condition which says that the frequencies are separated by more than the coherent bandwidth of the channel such as same fades will not be experienced.

The coherent bandwidth of the channel is defined as the minimum frequency separation between independent fades. It is also inversely proportional to the delay spread of the channel.

**Polarization Diversity:** It contains a combination of a pair of antennas with orthogonal polarizations (i.e. horizontal/vertical, ± slant 45°, Left-hand/Right-hand CP etc.). When the reflected signals travel through a certain medium they can undergo polarization changes which depend on that medium through which they are travelling.

**Space Diversity:** This is one of the oldest techniques and its popularity is increasing as it is considered as the most reliable method of transmission therefore, for many wireless communication systems, space diversity is a strong contender. By using spatially separated multiple antennas we can reduce the probability of losing the signal by combining the antenna signals in order to increase the received average power [5].

Since multiple antenna wireless systems can be used to achieve antenna diversity, but at the expense of bandwidth efficiency. So, by not compromising the bandwidth efficiency, various channel codes are designed for multiple antenna wireless systems. Space time codes ate bandwidth efficient codes that are suitable for multiple antenna systems without compromising the diversity over wireless channels. These codes are combination of convention channel coding design criteria, modulation techniques, and multiple antenna diversity techniques in their design. Moreover, this technique gives better error rate performance when compared to uncoded system [6].

So, spatial diversity can be obtained by using multiple antennas and space time codes [6-8]. G. J. Foschini from Bell Labs [9] in 1996 introduced space time codes for the very first time. These were used in transmitting diversity for the multiple antenna fading channels. The two main types of STC are:

1. Space time Trellis Codes (STTC).
2. Space time Block Codes (STBC).

The STTC were originally introduced by Tarokh et al., in [21] but these designs were not optimum design and hand crafted. As mentioned above, maximum diversity can be achieved by space-time block codes (STBC) which were proposed by Alamouti [10] and Tarokh et al., [11]. This paper provides a simple transmit diversity scheme in a flat fading Multiple input Multiple output channel. The present MIMO techniques are very useful in flat fading frequency channels. Orthogonal Frequency Division Multiplexing converts a wide band frequency to multiple narrow bands which almost have flat frequency [17]. So, we can use MIMO with OFDM to transmit data on wide band frequencies achieving high efficiency and low bit error rate, Space time code can be shown as [10].

$$\begin{array}{cc} & \text{time} \longrightarrow \\ \begin{bmatrix} S(i) \\ S(i+1) \end{bmatrix} = \begin{bmatrix} S(i) & -S^{*}(i+1) \\ S(i+1) & S^{*}(i) \end{bmatrix} & \downarrow \\ & \text{space} \end{array}$$

OFDM reduces the effect of frequency selective channel. This is done by dividing the data stream that is to be transmitted into multiple parallel channels and the channel is thus divided into a number of parallel narrowband sub channels such that each sub channel has lower data rate. Thus OFDM converts the frequency selective fading to approximate flat fading [12-13].

Orthogonal frequency division multiplexing is quite popular because of its simplicity of implementation in the digital domain since it can be implemented by using DFT. Moreover, OFDM is bandwidth efficient because parallel subcarriers are orthogonal to each other and thus no interference occurs. However system performance in mobile environment has been affected by two impairments; firstly, the Inter-block Interference (IBI) which is caused by temporal channel dispersion and secondly, Inter-carrier Interference (ICI) which occurs due to temporal channel variation. By using the cyclic prefix (CP), the IBI can be eliminated completely but to remove ICI, channel estimation has to be performed accurately which further increases the complexity of the receiver [14-15].

The other most important strategy used by wireless systems of communication is known as MIMO which enhances the quality as well as data rate of the system. By using a number of antennas at the transmitter and receiver side, this scheme is implemented. However, by using proper coding techniques, it can also be implemented more efficiently. The advantage of spatial and temporal diversity is taken to combat the random fading which is introduced by multi-path propagation of the signal. Thus, it ensures proper use of bandwidth. There is also an elementary gain when transmission of data is done over a matrix rather than vector channel. By transmitting data over MIMO channels, maximization of data rate or diversity has been ensured. Space-Time coding codes the information across antennas (space) and time. Space Time Block Codes were used to significantly improve the data rate and also reduce the error rate thus improving the performance of the communication channel. Space Frequency Block Codes were shown to be more effective in frequency selective fading channels as the code is simultaneously transmitted on neighboring sub carriers. The OFDM when used with frequency selective fading converts the channel into several flat fading channels [17]. The advantages of combining Space Frequency Block Coding with OFDM were explained [18].

## 1.2 Problem Statement

- Firstly, the Space-frequency block coded OFDM wireless communication system is investigated for fast fading wireless channel.
- Secondly, classical ZF receiver is used for detection, which is compared with the Matched filter.
- Subsequently, a low complexity ZF receiver is employed which reduces the complexity of the present receiver as the pseudo inversion is not required in this case.
- Further, we presented low complexity ZF receiver for different transmit and received diversity systems like two transmit and one receive antenna, three transmit and one receive antenna, three transmit and two receive antenna, and three transmit and three receive antenna.

## 1.3 Organization of Report

- In Chapter 1, the basic research work related to the fading such as the reasons that why and how fading occurs and how means to tackle when fading occurs in a mobile environment is described. Moreover, brief description of orthogonal frequency division multiplexing, MIMO-OFDM along with space-time codes or space-frequency codes is given.
- In Chapter 2, literature survey related to space frequency block codes is done and discussed briefly.

- In Chapter 3, fading is discussed in detail which includes the various fading parameters and different fading models and moreover, diversity techniques to combat fading are discussed briefly along with the various combining methods.
- Chapter 4 briefly discusses the Orthogonal frequency division multiplexing including the use of cyclic prefix with OFDM systems and its pros and cons.
- Chapter 5 describes how transmission of symbols is done in Space-time block coded OFDM and space-frequency block coded OFDM with relevant analysis of Space frequency block coded OFDM system.
- Chapter 6 includes the simulation results for Space-frequency block coded OFDM system for Zero-Forcing receiver and Low complexity Zero-Forcing receiver
- Chapter 7 includes the conclusion along with the future scope.

# CHAPTER 2

# LITERATURE REVIEW

In Ref. [18], transmitter diversity scheme is presented for the frequency selective fading channels in case of wireless communication. This scheme makes use of orthogonal frequency division multiplexing (OFDM) for converting the frequency selective fading channel to flat fading sub channels. Thus, space frequency codes are implemented. Simulation results shows that new presented space-frequency OFDM (SF-OFDM) transmitter diversity technique gives the same performance space-time OFDM (ST-OFDM) transmitter diversity system in case of slow fading environment but SF-OFDM performs better in the fast fading environments. Secondly, advantages of SF-OFDM over the ST-OFDM transmitter diversity technique are also described.

In Ref. [19], a low complexity Zero-Forcing receiver is designed for two or three transmit antenna and one receive antenna. Generally, a assumption has been observed in case of STBC-OFDM that the channel coefficients will be same for the adjacent subcarriers but in this paper, SFBC-OFDM has been analyzed in the broadband wireless channel but with the condition that the channel coefficients are not same for adjacent subcarriers and on using Matched Filter (MF) receiver, it is found that it causes error floor in bit error rate performance. So, the above receiver has been designed to overcome the shortcomings of the MF.

In Ref. [20], SFBC-OFDM is compared with STBC-OFDM and the Space frequency codes give better performance than the space time codes in the fast fading channel environment. However, if complex orthogonal code having code rate one is considered then it does not exist if more than two antennas are there. A quasi-orthogonal (QO) SFBC-OFDM system is presented to amplify the throughput. This case is observed for four transmit antennas. Moreover, the advantages of the SFBC in mobile communication environment is described and it is shown that the improved throughput achieves code rate one. The inference is finally drawn that the SFBC performs better than the STBC in case of fast fading channel.

In Ref. [21], as two g-based transmit diversity block coded OFDM system was designed by King in 2000 for space-time block coded OFDM and space frequency block coded OFDM. Least square (LS) detector was employed by him under an assumption that the channel is constant over the duration of a space-time or frequency codeword but the situation becomes different when the frequency selectivity of the channel is taken into consideration. Moreover, three different novel detectors for Space-time block coding has been recommended by the Antony to lessen the rapid variation occurred due to the channel. So, in this paper the above detectors are employed in case of g-based Time Diversity Block Coded OFDM (TDBC-OFDM) systems which improves the earlier g-based TDBC-OFDM. Moreover, the results are evaluated using computer simulation which shows significant performance improvement over highly dispersive channels. So, different detectors such as Zero-Forcing detector forces the special ISI to zero, DF detector lessens the spatial ISI by performing whitened-matched filtering and ML detector decreases the spatial ISI and noise simultaneously. Since ML detector gives best performance with respect to the ZF detector and DF detector but the complexity is more in case of ML detector than the other detectors. However, by using these detectors, TDBC-OFDM system shows better results when applied to the wideband wireless applications in highly dispersive channels.

In Ref. [22], division of the orthogonal frequency division multiplexing systems which uses Alamouti transmit diversity technique is done via two methods, i.e. Alamouti Space time block-coded OFDM and Space-frequency block-coded OFDM. These systems will undergo from time and frequency selectivity of channels in case of time-varying multipath Rayleigh fading channels. Nowadays, numerous detection techniques have been explored and implemented to enhance the bit error rate (BER) performance of above mentioned systems. In this paper, the analysis has been done on various detectors to achieve maximum achievable capacities. This study is based on the probability density function (pdf) of the effective instantaneous signal-to-noise ratio (SNR) which is obtained by each detector. Further, the analytical expressions for these systems with various detectors are deduced for achievable average capacities.

In Ref. [23], closed-form terminology for the bit error rate (BER) performance of space-frequency block coded OFDM systems are exploited and then investigated for frequency selective fading channels. In this study, numerous errors are obtained during the estimation of the channel which is further addressed with respect to BER performance. This is done by considering both M-ary phase shift keying and M-ary quadrature amplitude modulation. Moreover, analytical results are presented for different forms of SFBC-OFDM and then the comparisons made accordingly. Therefore, it has been concluded that the simulated results are quite similar to the results given by the closed form methods and the depreciation in the results due to errors in channel estimation are shown.

In Ref. [24], it has been described that in broadband wireless access, it is more beneficial to use the Space-frequency block coded OFDM signals in case, where the wireless channel is greatly time and frequency selective thus making the system vulnerable to inter-symbol interference (ISI) and inter-carrier interference (ICI) as well. Therefore, due to the change in channel characteristics as mentioned subjects in the termination of assumption of 'quasi-static' fading which further leads to the occurrence of ISI. In contrast, time-selectivity of channel causes ICI which becomes reason of losing the orthogonality among the subcarriers. Thus, a system is presented which calculates the performance of an interference cancelling receiver employed for SFBC-OFDM and it also helps in combating the effects of ISI and ICI when the channel is highly time/frequency selective.

In Ref. [25], an investigation has been done effects of cancelling ISI on the STFBC-OFDM system by taking time and frequency selectivity of channel into consideration. Data symbols are encoded into many intervals, number of subcarriers and sent over many transmitting antennas in case of STFBC–OFDM. Therefore, the impact of inter-carrier interference on STFBC–OFDM is less than on the STBC-OFDM and SFBC-OFDM system under time or frequency selective fading. Though, STFBC–OFDM experiences ICI beneath time and frequency selective fading, yet the influence are lower. According to the simulation results, proposed system using ICI cancellation performs 3.5 dB better at the fourth iteration when compared to the system which is not using ICI cancellation.

In Ref. [26], study has been done on the Carrier interferometry orthogonal frequency division multiplexing (CI-OFDM) system which is quite popular and hence studied in case of the multi-carrier communication system. The information symbols are mushroomed across the N-subcarriers by making use of orthogonal CI spreading codes when CI-OFDM system is taken. With this system, reduction in PAPR and diversity gain is observed such that there is no loss in the communication throughput. In contrast, the MIMO antenna array systems and STF systems are studied in parallel. Performance evaluation for *2*x*1* and *2*x*2* system has been done for both MIMO OFDM and MIMO CIOFDM systems in this paper. SFBC is implemented into MIMO OFDM system and MIMO CIOFDM system as well. Simple IFFT operation is applied to carrier allocation for realizing CI-OFDM system. So, significant reduction is observed in PAPR in case of MIMO SFBC CI-OFDM when compared with MIMO SFBC-OFDM system. Moreover, the out-of band re-growth of signal spectrum in MIMO SFBC CI-OFDM system is significantly lower than MIMO SFBC OFDM. Additionally, the considerable improvement in BER is obtained when MIMO SFBC CI-OFDM system uses Narrow band interference (NBI) channel. Therefore, it could be anticipated that for MIMO SFBC CI-OFDM system, this system may be quite useful when we are dealing with High power amplifier (HPA) and NBI channel.

In Ref. [27], a novel SFBC-OFDM scheme has been designed which integrates SFBC-OFDM with FIR-ICI mitigation equalization. Since it is quite difficult to estimate the channel accurately using scattered pilots as channels parameters have fast varying nature, but exact estimate of channel is required for ICI mitigation for MIMO-OFDM. A novel space-frequency block coding OFDM scheme for doubly selective channels has been presented which reduces the complexity of channel estimation. Here, banded and sparse structure of the channel has been proposed which is employed in both the frequency and time domains. Further, as described earlier a finite-impulse-response minimum-mean-square error (FIR-MMSE) ICI cancellation algorithm for mobile SFBC-OFDM has been designed; itseffectiveness is demonstrated for digital video broadcasting-handheld (DVB-H) systems.

In Ref. [28], a new scheme i.e. adaptive switching between the Space-time block coded OFDM and Space-frequency block coded OFDM, is proposed. This scheme provides with the block structure which is quite similar to the implementation of STBC-OFDM in time domain. So, in this paper, a united block structure is adopted for SFBC-OFDM and STBC-OFDM. Moreover, this scheme shows significant reduction in complexity over the present schemes.

In Ref. [29], a novel SF combination method is suggested for the existing OFDM system (Alamouti coded) in perspective of cooperative communication. Due to the existence of multiple carrier frequency offsets (MCFOs), there arise issues in regular space frequency decoding. Here, in this method a new method has been proposed which helps in mitigating the inter-carrier interference (ICI) by taking advantage of already present MCFO mitigating algorithms. This method makes use of two sets of signal which are separately synchronized. Other methods such as Iterative interference cancellation and maximum-ratio-combining-like methods are also employed to thereafter enhance the performance of the system with least computational complexity. Hence, better performance is resulted in terms of bit error rate (BER) and additionally, secures the system from multiple CFOs, when compared to existing techniques.

In Ref. [30], a new method which is more efficient and having lower complexity is suggested for MIMO detection in case of double space-frequency block coded OFDM system. This MIMO detector includes three step-filtering approach which is used to decorrelate the space-frequency coded signal and this does not include direct matrix inversion method. In this technique, weighing factors are assigned to each subcarrier in frequency domain to compensate deterioration in performance of the SFBC system which is caused due to low correlation between subsequent subcarriers. So, it is observed that the scheme employed in D-SFBC system performs well as compared to the other MIMO detection methods such as V-BLAST based iterative interference cancellation methods. This evaluation is done for frequency selective fading channel. Therefore, loss in orthogonality among the subcarriers can be compensated by applying the weighing factors to subcarriers as mentioned above. So, ML detector is employed in D-SFBC system having four transmit antennas.

In Ref. [31], a computationally efficient pilot aided channel estimation technique for space-frequency block coding OFDM systems under frequency selective channels has been discussed. This method is based on the use of eight pilots described in Wimax standard to estimate the channel parameters at constant interval. In this paper, he pilots are also coded in the same way as coding is done in SFBC so as to reduce the estimation computations, but can be modulated using different modulation schemes to decreases the estimation error. This technique gives tradeoff between accurate channel estimation and efficient bandwidth usage as more pilots are used which would certainly allow the algorithm to perform a more accurate estimation but at the cost of less transmitted data. In this paper, the evaluation of performance of system is done for high mobility applications as well with pilots modulated by the application of different modulation schemes. Simulation results are shown for different number of antenna at the receiver, various values of Doppler shifts and different modulations for pilot and data subcarriers.

In Ref. [32], space-time -frequency transmit diversity with orthogonal designs is considered in a broadband OFDM system. In this paper, an outer error control code, a bit interleaver and orthogonal spatial transmit diversity are concatenated on the basis of capacity to give an attractive MIMO which is more simple and less prone to channel imperfections. Therefore, a more simple comber technique at the receiver has been introduced which works both in time-varying as well frequency selective channels.

## CHAPTER 3

# FADING

### 3.1 Introduction to Fading

In wireless communication, a phenomenon called fading is defined as the variation of signal amplitude over time and frequency. Fading may occur due to multipath propagation which is cited to as multi-path fading. A rapid change in strength of a signal is observed over a small distance, random frequency modulation and time echoes due to propagation delay are caused by multipath waves [33]. In radio wave propagation, factors such as speed of the mobile subscriber (i.e. relative motion between the base station and mobile station can cause Doppler shift), speed of the object nearby and the transmitted signal’s bandwidth influences fading. In addition to it, an additive noise plays an important role in degradation of a signal, similarly fading also acts as another source of signal degradation which is non-additive in nature.

Classification of the fading phenomena can be done as large scale fading and small scale fading. When mobile moves through a greater distance, large scale fading occurs. It is caused by the path loss of the signal which is a function of two factors i.e. distance and shadowing by big objects such as buildings and vegetation such as trees. Shadowing is a slow fading process. It is characterized by variation of median path loss between the transmitter and the receiver in fixed locations. It thus implies that the average path loss and shadowing comes under the large scale fading and similarly if small scale fading is taken into consideration, it occurs due to the rapid variations in the level of the signal due to the constructive and destructive interference of multiple signal paths when the mobile station moves smaller distances [34].

### 3.2 Characteristics of Multipath Fading

There are some parameters which are used to analyze the various multipath channels. These parameters can be deduced from the power delay profile. The power delay profile shows the plot of the arrival time (in seconds) of the various path waves and the received power (dBm). These parameters can be classified as:

- Time dispersion parameters comprise the root mean square delay spread, excess delay spread and the mean delay spread.
- Frequency dispersion parameters comprise the coherence bandwidth and the coherence time.

The various parameters can be described briefly as:

- Delay spread

  In this case, the reflected parts of the signal arrive at the receiver but later than the original signal. RMS delay spread ($\sigma_\tau$) is used to characterize this delay spread in terms of second order moment of the channel power profile. Typical values for outdoor are in microseconds and for indoor radio channel and for indoor radio channel, it is in nanoseconds [35].

- Coherence Bandwidth

  If range of frequencies is taken such that the channel over them is considered as flat, this is defined as the Coherence bandwidth ($B_c$). Moreover, flat channel can be defined as the channel which however passes all the spectral components with nearly equal gain and linear phase. Flatness is defined as the correlation between the two frequency components. Coherence bandwidth is used to measure the frequency response of the channel and is inversely proportional to the RMS delay spread. The signal gets distorted severely when the signal bandwidth ($B_s$) is greater than channel bandwidth ($B_c$) [35].

- Doppler shift

  Doppler shift occurs when the transmitter is moving with respect to the receiver. The frequency of the signal is shifted due to relative motion, thus the frequency at the receiver is from the frequency at the transmitter. Otherwise it could be said that the frequency perceived at the receiver is different from the one that was originally emitted [35].

Doppler shift is given by:

$$f_d = (\frac{1}{2\pi})(\Delta\Phi / \Delta \mathrm{t}).\cos\theta$$

- Doppler spread

  A channel shows a time varying nature when there is a movement in either the source or the destination. Doppler spread ($B_d$) is defined as the measure of the maximum broadening of the spread spectrum due to Doppler shift.

- Coherence time

  Coherence time ($T_c$) is that time period where the two received signals have high amplitude correlation.

- Coherence distance

  Coherence distance is defined as the minimum distance between points in space for which the signals are uncorrelated. This distance is quite significant for multiple antenna systems [36].

Also fading channels can be classified based on the time dispersion parameters as:

- **Frequency non-selective fading or flat fading-** This occurs when the gain of the channel is constant and phase response is linear over a bandwidth which is larger than the bandwidth of the transmitted signal ($B_c$>$B_s$). The spectral components of the signal are preserved at the receiver but gain changes. Narrow band signals are categorized in this category since their bandwidth is smaller compared to the channel bandwidth. Variation in gain and in the frequency spectrum is a challenge brought by the flat fading channel. Distortion in the gain may cause deep fade thus require significant increase in the power of some frequencies. Deep nulls in the signals may be caused by destructive interferences which is a common problem in case of narrow band signals since any null in a frequency may cause loss of the signal. There are many ways to annul or lessen the distortion [37]. One of the popular methods used is diversity. There is less probability of experiencing fades at the same time as the channels are independent. Space diversity is one of most effective and efficient technique compared to time and space. In this case, multiple antennas are placed slightly apart in space to create independent paths to achieve uncorrelated channel. Coding is another technique which spreads the signal power among the bandwidth and decreases the power allocated in the null frequencies. As a result, loss occurs in the smaller portions of the signal power. Another technique is by using orthogonal frequency division multiplexing which converts a channel into a number of subcarriers which are orthogonal to each other.

- **Frequency selective fading-** This occurs when the gain of the channel is constant and phase response is linear over a bandwidth which is smaller than the bandwidth of the transmitted signal. A distorted signal is received at the receiver side and the channel introduces inter-symbol interference. This wideband channel model is approximated by number of delta functions which fade independently. There are several ways to annul ISI [37] such as equalization which inverts the effect of the channel. In case of OFDM, each subcarrier undergoes flat fading since its bandwidth is less than the coherence bandwidth.

Fading can also be classified based on frequency dispersion parameters as:

- **Slow fading:** In this case, the impulse response of the channel changes at a rate much slower than the transmitted baseband signal. The channel is considered as constant over one or other many reciprocal bandwidth intervals. In other words, if the signal duration is less than the coherence time, the channel is said to be a slow fading channel.

- **Fast fading:** In this case, the impulse response of the channel changes rapidly within the symbol duration. When the signal duration is greater than the coherence time, the channel is said to be a fast fading channel.

## 3.3 Fading Channel Model

Since the behavior of the multipath wireless channel is such that the amplitude and power of the received signal is random, so a brief introduction of statistical models is described below [35].

### 3.3.1. Rayleigh Fading Model

This is a commonly used method in wireless communication system. The Rayleigh fading channel model is widely used when there is no line of sight (NLOS) path between the transmitter and the receiver. This model assumes that the magnitude of the received signal fades in accordance with the Rayleigh distribution, i.e. the radical component of the sum of two uncorrelated Gaussian random variables. The probability density function (pdf) of a Rayleigh random variable is given by [38]:

$$P_{AB} = (\frac{r}{\sigma^2}) \exp^{(-\frac{r}{2\sigma^2})} \quad ; r \geq 0$$

Where $r$ is the amplitude of the equivalent baseband signal, $\sigma^2$ is the variance of zero mean random variable A and B, which are independently identical distributed Gaussian variables. The Rayleigh fading model is the worst fading case because it does not consider any LOS between the transmitters.

### 3.3.2. Ricean fading model

When the line of sight is considered, the direct path is the favorable component which has the probability to go into deeper fade when compared to the multipath components. Such signal is approximated by the Ricean distribution. As the dominating component goes into more fade the signal characteristics changes from Ricean to Rayleigh distribution. The Ricean distribution is given by:

$$P(\mathrm{r}) = (\frac{r}{\sigma^2}) \exp^{-\frac{(\mathrm{r}^2 + \mathrm{A}^2)}{2\sigma^2} . \mathrm{I}_{o} . (\frac{A}{\sigma^2})} \quad ; (A \geq 0 ; r \geq 0)$$

Where $A$ denotes the peak amplitude of the dominant signal, $\mathrm{I}_o(.)$ is defined as modified Bessel function of the first kind and having order as zero [35].

### 3.4 Diversity

The number of challenges related to signal in a wireless communication can cause severe attenuation, i.e. fading, which makes it difficult for the receiver to determine the transmitted signal accurately. So, one of the promising way to overcome such challenge is the use of diversity technique i.e. providing the receiver with the different replicas of the transmitted signal. If these replicas fade independently, so there are less chances that of all the copies of the transmitted signal will go in deep fade simultaneously. So the transmitted signal can be reliably decoded from the received signal.

This can be done by selecting a signal having highest signal to noise ratio (SNR) or by combing to multiple received signals. Diversity causes lower outages, which is a scenario where the effective SNR at the receiver goes through the deep fade and drops below the received threshold for reliably recovery of the transmitted signal, when compared with a network where it does not exist [39]. Different diversity techniques are:

- **Time diversity:** This occurs when the transmitted information is replicated in different time slots. The spacing between the time slots is such that it exceeds the coherent time of the channel. The main disadvantage of the time diversity is that it requires a long, slow fading channel and does not utilize the bandwidth efficiently. Error-correcting codes and inter-leavers can be used with the time diversity to annul the effects the above disadvantages [40].

- **Frequency diversity:** This takes place when the same information is transmitted or received simultaneously on two or more independently fading carrier frequencies. To achieve frequency diversity, the carrier frequencies should be separated by more than the coherent bandwidth of the channel. The main disadvantage of this scheme is that it is not bandwidth efficient followed by redundancy [40].

- **Antenna diversity:** This occurs when multiple antennas are used at either the receiver or the transmitter side of communication network. The multiple antennas need to be separated sufficiently (i.e. more than half of the wavelength) to achieve level of performance that cannot be achieved using single antenna [35]. Different forms of antenna diversity are:

1. **Spatial diversity:** This uses multiple antennas to eliminate the signal fading from the multipath environment. When number of antennas are placed at the receiving end of the communication system it is defined as receive diversity, while such situation if at transmitting end then called transmit diversity [41].

2. **Pattern diversity:** This uses two or more antennas with minimum overlapping patterns which provide higher overall pattern coverage [41].

3. **Polarization diversity:** It uses vertical and horizontal polarized signals to achieve diversity. As a result of the scattering, the arriving signal, which is not polarized, can be split into two orthogonal polarizations. If the signal goes through random reflections, its polarization state can be independent of the transmitted polarization. Polarization diversity can only provide a diversity of an order of two and not more [41].

### 3.5 Combining Methods

The multiple versions of the signals provided at the receiver by the various diversity techniques need to be properly combined to improve the performance of the system. There are three main combining methods [42] that can be used at the receiver.

1. **Maximum ratio combining (MRC)** - In this method, multiple versions of the same information bearing signal received over different diversity branches are combined so as to maximize the instantaneous SNR at the combiner output. It is a classical and powerful technique that mitigates the effects of severe fading at the receiver [43].

2. **Selection combining**- In this method, amongst the multiple versions of the different diversity branches, the signal with the highest SNR is selected for decoding [43].

3. **Hybrid combining** or generalized selection combining- This is a method in which a subset of available diversity branches is selected based on the branch SNR and combined per MRC rule [44].

# CHAPTER 4

# ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

## 4.1 Introduction to OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is one of the most popular modulation techniques that is used to halt the frequency-selectivity of the transmission channels, thus achieving higher data rate with no inter–symbol interference. OFDM is one of the important multicarrier techniques which are adopted by many wireless communication standards.

The solution to this problem can be the use of various adaptive equalization techniques at the receiver, so that the effects of ISI will be combated, but it less feasible to operate this equalization in the real time conditions at several Mbps with minimum and low cost hardware. Thus, OFDM could be the better option which eliminates the requirement of the complex equalization.

Moreover, Fast Fourier transform algorithm makes this technique more popular by time because of its simple implementation. The basic idea of OFDM systems include the transmission of the symbols over multiple orthogonal subcarriers, so that Inverse Fast Fourier transform could be performed with transmitted symbols at the transmitter, and FFT is performed with received symbols at the receiver.

The basic principles and details of OFDM transmission was presented in [45-47]. Another advantage of OFDM is to convert a frequency-selective wideband channel into several frequency-flat narrow band channels. Another advantage of OFDM is to convert a frequency-selective wideband channel into several frequency-flat narrow band channels. Thus the complexity of receiver for OFDM systems is much simpler than that of receivers in single-carrier systems. However, OFDM systems will be sensitive to channel variation, which induce inter-carrier interference by destroying the orthogonality between subcarriers.

## 4.2 Principle of OFDM

In contrast to a single carrier systems where modulation of data is done on a single carrier of rate $R_s$, multicarrier systems such as OFDM generally transmit data simultaneously on$N_s$subcarriers which are modulated at a rate ($R_s/ N_s$). There is no change in the total rate which is same for both the single carrier and the multicarrier system. Moreover, each subcarrier is little sensitive to the delay spread of the channel.

In common, two operations are performed on the OFDM symbols. First, an IFFT operation is performed to obtain symbols in the time domain from its image in the frequency domain. Then, a guard interval or cyclic prefix is added to the signal which has obtained. Cyclic prefix is generally a copy of last symbols of the transmitted data which has to be added at the beginning of the stream, followed by a condition that the length of the copied stream must be larger than the delay spread of the channel. Moreover, the OFDM systems are known as bandwidth efficient systems. So, in a multicarrier transmission, to have a system which is bandwidth efficient, the spacing between two subcarriers is important. If there is larger spacing between the subcarriers, the higher bandwidth is thus needed to transmit a signal with similar rate and hence the spectral efficiency is lower. To solve the inefficiency in bandwidth, OFDM has been introduced where the centre of one subcarrier is positioned such that it lands into the null of the neighboring subcarrier. The notion of orthogonality was first been introduced by Chang in [48].

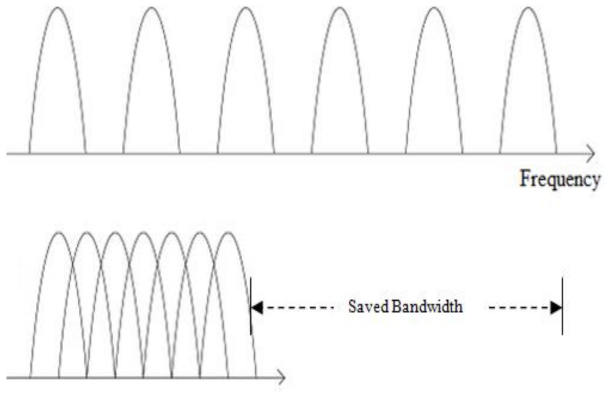

Fig. 4.1. Multicarrier modulation vs. OFDM

Now, OFDM is explained in detail. The input symbols $\{s_k(i)\}_{i=1}^{N}$ denotes the transmit symbols for the $k^{th}$ OFDM block. These symbols may come for instance from the complex constellation. $N$ denotes the number of OFDM subcarriers i.e. the number of constellation symbols to be transmitted in one OFDM block. Hence, after the serial to parallel conversion of the input symbol stream, $N$-pt IFFT operation is performed to obtain $\{x_k(i)\}_{i=1}^{N}$. Again, parallel to serial conversion is performed and a cyclic redundancy of length $\nu$ (the number of CP samples) is added as a prefix in such a way that $x_k(-i) = x_k(N-i)$ for $i=1,2,.....\nu$ as shown in the figure below:

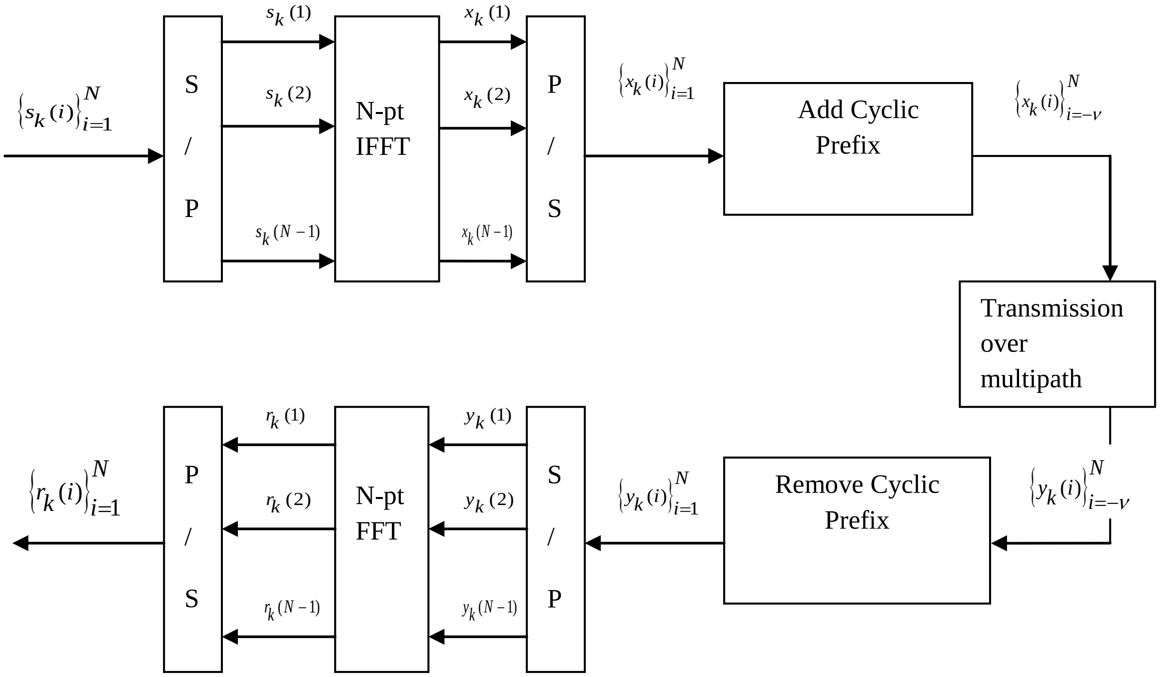

Fig. 4.2. Typical OFDM Transmitter – Receiver structure

The transmission of input signal on a multipath channel having the Channel Impulse Response (CIR) of the multipath channel of length L represented by a vector as:

$$\mathbf{h} = [h_0 \quad h_1 \quad \dots \quad h_{L-1}]^T \in C^N \tag{4.1}$$

The result after convolution of input and channel vector for $k^{th}$ channel output symbol

$$\mathbf{y_k} = [y_k(0) \quad y_k(1) \quad \dots \quad y_k(N-1)]^T \in C^N \tag{4.2}$$

Or the above equation can be expressed as

$$\begin{bmatrix} y_k(0) \\ y_k(1) \\ \vdots \\ \vdots \\ \vdots \\ y_k(N-1) \end{bmatrix} = \begin{bmatrix} h_{L-1} & \cdots & h_\nu & \cdots & h_0 & 0 & \cdots & \cdots & \cdots & 0 \\ 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & \cdots & \cdots & \cdots & h_{L-1} & \cdots & h_\nu & \cdots & h_0 \end{bmatrix} \begin{bmatrix} x_{k-1}(N-E) \\ \vdots \\ x_{k-1}(N-1) \\ x_k(\nu) \\ \vdots \\ x_k(0) \\ \vdots \\ x_k(N-1) \end{bmatrix} + \hat{\eta}_k \qquad (4.3)$$

where $E = L - \nu - 1$ is the channel length exceeding the duration of Cyclic Prefix $\nu$ .The Inter-Symbol Interference occurs only when the CIR length $L$ exceeds the duration of CP, i.e. $E > 0$.

For simplification, we consider the CP length to be greater than CIR length for the discussion of insufficient CP scenario. The incorporation of CP property $x_k(-i) = x_k(N-i)$ for $i=1,2,.....\nu$ ; in case of CIR being shorter than the duration of CP leads to the following eq.

$$\begin{bmatrix} y_k(0) \\ y_k(1) \\ \vdots \\ \vdots \\ \vdots \\ y_k(N-1) \end{bmatrix} = \begin{bmatrix} h_0 & 0 & \cdots & 0 & h_{L-1} & \cdots & h_1 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & h_{L-1} \\ h_{L-1} & \ddots & \ddots & \ddots & \ddots & \ddots & 0 \\ 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & h_{L-1} & \cdots & \cdots & h_0 \end{bmatrix} \begin{bmatrix} x_k(0) \\ x_k(1) \\ \vdots \\ \vdots \\ \vdots \\ x_k(N-1) \end{bmatrix} + \hat{\eta}_k \qquad (4.4)$$

The $N \times N$ matrix we get is a circulant matrix i.e. its rows are circularly shifted versions of each other. After that FFT operation is performed after the removal of CP. Interesting to note here is the fact that the effective $N \times N$ channel matrix now gets circulant i.e. its rows are circularly shifted versions of each other. However, this circulant nature of the effective channel matrix is void if the channel is time variant, because in that case the CIR coefficients appearing in a row (corresponding to a sample of the OFDM symbol) are potentially different than the CIR coefficients appearing in some other row.

The eq. (4.3) becomes eq. (4.4) in case of the sufficient Cyclic Prefix and time-invariant channel where channel matrix in eq. (4.4) becomes truly circular. Therefore, the system can be shown as:

$$x_k = \mathbf{F}\mathbf{H}_{\mathbf{CIRC}}\mathbf{F}^{\mathbf{H}} s_k + \eta_k \tag{4.5}$$

Where $\mathbf{F} \in C^{N \times N}$ is the normalized Fourier matrix (unitary in nature i.e. $\mathbf{F}\mathbf{F}^H = \mathbf{I}_N$). The vectors $s_k, r_k, \eta_k \in C^N$ are frequency domain versions of $x_k, y_k, \tilde{\eta}_k \in C^N$ and are achieved by linear transformations via the Fourier matrix, as clear from the diagram. Now because the Eigen Value Decomposition (EVD) of a circulant matrix such as $\mathbf{H}_{CIRC}$ can be given as:

$$\mathbf{H}_{CIRC} = \mathbf{F}^{\mathbf{H}}\mathbf{\Lambda}\mathbf{F} \tag{4.6}$$

**F** being the unitary Fourier matrix and the diagonal matrix $\mathbf{\Lambda} \in C^{N \times N}$ containing eigen values of the circulant matrix can be given in this case as

$$\mathbf{\Lambda} = \mathbf{H} \tag{4.7}$$

The matrix $\mathbf{H} \in C^{N \times N}$ is defined to be a diagonal matrix containing the Channel Frequency Response (CFR) coefficients along its main diagonal. By using eq. (4.6) and (4.7), the system model in eq. (4.5) reduces to

$$\mathbf{Y}_k = \mathbf{H}\mathbf{X}_k + \eta_k \tag{4.9}$$

We note that the fading multipath channel boils down to a number of interference-free parallel sub-channels whereby, each of the received sub-carrier can be given as the corresponding transmitted subcarrier scaled by a scalar complex fading coefficient (CFR at that sub-carrier) and corrupted by the additive noise. The detection scheme at the receiver can be as simple as just dividing the received subcarrier by the estimated Channel Frequency Response. Presented below in Fig. 4.3 is a comprehensive graphical representation of the OFDM system model, whereby we note the existence of interference-free parallel sub-channels in the frequency domain.

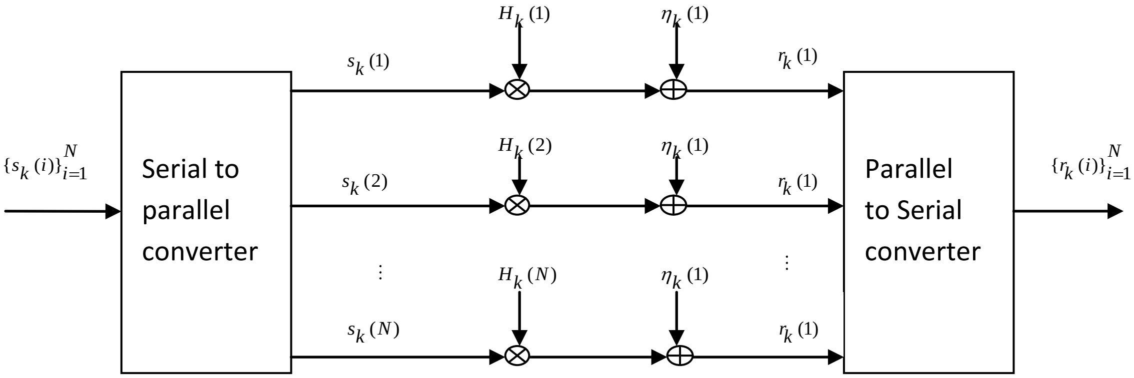

Fig. 4.3. Effective OFDM system model with a cyclic prefix exceeding CIR length and the channel being constat during the transmissiion of one ofdm block.

### 4.3 Advantages and Drawbacks of OFDM

- Single carrier transmission may not be useful in wideband wireless systems because it requires high complexity equalizer to deal with the ISI problem of the multipath frequency selective channels. Moreover, it has been seen that OFDM is easy to implement with the use of FFT. OFDM is also a bandwidth efficient modulation technique since the parallel subcarriers overlap but are orthogonal to each other without causing interference. Furthermore, the use of cyclic prefix helps the system to combat the effect of multipath fading and minimize the effects of ISI.
- On using MIMO with OFDM, each subcarrier can be modulated using different modulation techniques M-PSK or M-QAM according to the requirement of the system.
- OFDM appears to be a very powerful modulation technique for systems working under frequency selective channels.
- On the other hand, when issues such as frequency offset and phase noise is considered, OFDM is more sensitive.
- Furthermore, OFDM has a relatively large Peak to Average Power Ratio (PAPR) which tends to reduce the power efficiency of the RF amplifier [49-50].

# CHAPTER 5

# SPACE-TIME CODES AND SPACE-FREQUENCY CODES

## 5.1 Introduction to Space-Time Codes or Space-Frequency Codes

Here, we are considering a communication system which uses space-time or space-frequency block coding with two transmit antennas and at least one receive antenna. The block diagram of such a communication system is depicted in Fig. 5.1.

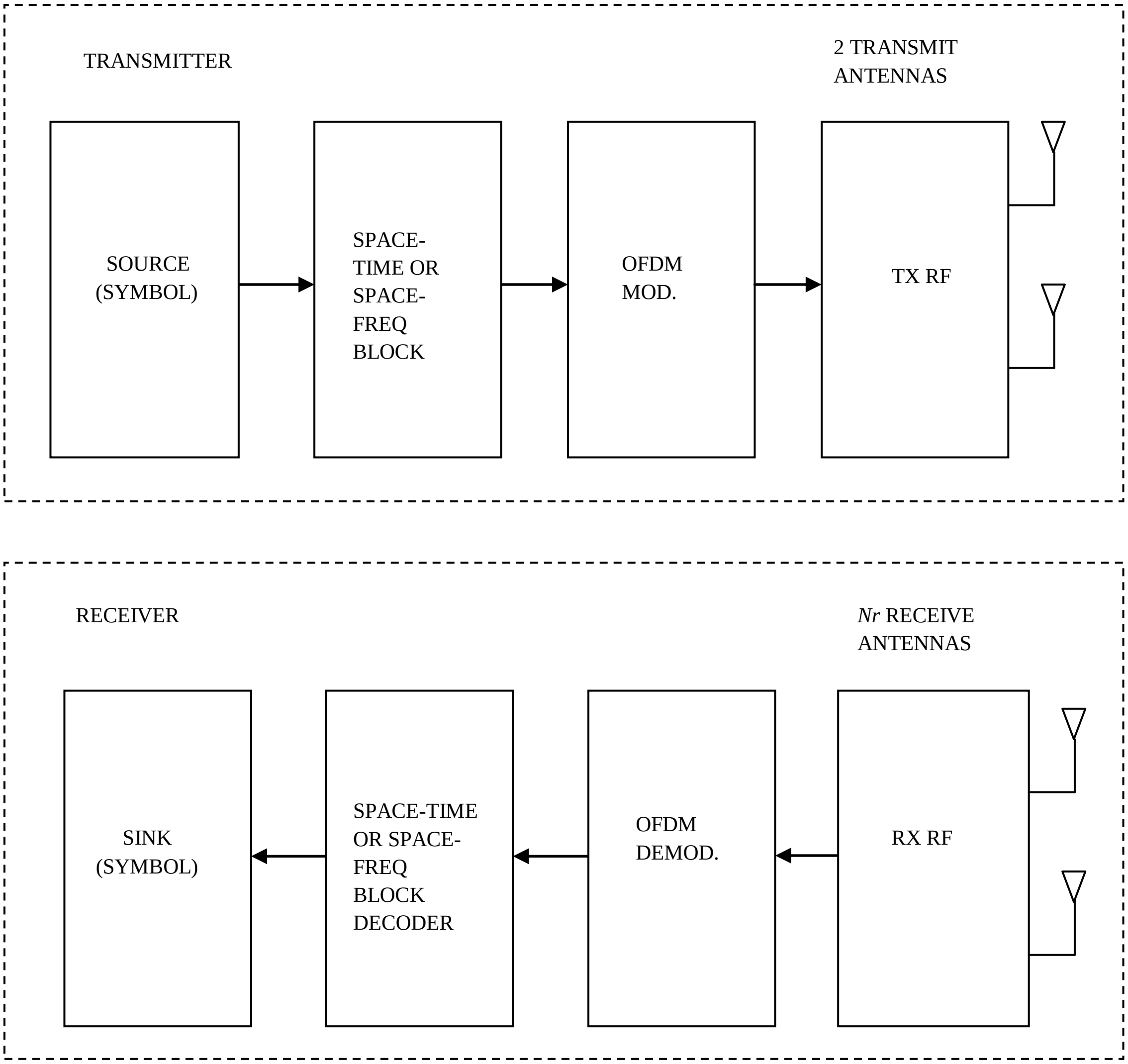

Fig. 5.1. System block diagram of Space-time block code or Space-frequency block code.

At the transmitter side the information blocks of symbols are passed to the space-time/ space-frequency block encoder, where each block contains two symbols. The space-time/space-frequency block encoder generates the code words of length $N_r = 2$, where $M$ corresponds to the number of transmit antennas. These code words are passed to the OFDM modulator and the radio frequency (RF) front-ends, which modulate the information onto the carrier frequency. On the receiver side up to $N_r$ receiver antennas can be used for reception. The RF signals are down-converted and digitized in the RF front-ends and then passed to the OFDM demodulator and the space-time/space-frequency block decoder. The space-time or space-frequency block decoder interprets the received signals and generates estimates for the transmitted information symbols, which are again provided in blocks of two symbols.

### 5.1.1 Space-Time Block Codes in OFDM

If the required guard interval is provided to the OFDM symbol, each of the subcarrier provides a flat fading MIMO channel. Therefore, we can apply the space time block code to each subcarrier. Moreover it is assumed that the adjacent sub-carriers have same channel coefficients or the channel remains constant when the space-time block coded matrix is transmitted i.e. during an OFDM symbol duration $T_{s,OFDM}$ whereas in case of single carrier system, the OFDM symbol duration is $N_s T_{s,sc}$ where $T_{s,sc}$ would be the symbol duration in a single carrier system. Therefore the performance of space-time block codes will degrade in fast fading environments especially if more than two transmit antennas are applied.

A Space-time block code can be defined by matrix **K** and this matrix consists of the linear combinations of the transmitted symbols and their conjugates. The matrix for two transmit antennas can be defined as [38].

$$\mathbf{K} = \begin{bmatrix} s_1 & s_2 \\ -s^*_2 & s^*_1 \end{bmatrix} \tag{5.1}$$

Here in the above case, the number of columns corresponds to number of transmit antennas $M_t$ and the number of rows to the number of time slots or number of symbols transmitted per antenna $N_t$. It can be seen from the matrix in (5.1) that at time $t$, $s_1$ and $s_2$are sent simultaneously from antenna 1 and 2 respectively and at time $(t+T)$, where $T$ is the symbol duration, $-s^*_2$ and $s^*_1$ is transmitted from antenna 1 and 2. From eq. (5.1), it can be observed that full diversity is accomplished as one symbol is transmitted from each antenna during each time slot. Moreover, the sequences sent are orthogonal in nature. Let us consider four symbols $s_1$, $s_2$, $s_3$, $s_4$. The above procedure using these four symbols can be shown by the help the Fig. 5.2 below:

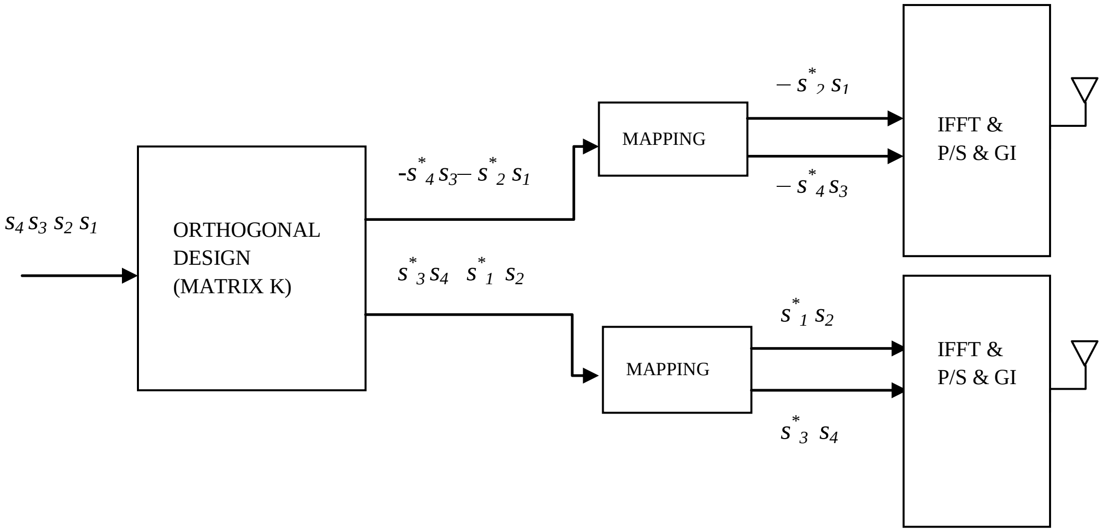

Fig. 5.2. Arrangement of symbols in Space- time Block Coded OFDM with $N_t$ =2.

### 5.1.2 Space-Frequency Block Codes in OFDM

The symbols in this case are sent over the neighboring subcarriers of the same OFDM symbol instead of sending the symbols on same subcarrier of subsequent OFDM symbol. This is done to avoid the problem occurred due to fast channel variations in time [51]. Moreover, transmission delay is also decreased. However, the channel should not be changing over neighboring subcarriers. This situation is true in channels having low frequency-selectivity. Perhaps it can be done using a large number of subcarriers so that the spacing between the subcarriers is made narrow.

In case of heavily frequency-selective channels, the performance of space-frequency block codes deteriorates. In such case the assumption of constant channel coefficients over a space frequency block code matrix is not fulfilled. This problem becomes more severe when the scheme has to be employed for more than two transmit antennas. As per space- time block codes, the arrangement of symbols in space-frequency block codes can be observed as shown in Fig. 5.3 below:

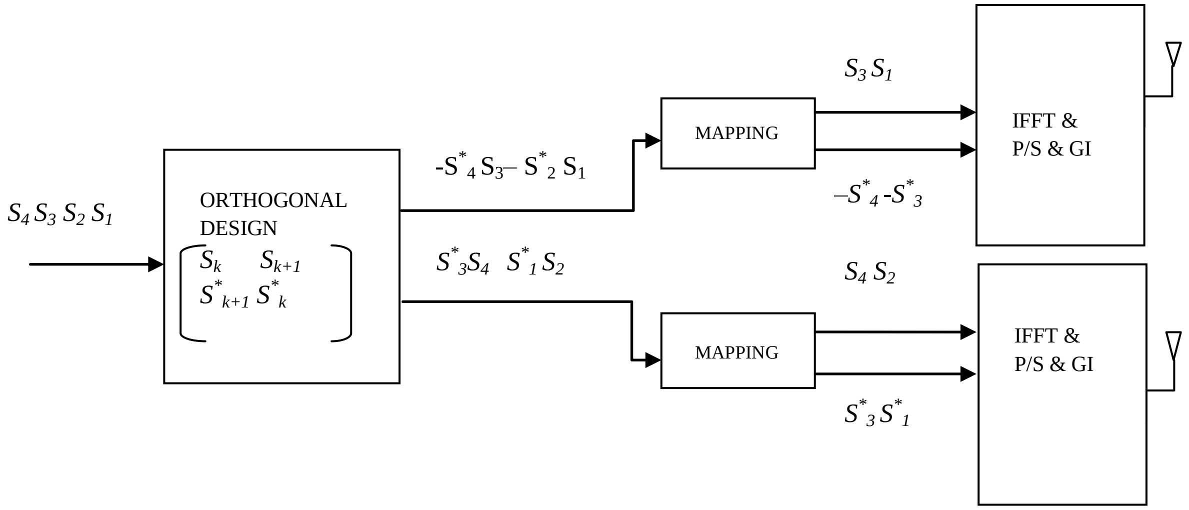

Fig. 5.3. Arrangement of symbols in Space-frequency Block Coded OFDM with $N_t$=2

Similarly the above case can be shown for three transmit antennas

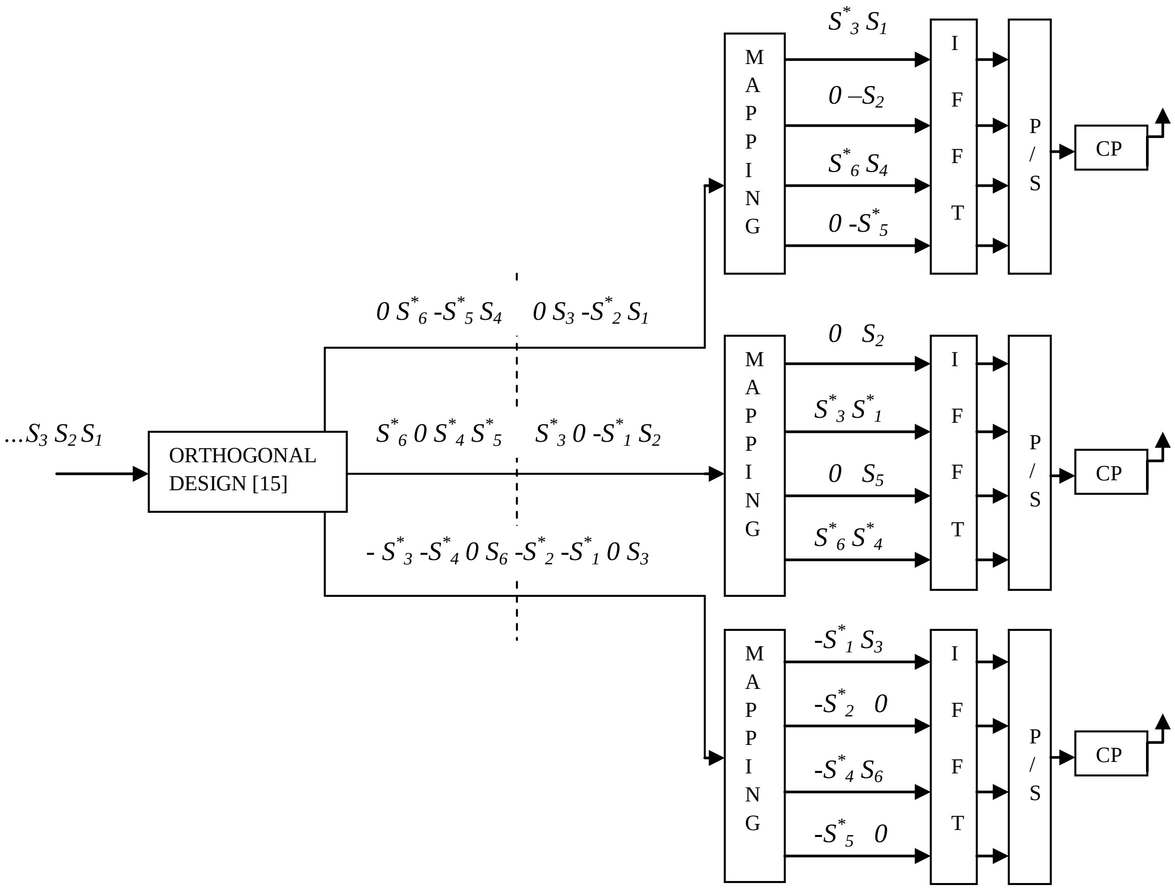

Fig. 5.4. Arrangement of symbols in Space-frequency Block Coded OFDM with $N_t$=3

## 5.2 Space-Frequency Block Coding

Here, we consider an Space- frequency Block coded OFDM system having $k$ subcarriers, $N_t$transmit and one receive antenna. For each OFDM symbol $n$, the serial data symbols are first converted to a data vector $\mathbf{S}_n$ with the duration $kT_s$ by the serial to parallel converter where $T_s$ is the symbol duration.

The data symbol vector is given by

$$\mathbf{S}_n = \left[ S_0,\ S_1,\ \ldots\ldots\ldots\ldots\ldots..,\ S_{N-2},\ S_{N-1} \right]^T \tag{5.2}$$

The above vector then space- frequency encoded and split into $N_t$ vectors $C_{n,i}$

$$\mathbf{C}_{n,1} = \left[ S_0, -S_1^{\,*} \ldots\ldots\ldots, S_k, -S^{*}{}_{K+1}, \ldots\ldots., S_{N-2}, -S^{*}{}_{N-1} \right]^T \tag{5.3}$$

$$\mathbf{C}_{n,2} = \left[\ S_1\ , S_0^{\,*}, \ldots\ldots\ldots, S_{k+1}, S^{*}{}_{K}, \ldots\ldots., S_{N-1}, S^{*}{}_{N-2} \right]^T \tag{5.4}$$

where $\mathbf{C}_{n,1}$, $\mathbf{C}_{n,2}$ are transmitted from the first and second antenna respectively.

The orthogonal SFBC matrix let suppose consists of $Q$ symbols over $T_f$ sub-carriers, therefore, giving the transmission rate of $R=Q/T_f$.

Then by using Inverse Fast Fourier Transform (IFFT), each $\mathbf{C}_{n,i}$ is modulated into an OFDM symbol and Cyclic Prefix (CP) is added.

The transmitted signal $\mathbf{s_n}$ is derived from the IDFT of encoded symbol $S_k$ as

$$s_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k \exp^{\left(\frac{j2\pi nk}{N}\right)} \qquad ;\ -N_{cp} \le n \le N-1 \tag{5.5}$$

Where $N$ is OFDM symbol length and $N_{cp}$ is the length of the cyclic prefix.

The received signal after the removal of cyclic prefix (CP) and after application of FFT, is obtained in the form of vector as written below:

$$\mathbf{R}_n = \sum_{i=1}^{N_t} \mathbf{C}_{n,i} \mathbf{\Lambda}_{n,i} + \mathbf{N}_n \tag{5.6}$$

Where $\mathbf{R}_n$ is the received vetor, $\mathbf{\Lambda}_{n,i}$ is a diagonal channel matrix (the matrix elements are FFT of $\Lambda_{n,i}$), $\mathbf{N}_n$ is the noise vector ( the matrix elements are FFT of additive white Gaussian noise with zero mean and $\sigma^2{}_n$ variance of real dimension).

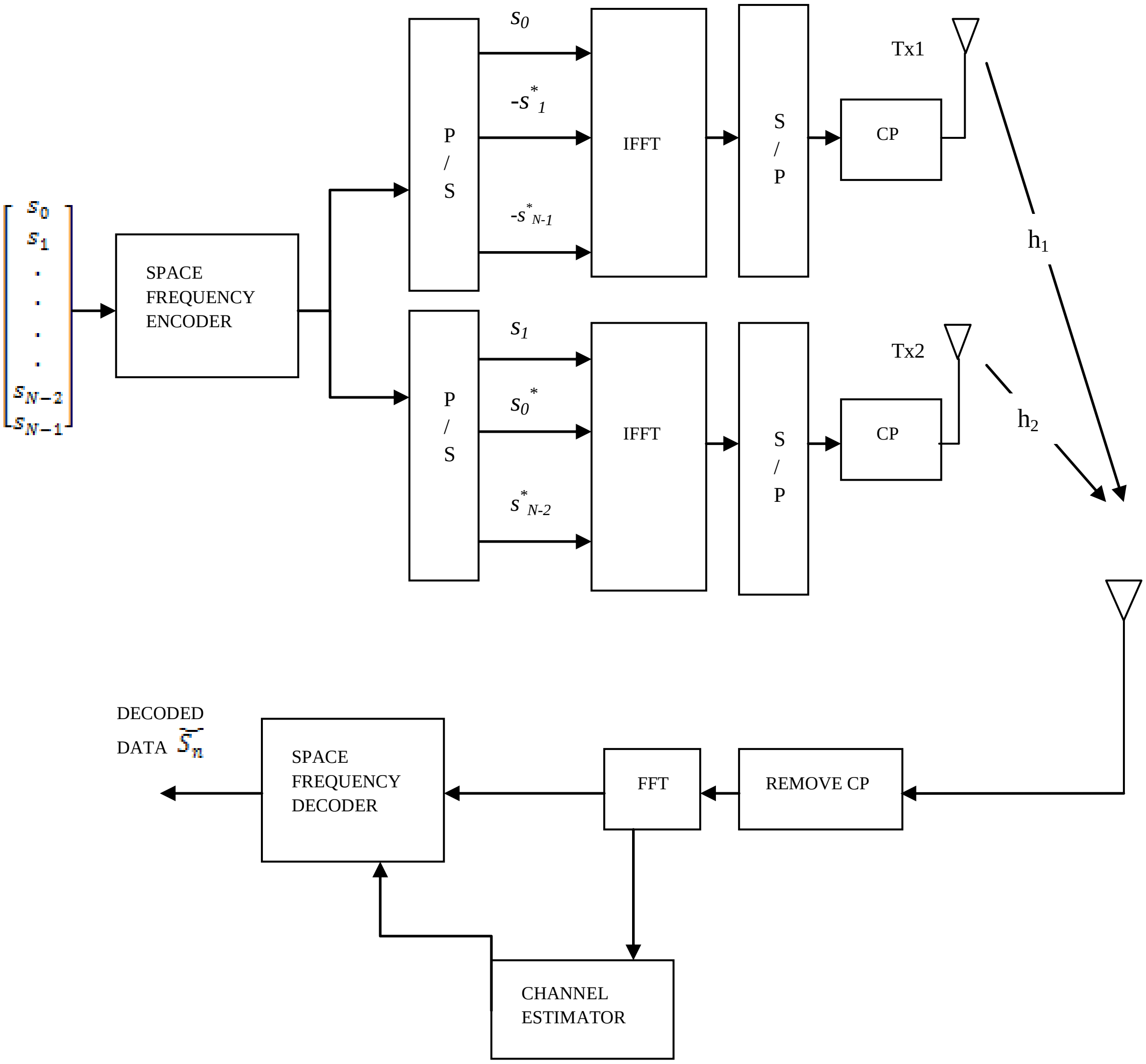

Fig. 5.5. Schematic diagram of SFBC-OFDM implementation.

### 5.2.1 Two Transmit Antenna and One Receive Antenna

First we are considering the case of two transmitting antennas and one receiving antenna. Here we apply the Alamouti STBC [25] scheme in two adjacent subcarriers using two symbols. Thus, the data vector S is encoded into two vectors $\mathbf{C}_1$ and $\mathbf{C}_2$ respectively which are transmitted from the first and second antenna simultaneously.

Taking $\mathbf{C}_1$ and $\mathbf{C}_2$ into eq. (5.6) and organizing the received vector into blocks, we obtain

$$\mathbf{R}_k^{'} = \mathbf{\Lambda}_k^{'}\mathbf{S}_k^{'} + \mathbf{N}_k^{'} \tag{5.7}$$

where the sub-carrier block index is $k^{'}=1,2,.....k/T_f$.

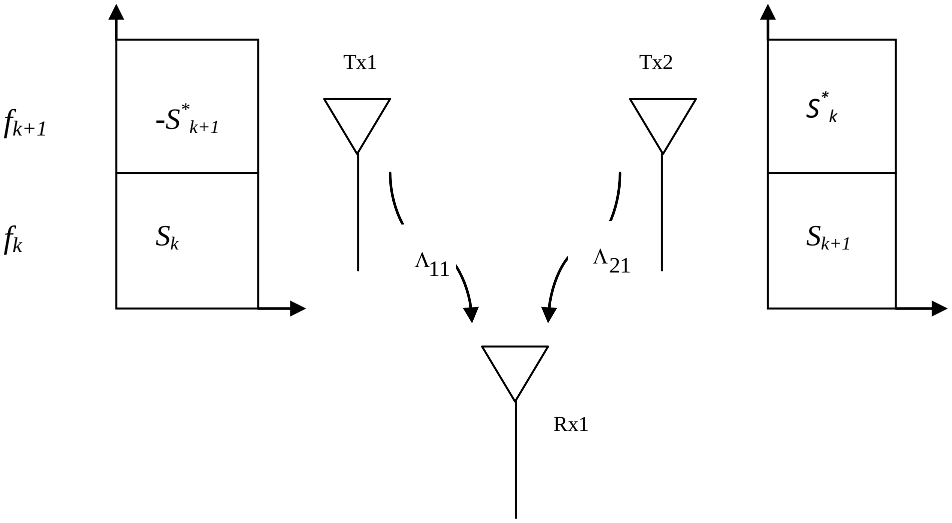

Fig. 5.6. Channel definition in $2\times1$ diversity scheme

So, the received signal in the frequency domain in case of 2x1 system is given by:

$$R_1 = \Lambda_{11}S_1 + \Lambda_{21}S_2 + N_1$$
$$R^*_2 = \Lambda^*_{21}S_1 - \Lambda^*_{11}S_2 + N^*_2$$

$$\begin{bmatrix} R_1 \\ R_2^* \end{bmatrix} = \begin{bmatrix} \Lambda_{11} & \Lambda_{21} \\ \Lambda_{21}^* & -\Lambda_{11}^* \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2^* \end{bmatrix}$$

The above matrix can be written into generalized form such as:

$$\begin{bmatrix} R_k \\ R_{k+1}^* \end{bmatrix} = \begin{bmatrix} \Lambda_{1,k} & \Lambda_{2,k} \\ \Lambda_{2,k+1}^* & -\Lambda_{1,k+1}^* \end{bmatrix} \begin{bmatrix} S_k \\ S_{k+1} \end{bmatrix} + \begin{bmatrix} N_k \\ N_{k+1}^* \end{bmatrix} \tag{5.8}$$

Where $\mathbf{R}_k^{'} = \begin{bmatrix} R_k \\ R_{k+1}^* \end{bmatrix}$ is the received vector; $\mathbf{S}_k^{'} = \begin{bmatrix} S_k \\ S_{k+1}^* \end{bmatrix}$ is the transmitted vector; $\mathbf{N}_k^{'} = \begin{bmatrix} N_k \\ N_{k+1}^* \end{bmatrix}$ is the noise vector; $\mathbf{\Lambda}_k^{'} = \begin{bmatrix} \Lambda_{1,k} & \Lambda_{2,k} \\ \Lambda_{2,k+1}^* & -\Lambda_{1,k+1}^* \end{bmatrix}$ is the channel transfer matrix.

For frequency flat case, it is assumed that the adjacent two carriers have same characteristics i.e. $\Lambda_{1,k} \approx \Lambda_{1,k+1}; \Lambda_{2,k} \approx \Lambda_{2,k+1}$ but here in this case it is considered that the coefficients of the channel are not equal for each antenna because this condition fails in case of highly frequency selective channels. The matched filter (MF) receiver can be applied to eq. (5.7) to obtain the reconstructed symbols as:

$$\hat{\mathbf{S}}_k^{'} = \mathbf{\Lambda}_k^{'mf} \mathbf{R}_k^{'} \tag{5.9}$$

Where $\mathbf{\Lambda}_k^{'mf} = \mathbf{\Lambda}_k^{'H}$ (transpose conjugate of $\mathbf{\Lambda}_k^{'}$)

Therefore, the symbols are then detected separately as:

$$\hat{\mathbf{S}}_k^{'} = \mathbf{\Lambda}_k^{'mf} \left[ \mathbf{\Lambda}_k^{'} \mathbf{S}_k^{'} + \mathbf{N}_k^{'} \right] \tag{5.10}$$

$$\hat{\mathbf{S}}_k^{'} = \begin{bmatrix} |\Lambda_{1,k}|^2 + |\Lambda_{2,k+1}|^2 & \Lambda_{1,k}^* \Lambda_{2,k} - \Lambda_{2,k+1} \Lambda_{1,k+1}^* \\ \Lambda_{2,k}^* \Lambda_{1,k} - \Lambda_{1,k+1} \Lambda_{2,k+1}^* & |\Lambda_{2,k}|^2 + |\Lambda_{1,k+1}|^2 \end{bmatrix} \begin{bmatrix} S_k \\ S_{k+1} \end{bmatrix} + \hat{\mathbf{N}}_k^{'} \tag{5.11}$$

Moreover, it can be represented as

$$\hat{\mathbf{S}}_k^{'} = \begin{bmatrix} D_k & \varepsilon_k \\ \varepsilon_k^* & D_{k+1} \end{bmatrix} \begin{bmatrix} S_k \\ S_{k+1} \end{bmatrix} + \hat{\mathbf{N}}_k^{'} \tag{5.12}$$

Where $D_k, D_{k+1}$ is the diversity gain and $\varepsilon_k, \varepsilon_k^*$ are the interference terms. The normalized MF receiver can be obtained using diversity gain as

$$\boldsymbol{\Lambda}_k^{'nmf} = diag\left(\frac{1}{D_k}, \frac{1}{D_{k+1}}\right)\boldsymbol{\Lambda}_k^{'mf} \tag{5.13}$$

Though maximum diversity can be achieved using MF receiver, but interference can be caused by the symbol carried by the adjacent subcarriers which further give rise to the noise. To avoid such condition that may occur due to noise, classical zero forcing (ZF) receiver can be employed such as:

$$\hat{\mathbf{S}}_k^{'} = \left[\boldsymbol{\Lambda}_k^{'H}\boldsymbol{\Lambda}_k^{'}\right]^{\mathbf{-1}}\boldsymbol{\Lambda}_k^{'H}\mathbf{R}_k^{'} \tag{5.14}$$

$$\left[\boldsymbol{\Lambda}_k^{'H}\boldsymbol{\Lambda}_k^{'}\right]^{\mathbf{-1}}\boldsymbol{\Lambda}_k^{'H} = \frac{1}{\Lambda_{1,k}\Lambda_{1,k+1}^* + \Lambda_{2,k}\Lambda_{2,k+1}^*}\begin{bmatrix}\Lambda_{1,k+1}^* & \Lambda_{2,k} \\ \Lambda_{2,k+1}^* & -\Lambda_{1,k}\end{bmatrix} \tag{5.15}$$

Estimated signal $S_k^{'}$ can be obtained as

$$\hat{\mathbf{S}}_k = \frac{1}{\Lambda_{1,k}\Lambda_{1,k+1}^* + \Lambda_{2,k}\Lambda_{2,k+1}^*}\left(\Lambda_{1,k+1}^* R_k + \Lambda_{2,k}R_{k+1}^*\right) \tag{5.16}$$

$$\hat{\mathbf{S}}_{k+1} = \frac{1}{\Lambda_{1,k}\Lambda_{1,k+1}^* + \Lambda_{2,k}\Lambda_{2,k+1}^*}\left(\Lambda_{2,k+1}^* R_k - \Lambda_{1,k}R_{k+1}^*\right) \tag{5.17}$$

### 5.2.2 Three Transmitter and one Receiver Antenna

If orthogonal STBC in [15] is applied through four adjacent subcarriers using the three symbols at each OFDM symbol. We map $3K/4$ information symbols onto $K$ subcarriers since the code rate is $3/4$ .The OFDM vector is encoded into three vectors **C***1***, C***2***, C***3* and then these vectors are transmitted from the three antennas simultaneously.

The received vector can be given as per in eq. (5.6):

$$\mathbf{R_k^{'}} = \begin{bmatrix}\Lambda_{1,k} & \Lambda_{2,k} & \Lambda_{3,k} \\ \Lambda_{2,k+1}^* & \Lambda_{1,k+1}^* & 0 \\ -\Lambda_{3,k+2}^* & 0 & \Lambda_{1,k+2}^* \\ 0 & -\Lambda_{3,k+3}^* & \Lambda_{2,k+3}^*\end{bmatrix}\begin{bmatrix}S_k \\ S_{k+1} \\ S_{k+2}\end{bmatrix} + \mathbf{N_k^{'}} \tag{5.18}$$

Similar to the above case, for frequency flat channel, the coefficients of the channel are equal for adjacent subcarriers but this condition terminates in frequency selective channels where channel coefficients are not same for adjacent subcarriers.

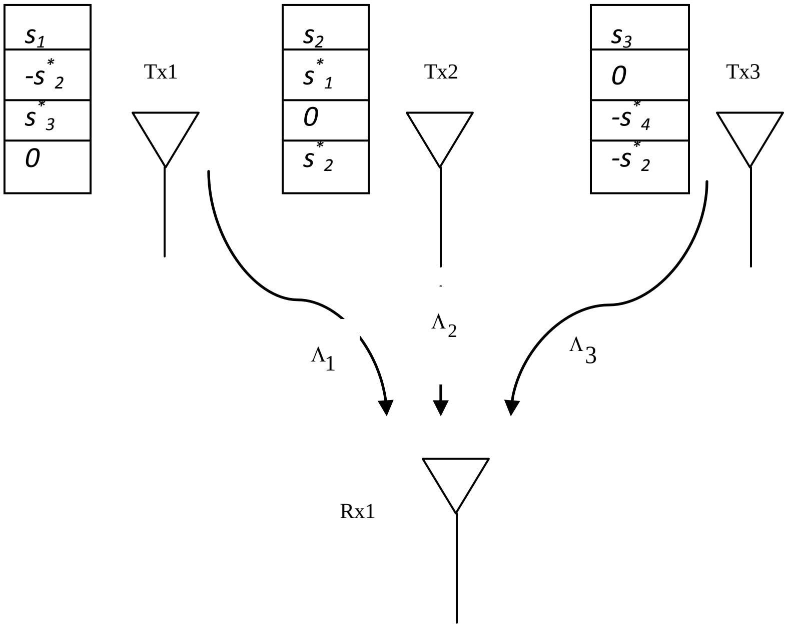

Fig. 5.7. Channel definition in $3\times1$ diversity scheme

Using eq. (5.9), the resulting matrix is given as:

$$\hat{\mathbf{S}}_k^{'} = \begin{bmatrix} |\Lambda_{1,k}|^2+|\Lambda_{2,k+1}|^2+|\Lambda_{3,k+2}|^2 & \Lambda_{1,k}^*\Lambda_{2,k}-\Lambda_{2,k}\Lambda_{1,k+1}^* & \Lambda_{1,k}^*\Lambda_{3,k}-\Lambda_{3,k+2}\Lambda_{1,k+2}^* \\ \Lambda_{2,k}^*\Lambda_{1,k}-\Lambda_{1,k+1}\Lambda_{2,k+1}^* & |\Lambda_{2,k}|^2+|\Lambda_{1,k+1}|^2+|\Lambda_{3,k+3}|^2 & \Lambda_{2,k}^*\Lambda_{3,k}-\Lambda_{3,k+3}\Lambda_{2,k+3}^* \\ \Lambda_{3,k}^*H_{1,k}-\Lambda_{1,k+2}\Lambda_{3,k+2}^* & \Lambda_{3,k}^*\Lambda_{2,k}-\Lambda_{2,k+3}\Lambda_{3,k+3}^* & |\Lambda_{3,k}|^2+|\Lambda_{1,k+2}|^2+|\Lambda_{2,k+3}|^2 \end{bmatrix} S_k^{'} + \hat{\mathbf{N}}_k^{'}$$

$$\hat{\mathbf{S}}_k^{'} = \begin{bmatrix} D_k & \varepsilon_k & \varepsilon_{k+1} \\ \varepsilon_k^* & D_{k+1} & \varepsilon_{k+2} \\ \varepsilon_{k+1}^* & \varepsilon_{k+2}^* & D_{k+2} \end{bmatrix} \mathbf{S}_k^{'} + \hat{\mathbf{N}}_k^{'} \tag{5.19}$$

where $D_k, D_{k+1}, D_{k+2}$ are the diversity gains, $\varepsilon_k, \varepsilon_{k+1}, \varepsilon_{k+2}$ are the interference terms.

The normalized MF receiver is then

$$\mathbf{\Lambda}_k^{'nmf} = diag\left(\frac{1}{D_k}, \frac{1}{D_{k+1}}, \frac{1}{D_{k+2}}\right)\mathbf{\Lambda}_k^{'mf} \tag{5.20}$$

Similar to the case of two transmit antennas and one receive antenna, the zero forcing receiver which implies a $4\times 3$ pseudo-inversion, can be employed.

### 5.2.3 Three Transmit Antennas and Two Receive Antennas

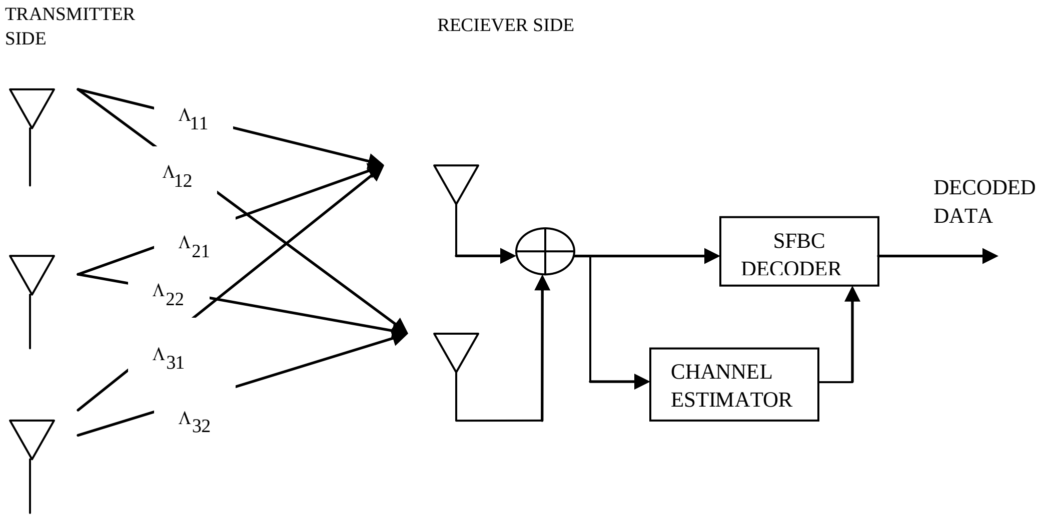

Fig. 5.8. Channel definition in $3\times 2$ diversity scheme

The received signal will be given as:

$$R_k' = \Lambda_{k1}' S_k' + \Lambda_{k2}' S_k' + N_k' \tag{5.21}$$

Now, the signals received at the Receiver 1 is

$$R_1 = \Lambda_{11} S_1 + \Lambda_{21} S_2 + \Lambda_{31} S_3$$

$$R_2^* = \Lambda_{21}^* S_1 - \Lambda_{11}^* S_2$$

$$R_3^* = -\Lambda_{31}^* S_1 + \Lambda_{11}^* S_3$$

$$R_4^* = -\Lambda_{31}^* S_2 + \Lambda_{21}^* S_3$$

The signal received at the Receiver 2 is

$$R_1 = \Lambda_{12} S_1 + \Lambda_{22} S_2 + \Lambda_{32} S_3$$

$$R_2^* = \Lambda_{22}^* S_1 - \Lambda_{12}^* S_2$$

$$R_3^* = -\Lambda_{32}^* S_1 + \Lambda_{12}^* S_3$$

$$R_4^* = -\Lambda_{32}^* S_2 + \Lambda_{22}^* S_3$$

Therefore, according to eq. (5.21) the final matrix is given as

$$\mathbf{R}' = \begin{bmatrix} \Lambda_{11} & \Lambda_{21} & \Lambda_{31} \\ \Lambda_{21}^* & -\Lambda_{11}^* & 0 \\ -\Lambda_{31}^* & 0 & \Lambda_{11}^* \\ 0 & -\Lambda_{31}^* & \Lambda_{21}^* \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} + \begin{bmatrix} \Lambda_{12} & \Lambda_{22} & \Lambda_{32} \\ \Lambda_{22}^* & -\Lambda_{12}^* & 0 \\ -\Lambda_{32}^* & 0 & \Lambda_{12}^* \\ 0 & -\Lambda_{32}^* & \Lambda_{22}^* \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} \qquad (5.22)$$

$$\mathbf{R}' = \begin{bmatrix} \Lambda_{11} + \Lambda_{12} & \Lambda_{21} + \Lambda_{22} & \Lambda_{31} + \Lambda_{32} \\ \Lambda_{21}^* + \Lambda_{22}^* & -\Lambda_{11}^* - \Lambda_{12}^* & 0 \\ -\Lambda_{31}^* - \Lambda_{32}^* & 0 & \Lambda_{11}^* + \Lambda_{12}^* \\ 0 & -\Lambda_{31}^* - \Lambda_{32}^* & \Lambda_{21}^* + \Lambda_{22}^* \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} \qquad (5.23)$$

On applying eq. (5.9), we will get a matrix having diversity gain and some interference terms as in case of $3 \times 1$ system.

Now, a low complexity ZF receiver has been employed to annul the interference terms which has been caused by MF receiver and obtained diversity gains as in the classical ZF receiver. In case of $N_t = 2$ , the matrix as given below is employed:

$$\mathbf{\Lambda}_k^{'mzf} = \begin{bmatrix} \Lambda_{1,k}^* & \dfrac{\Lambda_{2,k+1}}{A_k} \\ \Lambda_{2,k}^* & \dfrac{-\Lambda_{1,k+1}}{A_k^*} \end{bmatrix} \qquad (5.24)$$

Which satisfies $\mathbf{H}_k^{'mzf} \mathbf{H}_k^{'} = diag(\overline{D}_k, \overline{D}_{k+1})$ .

In the above eq. (5.24), $A_k = K_{i,m}^* K_{2,k+1}$ is the compensation term and $K_{i,m} = \dfrac{\Lambda_{1,m}}{\Lambda_{i,k}}$ for $m = k+1, ....., k+T_f - 1$ is the difference between the channel coefficients belonging to the same subcarrier block.

The final matrix according to eq. (5.9) will be

$$\hat{\mathbf{S}}_k^{'} = \begin{bmatrix} |\Lambda_{1,k}|^2 + \dfrac{|\Lambda_{2,k+1}|^2}{A_k} & 0 \\ 0 & |\Lambda_{2,k}|^2 + \dfrac{|\Lambda_{1,k+1}|^2}{A_k^*} \end{bmatrix} \begin{bmatrix} S_k \\ S_{k+1} \end{bmatrix} + \hat{\mathbf{N}}_k^{'}$$

The diversity gains will be then $\overline{D}_k = |\Lambda_{1,k}|^2 + \dfrac{|\Lambda_{2,k+1}|^2}{A_k}$ and $\overline{D}_{k+1} = |\Lambda_{2,k}|^2 + \dfrac{|\Lambda_{1,k+1}|^2}{A_k^*}$ and the interference terms caused in the previous case are annulled. The normalized matrix is given as $\mathbf{\Lambda}_k^{'szf} = diag\left(\dfrac{1}{\overline{D}_k}, \dfrac{1}{\overline{D}_{k+1}}\right)\mathbf{\Lambda}_k^{'mzf}$, where $\mathbf{\Lambda}_k^{'szf}$ is exactly the inverse of $\mathbf{\Lambda}_k^{'}$ which is obtained on applying $2 \times 2$ matrix inversion.

Similar results can be obtained by extending the above scheme for $N_t = 3$ such as:

$$\mathbf{\Lambda}_k^{'mzf} = \begin{bmatrix} \Lambda_{1,k}^* & \dfrac{\Lambda_{2,k+1}}{A_k} & \dfrac{-\Lambda_{3,k+1}}{B_k} & 0 \\ \Lambda_{2,k}^* & \dfrac{-\Lambda_{1,k+1}}{A_k^*} & 0 & \dfrac{-\Lambda_{3,k+1}}{C_k} \\ \Lambda_{3,k}^* & 0 & \dfrac{\Lambda_{1,k+1}}{B_k^*} & \dfrac{\Lambda_{2,k+1}}{C_k^*} \end{bmatrix} \tag{5.25}$$

where $A_k = K_{1,k+1}^* K_{2,k+1}; B_k = K_{1,k+2}^* K_{3,k+2}; C_k = K_{2,k+3}^* K_{3,k+3}$ are the compensation terms.

$$\hat{\mathbf{S}}_k^{'} = \begin{bmatrix} |\Lambda_{1,k}|^2 + \dfrac{|\Lambda_{2,k+1}|^2}{A_k} + \dfrac{|\Lambda_{3,k+2}|^2}{B_k} & 0 & 0 \\ 0 & |\Lambda_{2,k}|^2 + \dfrac{|\Lambda_{1,k+1}|^2}{A_k^*} + \dfrac{|\Lambda_{3,k+3}|^2}{C_k} & 0 \\ 0 & 0 & |\Lambda_{3,k}|^2 + \dfrac{|\Lambda_{1,k+2}|^2}{B_k^*} + \dfrac{|\Lambda_{2,k+3}|^2}{C_k^*} \end{bmatrix} \mathbf{S}_k^{'} + \hat{\mathbf{N}}_k^{'}$$

The diversity gain will be

$$\overline{D}_k = |\Lambda_{1,k}|^2 + \frac{|\Lambda_{2,k+1}|^2}{A_k} + \frac{|\Lambda_{3,k+2}|^2}{B_k}\,;\ \overline{D}_{k+1} = |\Lambda_{2,k}|^2 + \frac{|\Lambda_{1,k+1}|^2}{A_k^*} + \frac{|\Lambda_{3,k+3}|^2}{C_k}\,;$$

$\overline{D}_{k+2} = |\Lambda_{3,k}|^2 + \frac{|\Lambda_{1,k+2}|^2}{B_k^*} + \frac{|\Lambda_{2,k+3}|^2}{C_k^*}\,,$ thus making the other terms which was the interference caused by the adjacent subcarriers becomes zero.

Moreover,

$$\mathbf{\Lambda}_k^{'smf} = diag\left(\frac{1}{D_k}, \frac{1}{D_{k+1}}, \frac{1}{D_{k+2}}\right)\mathbf{\Lambda}_k^{'mzf}$$

Thus, the low complexity receivers given above eliminate the interference terms caused due to neighboring subcarriers while providing diversity gains. This method gives the ZF solution since it satisfies the equality eq. i.e. $\mathbf{\Lambda}_k^{'smf}\mathbf{\Lambda}_k^{'} = \mathbf{I}$. This method is quite useful because it avoids the inversion of the channel transfer matrix.

# CHAPTER 6

## SIMULATION RESULTS

The simulation results presented are verified using MATLAB Version 7.10.0.499 through computer simulation. The Bit error rate performace has been evaluated for $(2\times1), (3\times1), (3\times2), (3\times3)$ systems in Rayleih fading enviornment with additive white gaussian noise using QPSK modulation. Wireless channels from each transmit to receive antenna are modeled as independent Rayleigh fading using Jakes model. The above mentioned system has been evaluated for normalized Doppler frequency $f_d t_s = 0.5$ and $f_d t_s = 0.01$ where $f_d$ is doppler's shift and $t_s$ is sampling rate. The evaluation is done for frequency selective case, in which the channel cofficients are not considered constant over adjacent subcarriers.

**6.1** Comparison of Bit Error Rate performance of Space-frequency block coded (SFBC) OFDM system for various modulation techniques is shown. QPSK SFBC shows 2dB reduction in performance when compared to BPSK SFBC and in contrast, QAM SFBC shows 2dB reduction in performance when compared to QPSK SFBC.

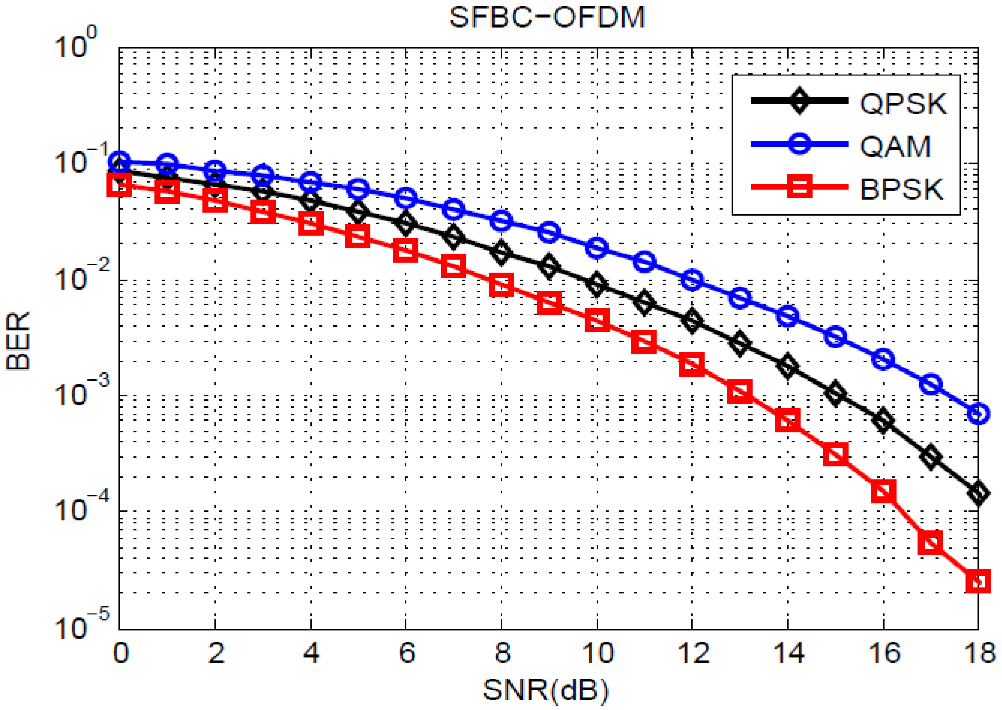

Fig.6.1. QPSK SFBC-OFDM vs QAM SFBC-OFDM vs BPSK SFBC-OFDM , *N*=64

**6.2** Here, the resutls are investigated for frequency flat case, where channel will be same for adjacent subcarrier and this is done by comparing three transmit and one receive antenna, and three transmit and two receive antenna, and three transmit and three receive antenna. Atleast, 3dB difference in SNR is obtained at $10^{-2}$ BER in $3\times1$ and $3\times2$ system and 1 dB difference is observed for $3\times2$ and $3\times3$ system with significant diversity gain.

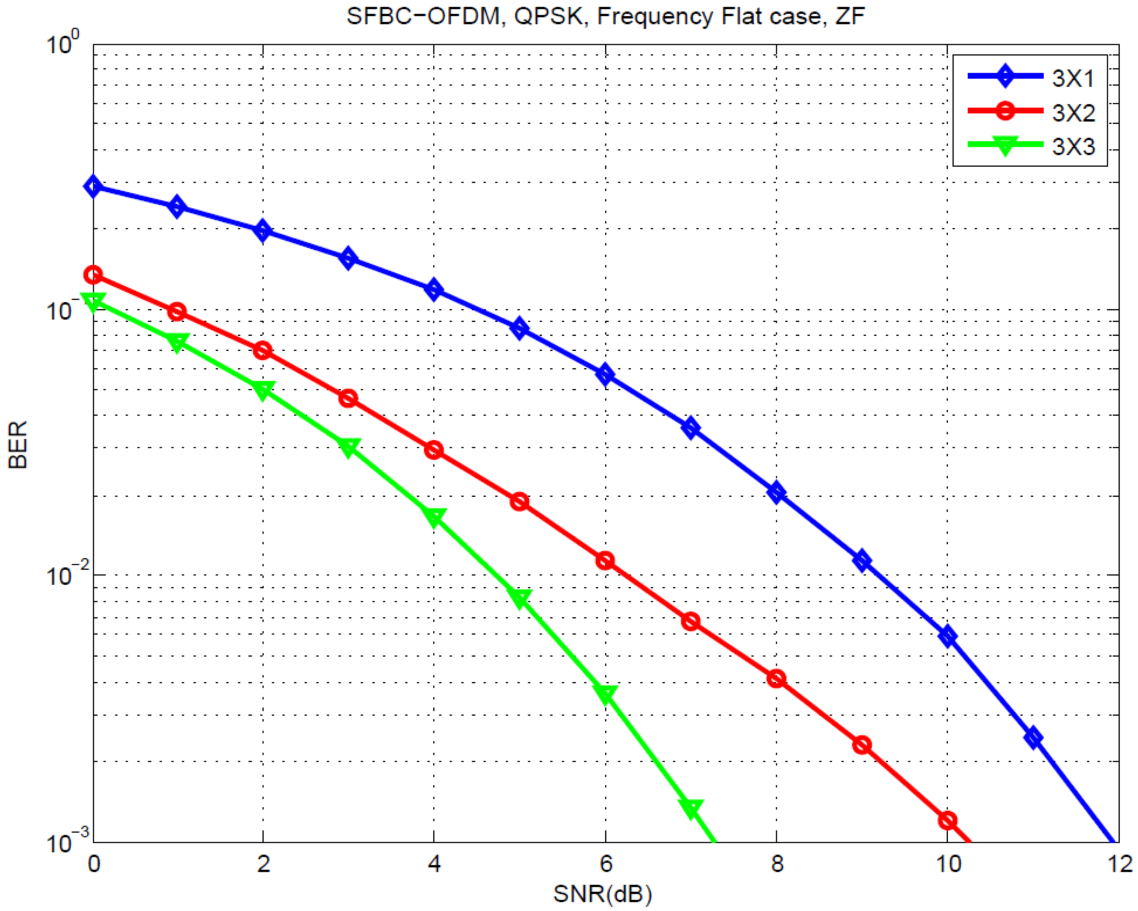

Fig. 6.2. Bit Error Rate performance of $(3\times1)$ vs $(3\times2)$ vs $(3\times3)$ SFBC-OFDM System, *N*=64.

**6.3** Low complexity scheme has been employed on conventional ZF receiver for two transmit antennas and one receive antenna. The result for normalize Doppler frequency has been shown in Fig. 6.3 and it has been observed that the result obtained for any change in Doppler frequency will be same. Therefore, it could be inferred that $(2\times1)$ system is independent of Doppler shift.

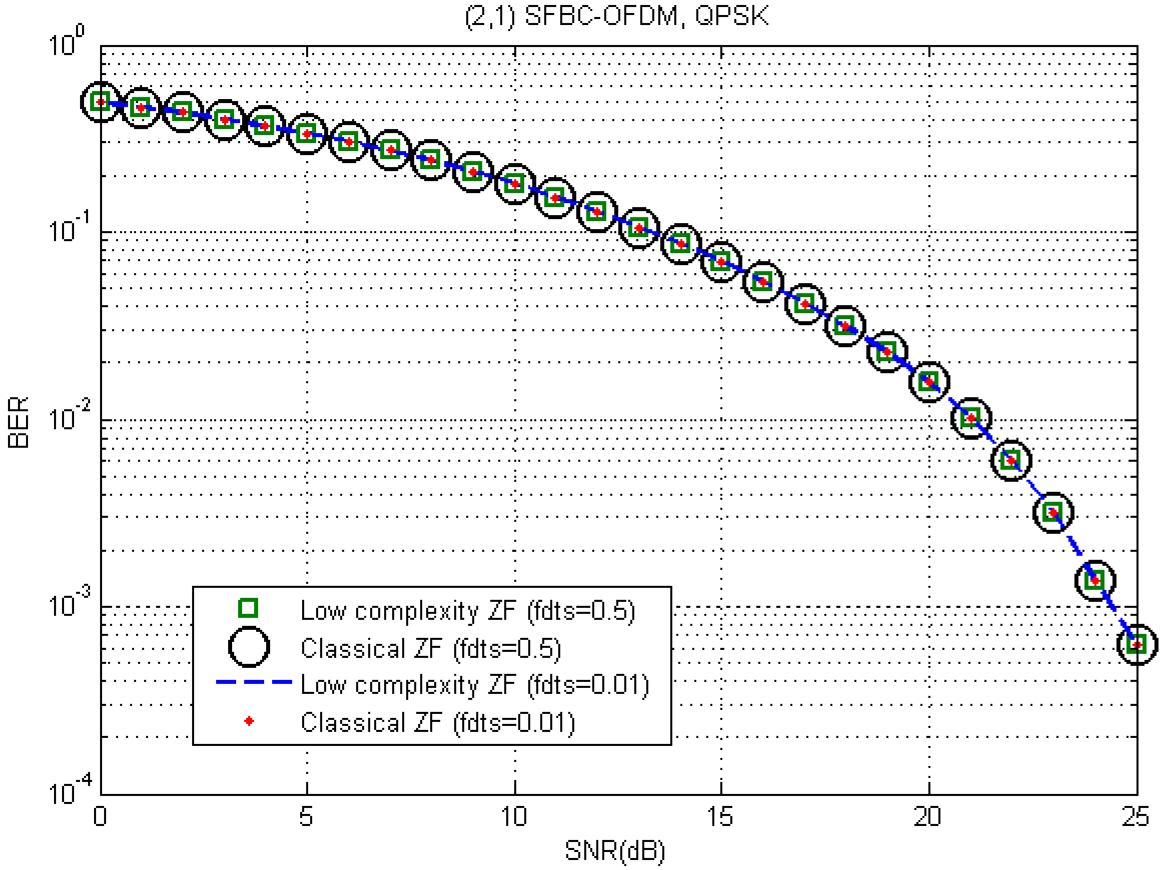

Fig. 6.3. BER performance of $(2\times1)$ SFBC-OFDM system

**6.4** Comparison of results have been done between Low complexity ZF receiver, classical ZF receiver and MF receiver for normalized Doppler frequency $f_d t_s = 0.5$ and $f_d t_s = 0.01$ for $(3\times1)$ system in fast fading environment. In Fig. 6.4.1, comparision has been shown for Normalized doppler's frequency, which shows that the performance of Low complexity ZF is better than the MF receiver but classical ZF outperforms the Low complexity ZF receiver, but application of Low complexity receiver avoids the use of psuedo invesion of channel matrix. Approximately 2dB difference at $10^{-1}$ is observed in performance of the Low complexity ZF and classical ZF receiver.

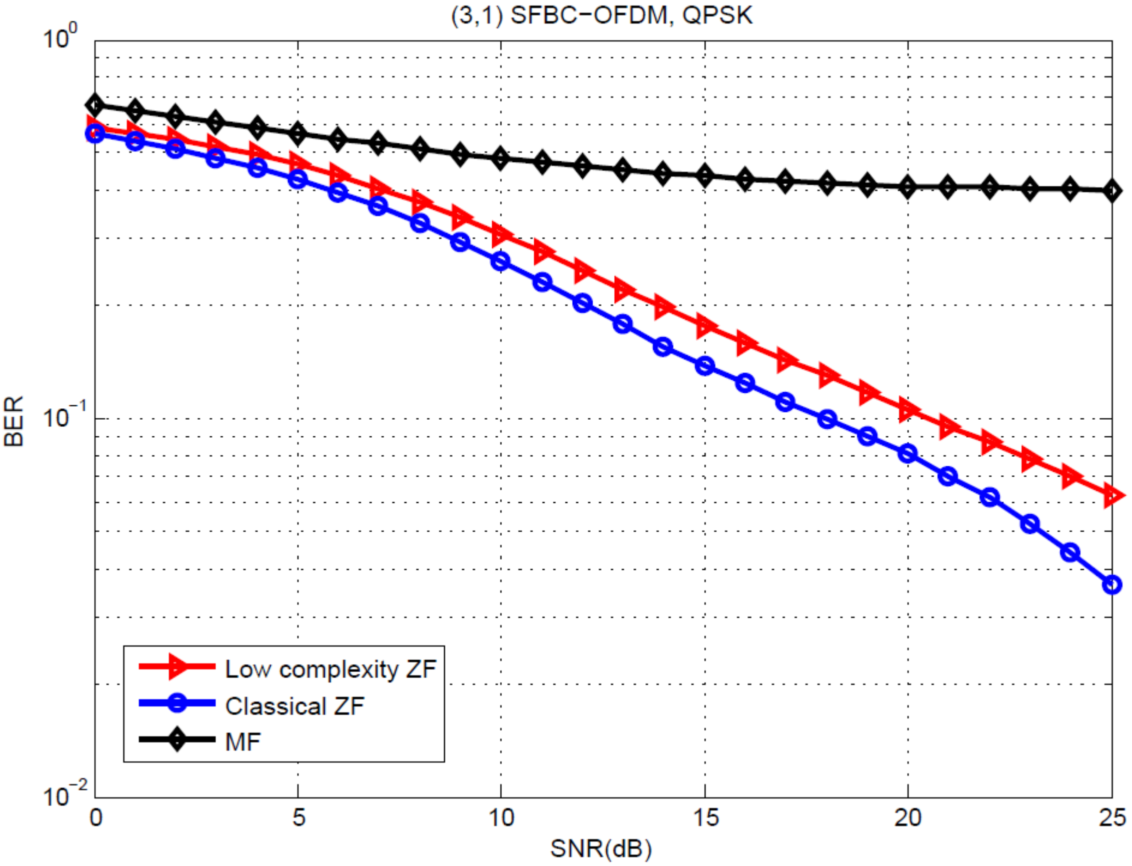

Fig. 6.4.1. BER performance of $(3\times1)$ SFBC-OFDM system for $f_d t_s = 0.5$.

In Fig. 6.4.2, the Bit error rate performance has been presented of Low complexity ZF and classical ZF and MF receiver for $f_d t_s = 0.01$, which shows that the performance of the Low complexity ZF and classical ZF receiver becomes identical.

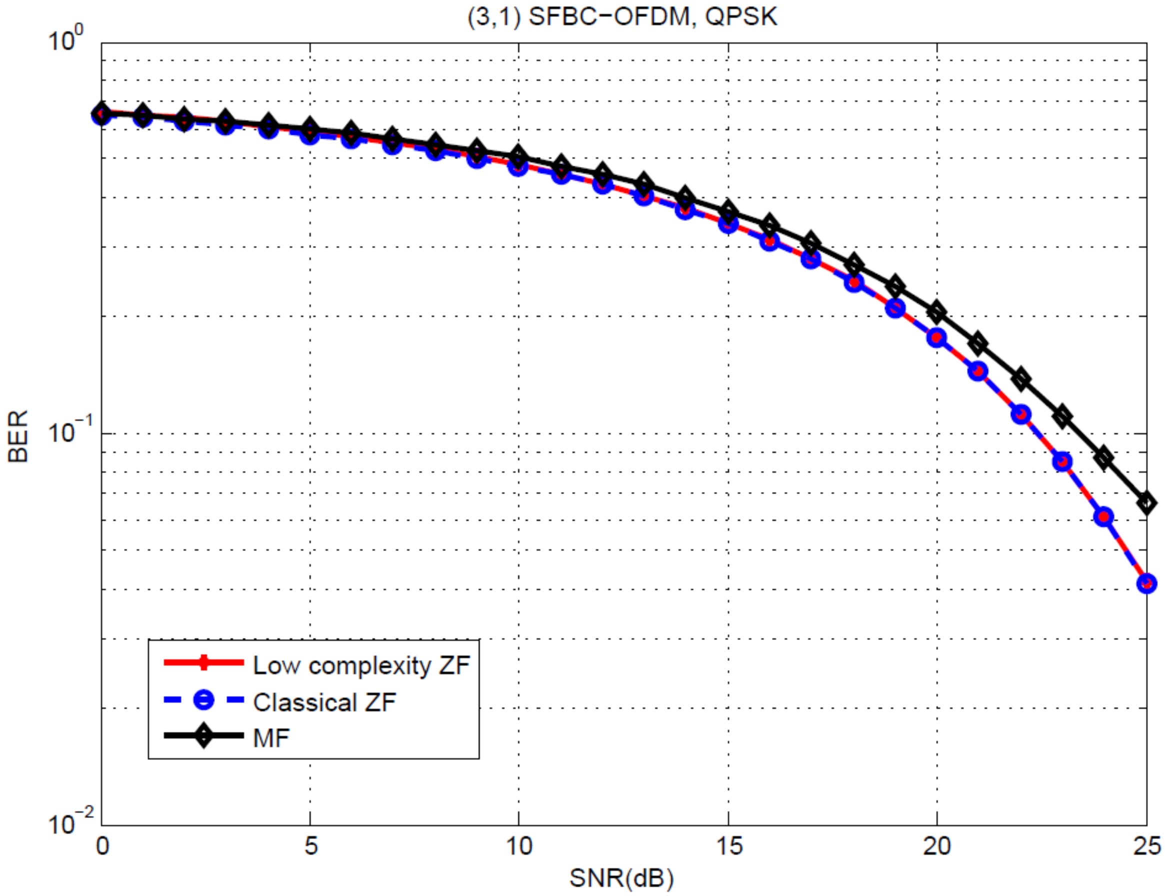

Fig. 6.4.2. BER performance of $(3\times1)$ SFBC-OFDM system for $f_d t_s = 0.01$.

**6.5** Comparison of results have been done between Low complexity ZF receiver, classical ZF receiver and MF receiver for normalized Doppler frequency $f_d t_s = 0.5$ and $f_d t_s = 0.01$ for $(3 \times 2)$ system. In Fig. 6.5.1, comparision has been shown for Normalized doppler's frequency, which shows that the performance of Low complexity ZF is better than the MF receiver but classical ZF outperforms the Low complexity ZF receiver. Approximate difference of 2dB is observed at $10^{-2}$ in performance of the Low complexity ZF and classical ZF receiver.

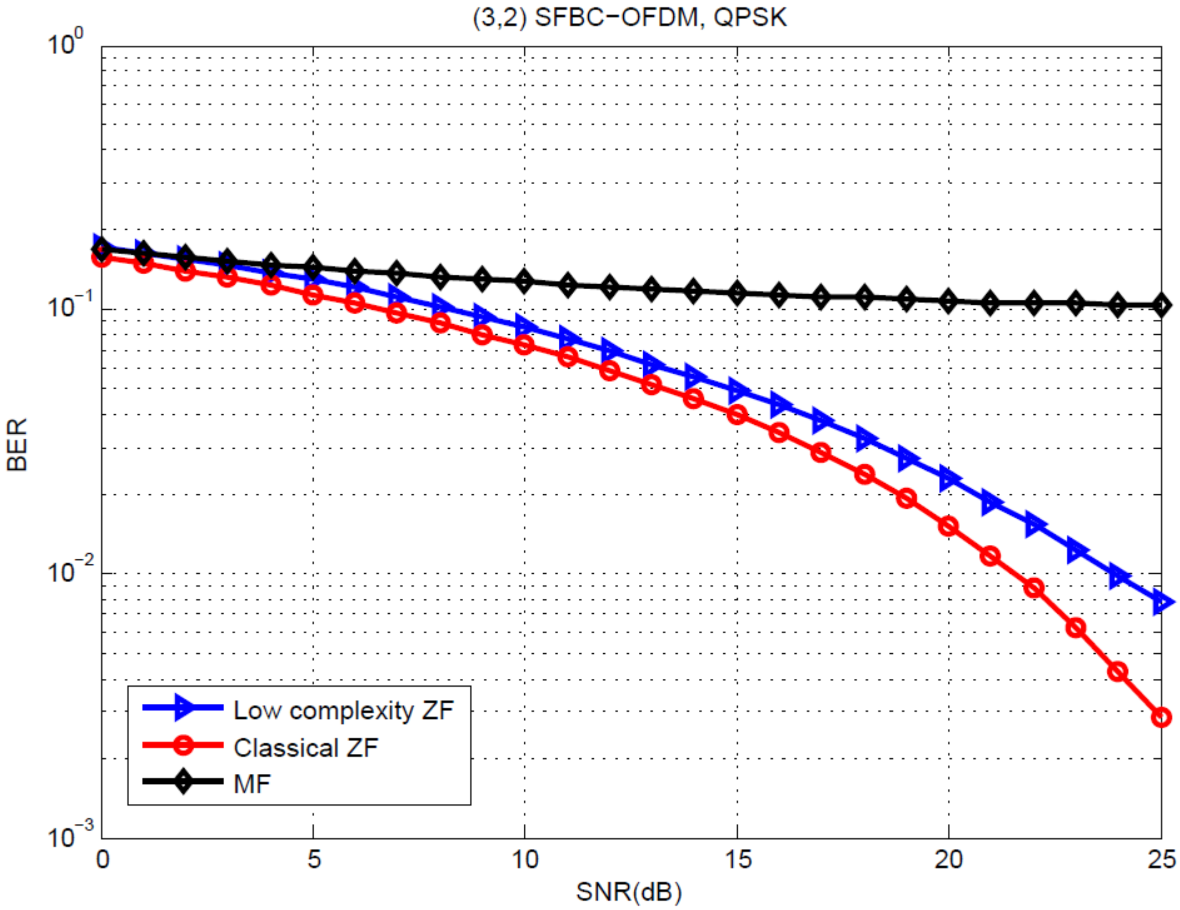

Fig. 6.5.1. BER performance of $(3 \times 2)$ SFBC-OFDM system for $f_d t_s = 0.5$.

In Fig. 6.5.2, the Bit error rate performance has been presented of Low complexity ZF and classical ZF and MF receiver for $f_d t_s = 0.01$, which shows that the performance of the Low complexity ZF and classical ZF receiver becomes identical.

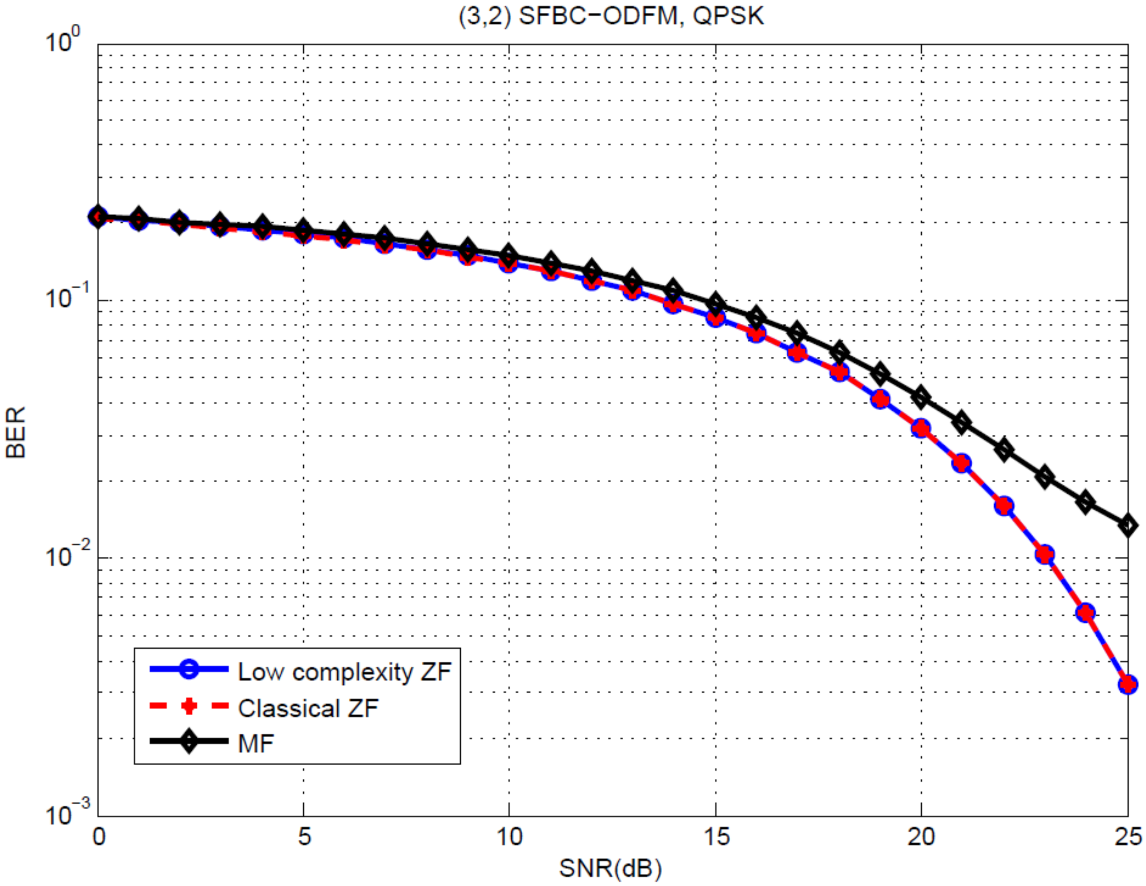

Fig. 6.5.2. BER performance of $(3\times 2)$ SFBC-OFDM system for $f_d t_s = 0.01$.

**6.6** Comparison of results have been done between Low complexity ZF receiver, classical ZF receiver and MF receiver for normalized Doppler frequency $f_d t_s = 0.5$ and $f_d t_s = 0.01$ for $(3 \times 3)$ system. In Fig. 6.6.1, comparision has been shown for Normalized doppler's frequency, which shows that the performance of Low complexity ZF is better than the MF receiver but classical ZF outperforms the Low complexity ZF receiver. Moreover, for the MF receiver, it has been observed that the performance is consistantly poor for all the three cases but better results are obtained for lower fade rate.

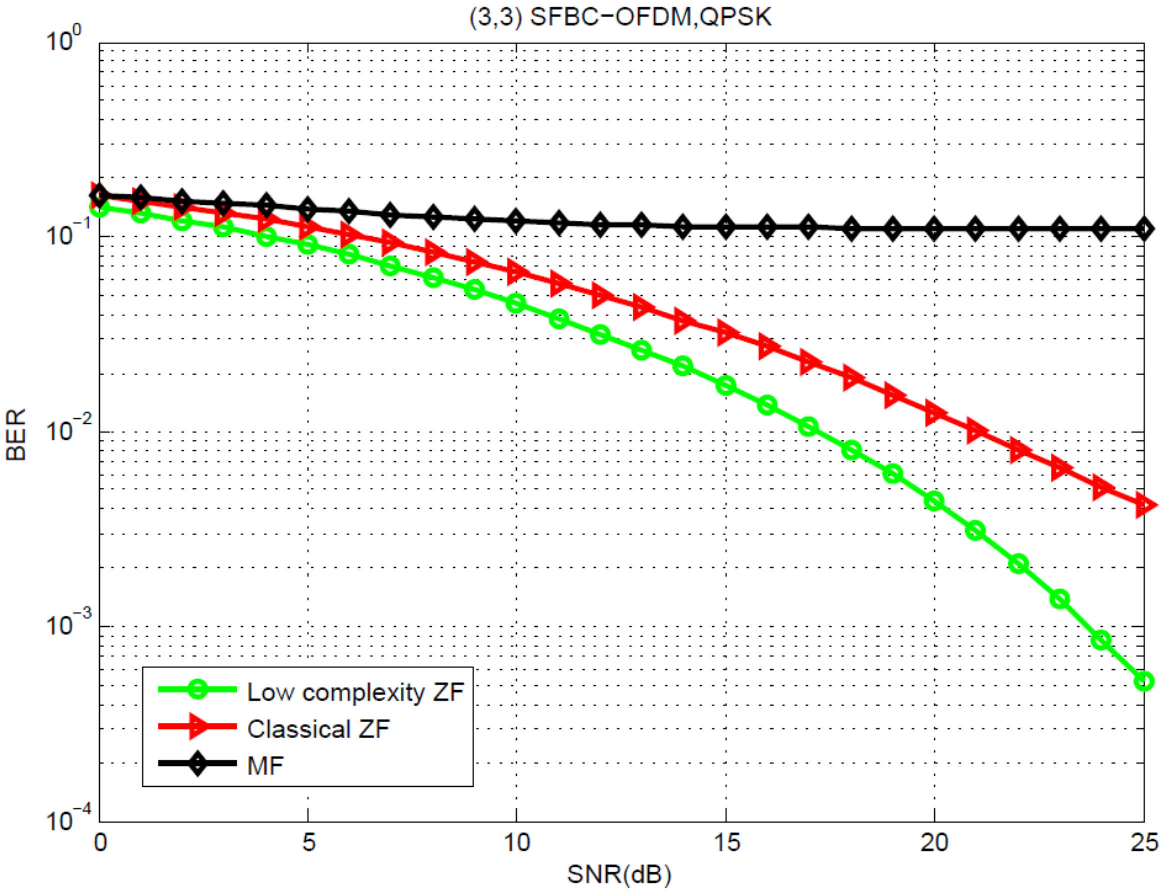

Fig. 6.6.1. BER performance of $(3 \times 3)$ SFBC-OFDM system $f_d t_s = 0.5$.

In Fig. 6.6.2, the Bit error rate performance has been presented of Low complexity ZF and classical ZF and MF receiver for $f_d t_s = 0.01$, which shows that the performance of the Low complexity ZF and classical ZF receiver becomes identical. In this case, the BER performance of MF receiver starts degrading after 20 dB when compared to the other three cases having fade rate of 0.01.

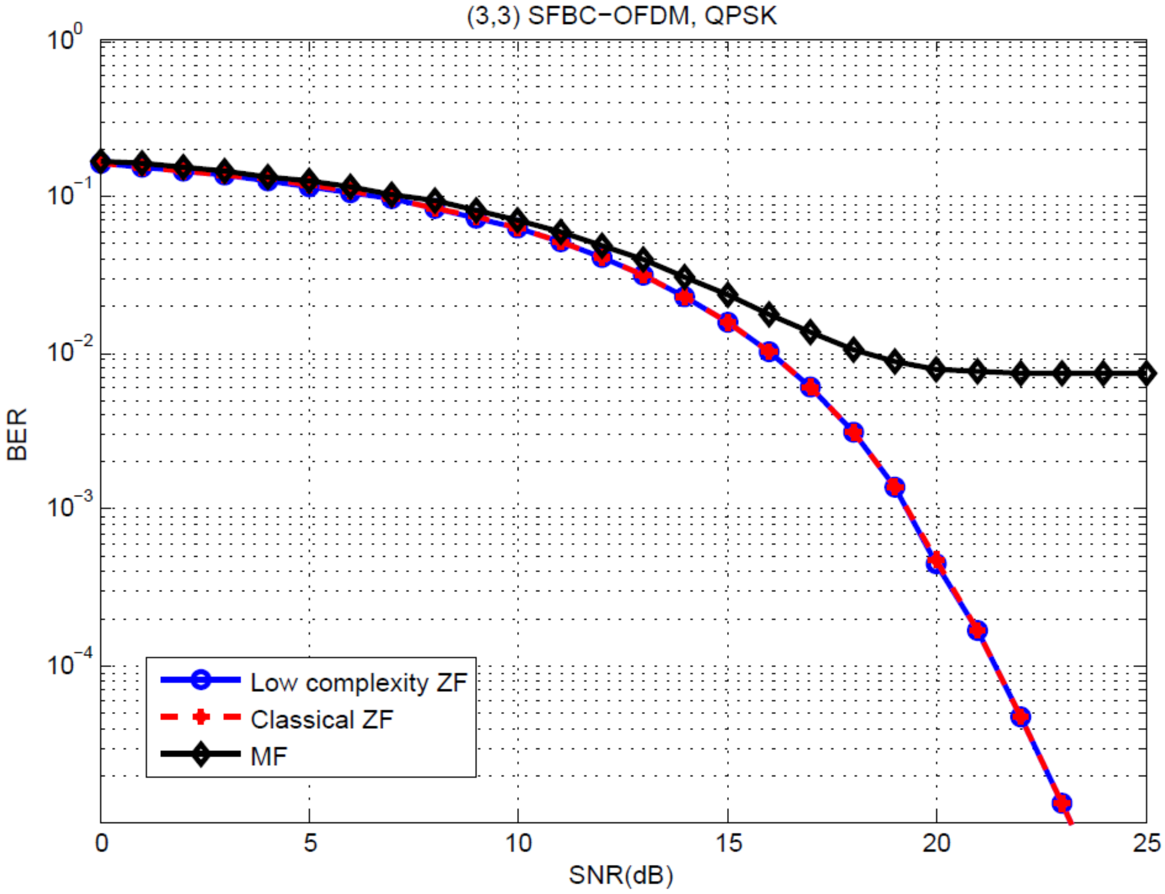

Fig. 6.6.2. BER performance of $(3\times3)$ SFBC-OFDM system for $f_d t_s = 0.01$

## CHAPTER 5

# CONCLUSION AND FUTURE SCOPE

### 6.1 Conclusion

In this thesis, our focus is on the reduction of computational complexity by employing a low complexity zero-forcing receiver with space-frequency block-coded orthogonal frequency division multiplexing system, which reduces the complexity by eliminating the use of pseudo inversion of channel matrix in case of more than two transmit and receive antennas. The receiver is so designed that the extra terms i.e. interfering terms other than the diagonal elements of the estimated channel matrix becomes zero, thus reducing the complexity of the system nearly to half. The simulation is performed under a condition that the channel coefficients for the adjacent subcarriers will not remain static as the channel is severely frequency selective. In this thesis, we have presented results for two transmitter and one receiver, three transmitter and one receiver ,three transmitter and two receiver and three transmitter and three receiver system for these two cases i.e. normalized Doppler frequency $f_d t_s = 0.5$ and $f_d t_s = 0.01$. If $(2\times 1)$ system is considered, it is independent of fade rate i.e. the BER performance of the low complexity receiver and classical ZF receiver will be identical for any fade rate, but the other systems are vulnerable to the change in fade rate. As fade rate increases, the performance of the system degrades. The low complexity receiver shows significant difference in performance in terms of BER over the classical ZF receiver and MF receiver for normalized Doppler frequency $f_d t_s = 0.5$ and $f_d t_s = 0.01$. So, it is observed that for $(3\times 1)$, $(3\times 2)$, $(3\times 3)$ systems, at lower fade rate, the performace of low complexity receiver becomes equal to the classical ZF receiver and also, performance of MF receiver becomes better.

Therefore, it can be inferred that low complexity receiver can be employed for higher spatial diversity schemes as the performance of low complexity receiver becomes equal to the performance of classical ZF receiver for lower fade rate, thus reducing the computational complexity of the system. So, the application of ZF receiver could be extended in broadband wireless networks.

## 6.2 Future scope

- In this thesis, main concern is given on the QPSK modulation technique. The results are obtained using QPSK modulation for various systems such as three transmission antennas and one, two, three receive antennas. These results can be obtained using higher modulation techniques such as MSK, GMSK which is subjected to future research.
- Moreover, we have not considered effect of channel estimation in our work, which is again subjected to future research.
- Impulse noise has not been considered in this thesis, so the performance of the given system can be evaluated under the impact of impulse noise, which is a subject of future research.

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