Performance Analysis of STBC MIMO-OFDM Transceiver using ICI Self Cancellation and Cooperative Diversity

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

MASTER OF ENGINEERING

IN

WIRELESS COMMUNICATION ENGINEERING

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JULY-2015

DECLARATION

I, **Rajni Goyal,** hereby declare that the thesis entitled **"Performance Analysis of STBC MIMO-OFDM Transceiver using ICI Self Cancellation and Cooperative Diversity"** is an authentic record of my own work carried out towards the partial fulfilment for the award of degree of Master of Engineering in Wireless Communication at Thapar University, Patiala, under the supervision of **Ankush Kansal**, Assistant 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 any other degree.

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This is to certify that the above statement made by the student is correct to the best of my knowledge and belief.

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ACKNOWLEDGEMET

The real spirit of achieving a goal is through the way of excellence and austere discipline. I would have never succeeded in completing my task without the cooperation, encouragement and help provided to me by various personalities.

With deep sense of gratitude I express my sincere thanks to my esteemed and worthy supervisor, **Ankush Kansal,** Assistant Professor, Department of Electronics and Communication Engineering, Thapar University, Patiala for his valuable guidance in carrying out work under his effective supervision, encouragement, enlightenment and cooperation. Most of the novel ideas and solutions found in this thesis are the result of our numerous stimulating discussions. His feedback and editorial comments were also invaluable for writing of this thesis.

I shall be failing in my duties if I do not express my deep sense of gratitude towards **Dr. Sanjay Sharma,** Professor and Head of the Department of Electronics and Communication Engineering, Thapar University, Patiala, and **Dr. Hemdutt Joshi**, Assistant Professor, Program Coordinator of Wireless Communication, who have been a constant source of inspiration for me throughout this work, and for providing us with adequate infrastructure in carrying the work.

At last but not the least my gratitude towards my father **Mr. Bhim Sain** and mother **Mrs. Santosh Rani**, who always supported me in doing the things my way and whose everlasting desires, selfless sacrifice, encouragement, affectionate blessings and help made it possible for me to complete my degree. I would also like to render my gratitude to the Almighty God who bestowed self-confidence, ability and strength in time to complete this task and for not letting me down at the time of crisis and showing me the silver lining in the dark clouds.

Rajni Goyal

ABSTRACT

OFDM is popularly used techniques in modern broadband communication systems that are used for high data rate applications and for non-line of sight communication. OFDM is the best technology used for transmitting large data rates over smaller bandwidth. MIMO systems are used for obtaining diversity gains, array gain, spatial multiplexing and Interference reduction and avoidance. The combination of MIMO-OFDM gives the benefits of both OFDM and MIMO systems like high spectral efficiency and diversity gains. So, it can be said that MIMO in combination with OFDM is a promising technology for future wireless communication systems.

In this thesis work, analysis of MIMO-OFDM communication systems using Space-Time Block Codes (STBC) under frequency selective channels have been carried out in terms of BER performance. BER analysis of STBC MIMO-OFDM using ICI self cancellation technique and cooperative diversity for both Rayleigh and Rician channels have been done. The OFDM system suffers from inter-carrier interference (ICI) due to the frequency offset that has been introduced in radio channels. Here in this thesis this problem have been answered by using ICI self Cancellation method in STBC based MIOM-OFDM system. To evaluate the performance of a STBC MIMO-OFDM system, physical layer of the same is simulated by using matlab.

In the given thesis, a general STBC structure is proposed for 2x2 MIMO OFDM systems. The detection technique used is zero-forcing Equalization. Modulation technique employed in the given thesis to implement generalized STBC MIMO-OFDM system is MPSK and same has been used for STBC MIMO-OFDM with cooperative diversity. Modulation technique used for STBC MIMO-OFDM system using ISI self cancellation technique is BPSK. Rician and Rayleigh channels have been used for analysis purpose and how they affect the BER of the system is presented in the thesis. The improvement of 7dB in SNR at BER of $10^{-2.5}$ has been achieved for FFT based STBC MIMO-OFDM with cooperative diversity as compared to STBC MIMO-OFDM system without cooperative diversity. The proposed system with CFO of 0.3 has achieved an improvement of 3dB at BER of $10^{-3.7}$ as compared to the system having no ICI self cancellation. If the normalized CFO is 0.15 then there is an improvement of 3dB at BER of 10^{-3} has been achieved for said system.

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LIST OF ABBREVIATIONS

AAF	Amplify and Forward
ADC	Analog to Digital Converter
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CFO	Carrier Frequency Offset
CIR	Carrier to Interference Power Ratio
CP	Cyclic Prefix
CPM	Continuous Phase Modulation
CSI	Channel State Information
DAB	Digital Audio Broadcasting
DAC	Digital to Analog Converter
DAF	Decode and Forward
DFT	Discrete Fourier Transform
DPSK	Differential Phase Shift Keying
DVB	Digital Video Broadcasting
ERC	Equal Ratio Combining
FFT	Fast Fourier Transform
FRC	Fixed Ratio Combining
GMSK	Gaussian Minimum Shift Keying
ICI	Intercarrier Interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Intersymbol Interference

LAN	Local Area Network
LDPC	Linear Dispersive Parity Check
LTE	Long Term Evolution
MAC	Medium Access Control
MAN	Metropolitan Area Network
MCM	Multicarrier Modulation
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MMSE	Minimum Mean Square Error
M-PSK	M ary Phase Shift Keying
M-QAM	M-ary Quadrature Amplitude Modulation
MRC	Maximum Ratio Combining
MRRC	Maximal Ratio Receiver Combining
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio
QPSK	Quadrature Phase Shift Keying
RMS	Root Mean Square
SDM	Spatial Division Multiplexing
SEP	Symbol Error Probability
SFBC	Space Frequency Block Codes
SIC	Successive Interference Cancellation
SIMO	Single Input Multiple Output
SINR	Signal to Interference Noise Ratio
SNR	Signal to Noise Power ratio

STBC	Space Time Block Codes
STD	Spatial Transmit Diversity
STFBC	Space Time Frequency Block Codes
STTC	Space Time Trellis Coding
SVD	Singular Value Decomposition
V-BLAST	Vertical-Bell Laboratories Layered Space-Time
WiMax	Worldwide Interoperability for Microwave Access
ZF	Zero Forcing
3GPP	3rd Generation Partnership Project
4G	4th Generation

CHAPTER 1: INTRODUCTION

1.1 Preamble

High transmission speed and spectral efficiency are the most important requirements of broadband communication in near future because of applications of video, internet services and audio [1-4]. The usage of MIMO systems in multipath environment improves channel capacity and helps to achieve higher data rate without affecting the bandwidth or input power. MIMO systems have been used extensively since the well known STBC technique [5] have been introduced by Alamouti, that provides data coded in spatial and temporal domain in order to make the transmission more reliable, because unwanted copies of the parent signal are transmitted on independent fading channels. Extensive research has been going on STBC from past few years [6-8]. STBC and MIMO have been predominantly adopted by IEEE 802.11n standard [9] so as to attain high data rate and to have more efficient reception as compared to single antenna systems [10].

Wireless communication channels in practice are either frequency selective or time varying mainly in case of wireless mobile and broadband applications. In order to tackle these problems, combination of MIMO with OFDM has been exploited, this combination has been successfully adopted for current and future communication standards like WiMax and LTE [11-13]. OFDM can combat the changes that have been caused by frequency selective channels. This happens because of the division of the input data stream into parallel data streams and wideband channel has been divided into parallel narrowband sub channels and as a result of this each sub channel has much lower data rate. OFDM provides simplicity of implementation because of the use of DFT in digital domain. The major advantage of OFDM is the bandwidth efficiency because of the because of the orthogonal subcarriers. OFDM has been considered as an efficient modulation technique in multipath frequency selective fading environment with the application of CP [3].

One of the most useful combinations of MIMO and OFDM and system is STBC-OFDM that has been given in [14]. In addition to temporal and spatial diversity, Combination MIMO-OFDM also offers frequency diversity. MIMO-OFDM has been successfully adopted by many standards like IEEE 802.16a, IEEE 802.11n and 3GPP [12, 15, 16]. For STBC OFDM, receiver must know about the various channel parameters so as to recover the transmitted symbols. So, channel estimation with minimum hardware complexity and maximum accuracy is an important topic for research in MIMO-OFDM systems.

1.2 OFDM

OFDM is a popular technique that has been used for transmitting data on wireless channels [17]. OFDM is successfully used in various wireless standards like digital audio broadcasting (DAB), digital video broadcasting (DVB-T), and the MAN standard IEEE 802.16a [18]. OFDM has been used for communicating signals over short range like, for vehicle to road side communications. It is the best technology for 4G systems.

OFDM converts a frequency selective channel to a group of flat fading channels. The subcarriers have been arranged so that they have minimum frequency separation in order to have orthogonality between the time domain waveforms of the signal. So it can be said that the available bandwidth has been used very efficiently. If CSI is known at the transmitting end, then in order to match the channel the transmitter can adapt its way for signalling. Because of the usage of large number of narrow sub spaced channels by OFDM, the ideal capacity provided by a frequency selective channel has been approached by above mentioned adaptive strategies. In real word, adaptive bit loading techniques have been used to achieve this, where signal constellations of different sizes have been transmitted on the subcarriers.

In OFDM block multicarrier modulation technique, block consisting of N symbols has been transmitted on N parallel subcarriers. OFDM symbol duration is N times larger as compared to single-carrier system. Implementation of OFDM has been done as an IDFT applied on the block of N data symbols that have been followed by an ADC. In order to eliminate the effects of ISI, every single block of IDFT coefficients has been preceded by a CP, but the length of the CP is equal to channel length. For this, the linear convolution of channel and transmitted sequence has been transformed into circular convolution. It leads to the complete elimination of ISI effects. Further this approach allows the receiver to make use of FFT for Implementing OFDM [17]. Same techniques can be used for single carrier systems, by using a CP in front of a data block, by employing frequency domain equalization the receiver end.

OFDM systems can efficiently handle ISI that comes into play because of frequency selective multipath fading occurring in wireless environment. Every subcarrier has been modulated at much low symbol rate resulting in a symbol duration that has been much longer as compared to the channel impulse response. So it almost removes the ISI. Further if the guard interval has been present between adjacent OFDM symbols then ISI has been removed completely. Guard interval should be longer as compared to the multipath delay. Although every data sub-carrier has been operating at much lower data rate, still high we can achieve high data rate by using huge number of subcarriers. There is almost no effect or very small effect of ISI on OFDM systems so the equalizer is not employed at the receiver.

In comparison to other transmission techniques OFDM is having large number of advantages. Most important among them is high spectral efficiency. Because of orthogonality there occurs a very fine mathematical relationship among the frequencies used by various sub channels that has been employed in OFDM system. Every frequency used is an integer multiple of basic frequency. This provides the insurance that even if the sub channels are overlapped still there is no interference among the various sub channels. As a result of this high spectral efficiency is obtained.

OFDM is used in the IEEE 802.16a MAN/LAN and IEEE 802.11a LAN standards. The IEEE 802.11a LAN gives a speed of 54Mbp/s by using channel spacing of 20-MHz, resulting in a bandwidth efficiency of 2.7 b/s/Hz [18]. The final throughput has been highly influenced by MAC protocol. Similarly IEEE 802.16a [19] can operate in different modes that depend on the channel conditions, providing us with the data rate from 4.20 to 22.91 Mb/s using a bandwidth of 6 MHz, resulting in bandwidth efficiency of 0.7 to 3.82 bits/s/Hz.

1.3 MIMO

If multiple antennas are used at both transmitting and receiving end than the resulting system is termed as MIMO system. Advantage provided by spatial diversity has been employed in MIMO systems by spatially separating the antennas in a rich multipath scattering environment. Implementation of MIMO systems can be done in various ways in order to have capacity gain, diversity gain and combat the fading. Basically three types of MIMO techniques are available. First technique provides improved power efficiency by maximization of spatial diversity. These type of techniques include STTC [20], STBC [5] and delay diversity. Second type makes use of layered approach and then results in an increased capacity. Most popular example of this is V-BLAST that has been in [21] in which full spatial diversity cannot be achieved. Third type makes use of CSI at the transmitter. In this technique decomposition of channel coefficient matrix is done employing SVD and then the result obtained after decomposition that is the decomposed matrices are used as post and pre filters at the receiver and transmitter to obtain near capacity [8].

1.4 MIMO-OFDM

MIMO systems with spatial multiplexing are known to improve the throughput, but on the other side if much higher values of throughputs are required, then the multipath nature of the environment leads to frequency selective channels in MIMO. Whereas, OFDM system can transform those channels to a group of parallel frequency- flat fading MIMO channels with increased frequency efficiency. That’s, why MIMO-OFDM [22] is considered as the best technique for new generation of wireless networks.

Therefore, MIMO-OFDM, that is using multiple transmitting and multiple receiving antennas in an OFDM technique became a best solution to single carrier transmission technique. But the complexity of channel estimation increases in comparison to SISO systems because of increase in number of channels. Complexity is further increased when the channel present between ith transmitting antenna to mth receiving antenna is of frequency selective type. By employing OFDM, data symbols are being sent over various parallel sub-carriers by employing computationally efficient IFFT/FFT method [23].

The MIMO systems in combination with OFDM, are used for the efficient and easy transmission of symbol in space, frequency and time. To obtain the benefits of diversity from the channel, various coding schemes have been used. Simplest and easiest is the Alamouti STBC [5] that can take the advantage of both temporal and spatial diversity. Various other codes are also given that can attain some or the entire diversity present in the used channel.

In case of open-loop schemes, basically two approaches have been used for implementation of MIMO systems. One of them is to increase STD with the usage of space-frequency and space-time coding. Other one is raising the capacity of the channel by using SDM that can simultaneously transmit various data symbols by using multiple transmitting antennas. STD eliminates channel fading impairments and the noise that is present in the channel, on the other hand SDM results in an increase in capacity of the channel [24].

1.5 ICI

In OFDM systems, subcarrier spectrum overlaps but the subcarriers are orthogonal to each other. It implies that the where there is maximum of a subcarrier, all the other subcarrier spectra have their minimum there. Sampling of data symbols present on individual subcarriers have been done at maximum number of points at the receiver end and then demodulation is performed to free the individual subcarriers from any type of interference. Interference that occurs because of the presence of individual symbols on consecutive sub-carriers has been known as intercarrier interference [25-26].

Orthogonality between the subcarriers cab be seen either in frequency or time domain. In time domain, every subcarrier is sinusoid having integer number of cycles present in single FFT interval. Whereas, in frequency domain it is equivalent to the subcarriers with maximum value at their own central frequency and zero value at the central frequency of any other subcarrier. There is loss of orthogonality if the subcarrier is having a nonzero spectral value present at various other subcarrier frequencies. In time domain the sinusoidal signal present is no longer having an integer cycle numbers occurring in the FFT interval. If there is a variation in multipath channel for one symbol time then it leads to ICI. On occurrence of this the doppler shift on every multipath component leads to a frequency offset present on subcarriers, that results in orthogonality loss. Finally it is concluded that the any offset occurring between receiver and transmitter subcarrier frequencies can introduce ICI in an OFDM symbol.

Further because of the orthogonality present between subcarriers, we can get symbols at the receiving end without any interference. But orthogonality comes into play till the subcarrier frequencies are harmonics of a fundamental frequency. But if the subcarrier frequency have been changed at the receiver because of any reason then there is loss in orthogonality of subcarriers & occurrence of ICI. This results in degradation of the signal. This frequency change is termed as frequency offset. Frequency offset occurs because of two reasons:

1. Doppler effect
2. Mismatch in receiver and transmitter frequency.

1.6 Cooperative Diversity

If the signal is transmitted by wireless means then signal quality may occasionally suffer from poor quality of channel because of fading that occurs due to multi-path propagation. In order to mitigate these effects diversity can be employed for transferring various signal samples over independent channels. Cooperative diversity has been obtained here by employing a third station in the form of a relay.

Various relaying protocols, combining methods and their results on performance of system have been examined.

1.7 Organization of Thesis

The thesis consists of four chapters that are organized in the given manner:

Chapter 1: Introduction: background of research, introduction to OFDM system, MIMO system, STBC MIMO-OFDM system, Carrier frequency offset and Cooperative diversity.

Chapter 2: Literature Review: detailed study of research papers has been discussed.

Chapter 3: Detailed study of OFDM, MIMO, STBC MIMO-OFDM, CFO and Cooperative diversity along with various system models has been done. Mathematical expression for BER analysis of MPSK OFDM system has also been derived here.

Chapter 4: All the results obtained are provided in this chapter. That includes simulation for BER analysis of STBC MIMO-OFDM with MPSK modulation, Effect of CFO on the proposed system, ICI self cancellation scheme, comparison of this with system having ICI, finally STBC MIMO-OFDM with cooperative diversity, then the comparison of this with STBC MIMO-OFDM system

Chapter 5: Conclusion: here the entire work is concluded based on various results obtained and the future scope for the same has been discussed.

CHAPTER 2: LITERATURE REVIEW

2.1 OFDM

T. Hwang *et al.* [27] did a survey on orthogonal frequency division multiplexing and came to the conclusion that OFDM can effectively eliminate the Intersymbol interference present in wireless channels because of the presence delay spread. Due this it has been adopted by many wireless standards and is effectively used in wireless communication. Study of basic OFDM, various modulation techniques and various methods to improve the working of OFDM system model along with channel estimation, time and frequency offset detection and correction, reduction of PAPR ratio have been addressed. Various advantages of OFDM system over MCM are also given.

It had been proved that by employing adaptive modulation, performance of OFDM system has been improved significantly if perfect CSI is present at the transmitter. But it is very difficult to have perfect CSI available at the transmitting end because estimation errors and feedback overhead. In this paper study of coding rate and optimal constellation size for the case of non availability of CSI at the transmitting end in case of frequency-selective fading channels has been done. It has been demonstrated by G. Lim *et al.* [28] that with the increase in the size of the constellation for each subcarrier there is no decrease in the outage capacity. Further it has been shown that instead of adaptation in constellation size according to the SNR of the receiver and estimated RMS delay spread, rate of used error control code can be adapted. Lastly it has been concluded that highest spectral efficiency can be achieved for RMS delay spread for which the diversity gain and CP overhead are balanced.

A. Clark *et al.* [29] says that in case of power limiting OFDM system employing N number of transmitting subcarriers on a Rayleigh fading channel, instantaneous capacity distribution can be estimated as Gaussian distribution. Further the variance and the mean for this distribution has been derived. Simulation results for 32768 and 1024 number of subcarriers have been closely approximated by theoretical results. With the subcarrier number approaching infinity having no constraint on bandwidth leads to capacity of the system approaching capacity of flat fading channel with infinite bandwidth. So at the end it has been concluded that infinite-bandwidth, power limited systems using OFDM can successfully achieve the capacity provided by jakes' model.

T. L. Singal *et al.* [30] provides the basic method for selection of a particular modulation technique. The Modulation scheme chosen must provide narrow power spectrum and best spectral efficiency. Family of constant envelope techniques and linear modulation techniques had been presented in the paper. In wireless mobile communication systems both of the above mentioned modulation schemes have been used to a great extent. Based on the priority set in the system, the selection of one of these techniques is done. If moderate hardware complexity and efficient utilization of bandwidth is main requirement then QPSK is a good choice. But in case of better error rate performance, constant envelope and narrow power spectrum continuous phase modulation schemes are better. GMSK is the best solution when non-linear power amplifiers and tolerance against filter parameters are key features. By using various modulation schemes further improvement in spectral efficiency can be obtained. For spectrum efficient mobile devices, combination of robust coder with various digital modulation schemes that can withstand high bit error rate with much less channel coding is the best choice.

An exact analysis of symbol error rate of coherent M-PSK modulation and M-QAM modulation is given by A. Mraz *et al.* [31]. Analysis is performed in the presence of various types of fading channels, additive white Gaussian noise and arbitrary number of interfering sources. Results obtained for M-PSK and M-QAM have been extended for equally spaced carriers of interferers for OFDMA transmission. Moreover the results obtained can be utilized to predict the bit error rate and even capacity of the wireless channel.

The survey done by Y. Rahmatallah *et al.* [32] provides a broader understanding of a major problem present in OFDM systems that is high PAPR ratio. Further the literature is full of various PAPR reduction techniques that can substantially reduce PAPR but at the cost of increased BER, transmitted power and increased complexity. Various important features of PAPR reduction techniques along with their impact on critical design factors have been discussed. High PAPR drives the power amplifiers at the transmitting end into the saturation condition leading to spectral spreading and non-linear distortions. It has been concluded that a proper technique must be selected based on available resources and system requirements because no technique can perform well in all circumstances.

OFDM is a modulation technique that utilizes bandwidth very efficiently but suffers from time and frequency synchronization errors. Carrier frequency offset, timing of the symbol and sampling frequency offset are very sensitive issues so they are needed to be compensated otherwise they will cause ISI, degradation in SNR, ICI and reduction in signal power giving a way to deteriorated system performance. Different fine and coarse synchronization techniques have been surveyed and it is concluded that coarse synchronization techniques are sufficient in bursty communications. On the other hand fine synchronization techniques are used in continuous transmission for tracking and correcting the residual errors as stated by H. Zhou *et al.* [33].

2.2 MIMO

Usage of multiple antennas has gained importance during the last decade both in the industry and academics as said by J. Mietzner *et al.* [34]. MIMO systems can be used to obtain multiplexing gain and diversity gain resulting in an improvement in error performance and bit error rate of a wireless system respectively. In this paper transmitting and receiving structures for spatial diversity, spatial multiplexing, and outer channel coding and smart antenna techniques are discussed. Although a lot of work has been done on MIMO systems still there are various open problems that need to be addressed specially in the areas like multiuser scenarios, closed loop MIMO techniques and cooperative diversity.

S. M. Alamouti [5] presented a basic two branch diversity technique. Same diversity order is provided by two transmitting and one receiving antenna scheme as is provided by one transmitting and two receiving antenna in case of MRRC. Further it is depicted that the scheme can be generalized for N receiving antennas and two transmitting antennas so as to achieve a diversity order of 2N. The clearest use of the technique is an improvement in diversity at all the remote locations in wireless systems because in spite of using two receiving antennas and two transmitting antennas can be used.

Performance of space-time block codes for transmitting data over Rayleigh channels with the use of multiple transmitting antennas have been discussed here. Data encoded by using space time block codes has been split into N data streams that are transmitted simultaneously by using N transmitting antennas. V. Tarokh *et al.* [35] has described both encoding and decoding algorithms. Encoder and decoder employed for these codes are very simple. Simulation results have shown that by increasing the number of transmitting antennas significant gains can be attained.

2.3 MIMO-OFDM

Y. Li *et al.* [36] said that MIMO systems can be used to increase the capacity of the channel by a factor depending on minimum number of used transmitting and receiving antennas. Further OFDM can be used for MIMO systems to eliminate intersymbol interference and thus resulting in an improved system capacity. SIC techniques and pre whitening techniques for MED decoding are proposed here. By using these techniques in 4x4 OFDM systems data transmission rate has reached to 4 Mb/s over wireless channel of bandwidth 1.25 MHz, by utilizing a 10-11 dB SNR for 10% WER, all this depends on various signal detection techniques employed and the kind radio environment. So it is concluded that for high data rate systems MIMO-OFDM can be used.

Y. Wu *et al.* [37] says that the designing of space-time codes is done taking into consideration the optimization of diversity and gains. This approach gives a way to various examples, One of them is space time block codes. The coding loss that is linked with some types of space time coding has also been reduced by employing some forms of space time coding. Code diversity is complementary and alternative approach for space time codes. Code diversity can be seen as integration of space time codes with restricted set of beams. It has been demonstrated that various code diversity not only gives better utilizing of diversity but also provides some coding advantages. It is shown that the capacity loss that has been associated with some types of space-time codes has also been reduced by coding diversity. It has been clearly depicted that as compared to different low-rate feedback techniques robustness of code diversity scheme is more. A new group of full-rate circulant codes have been introduced and the benefits of suboptimal linear decoding in association with code diversity are also given.

Bit-loaded OFDM with the usage of convolution coding is an emerging technology for transmission of data in frequency-selective quasi-static channels. Moreover further improvement in data rate can be obtained by combining MIMO with loaded OFDM. Due to non-availability of correct analytical techniques for error rate, a novel method for analysis of FER and BER of MIMO-OFDM systems and bit-loaded coded OFDM have been developed. The analysis is done using SVD over quasi-static frequency-selective channels with nonideal interleaving. Numerical results presented by M. M. Avval *et al*. [38] shows that the technique used in this paper gives an accurate estimation for the error rate analysis of Loaded Bit interleaved coded MIMO-OFDM systems. Analysis done has been used in three applications that are, adaptive coded modulation, adaptive interleaving, and bit loading. It is clearly shown that in case of coded OFDM with bit-loading algorithms the relative performance is system dependent. The best performance is guaranteed by the proposed SL algorithm but at the cost of higher complexity. Whereas adaptive interleaving has been proved to be a good alternative to coded OFDM with bit loading. Finally, by applying the expression derived for FER to an adaptive coded-modulation technique a good output close to ultimate limit has been obtained.

MIMO antenna with OFDM is considered as most efficient technology for high data rate services. MIMO-OFDMA systems with multi-cell bit-interleaving and convolution coding have been studied to develop an analytical expression for average error probability. For interference mitigation, both randomized multi-user and coordinated access technologies are used. In such conditions, the analytical analysis must take into account the correlation between the various fading channels. The analysis is done for various multiple antenna techniques, like spatial diversity and Beamforming that make use of orthogonal space time coding. Simulation results given by D. Molteni *et al.* [39] shows that the analysis is applicable to wide range of systems, interference conditions and propagation scenarios. Lastly the proposed analysis showed a great accuracy with a considerable computation cost reduction with common link simulations.

Z. Iqbal *et al.* [40] presented an analysis of the performance of four different kind of interleaving and channel coding techniques for MIMO-OFDM systems. Further these techniques are compared on the basis of power dissipation, hardware implementation requirement and BER. It has been concluded that out of four interleaving and coding techniques, per antenna interleaving and the cross-antenna coding outperforms under all SNR conditions for every modulation scheme. It is considered as the best scheme when power dissipation and hardware resources are the main considerations that are an important factor in case of consumer electronics.

2.4 STBC MIMO-OFDM

R. S. Blum *et al.* [41] studied improved space-time codes for MIMO OFDM wireless systems using QPSK modulation for a case of two transmitting and receiving antenna. It has been very clear that the proposed system using space-time code has shown a 2-dB improvement as compared to the previous codes at 5-Hz fading. Further a 4-antenna and a

16-state code has been proposed that can achieve an additional improvement of 2-dB with much lower complexity.

Evaluation of the performance of a wireless system is done using multicarrier OFDM in combination with MIMO and STBC. BER expression for MIMO-OFDM with and without STBC has been presented taking into account timing jitter and fading with DPSK, DQPSK and QPSK schemes. The results are attained with and without ½ rate convolution codes with hard decision decoding. Analysis proved that the reliability of a wireless system can be improved by using STBC coded MIMO-OFDM systems. It has been shown that the best improvement is obtained in case of QPSK. In further research Smart antennas can be employed to obtain the performance of MIMO-STBC systems as concluded by A. K. M. Nazrul *et al.* [42].

2.5 Signal Detection in MIMO-OFDM System

M. B. Breinholt *et al.* [43] developed various equalization techniques that can lead to frequency reuse in OFDM systems. Foremost, focus is given to a single strong interfering base present at the mobile. Base causing interference is considered to be asynchronous because its cyclic prefix is not synchronized in time with the cyclic prefix of desired base station. Different methods for overcoming the above mentioned problem have been developed based on various channel shortening techniques. The best method works by aligning the cyclic prefixes and at the same time holding the length of all the channels equal to the length of cyclic prefix or less than this. Two set of space time filters have been designed for a case of two receiving antennas present at mobile station. Further, the paper presets the simulation results for the case, when the excessive channel length of the base station that is interfering is greater than zero. Further it is indicated that by using the recently proposed techniques there is improvement in uncoded BER.

MIMO-OFDM is the best technology for 4G wireless systems. Various signal detection techniques have been studied by X. Zhang *et al.* [44]. These techniques include zero forcing detection, MMSE detection and V-Blast detection method. Further simulation of these detection techniques is done for various modulation schemes and then the most optimal among these techniques is chosen. It has been find out that V-blast detection algorithm is more superior to other two detection techniques. By further comparing it has been found that MMSE-SIC technique is better than ZF-SIC.

S. Singh presented a comparison between different optimization techniques that are used in detection of spatially multiplexed transmitted symbols available in MIMO OFDM systems. The criterion for the evaluation of various detection techniques is BER evaluation for a given value of SNR. The various detection techniques used for a 2X2 MIMO system are zero forcing, maximum likelihood and minimum mean square error. LDPC decoder has been employed by the receiver to decode the Binary Phase Shift Keying signal. Simulation results given by S. Singh *et al.* [45] present a clear picture that ML detection is better than ZF and MMSE detection.

T. T. Nguyen *et al.* [46] says that MIMO SDM is a potential technique that can provide enormous system capacity and can achieve high BER. Systems have to be designed with low complexity and high performance for detecting and reconstructing the signal on the receiver. Various detection algorithms such as linear detection algorithms, maximum likelihood and ordered successive interference cancellation have been studied and are simulated. Discussion and simulation of MIMO-OFDM SDM system has been done. This technique can allow the system to transmit the data at high speed and making the system robust for frequency selective fading. MIMO-OFDM SDM systems along with a special technique for pilot insertion used for estimating the channel has been simulated so as to carry out the comparison between the performances evaluations of different detector algorithms.

OSTBC with MIMO is popular way to add spatial diversity. OFDM can further make the system insensitive to frequency selective fading occurring at high data rates. Combination of the OFDM system with linear STBC codes suffers from major drawback that is high PAPR. But by using continuous phase modulation PAPR can be reduced, that is CPM-OFDM can take the advantage of the trade-off occurring between bandwidth efficiency and power that is provided by CPM along with robustness to fading of OFDM. To achieve further increase in throughput, while having similar robustness to fading and low PAPR, a new diversity technique known as space time frequency technique has been introduced. The technique is based on usage of L2-orhtogonal multi-h STBC codes on MIMO OFDM. These techniques are used for Rayleigh frequency selective channels employing semi-coherent detection. Further it is shown that these techniques can provide improved spectral efficiency with a low decoding complexity by using zero-forcing detection algorithms as said by M. A. Hisojo *et al.* [47]

2.6 CFO in MIMO-OFDM System

A. K. Dutta *et al.* [48] carried out CFO estimation for MIMO-OFDM systems with noisy frequency selective wireless channels considered with both multiuser and single user scenarios. A new approach for parameter estimation has been developed. In this approach continuous-value based CFO parameter has been discretized into discrete bins and then a detection theory that is analogous to MBER optimization for the detection of finite-alphabet received signal. Using the above mentioned approach a novel technique for the estimation of CFO has been studied further its performance is studied using monte-carlo simulations. Expressions for variance of CFO and resultant BER for single user scenarios have been obtained. It is obvious from the results obtained after simulation that overall BER performance of MIMO-OFDM has been improved by using the proposed method.

Combination of MIMO with OFDM has been considered as best technology for coming wireless communication. But the working of MIMO-OFDM is very sensitive to CFO that leads to ICI. So, the estimation of CFO plays a great role in MIMO-OFDM systems. Here a new technique has been proposed for the estimation of CFO that makes use of training sequences made of repeated pseudo-noise sequences. In the above mentioned technique use of single-g estimators is done for CFO acquisition so as to attain a large range for estimation. Multiple-g estimators have been used for CFO tracking so as order to improve the accuracy of estimation. Simulation results presented by L. M. [49] made it very clear that estimators used in our scheme showed superior performance as compared to Schenk's scheme for both AWGN and multipath channel.

2.7 MIMO-OFDM System with Cooperative Diversity

M. S. Back *et al.* [50] says that OFDMA is a promising technology for wireless systems. To further improve the performance of OFDMA, MIMO systems are used along with them. Transmit diversity provides a clear advantage to a OFDMA uplink system used in broadcasting but more than two antennas cannot be employed because of size, hardware limitations and cost of the system. To combat these limitations cooperative diversity technique has been applied. So here, focus is on designing and performance analysis of MIMO-OFDMA uplink system. For high-rate and reliable transmission efficient transmission codes have been proposed for both two-sided and single sided transmission. Line-of-sight propagation is one of the important parameters so as to improve the system performance in wireless communication environment. It has been shown clearly that

MIMO-OFDMA system with given cooperative diversity techniques is having very high performance gain if the SNR present in inter-user is high as compared to uplink channel. Obtained results had also been applied to various OFDMA-based systems like IEEE 802.16 and many more.

D. Darsena *et al.* [51] considered a cooperative network, in which the communication between destination and source is possible by using multiple relaying nodes. In order to cope with the nature of available channel, every network node makes use of multiple antennas and OFDM modulation. Performance evaluation of the proposed system is done on the basis of SEP. An optimal design of relaying matrix and precoding have been proposed that can achieve that can achieve minimum-SEP. The proposed system can exploit the full distributed diversity provided by the cooperative approach, but an accurate CSI is required to be known at the source and at the various relays present.

2.8 Gaps in Study

1. Space time coded OFDM could not achieve high rate and multipath diversity but Space frequency OFDM can have full rate and maximum diversity but at the expense of high decoding complexity [2].
2. It had been proved that by using adaptive modulation for OFDM systems their performance had been improved significantly if the transmitter had the perfect knowledge of CSI. But it is difficult to have perfect CSI available at the transmitter [27].
3. There are various ICI cancellation techniques used in OFDM systems such as frequency domain equalization and pulse shaping. Further frequency domain equalization cancels the ICI introduced by fading distortion but does not eliminate the ICI that has been introduced by Doppler shift, frequency mismatch between transmitter and receiver. Moreover it is not suitable for multipath components and channel estimation is also very complex and expensive. Implementation of pulse shaping technique is also very complex [53].
4. Although transmitting diversity proved to be an advantage for OFDMA uplink systems used in broadcasting, but in practical OFDMA systems one cannot employ more than two antennas due to size, cost and hardware limitation [50].

2.9 Objective of Thesis

1. Objective is to do BER analysis of 2X2 STBC coded MIMO-OFDM system in various fading channels such as Rayleigh and rician channel with M-PSK modulation

2. Second Step represents the effect of ICI on 2x2 STBC MIMO-OFDM system and various mitigation techniques.

3. Third step is the BER analysis of STBC MIMO-OFDM system with cooperative diversity for both Rayleigh and rician channel with M-PSK modulation.

2.10 Methodology

OFDM is a Multicarrier modulation technique used for parallel data transmission. In MIMO systems multiple antennas are used at both the transmitting and receiving end. Combination of MIMO-OFDM has been used in the research work. Further STBC encoding of the same has been done to improve the system performance. ICI problem in OFDM systems has been addressed and ICI self cancellation technique has been applied to STBC MIMO-OFDM system. Further BER analysis of the STBC MIMO-OFDM system has been done using cooperative diversity.

CHAPTER 3: MIMO-OFDM SYSTEM

3.1 OFDM

3.1.1 Principle

Compared to single carrier systems that use only one carrier of rate R_s to modulate the data, the multicarrier systems like OFDM can be used to simultaneously transmit the data using $N_s^{'}$ subcarriers that are modulated at a rate $\frac{R_s}{N_s^{'}}$. The total rate is still similar to single carrier systems whereas in this case individual subcarriers are less sensitive to delay spread offered by the channel.

System model of baseband OFDM transmitter has been shown in the figure 3.1. After the generation of the signal, the bits generated can be modulated using any digital modulation technique and then coding can be done using various coding techniques such as SFBC, STBC and STFBC. Two operations are performed on OFDM symbols these are IFFT and the insertion of cyclic prefix or guard interval. IFFT is done to convert the symbols from frequency domain to time domain. CP is the copy of the ending part of the symbol that is inserted at the starting of the symbol. This extension in symbol is done in the time domain so that the length of the symbol must be longer as compared to delay spread of the channel.

Complex symbols $S_j^{'}\ \ j = 1, 2......$ should be regrouped into blocks of $N_s^{'}$ length having transmission time of $N_s^{'}T_s^{'}$. So this leads to the formation of a single OFDM symbol whose length is $T_{sym}^{'}$ (here $T_{sym}^{'} = N_s^{'}T_s^{'}$). Suppose $g_{r,s}^{'}(t)$ represents OFDM signal that is transmitted on $N_s^{'}$, $f_k^{'}\ \ k = -N_s^{'}/2.....N_s^{'}/2-1$ so as to generate an output.

For the time $[jT_s^{'}, (j+1)T_s^{'}]$, the OFDM signal that has been generated is given as:

$$x_r^{'}(t) = \sum_{s=-N_s^{'}/2}^{N_s^{'}/2-1} S_{r,s}^{'} g^{'}(t-(j+1)T_s^{'}) e^{j2\Pi f_k^{'}t} \tag{1}$$

Above expression shows the $r-th$ OFDM symbol, while $S_{r,s}^{'}\ \ s = N_s^{'}/2....N_s^{'}/2-1$ shows that $N_s^{'}$ complex symbols S_j it carries.

The signal that is received can be represented as:

$$r'(t) = \sum_{r=1}^{\infty} \sum_{s=-N_s'/2}^{N_s'/2-1} S'_{r,s} g'(t-(j+1/2)T_s') e^{j2\Pi f_s t} + n_s'(t) \tag{2}$$

Where $n_s'(t)$ depicts the white Gaussian noise at the $s-th$ subcarrier.

At the receiving end the transmitted symbols are recovered by employing appropriate filter followed by an appropriate sampler.

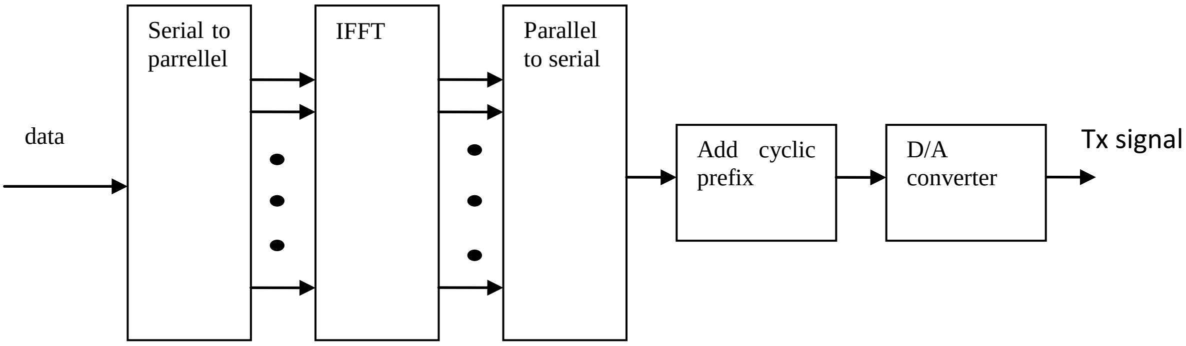

Figure 3.1: OFDM Transmitter Block Diagram

3.1.2 Orthogonality

The spectral efficiency has been given by the transmitted bit rate present in frequency domain. In a multicarrier system for transmission, spacing occurring between two subcarriers is very important to have a bandwidth efficient system.

If the spacing occurring between subcarriers is large, much higher bandwidth is required for transmitting a signal with same rate, thus a lower spectral efficiency is provided.

It has been clear from the figure 3.2 that by using non-overlapping subcarriers inter-channel interference can be eliminated but at the cost of reduced bandwidth efficiency.

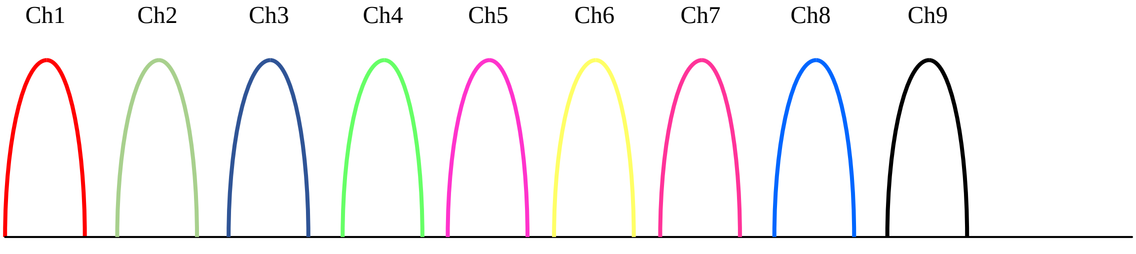

Figure 3.2: Conventional Multicarrier Technique [53]

To solve the above mentioned problem, OFDM has come into picture in which the centre of a subcarrier has been positioned in such a way so that it lands on the null of adjacent subcarrier as shown in figure 3.3. The concept of orthogonality has been introduced by Chang [52]. As depicted in figure 3.3, almost 50% bandwidth has been saved by using overlapping of subcarriers.

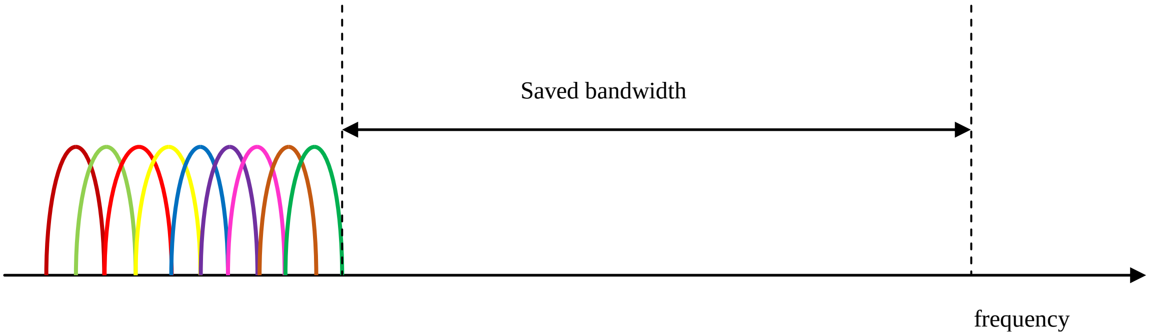

Figure 3.3: OFDM Multicarrier Modulation Technique [53]

3.1.3 Cyclic prefix

The introduction of CP in-between two adjacent OFDM symbols has been used in terrestrial systems for reducing the effect of delay spread because of multipath channels. For simplifying the synchronization, a copy of the ending portion of the transmitted OFDM symbols has been added in front of the data stream, after performing IFFT operation. CP length is adjustable and can be set so as to attain a bandwidth efficient system.

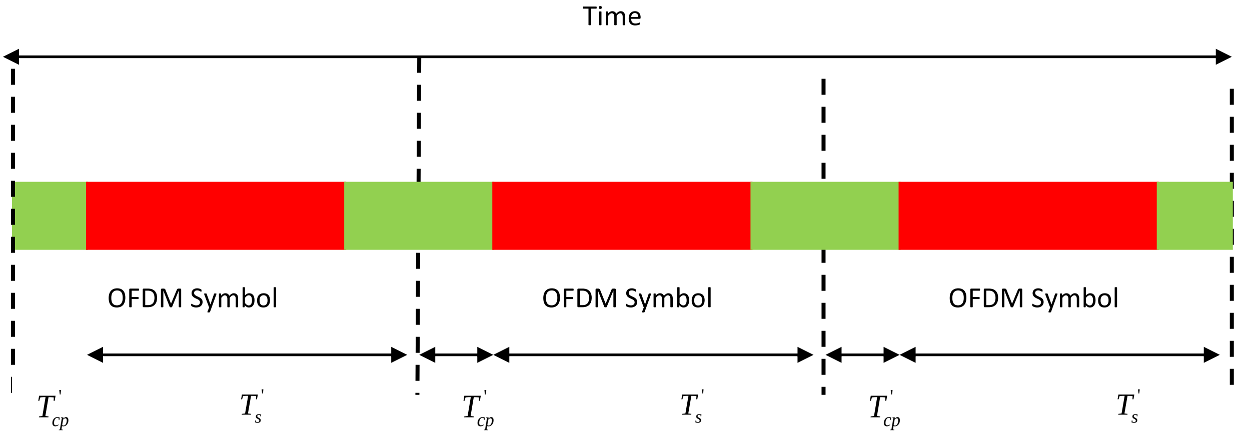

Figure 3.4: Time Domain Representation of OFDM Symbols [53]

Let us consider that the P denotes the OFDM symbols present at the last where $N_s^{'}$ represents the total number of subcarriers. The CP prefix has a length that depends on 4 factors:

1. Channel length: in order to have perfect equalization, the channel length L, should be smaller than the length of CP, P, that is P>L.
2. System performance: as the CP shows the redundancy caused by the ending part of symbol, the efficiency of the spectrum has been reduced and can be given by $N_s^{'} / (N_s^{'} + P)$. Whereas to get the spectral efficiency near to 1, $N_s^{'}$ must tend to infinity.
3. Complexity: the FFT operation is done on blocks that are of size $N_s^{'}$, so to have a feasible system, $N_s^{'}$ cannot be increased to a large extent. In that scenario a trade-off between spectral efficiency and complexity has been done. Basically the value of $N_s^{'}$ must be equal to 4P, that can lead to a spectral efficiency of 25%.
4. Channel type: to get circularity of convolution, the channel should be constant one an OFDM symbol is transmitted. In these cases, diversity provided by the system remain the same even if there is an increase in $N_s^{'}$. Thus, $N_s^{'}$ can be chosen on the basis of channel type.

3.1.4 Advantages and Drawbacks of OFDM

Single carrier transmission is not very useful in case of wideband systems because an equalizer with high complexity has been required to cope with ISI caused by multipath frequency selective channels. Moreover, it has been made clear that by using FFT OFDM is very easy to implement. Because of the presence of orthogonal parallel subcarriers overlap, the bandwidth efficiency of OFDM is very high. Further it has been proved that because of presence of cyclic prefix the system is able to minimize the ISI and combat the effects of multipath fading. One more advantage of OFDM is that individual subcarriers can be modulated with the use of different modulation techniques such as M-QAM and M-PSK.

In case of systems that make use of frequency selective channels, OFDM has been considered as a best modulation technique. But the OFDM systems are very sensitive to frequency offset and phase noise. Further OFDM systems suffer from the problem of high PAPR value.

Because of the above mentioned advantages, OFDM has been considered as a powerful modulation technique for communication. Till now, OFDM has been a topic of great research, as various methods have been developed to reduce PAPR by using techniques such as compression, peak windowing and clipping hence making OFDM more better [54-55].

3.2 MIMO

3.2.1 MIMO System Model

MIMO systems are categorized into three categories. Multiple antennas at the transmitting side that are usually used for beam forming. Multiple antennas employed at either transmitting or receiving end for obtaining different diversity schemes. The final category includes systems having multiple antennas at both transmitting and receiving side in order to obtain spatial multiplexing.

In radio communication multiple antennas are being used at both the receiving and transmitting side. While using spatial multiplexing different type of symbols have been transmitted by different antennas on the radio link while using same frequency in the same time interval. To obtain correct operation, in case of spatial multiplexing multipath propagation is assumed, because in the presence of rich scattering multipath environment MIMO gives better channel capacity. This fact is very clearly given in [54].

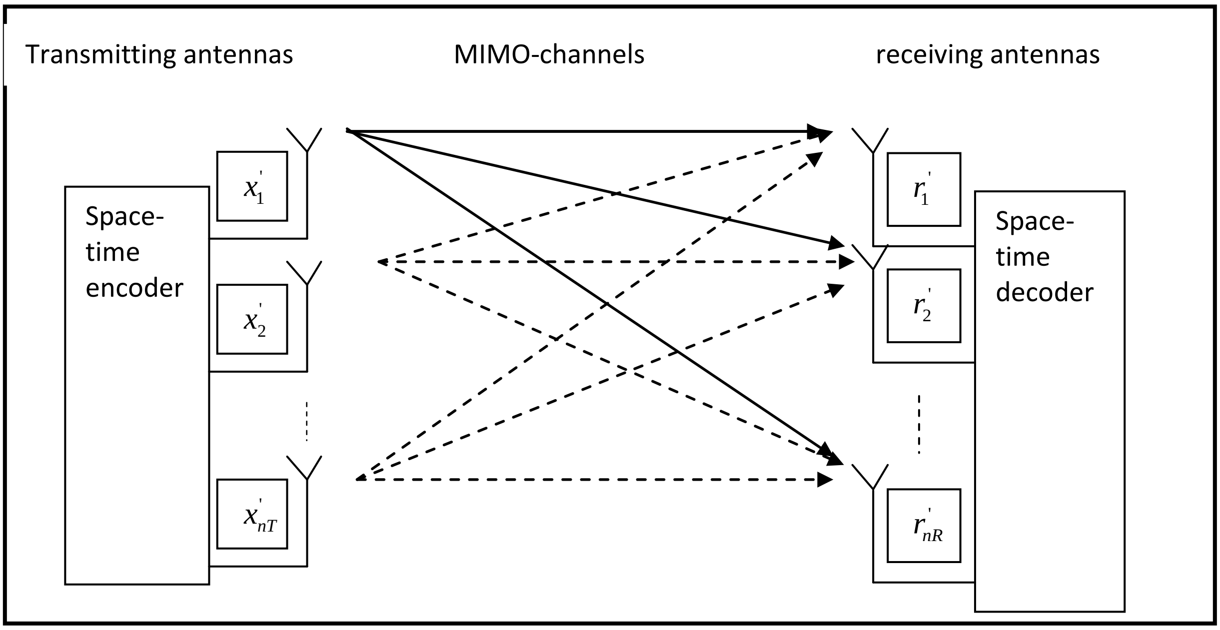

Figure 3.5: Block Diagram of a MIMO System

Assume a single MIMO system with point-to-point links with arrays of $n_r^{'}$ receiving and $n_t^{'}$ transmitting antennas. Our focus is on linear system model used in discrete time. Diagram for the same is given in figure 3.2.1. The signals that are being transmitted in every symbol period can be written as $n_t^{'}X1$, and the jth component $x_j^{'}$ shows the signal being transmitting from antenna j. Since we are considering a Gaussian channel so as per information theory [55], best distribution of the signal being transmitted is Gaussian. So, individual elements of $x^{'}$ are supposed to have zero mean and are considered as independent identically distributed variables. Transmitted signal in covariance matrix form is represented as:

$$R_{x^{'}x^{'}} = E\{x^{'}x^{'H}\} \tag{3}$$

Here the expectation of the signal is given by $E\{.\}$ and hermitian of a matrix $A^{'}$ is given by $A^{'H}$ that indicates transpose followed by component-wise conjugate of $A^{'}$. Irrespective of the number of transmitting antennas, the total power being transmitted has been constraint to $P^{'}$. The same can be expressed as:

$$P^{'} = tr(R_{x'x^{'}}) \tag{4}$$

here $tr(A^{'})$ represents the trace of a matrix $A^{'}$, sum of the elements of $A^{'}$ that are present on the diagonal helps to obtain this. If the transmitter has no CSI than it has been assumed that the signals transmitting from individual antennas are having same power that is given by: $R_{x^{'}x^{'}} = \frac{P^{'}}{n_T^{'}} I_{nT^{'}}$

here $I_{nT^{'}}$ is $n_T^{'}Xn_T^{'}$ identity matrix.

The transmitted signal bandwidth is considered to be very narrow, resulting in a flat frequency response. In another way it can be said that the channel has no memory.

Description of channel can be given by a complex matrix $n_R^{'}Xn_T^{'}$, that has been denoted by $H^{'}$. The jth, ith term of the matrix $H^{'}$ can be represented by $h_{ji}^{'}$ that depicts the fading coefficients occurring between the ith transmitting antenna to jth receiving antenna. In order to obtain the normalization it has been supposed that the power received by every $n_R^{'}$ receive branch has been equal to total power being transmitted. Physically, it implies that the attenuations, amplifications including antenna gains and shadowing have been ignored. This leads to the attainment of $H^{'}$ with the application of a normalization constraint on its elements, when the channel has fixed coefficients, as:

$$\sum_{i=1}^{n_T^{'}} \left| h_{ji}^{'} \right|^2 = n_T^{'},\ j = 1, 2, ...n_R^{'} \tag{5}$$

It has been assumed that the receiver knows the channel matrix but same is not applicable for transmitter all the time. Training sequence can be transmitted to estimate the channel matrix at the receiver. Transmitter is able to know the estimated CSI via a feedback channel. Various components of $H^{'}$ may be random or deterministic. Examples that make use of Rician and Rayleigh distributions of channel matrix relevant for wireless communication are discussed here. For most of the situations Rayleigh distribution is discussed.

Noise matrix $n_R^{'} X1$ at the receiver is represented by $n^{'}$. The terms of this matrix are statistically independent complex Gaussian variables with zero-mean, having real and imaginary parts with equal variance and are independent. Noise occurring at the receiver has a covariance matrix that is given by:

$$R_{n^{'}n^{'}} = E[n^{'} n^{'H}] \tag{6}$$

As there is no correlation present between the various terms of $n^{'}$, the covariance matrix can be written as:

$$R_{n^{'}n^{'}} = \sigma^2 I_{n^{'}n^{'}} \tag{7}$$

Same noise power of $\sigma^2 I_{n^{'}n^{'}}$ has been present at every $n_R^{'}$ receive branch.

Maximum likelihood principle is used by the receiver. The column matrix $n_R^{'} X1$ represented by $r^{'}$ denotes the received signals and the receiving antenna used is referred by each complex term in the given matrix. Average power present at the output of a receive antenna is given by $P_r^{'}$. Whereas average SNR occurring at every receiving antenna has been given by:

$$\gamma = \frac{P_r^{'}}{\sigma^2} \tag{8}$$

It has been assumed that the total power received per antenna has been equal to total power transmitted, SNR has been defined as the ratio of total power transmitted to the power of noise present on each receiving antenna and it does not depend on $n_T^{'}$. So the SNR can be written as:

$$\gamma = \frac{P^{'}}{\sigma^2} \tag{9}$$

With the use of linear model received signal vector can be given by:

$$r^{'} = H^{'}x^{'} + n^{'} \tag{10}$$

Covariance matrix of the received signal defined by $E\{r^{'}r^{'H}\}$, by using the above mentioned equation can be given as:

$$R_{r^{'}r^{'}} = H^{'}R_{x^{'}x^{'}}H^{'H} \tag{11}$$

Whereas the total power of the received signal is given by $tr(R_{r^{'}r^{'}})$.

While doing MIMO transmission the time variant channel matrix can be given as:

$$H^{'}(\tau,T) = \begin{pmatrix} h_{1,1}^{'}(\tau,t) & \dots & h_{1,n_R^{'}}^{'}(\tau,t) \\ \vdots & \ddots & \vdots \\ h_{n_T^{'},1}^{'}(\tau,t) & \cdots & h_{n^{'},n_R^{'}(\tau,t)}^{'} \end{pmatrix} \tag{12}$$

Here the term $h_{nT^{'},nR^{'}}^{'}(\tau,t)$ represents the complex time varying transfer function of the channel present at between the $n_{t-th}^{'}$ transmitting and $n_{r-th}^{'}$ receiving antenna. $n_T^{'}$ and $n_R^{'}$ shows the number of transmitting and receiving antennas present respectively.

From the Shannon's law, capacity of a MIMO channel is given [54] which is:

$$C^{'} = \max_{tr(R_{x^{'}x^{'}}) \le p} \log_2(\det(I^{'} + H^{'}R_{x^{'}x^{'}}H^{'H})) \tag{13}$$

$H^{'}$ is the channel matrix and $H^{'H}$ represents the transpose conjugate, identity matrix is given by $I^{'}$ and the covariance matrix is given by $R_{x^{'}x^{'}}$.

3.2.2 Advantages of MIMO Systems

Array gain

Array gain has been defined as average SNR increase present at the receiver part that occurs because of the coherent combining of multiple antennas present at both receiving and transmitting end. If the CSI is assumed to be known to the multiple antennas present at transmitter, the transmitter weigh transmission of signal with weights, which can depend on coefficients of the channel, so that the combining occurring at the MISO case is coherent. The resulting gain present in this case is known as array gain. Whereas, if transmitting antenna has one antenna and no CSI and receiving side has multiple antennas with perfect CSI, then the incoming signals are suitably weighted by receiver and added coherently at the output, resulting in the signal enhancement. This represents the SIMO condition. Gain obtained in this case is known as receiver gain. Basically, MIMO systems need to have perfect CSI at both transmitting and receiving end to have the array gain.

Diversity gain

Multipath fading has been a major problem in wireless communications. Channel can be in deep fade, if the power of the signal is reduced significantly. This leads to very high BER. To overcome fading effects diversity has been used. This involves using of copies of the signal being transmitted over frequency, time and space.

Interference reduction and avoidance

When multiple users present in a wireless network share frequency and time resources interference occurs. But by exploiting the spatial diversity provided by the MIMO systems this interference can be removed. For example, when there is interference, the array gain results in an increase to noise tolerance and interference power, thus results in an improvement in SINR. The range and coverage of wireless communication has been improved to a great extent by avoidance and reduction in interference.

Spatial multiplexing

Spatial multiplexing leads to a linear increase in capacity of the system without requiring any additional power and bandwidth. This can be achieved only by using MIMO channels. Case of two transmitting and two receiving antennas can be taken and it can be further extended to general MIMO systems. The main data stream is splitted so as to have two bit streams of rate half as compared to main bit streams, these bit streams are then modulated and transmitted from the two transmitting antennas at the same time. If the receiver has perfect CSI it can recover these individual bit streams and then combine these bit streams so that the original bit streams can be recovered. As the receiver is having perfect CSI so it gives receive diversity, on the other hand the system is having no transmitter diversity because the bit streams present are completely from one-another as they carry entirely different data. So it can be concluded that the spatial multiplexing can increase the transmission rate that is proportional to the transmit-receive antenna pairs present.

3.3 Classification of MIMO Techniques

These can be categorized based on the type of channel knowledge available at the transmitter.

3.3.1 MIMO without any Transmit Channel Knowledge

If there is no CSI at the transmitter, the multiple antennas present at the both transmitting and receiving side can allow the extraction of diversity and thus results in an increase in channel capacity. It can be achieved by the use of space-time-codes that can lead of expansion of the symbols over time and space. STBCs are basic spatial temporal codes. A simple transmission diversity technique has been in 1998, by Alamouti for two transmitting antennas [5]. This method is developed to attain full diversity by using simple linear operations both at transmitter and receiver. Alamouti’s technique has been extended in [19] and [35].

3.3.2 MIMO having Partial Transmit Channel Knowledge

Array gain can also be exploited if the transmitter is having a partial CSI. In case of perfect CSI at the transmitter a feedback link with very high rate is required between the transmitter and the receiver. But if I only the quantized version of the channel have to be provided at the transmitter then the feedback link with much lower rate is required.

Antenna selection can rely on partial CSI, transmitting and receiving antennas can be chosen on the basis of order statics of H' that order statics is first and second order. This leads to selection of antennas with lowest correlation. It is quite obvious that, such a technique can only minimize the average error rate. So it can be said that such a technique can mostly provide small diversity advantage and coding gain.

3.3.3 MIMO System with Perfect Transmit Channel Knowledge

Firstly, let us focus on obtaining maximized diversity gain of a $n_R^{'} X n_T^{'}$ MIMO model. As it is clear that it can be obtained when all the transmitting antennas transmit the same signal after weighting it by a column vector $n_T^{'} X1$ given by $W_t^{'}$. The outputs at the receive antenna arrays have been combined to obtain a scalar signal $z^{'}$ by using a weighted summation according to vector $w_r^{'}$ given by $n_R^{'} X1$. Finally the transmission can be represented by:

$$y^{'} = \sqrt{E_s^{'}} H^{'} w_t^{'} c^{'} + n^{'}$$

$$r^{'} = w_r^{'H} y^{'}$$

$$= \sqrt{E_s^{'}} w_r^{'H} H^{'} w_t^{'H} c^{'} + w_r^{'H} n^{'} \qquad (14)$$

In order to maximize the receive SNR maximization of $\left\| w_r^{'H} H^{'} w_t^{'H} \right\|_{F^{'}}^2 / \left\| w_r^{'} \right\|_{F^{'}}^2$ has to be done. To achieve this SVD of $H^{'}$ is done and it is given as:

$$H^{'} = U_{H^{'}}^{'} \sum\nolimits_{H^{'}} V_{H^{'}}^{H}$$

(15)

Here $U_{H^{'}}$ and $V_{H^{'}}$ are $n_{R^{'}} Xr(H^{'})$ and $n_T^{'} Xr(H^{'})$ unitary matrices, where $r(H^{'})$ is the rank of matrix $H^{'}$ and

$$\sum_{H^{'}} = diagonal\{\sigma_1, \sigma_2, \sigma_{3,} ...., \sigma_{r(H^{'})}\} \qquad (16)$$

above equation is a diagonal matrix that contain the singular values of $H^{'}$. Using the above mentioned decomposition method for the channel matrix, it has been clearly given in [56] that the received SNR can be maximized when the transmit singular vector $w_t^{'}$ and the receive singular vector $w_r^{'}$ corresponds to $H^{'}$ with maximum singular value given by $\sigma_{\max} == \max\{\sigma_1, \sigma_2, ..., \sigma_{r(H^{'})}\}$. This technique is named as dominant eigenmode transmission, and equation (3.34) can be given as:

$$z^{'} = \sqrt{E_s^{'}} \sigma_{\max} c^{'} + \hat{n}^{'} \qquad (17)$$

here $\hat{n}' = w_r^{'H}$ variance of n' is given by σ_n^2

equation (3.37) clearly shows that array gain can be given by $\varepsilon\{\sigma_{\max}^2\} = \varepsilon\{\lambda_{\max}'\}$. In case of i.i.d Rayleigh channels the array gain be bounded as follows:

$$\max\{n_t', n_r'\} \le g_a' \le n_T' n_R' \tag{18}$$

For dominant eigenmode transmission the asymptotic array gain in case of i.i.d Rayleigh channel can be given by:

$$g_a' = (\sqrt{n_T'} + \sqrt{n_R'})^2 \tag{19}$$

If at high SNR error rate is upper and lower bounded then the diversity gain can be given by:

$$\breve{N}_\varepsilon' \left(\frac{\rho d_{\min}^{'2}}{4\min\{n_T' n_R'\}} \right)^{-n_t' n_r'} \ge \tilde{P}' \ge \breve{N}_\varepsilon' \left(\frac{\rho d_{\min}^{'2}}{4} \right)^{-n_T' n_R'} \tag{20}$$

Equation (x) says that slope of error rate is $n_T' n_R'$ which is a function of SNR.

3.4 MIMO using Alamouti Space Time Coding

Initially the transmit diversity scheme has been proposed by Alamouti by using STBC. Both encoding and decoding has been done on sets of two symbols that are modulated. So it can be said that the data bits have been first modulated and then mapped to the constellation points. The two modulated symbols entering the decoder can be represented by x_1' and x_2' . when then there is only one transmitting antenna then the above mentioned symbols are transmitted consecutively at two time instants given as t_1' and t_2' . After this the block of two symbols x_1' and x_2' has been send to encoder during each encoding operation, afterwards these are mapped to transmitting antennas according to the matrix given below

$$X' = \begin{pmatrix} x_1' & -x_2^{'*} \\ x_2' & x_1^{'*} \end{pmatrix} \tag{21}$$

Now the outputs from the encoder have been transmitted in two adjacent time periods from two transmitting antennas. Symbols x_1' and x_2' have been transmitted at the same time from transmitting antenna one and transmitting antenna two during the first time slot. Whereas in second time slot $-x_2^{'*}$ has been transmitted from first transmitting antenna and the symbol $x_1^{'*}$ has been transmitted from the second transmitting antenna [5].

It is obvious that the encoding has been done in both time and space domains. Transmitting vector from transmitting antenna one and two can be given by:

$$X^{'t1} = [x_1^{'}, -x_2^{*}]$$

$$X^{'t2} = [x_2^{'}, x_2^{'*}]$$

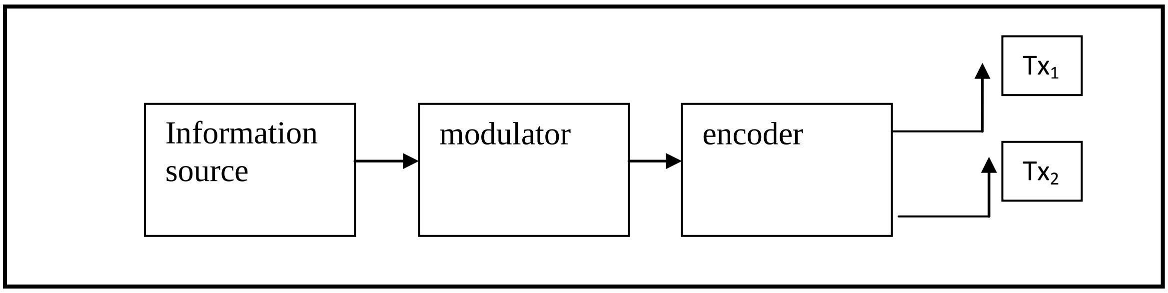

Figure 3.6: Alamouti Space Time Encoder

The key point Alamouti technique is that transmitting symbol sequences from the two transmitting antennas are orthogonal, so the dot product of two symbol sequences is zero, i.e.

$$X^{'t1}.X^{'t2} = x_1^{'} x_2^{'*} - x_2^{'*} x_1 \tag{22}$$

The code matrix is having the given property:

$$X^{'}.X^{'H} = \begin{pmatrix} |x_1^{'}|^2 + |x_2^{'}|^2 & 0 \\ 0 & |x_1^{'}|^2 + |x_2^{'}|^2 \end{pmatrix} \tag{23}$$

$$= \left(|x_1^{'}|^2 + |x_2^{'}|^2 \right) I_2^{'} \tag{24}$$

$I_2^{'}$ represents 2X2 identity matrix.

The symbols that are received by the receiver during two time slots are given by:

$$r_1^{'} = h_1^{'} x_1^{'} + h_2^{'} x_2^{'} + n_1^{*} \tag{25}$$

$$r_2^{'} = -h_1^{'} x_2^{'*} + h_2^{'} x_1^{'*} + n_2^{'} \tag{26}$$

Power spectral density of independent complex va

riables $n_1^{'}$ and $n_2^{'}$ per dimension is $N_0^{'}/2$ and these variables have zero mean.

3.5 CFO

3.5.1 Introduction

Communication systems making use of OFDM modulation suffers from various disadvantages that are caused by the environment. In order to attain the spectral efficiency and simple transmitter and receiver designs, various issues occurring in an OFDM system must be addressed carefully. For efficient transmission and reception of the signal the receiver must be synchronized with the transmitter in time, frequency and phase. Frequency offset present in an OFDM system is a result of two things: misalignment of the transmitting frequency and the frequency received at the receiver, mismatch occurring between transmitting and receiving sampling clocks. We are going to discuss Carrier frequency offset

OFDM systems are more prone to frequency errors when compared to single carrier systems. Frequency offset has been occurring at the receiver due to the instability of local oscillator and variation in the working conditions at transmitting and the receiving end, Doppler occurring because of the relative motion of receiver and transmitter, or the phase noise that occurs because of channel impairments. The degradation is the result of the ICI that has been caused by neighbouring subcarrier and the signal amplitude reduction of the desired subcarrier. As given in figure 3.9. Amplitude loss is caused because the wanted subcarrier has not been sampled at the peak point of the sinc function of DFT. Finally the adjacent subcarriers result in interference that occurs because the sampling of the signal does not occur at the zero crossings. Effect of CFO on SNR is studied by T. Pollet et al. [57]. For relatively small errors in frequency, degradation can be given by:

$$SNR_{loss}(dB) \approx \frac{10}{3\ln 10} (\Pi T^{'} f_{\Delta}^{'})^2 \frac{E_s}{N_o} \tag{27}$$

Here $T^{'}$ is sampling period $f_{\Delta}^{'}$ is the offset in frequency. Syst Δf em performance is determined by the type of modulation. It has been quite obvious that modulation schemes having large constellation points are more prone to offset in frequency as compared to modulation schemes with small constellations. This is because the SNR needed for modulation scheme with higher constellation are high even to get the same BER performance.

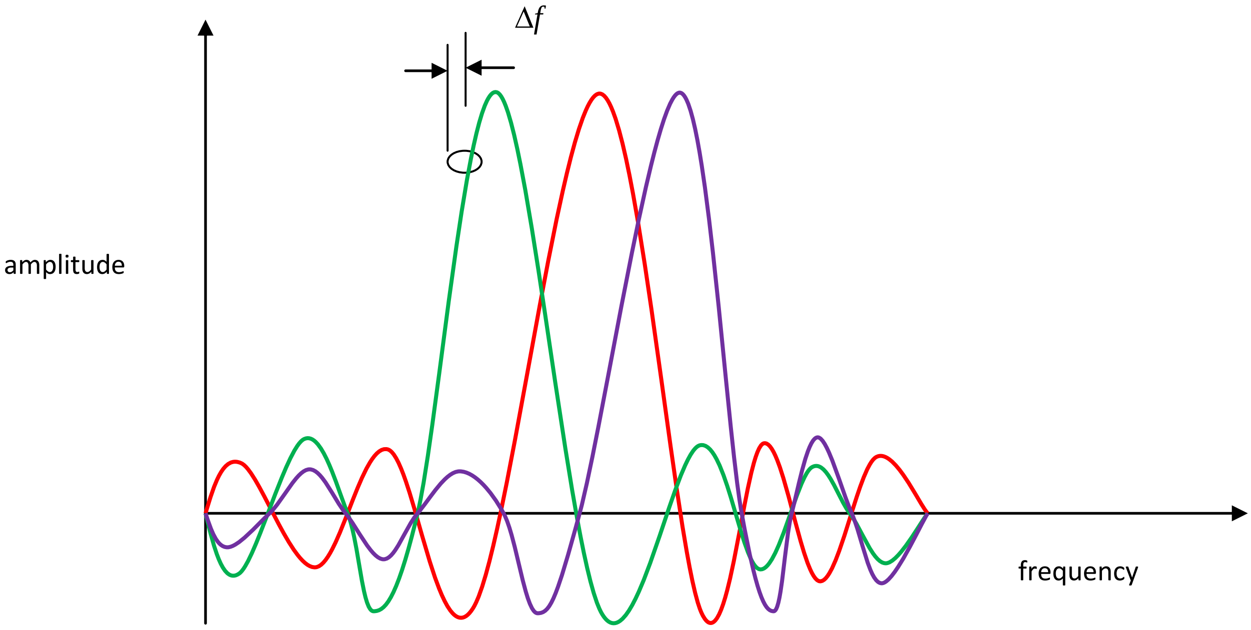

Figure 3.7: Orthogonality Loss Because of Sampling Offset [53]

It is supposed that subcarriers present in an OFDM system are represented by orthogonal frequency tones present at the output of A/D converter and then is given by:

$$\Phi_k^{'}(t) = e^{j2\Pi f^{'} kt/T^{'}} \tag{28}$$

And

$$\Phi_{k+m}^{'}(t) = e^{j2\Pi(k+m)t} \; / \, T^{'} \tag{29}$$

Here $T^{'}$ represents the sampling period. It has been assumed that because of frequency drift, the receiving station is having a frequency offset of $\delta^{'}$ occurring from $k-th$ to $(k+m)th$ tone and is given as:

$$\Phi_{k+m}^{'\delta^{'}}(t) = e^{j2\Pi\left(k+m+\delta^{'}\right)t} \; / \, T^{'} \tag{30}$$

Because of the presence of frequency offset there is an occurrence of interference between $(k+m)th$ and kth channels, as indicated by [58]

$$I'_m(\delta) = \int_0^{T'} e^{jk2\Pi t/T'} e^{-j}\left(k+m+\delta'\right)2\Pi t/T'dt = \frac{T'(1-e^{-j2\Pi\delta'})}{j2\Pi(m+\delta')} \tag{31}$$

And

$$\left|I'_m(\delta')\right| = \frac{T\left|\sin(\pi\delta')\right|}{\pi\left|m+\delta'\right|} \tag{32}$$

Total power loss because of this interference from all N' subcarriers can be given as:

$$\sum_m I'^2_m(\delta) = (T'\delta')^2 \sum_{m=1}^{N'-1} \frac{1}{m^2} \approx (T'\delta')^2 \frac{23}{14} N' >> 1(N' > 5enough) \tag{33}$$

3.5.2 ICI Reduction Methods

1. ICI self cancellation
2. Frequency domain equalization
3. Pulse shaping
4. Time domain windowing

3.5.2.1 ICI Self Cancellation

It has been observed that the variation between ICI coefficients of two adjacent subcarriers has been very small. It leads to the foundation of ICI self cancellation. In it one symbol is modulated in to two adjacent subcarriers rather than one data symbol modulated on one sub-carrier. Let us suppose that symbol $'a''$ is modulated on first subcarrier and $'-a''$ is modulated on second subcarrier. It results in cancellation of ICI generated between two subcarriers. Above method is best for the case of multipath fading channels because there is no need of channel estimation. This happens because of the random channel changes that occur in multipath case leading to failure of channel estimation.

ICI Cancellation Modulation

It has been assumed that in OFDM communication system, offset in frequency has been normalized by ε' that is the subcarrier separation, finally the signal received on $k'th$ subcarrier is given by:

$$y^{'}(k)=x^{'}(k)s^{'}(0)+\sum_{l=0,l\neq k}^{N^{'}-1}x^{'}(l)s^{'}(l-k)+n_{k}^{'},k=0,1,....,N^{'}-1 \tag{34}$$

Here $x^{'}(k)$ is the symbol transmitted on the $k-th$ subcarrier, $N^{'}$ is the total subcarriers and $n_{k}^{'}$ denotes noise sample. First term present on right side is the desired signal. ICI components are given by second term. Whereas ICI coefficient present between kth and lth subcarriers has been given by $s^{'}(l-k)$ and $s^{'}(l-k)$ can be written as:

$$s^{'}(l-k)=\frac{\sin(\pi(l+\varepsilon^{'}-k))}{N^{'}\sin\left(\frac{\pi}{N^{'}(l+\varepsilon^{'}-k)}\right)}.\exp\left(j\pi\left(1-\frac{1}{N^{'}}\right)(l+\varepsilon^{'}-k)\right) \tag{35}$$

It is quite obvious that variation of ICI coefficients presents between two adjacent subcarriers $\{s^{'}(l-k)\,\text{and}\,s'(l+1-k)\}$ has been small. So, if the data symbol pair $(a^{'},-a^{'})$ has been modulated on two consecutive subcarriers $(l,l+1)$ it leads to the cancellation of ICI signals that has been generated by l due to the presence of ICI signals that has been generated by $l+1$ subcarrier.

It is assumed that the transmitted symbols are given as:

$$x^{'}(1)=-x^{'}(0),x^{'}(3)=x^{'}(2),....,x'(n-1)=-x^{'}(n-2), \tag{36}$$

The signal that is received on kth subcarrier is given by:

$$y^{''}(k)=\sum_{\substack{l=0\\l=even}}^{N^{'}-2}x^{'}(l)\left[s^{'}(l-k)-s^{'}(l+1-k)\right]+n_{k}^{'} \tag{37}$$

Parallely the signal received on $k+1$ subcarrier becomes

$$y^{''}(k+1)=\sum_{\substack{l=0\\l=even}}^{N^{'}-2}x^{'}(l)\left[s^{'}(l-k-1)-s^{'}(l-k)\right]+n_{k+1}^{'} \tag{38}$$

ICI coefficient is given by:

$$s^{''}(l-k)=s^{''}(l-k)-s^{''}(l+1-k) \tag{39}$$

It has been founded that $s^{''}(l-k)<<s^{'}(l-k)$

ICI Cancelling Demodulation

ICI cancelling demodulation has to be done so as to further reduce ICI. Demodulation should work so that every signal that is present on $(k+1)th$ subcarrier multiplies with "-1" and then summation of this is done with the signal that is present on the kth subcarrier. Symbol decision is made based on the resultant sequence obtained. This can be given as:

$$y'''(k) = y''(k) - y''(k+1) \tag{40}$$

$$= \sum_{\substack{l=0 \\ l=even}}^{N'-2} x'(l)[-s'(l-k-1) + 2s'(l-k) - s'(l-k+1)] + n'_k - n'_{k+1} \tag{41}$$

ICI coefficients then obtained are

$$s'''(l-k) = -s'(l-k-1) + 2s'(l-k) - s'(l-k+1) \tag{42}$$

From various results obtained it has been concluded that when ICI cancelling modulation has been applied then ICI signals become smaller. Further reduction in ICI can be obtained by ICI cancelling demodulation.

Combination of ICI cancelling demodulation and modulation is known as ICI self-cancellation scheme.

Drawback

There is a drawback of the above mentioned scheme that it reduces bandwidth efficiency of the system because two subcarriers are used by same symbol.

Advantages

1. Can be efficiently used for multipath fading channels
2. Can be used efficiently for flat channels.
3. Estimation of channel is not needed.
4. Equalization of channel is not required.
5. Implementation of this scheme is very simple
6. It is very effective moreover complexity is also low.

3.5.2.2 Frequency Domain Equalization

Due to the presence of fading distortion present in channel ICI occurs in the OFDM demodulator. ICI pattern varies from one frame to other frame but it is invariant for all the symbols that are present in same demodulated data frame.

Noise enhancement occurs when we do compensation of the fading distortion that is present in the time domain. That’s why equalization in frequency domain is done in order to reduce the ICI with the help of various equalization techniques. ICI for each frame can be estimated by the insertion of frequency domain pilot symbols and it is clearly shown in figure 3.9 given below:

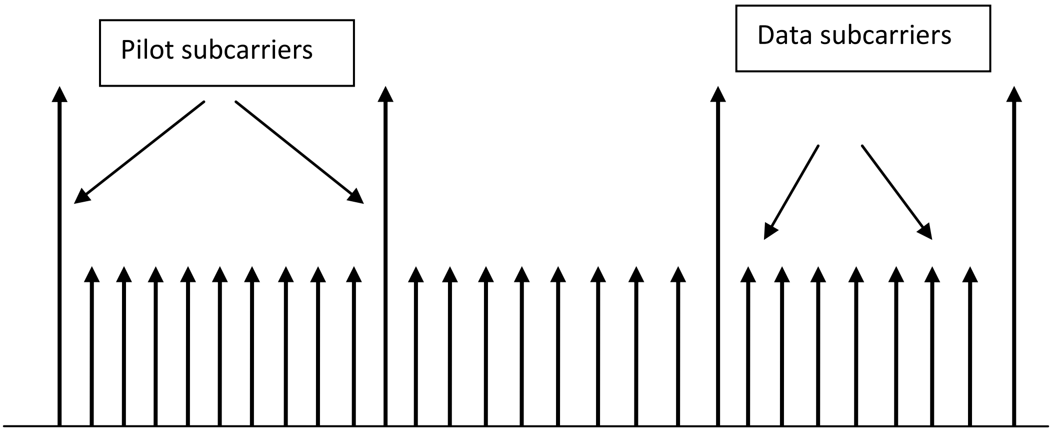

Figure 3.8: pilot subcarrier arrangement

For the elimination of ICI occurring in the frequency domain the equalizer coefficients can be obtained from pilot symbol pattern so an appropriate equalizer could be constructed.

Drawbacks

Above method leads to the reduction of ICI that has been introduced by fading distortion but it is not the main source of ICI. Presence of ICI is mainly due to Doppler shift and the occurrence of mismatch in frequency of transmitter and receiver. Moreover the addressing to these problems is not provided by the above method.

Given method is suitable only for flat fading, whereas in practice the channels available are frequency selective because of the presence of multipath components.

Moreover channel estimation is required for every frame. And it is a well known fact that the channel estimation is very complex, time consuming and expensive. So, this method is not very accurate results.

3.5.2.3 Pulse Shaping

As it is very clearly depicted in an OFDM spectrum that every carrier consists of a main lobe and a number of side lobes that are having reduced amplitude and are following them. Till the time orthogonality has been maintained no interference occurs between the carriers because of the presence of spectral null at the peak of every subcarrier.

But if a frequency offset is present there is a loss of orthogonality of the signal. Because of this some amount of side lobe’s power known as ICI will occur at centre of individual carriers. As the offset in frequency increases the ICI power also increases. Side lobes have been effectively reduced by using pulse shaping method. Ultimately leads to ICI power reduction.

Disadvantage

Implementation is very complex.

3.5.2.4 Time Domain Equalization

This is very clear that the power spectrum for an OFDM signal is very wide. So if the signal has to be transmitted using a band limited channel, some spectrum portion gets cut out, that will result in inter carrier interference.

In order to reduce the interference, signal wave spectrum should be concentrated. This can be obtained by doing the windowing of the signal. Generally, windowing is the process in which the signal to be transmitted has been multiplied by a suitable function. Same window has been employed at the receiver side in order to get back the original signal.

If Nyquist’s vestigial symmetry criterion has been satisfied by the product of window functions than the ICI can be eliminated.

Frame by frame windowing

Orthogonal multicarrier signal $s^{'}(t)$ that is time limited frame-by-frame can be given as:

$$s'(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{N'-1} w(t-kT')a_{n,k} \exp(jnw_{\Delta}(t-kT') \tag{43}$$

here nw_{Δ} $n = 0,1.........., N'-1$ frequencies of carrier signals that are equally spaced b w_{Δ}, $a_{n,k}$ represents a complex sequence. Length of $w(t)$ is given by T' , multicarrier signal that is present in every frame undergoes a change in its corresponding waveform because of $w(t)$.

By the correct selection of the window function and the separation between the carriers ICI for the signal can be eliminated. ICI has been calculated by carefully observing the cross correlation that is present between adjacent carriers of the signals that are transmitted. Condition for the elimination of ICI is given by:

$$a'_{n,k} a'^{*}_{m,k} \int_{-T'/2}^{T'/2} w^2(t) \exp(-jw_{\Delta}(n-m)t)dt = 0 \text{ for } m \neq n \tag{44}$$

If Nyquist's vestigial symmetry criterion has been fulfilled by $w^2(t)$ then the above condition is satisfied. $T'/2 \leq t \leq T'$ and T' is a time parameter

then $w(t)$ that satisfies Nyquist criterion is given:

$$w^2(t) = \begin{cases} x'(t) + y'(t), T'/2 \leq t \leq T'/2 \\ 0, otherwise \end{cases} \tag{45}$$

$x'(t)$ denotes a rectangular window function present over $[-T''/2, T''/2]$ whereas $y'(t)$ denotes an even function having odd symmetry for $-T''/2$ and $T''/2$.

T' can be given as $T' = T''(1+\alpha')$, we know that α' denotes the roll-off parameter occurring in raised cosine function. For ICI free condition frequency separation occurring between consecutive carriers is:

$$w_{\Delta} = \frac{2\pi(1+\alpha')}{T'} \tag{46}$$

For N' subcarriers total bandwidth requirement is $(1+\alpha')/T'_s$ and T'_s denotes the symbol interval of sequence that has been given as input and $T' = NT'_s$

Disadvantages

ICI that occurs because of the bandwidth limitation of the channel is reduced by above mentioned technique but this technique is not main source of ICI generation. Main source of ICI is the Doppler shift and the frequency mismatch present among the transmitter and receiver. The method cannot handle these two conditions. Hence frame by frame windowing has to be done and it results in reduction of the spectral efficiency to a great extent. So, this method is not very effective.

3.5.3 ICI Reduction using Self Cancellation

3.5.3.1 System Model

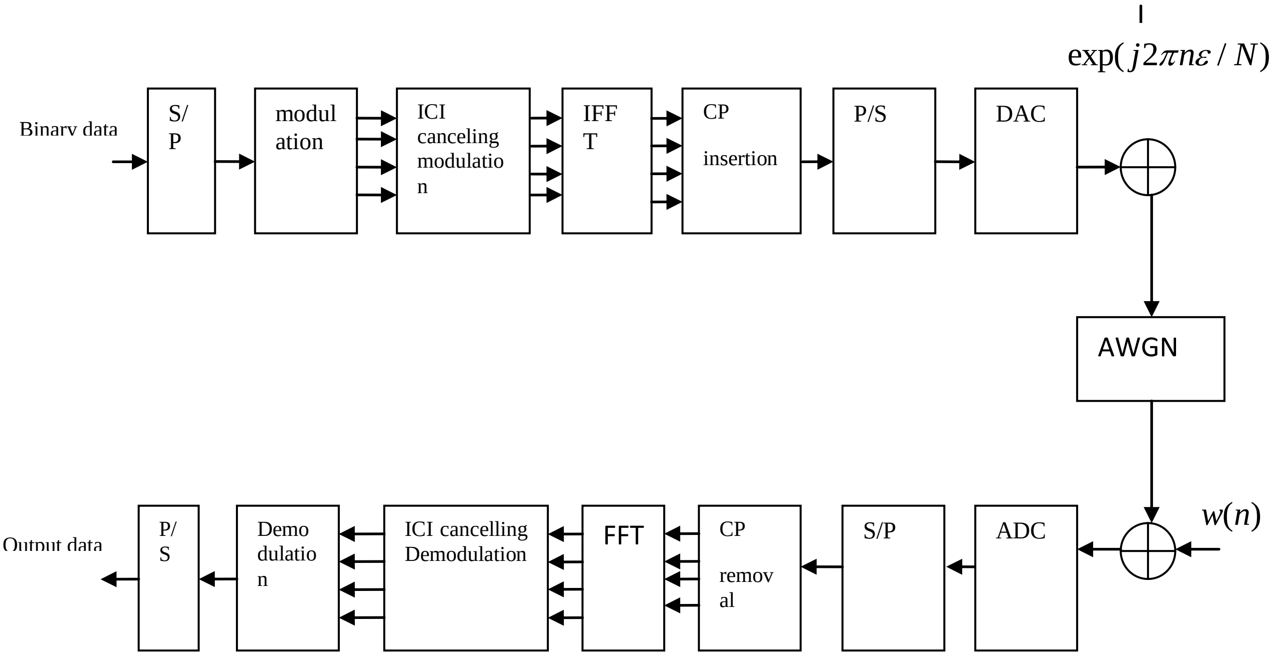

Figure 3.9 OFDM system model with ICI self cancellation technique

Serial input bit stream having high data rate has been given to a serial to parallel converter in order to have an output parallel stream with low data rate. Binary data stream has been taken as an input bit stream. Parallel bit stream with low data rate has been modulated in a signal mapper. Any modulation technique can be used. Now, the modulated data has been fed as an input data to ICI cancelling modulation. This provides us various ICI coefficients. After this, OFDM symbols are given to the IFFT block in order to give each subcarrier a specific frequency. These frequencies are selected in such a way so that these are orthogonal to each other. So we can say that orthogonality has been introduced in this block. By employing IFFT block OFDM symbols that are present in frequency domain gets converted into time domain. Afterwards, GI has been inserted to avoid intersymbol interference. Now OFDM symbols are feed to parallel to serial converter. A frame has been constituted by these symbols. One OFDM signal has been regarded as a combination of number of frames. Now this OFDM signal passes through a DAC. For further transmission DAC gives this OFDM signal to RF power amplifier. Because of the mismatch in frequency among transmitter and receiver there is occurrence of frequency offset. Frequency offset is also introduced by the Doppler shift. After this the signal passes through AWGN channel. Now the OFDM signal received at the receiver has been given to ADC and its output is fed to serial to parallel converter. After this guard interval has been removed and the entire signal is fed to FFT block. It gives us the OFDM symbols in frequency domain. These symbols undergo ICI cancellation demodulation. It is now given to signal demapper. Lastly, low data rate stream of parallel bits has been transformed back into bit stream with high data rate.

3.5.3.2 Analysis of Inter-Carrier Interference

The major disadvantage of OFDM is its liability to small frequency differences occurring at the transmitter and the receiver, termed as frequency offset. There are various reasons for this frequency offset such as Doppler shift and frequency differences between local oscillator frequency at transmitter side and receiver side. Here, frequency offset can be modelled as multiplicative factor present in the channel as given in figure 5.1

The signal that is received is represented as:

$$y^{'}(n) = x^{'}(n)e^{j2\pi n\frac{\varepsilon^{'}}{N^{'}}} + w^{'}(n) \tag{47}$$

Here $\varepsilon^{'}$ denotes the normalized frequency offset, which is, $\varepsilon^{'} = \Delta f / (1/N^{'}T)$ here Δf is the difference in frequency of the transmitter and receiver, and $N^{'}T$ represents the FFT period time interval [59]. AWGN that has been introduced in channel is given by $w^{'}(n)$ and $T^{'}$ symbol period of the subcarrier.

3.5.3.3 ICI Mechanism in Standard OFDM System

Channel frequency offset effect on the received signal is understood clearly by considering $Y^{'}(k)$ that is the received symbol present on the kth sub-carrier. In an OFDM system, it has been assumed that the offset in channel frequency has been normalized by the separation between subcarrier is $\varepsilon^{'}$. Signal that has been received on the kth is given by:

$$y^{'}(k) = x^{'}(k)s^{'}(0) + \sum_{l=0,l\neq k}^{N^{'}-1} x^{'}(l)s^{'}(l-k) + n_{k}^{'} \tag{48}$$

$k = 0,1,2,....N^{'} - 1$.

Here total number of subcarriers are $N^{'}, x^{'}(k)$ represents the symbol that is being transmitted on the kth subcarrier and the additive noise is represented by $n_{k}^{'}$. As per ICI components are concerned these are the interfering signals that are not transmitted on kth subcarrier but are transmitted by others. Complex ICI coefficients that are present in the received signal is given by $s^{'}(l-k)$. ICI coefficient occurring between lth and kth subcarriers is given by the sequence $s'(l-k)$, that is expressed as:

$$s^{'}(l-k) = \frac{\sin(\pi(l+\varepsilon^{'}-k))}{N^{'}\sin(\pi(l+\varepsilon^{'}-k)/N^{'})}\exp(j\pi(1-\frac{1}{N^{'}})(l+\varepsilon^{'}-k)) \tag{49}$$

Here normalized frequency offset has been represented by $\varepsilon^{'}$, and $\varepsilon^{'} = \Delta f/(1/N^{'}T^{'})$ whereas Δf is the difference in frequency occurring between the receiver and the transmitter, $N^{'}T^{'}$ represents the FFT interval period.

ICI self cancellation method is based on the fact that there is a gradual change imaginary and real parts of the ICI coefficients with respect to index k of the subcarrier, so , the difference present between adjacent ICI coefficients is small. ICI power level of the system can be estimated by using CIR [60]. When derivation of CIR expression is done then AWGN is not taken into account.

While doing modulation, single data symbol has been mapped to two adjacent subcarriers having weighting coefficients that are predefined. Calculation of weighting subcarriers is done carefully so that ICI coefficients occurring within adjacent subcarriers must be cancelled at the receiver end, that’s why this method is known as “self-cancellation”. But there is a reduction in bandwidth efficiency in case of self-cancellation technique. With this technique CIR will increase, leading to improvement in bit error rate. Further by doing simulations it has been observed that the major contribution for ICI is by the adjacent carriers. ICI self-cancellation technique makes use of this very fact.

The CIR is the ratio of power of the signal to the power of the interference components. Derivation of this has been done from $y^{'}(k)$ and is shown below. It has been assumed in the derivation that mean of the transmitted data is zero and transmitted symbols on various subcarriers are supposed to be statistically independent. Signal power of the received signal on kth subcarrier is given by:

$$E\left[c^{'}(k)^{2}\right]=E\left[\left|x^{'}(k)s^{'}(0)\right|^{2}\right] \tag{50}$$

Whereas power of ICI signal is given by:

$$E\left|(k)\right|^{2}=E\left[\left|\sum_{l=0,l\neq k}^{N^{'}-1}x^{'}(l)s^{'}(l-k)\right|^{2}\right] \tag{51}$$

Equation for CIR is given below

$$CIR=\frac{s^{'}(k)^{2}}{\sum_{l=0,l\neq k}^{N^{'}-1}s^{'}(l-k)^{2}}=\frac{\left|s^{'}(0)^{2}\right|}{\sum_{l=1}^{N^{'}-1}s^{'}(l)^{2}} \tag{52}$$

ICI self cancellation [61] technique has been developed in 2001 to suppress ICI occurring in OFDM

3.5.3.3.1 ICI Cancelling Modulation

Transmitted signals in case of ICI self-cancellation technique [59] has been constraint to

$$x^{'}(1)=-x^{'}(0),x^{'}(3)=-x^{'}(2),.........,x^{'}(n-1)=-x^{'}(n-2), \tag{53}$$

By making use of (5.3) the above mentioned transmitted symbol assignment permits the signal received on subcarriers $(k+1)$ and k is given by:

$$y^{''}(k)=\sum_{\substack{l=0\\l=even}}^{N^{'}-2}x^{'}(l)[s^{'}(l-k)-s^{'}(l+1-k)]+n_{k}^{'} \tag{54}$$

$$y^{''}(k+1)=\sum_{\substack{l=0\\ l=even}}^{N^{'}-2} x^{'}(l)[s^{'}(l-k-1)-s^{'}(l-k)]+n^{'}_{k+1} \tag{55}$$

ICI coefficient $s^{'}(l-k)=s^{'}(l-k)-s^{'}(l+1-k)$ has been denoted by [61]

$$s''(l-k)=s^{'}(l-k)-s^{'}(l+1-k) \tag{56}$$

3.5.3.3.2 ICI Cancelling Demodulation

Redundancy has been introduced in the received signal due ICI modulation because only one data symbol has been transmitted by each pair of subcarriers. This redundancy can be used to achieve improved power performance, while it surely results in decreased bandwidth efficiency of the system. In order to exploit the advantages provided by the redundancy, signal received on the subcarrier $(k+1)th$, has been subtracted from that present on kth subcarrier. Mathematically it can be written as:

$$Y^{'''}(k)=y^{''}(k)-y^{''}(k+1) \tag{57}$$

$$=\sum x^{'}(l)[-s^{'}(l-k-1)+2s^{'}(l-k)-s^{'}(l-k+1)]+n^{'}_{k}-n^{'}_{k+1} \tag{58}$$

Ultimately the ICI for the above mentioned signal becomes

$$s^{'''}(l-k)=-s^{'}(l-k-1)+2s^{'}(l-k)-s^{'}(l-k+1) \tag{59}$$

Combination of modulation and demodulation is termed as ICI self-cancellation. Higher CIR has been provided by the reduction of ICI occurring in the ICI self-cancellation technique [59].

From (5.11), theoretical value of CIR can be given as:

$$CIR=\frac{\left|-s^{'}(-1)+2s^{'}(0)-s^{'}(1)\right|^{2}}{\sum_{l=2,4,6}^{N^{'}-1}\left|-s^{'}(l-1)+2s^{'}(l)-s^{'}(l+1)\right|^{2}} \tag{60}$$

As it has been mentioned that , bandwidth efficiency of the system has been reduced by this scheme. But by making use of signals of large alphabet size it can be compensated. If we use the theoretical results for CIR improvement then it leads to increase in system power efficiency and provides better results for BER. So, there occurs a trade-off between power and bandwidth in case of ICI self-cancellation technique.

3.6 Cooperative Diversity

In case of wireless transmission of signal, the quality of the signal is occasionally affected badly by the poor channel quality because of the occurrence of fading due to multi-path propagation of the signal. In order to minimize such effects diversity is employed to transfer varying samples of the same signal on independent channels. We make use of third station as relay to realize diversity.

Further there have been various approaches so to implement diversity. MIMO systems are effectively employed to attain space, time or frequency diversity. But employing MIMO systems is not always possible or we can say that sometimes destination is just too far that having good quality of signal is just next to impossible. So, to get diversity there is an interesting way out in which an Adhoc network is build by employing an another mobile station known as relay. System model for the same is given in figure 3.7. When the sender $S^{'}$ is sending the data to destination $D^{'}$ the relay keeps on listening to this signal transmission. After processing the received data burst the relay sends it to the destination, here combination of these two received signals is done. As given in [62], orthogonal channels have been used for these transmissions.

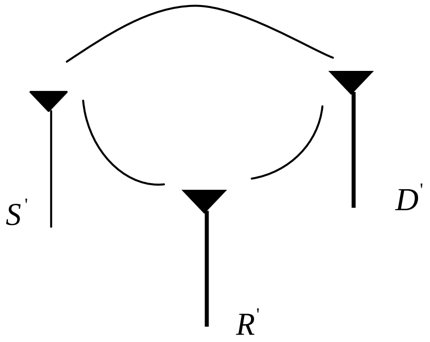

Figure 3.10: One Link is used for Direct Transmission of Data and in Other Link a Relay is used.

In this type of systems combination of various relaying protocols and combining methods have been used. Two transmission protocols that we are going to describe are: Decode and Forward and amplify and Forward. In simulation both of these are able to achieve full diversity as depicted in [62]. Three types of combining methods have been discussed that vary from each other in terms of CSI they use.

3.6.1 Cooperative Transmission Protocols

Here we discuss how the received data has been processed by the relay prior to its transmission to the destination.

3.6.1.1 Amplify and Forward

Amplify and forward method has been used only if the relay station is having limited computing power/time available in other words it can be said that if the time delay, generated because of decoding and encoding the message has to be kept low.

The basic idea behind AAF is very generic. The received signal at the relay station has been attenuated and it should be amplified before sending it again. There is a drawback of doing this that is the noise signal is also amplified.

Block wise amplification of the received signal occurs. It has been assumed that there occurs perfect estimation of the channel characteristics, if the incoming signal is given by:

$$y_d^{'}\left[n\right] = h_{s,d}^{'}[n^{'}].x_s^{'}[n^{'}] + z_{s,d}^{'}[n] = d_{s,d}^{'}.a_{s,d}^{'}[n].x_s^{'}\left[n^{'}\right] + z_{s,d}^{'}[n^{'}] \tag{61}$$

the amplification gain can be written as:

$$E\left[\left|y_r^{'2}\right|\right] = E\left[\left|h_{s,r}^{'}\right|^2\right]E\left[\left|x_s^{'}\right|^2\right] + E\left[\left|z_{s,r}^{'}\right|^2\right] = \left|h_{s,r}^{'}\right|^2 \xi + 2\sigma_{s,r}^2, \tag{62}$$

here r represents the relay and s represents the sender. Relay use a gain of $\beta^{'}$ so that the data that has been send from the relay station has same power as that of the sender.

$$\beta^{'} = \sqrt{\frac{\xi}{\left|h_{s,r}^{'}\right|^2 \xi + 2\sigma_{s,r}^2}} \tag{63}$$

This term needs to be calculated for each block and thus the channel characteristics of each block must be estimated.

3.6.1.2 Decode and Forward

In present scenario the transmission is rarely analogue and the various relays available are having enough computing power, that’s why DAF is a preferred method for data processing in the relay. Signal that has been received is first decoded and then coded again. This leads to avoidance of noise amplification that occurs in case of AAF protocol. Two main implementations of this system are present.

Relay needs to decode the parent message completely so this leads to high computing time, but at the same time this technique offers large number of advantages. If error correcting codes are present in parent message, the errors in received bits can be corrected at the relay station. But if no such codes are present checksum can be used by the relay in order to find out if there is any error present in the received signal.

But the source message might not be fully decoded always. The additional delay required to decode and process the source message fully is not permissible, because the relay is not having much computing capacity or in order to protect the sensitive data parent message need to be coded. In that case only decoding and encoding of signal is done symbol by symbol.

3.6.2 Combining Type

If with the same data there is more than one incoming transmission, then the signals need to be combined before comparing them.

3.6.2.1 Equal Ratio Combining (ERC)

If computation time is critical parameter, or the quality of channel cannot be estimated, then all the available signals are simply added. It is the simplest way of combining the signals, but the resulting performance is not that satisfactory.

$$y_d^{'}[n] = \sum_{i=1}^{k} y_{i,d}^{'}[n] \tag{64}$$

Since we are talking about only one relay, above equation can be written as:

$$y_d^{'}[n] = y_{s,d}^{'}[n] + y_{r,d}^{'}[n], \tag{65}$$

Here $y_{s,d}^{'}$ represents the signal that is received from sender and $y_{r,d}^{'}$ represents the signal that is received from the relay.

3.6.2.2 Fixed Ratio Combining (FRC)

By using fixed ratio combining performance of the system has been improved to a great extent. Now the received signals are not simply added, but are weighted by a constant ratio, that does not change much during the entire communication. Since the average channel quality has been represented by the ratio so the temporary influences affecting the channel can be ignored. Whereas, the influences that can change the average quality of the channel need to be considered. Since there is a slight change in the ratio of so a little computing time is needed. The FRC is given by:

$$y_d^{'}[n] = \sum_{i=1}^{k} d_{i,d}^{'} . y_{i,d}^{'}[n] \tag{66}$$

Here $d_{i,d}^{'}$ represents weighting of the signal $y_{i,d}^{'}$. If only one relay is used above equation can be simplified as:

$$y_d^{'}[n] = d_{s,d}^{'} . y_{s,d}^{'}[n] + d_{s,r,s}^{'} . y_{r,d}^{'}[n] \tag{67}$$

Here weight of direct link is represented by $d_{s,d}^{'}$ and that of multi-hop link by $d_{s,r,d}^{'}$

3.6.2.3 Maximum Ratio Combining (MRC)

MRC helps to attain the best possible results, in it each input signal is multiplied with its conjugated channel gain. It has been assumed that the attenuation and phase shift of the channel has been known at the receiver.

$$y_d^{'}[n] = \sum_{i=1}^{k} h_{i,d}^{'*}[n] . y_{i,d}^{'}[n] \tag{68}$$

But by employing single relay equation can be given as:

$$y_d^{'}[n] = h_{s,d}^{'*}[n] y_{s,d}^{'*}[n] + h_{r,d}^{'*}[n] y_{r,d}^{'}[n]. \tag{69}$$

3.6.3 MIMO OFDM with Cooperative Diversity System Model

3.6.3.1 Working

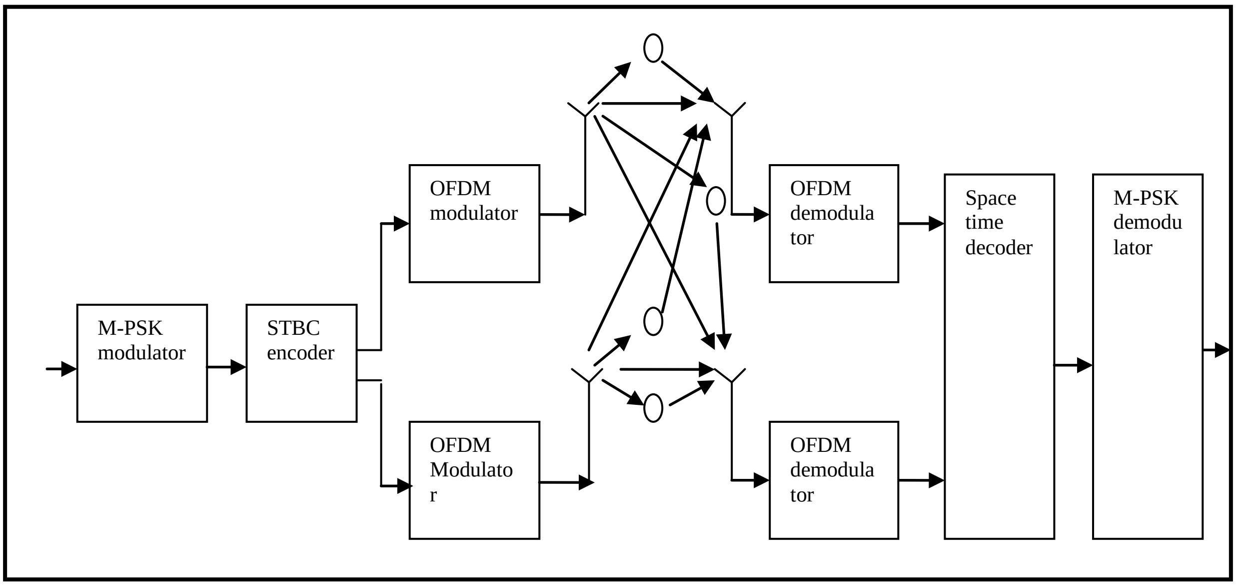

Figure 3.11: System Model of STBC MIMO-OFDM with Cooperative Diversity

The input signal $x'(t)$ is first modulated using MPSK modulation technique, afterwards STBC encoding of the same has been done. This is followed by OFDM modulation. Then cooperative diversity scheme is employed by using 4 relays. Further at the receiving end MRC combining technique is used. At the receiver side OFDM demodulation is performed that has been followed by space time decoding and finally M-PSK demodulation is done and output signal $y'(t)$ is obtained.

3.6.3.2 Exact BER Analysis of MPSK Modulation Scheme for OFDM system

Collection of signals modulated by using MPSK Modulation technique that are being transmitted on k^{th} subcarrier has been given by $G_k' = \{G_{1,k}', G_{2,k}', ..., G_{M,k}'\}$. Signal that has been up converted and presented at the transmitter is given by:

$$R_1'(t) = \frac{1}{\sqrt{2T_s'}}(R_1(t)e^{j2\Pi f_c t} + R_1^*(t)e^{-j2\Pi f_c t}) \qquad (70)$$

OFDM signal that has to be transmitted can be given by:

$$R_1(t) = \sum_{k=0}^{N_s-1} G_{q,k}' e^{j2\Pi kt/T_s'}, q = 1, 2, ..., M \qquad (71)$$

Signal obtained after MPSK modulation is given by:

$$G'_{q,k} = \sqrt{E''_s}\, e^{j\varphi'_{q,k}}, k = 0,1,.......N_s - 1, q = 1,2,M \qquad (72)$$

$\varphi'_{q,k} =$ Shows the phase of the q^{th} signal present on k^{th} subcarrier

$\sqrt{E''_s} =$ Gives the amplitude of the q^{th} signal

$E''_s =$ Represents the Average symbol energy

Further the received band pass signal is down converted by using $r_{LO}^{unbalanced}$ that is:

$$r_{LO}^{unbalanced}(t) = \chi' \sqrt{\frac{2}{T'_s}} \cos(2\Pi f_c t + \frac{\theta'_r}{2}) - j\gamma' \sqrt{\frac{2}{T'_s}} \sin(2\Pi f_c t - \frac{\theta'_r}{2}) \qquad (73)$$

$\chi', \gamma' =$ Depicts the amplitude imbalances that occur in the signal because of analog processing

$\theta'_r =$ Shows the deviation from perfect phase quadrature

Now cooperative diversity has been employed with only one station as relay and the protocol used for transmission of signal from relay is amplify and forward. Whenever there is more than one data stream with same data combining of these data streams has been done before doing the comparison. MRC combining technique has been used here. Incoming signal is affected by I/Q imbalances and is given by:

$$\begin{aligned}
r'''(t) &= r'''_I(t) + jr'''_Q(t) \\
&= A'_2 R_1(t) + A'_1 R_1^*(t) + \sqrt{\frac{2}{T'_s}} \left(\int_o^T A'_1 n''(t) e^{j2\Pi f_c t} dt + \int_o^T A'_2 n''(t) e^{-j2\Pi f_c t} dt\right) \\
&= A'_2 R_1(t) + A'_1 R_1^*(t) + \sqrt{\frac{2}{T'_s}} \left(\chi' \int_o^T n''(t) \cos(2\Pi f_c t + \frac{\theta'_r}{2}) dt - j\gamma' \int_o^T n''(t) \sin(2\Pi f_c t - \frac{\theta'_r}{2}) dt\right)
\end{aligned}$$

Where * depicts the complex conjugate, additive Gaussian noise is given by $n''(t)$, A'_1 and A'_2 imbalance coefficients, these are given as:

$$\begin{aligned}
A'_1 &= (\chi' e^{j\frac{\theta'_r}{2}} - \gamma' e^{-j\frac{\theta'_r}{2}})/2 \\
A'_2 &= (\chi' e^{-j\frac{\theta'_r}{2}} + \gamma' e^{j\frac{\theta'_r}{2}})/2
\end{aligned} \qquad (74)$$

Noise component that has been present on the final term of () can be written as $n_I^{''}$ and $n_Q^{''}$ respectively. The joint distribution for these is given below. These posses zero mean

$$E[n_I^{''} n_Q^{''}] = \rho_{IQ}\sigma^2, E[n_I^{''2}] = \chi^{'2}\sigma^2, E[n_Q^{''2}] = \gamma^{'2}\sigma^2$$

Here $\rho_{IQ} = \chi^{'}\gamma^{'}\sin\theta_r^{'}$ this depicts the correlation coefficient present between I/Q branches. $S_{q,k}^{'}$ represents the baseband signal that has been given to FFT block and is shown below:

$$\begin{aligned} S_{q,k}^{'} &= FFT[A_2^{'}R_1(t) + A_1^{'}R_1^{*}(t) + n_I^{''} + jn_Q^{''}] \\ &= A_2^{'}G_{q,k}^{'} + A_1^{'}G_{q',N_s-k}^{'*} + N_{I\_k}^{''} + jN_{Q\_k,}^{''} \\ k &= 0,1,........,N_{s-1,} \\ q',q &= 1,2,......M \end{aligned} \tag{75}$$

Here the MPSK modulated signal that has been transferred from $N_s - k - th$ subcarrier is $G_{q',N_{s-k}}^{'} \in G_{N_{s-k}}^{'} = \{G_{1,N_s-k}^{'}, G_{2,N_s-k}^{'},........,G_{M,N_s-k}^{'}\}$ and it leads to interchannel interference. $N_{I\_k}^{''}$ and $N_{Q\_k}^{''}$ are the noise components present on I/Q branches of k^{th} subcarrier, these have zero mean and are jointly Gaussian distributed, $E[N_{I\_k}^{''2}] = E[N_{Q\_k}^{''2}] = \sigma^2$

Substituting (72) and (74) in (76), we obtain

$$\begin{aligned} S_{q,k}^{'} &= R_{q,I\_k}^{'} + jR_{q,Q\_k}^{'} + N_{I\_k}^{''} + jN_{Q\_k}^{''}, \\ k &= 0,1,.....N_s - 1, q = 1,2,.......M \end{aligned} \tag{76}$$

Components of the signal that are present on I/Q branches of received signal are:

$$\begin{aligned} R_{q,I\_k}^{'} &= \frac{\sqrt{E_s^{''}}}{2}(\chi^{'}\cos(\psi_{q,k} - \frac{\theta_r^{'}}{2}) + \gamma^{'}\cos(\psi_{q,k} + \frac{\theta_r^{'}}{2})) \\ &+ \frac{\sqrt{E_s^{''}}}{2}(\chi^{'}\cos(\psi_{q',N_s-k} - \frac{\theta_r^{'}}{2}) - \gamma^{'}\cos(\psi_{i',N_s-k} + \frac{\theta_r^{'}}{2})), q' = 1,2,.....M \end{aligned} \tag{77}$$

$$\begin{aligned} R_{q,Q\_k}^{'} &= \frac{\sqrt{E_s^{''}}}{2}(\chi^{'}\sin(\psi_{q,k} - \frac{\theta_r^{'}}{2}) + \gamma^{'}\sin(\psi_{q,k} + \frac{\theta_r^{'}}{2})) \\ &+ \frac{\sqrt{E_s^{''}}}{2}(-\chi^{'}\sin(\psi_{q',N_s-k} - \frac{\theta_r^{'}}{2}) + \gamma^{'}\sin(\psi_{q',N_s-k} + \frac{\theta_r^{'}}{2})), q' = 1,2,.....M \end{aligned} \tag{78}$$

From () and () it is noted that due I/Q imbalances occurring at OFDM system's receiving end, signal that has been present on $N_s - k - th$ subcarrier will distort the signal transmitted on k^{th} subcarrier. In order to have the conditional probability $P\{S_{1,k}^{'} \in C_{1,k} \mid R_t^{'} = G_{1,k}^{'}\}$ such that the signal that has been received i.e $S_{1,k}^{'}$ belongs to $C_{1,k}$ which shows the correct decision region of $G_{1,k}^{'}$, usage of coordinate rotation shifting technique has been done , that is given as follows:

$$\begin{pmatrix} X_j^{'} \\ Y_j^{'} \end{pmatrix} = \begin{pmatrix} \cos\Phi_j^{'} & \sin\Phi_j^{'} \\ -\sin\Phi_j^{'} & \cos\Phi_j^{'} \end{pmatrix} \begin{pmatrix} I \\ Q \end{pmatrix}, j = 1, 2 \tag{79}$$

$P\{S_{1,k}^{'} \in C_s \mid R_t^{'} = G_{1,k}^{'}\}$ has been calculated by:

$$\begin{aligned} & P\{S_{1,k}^{'} \in C_s \mid R_t^{'} = G_{1,k}^{'}\} = P\{Y_1^{'} \le 0, Y_2^{'} \le 0\} \\ & = \int_{-\infty}^{0}\int_{-\infty}^{0} f(y_1^{'}, y_2^{'}, \rho_{Y_1^{'}Y_2^{'}}) dy_2^{'} dy_1^{'} \end{aligned} \tag{80}$$

$$\begin{aligned} & \int_{-\infty}^{-\frac{E[Y_1^{'}]}{\sqrt{Var[Y_1^{'}]}}} \int_{-\infty}^{-\frac{E[Y_2^{'}]}{\sqrt{Var[Y_2^{'}]}}} [2\Pi\sqrt{1-\rho^2_{Y_1^{'}Y_2^{'}}}]^{-1}.\exp\left[-\frac{1}{2}\frac{\left(-u^2 - 2\rho_{Y_1^{'}Y_2^{'}}uv + v^2\right)}{1-\rho^2_{Y_1^{'}Y_2^{'}}}\right] dvdu \\ & = Q\left(\frac{E[Y_1^{'}]}{\sqrt{Var[Y_1^{'}]}}, \frac{E[Y_2^{'}]}{\sqrt{Var[Y_2^{'}]}}, \rho_{Y_1^{'}Y_2^{'}}\right) \end{aligned} \tag{81}$$

Joint Gaussian probability density of $Y_2^{'}$ and $Y_1^{'}$ is $f(y_1^{'}, y_2^{'}, \rho_{y_1^{'}y_2^{'}})$ and there joint Gaussian distribution is given by:

$$\begin{aligned} & E[Y_j^{'}] = R_{Q\_k}^{'}\cos\Phi_j^{'} - R_{I\_k}^{'}\sin\Phi_j^{'}, j = 1, 2 \\ & Var[Y_j^{'}] = \sigma^2 \\ & \rho_{Y_1^{'}Y_2^{'}} = \cos(\Phi_1^{'} - \Phi_2^{'}) \end{aligned} \tag{82}$$

Correlation coefficient present between $Y_2^{'}$ and $Y_1^{'}$ is given by $\rho_{Y_1^{'}Y_2^{'}}$, variance of Y_j is given by $Var[Y_j^{'}]$. Further it has been observed that the signal that has been transmitted on $N_s - k - th$ which causes ICI in the signal that has to be received is one of the M baseband signals. Finally the SER for a signal point $G_{1,k}^{'}$ which has been transmitted on $k - th$ subcarrier is represented below:

$$P_{e\_G_{1,k}^{'}} = \frac{1}{M}\sum_{q'=1}^{M}[(1 - P\left\{S_{1,k}^{'} \in C_s \mid R_t^{'} = G_{1,k}^{'}\right\}).P\left\{G_{1,k}^{'}\right\}] \quad (83)$$

Further the BER is given by:

$$P_b = \frac{P_{e\_G_{1,k}^{'}}}{\log_2 M} \quad (84)$$

In the above section BER for MPSK modulated OFDM system has been obtained. In future this result can be extended to obtain the BER of STBC MIMO-OFDM system.

3.7 Signal Detection Techniques of MIMO-OFDM System

Various subcarrier signal detection techniques can be employed for detection of signal in MIMO-OFDM system. If the entire channel is considered it undergoes frequency selective fading, but the individual sub-carrier channels can be taken as flat fading channels, as a result MIMO signal detection algorithm of flat fading can be used for detection of all subcarriers of the MIMO-OFDM system. Parallely other optimization algorithms that are used for the detection of signal in MIMO can also be used for MIMO-OFDM systems. Detection methods used in MIMO-OFDM can be both linear and non-linear [63].

3.7.1 Minimum Mean Square Error Technique

MMSE technique is one of the commonly used detection techniques that are used in low SNR environment, have low complexity and better BER performance. For MIMO-OFDM MMSE detection solution is given by:

$$S_{MMSE}^{'} = \left(\Omega^H \Omega + \frac{\sigma^2 N^{'}}{\varepsilon_s^{'}}\right)^{-1} \Omega^H R^{'} \quad (85)$$

Where $E[.]$, denotes the statistical average of a random variable, $E[\left|E_i\right|^2] = \sigma_N^2$, $E[\left|x_i^{'}\right|^2] = \varepsilon_s^{'}$ In case of zero forcing detection interference occurring between antennas has been completely offset, and different data streams have been separated at the cost of increase in noise. Whereas MMSE is based on minimum mean square error, further it can be said that the mean square error between detector output and the actual symbols sent should be minimum, that is:

$$G'_{MMSE} = \arg\min_G \left|Gr - s'\right|^2 \tag{86}$$

Orthogonality is used :

$$E\{(G'_{MMSE} r - s)r^H\} = 0 \tag{87}$$

Further simplification gives:

$$G'_{MMSE} = H^H (HH^H + \sigma^2 I_n)^{-1} = H^H (H^H H + \sigma^2 I_n)^{-1} \tag{88}$$

Output signal after filtering can be estimated as follows:

$$\hat{s}_{MMSE} = G'_{MMSE} r = H^H r (H^H H + \sigma^2 I_n)^{-1} \tag{89}$$

Covariance matrix that has been estimated is given as follows:

$$\varphi'_{MMSE} = E\{(\hat{x} - x)(\hat{x} - x)\} = \sigma^2 (H^H H + \sigma^2 I_n)^{-1} \tag{90}$$

At high value of SNR MMSE detection algorithm converges to ZF algorithm. Received signal vector $\bar{r}$ and the channel matrix $\bar{H}$ is given as:

$$\bar{H} = \begin{bmatrix} H \\ \sigma I_n \end{bmatrix}, \bar{r} = \begin{bmatrix} r \\ o_{n,1} \end{bmatrix} \tag{91}$$

Type vector of $\hat{s}_{MMSE} = G_{MMSE} r = H^H r (H^H H + \sigma^2 I_n)^{-1}$ is given as:

$$\hat{s}_{MMSE} = \bar{H} + \bar{r} = (\bar{H}^H H)^{-1} \bar{H}^H \bar{r} \tag{92}$$

Now the covariance matrix becomes:

$$\varphi_{MMSE} = \sigma^2 (\bar{H}^H H)^{-1} = \sigma^2 \bar{H}^+ \bar{H}^{+H} \tag{93}$$

3.7.2 Zero Forcing Algorithm

In this technique the signal from each transmitting antenna has been considered s the desired signal, remaining part has been regarded as disturbance, because of this mutual interference occurring between various transmitting antennas is neglected. Algorithm is as follows:

For $k = 0,1,2,........K-1$, so that,

$$r'(k) = [r_1'(k), r_2'(k), ...r' n_r'(k)]^T$$

(94)

$$x'(k) = [x_1'(k), x_2'(k), ..., x_{n_T'}'(k)]^T \tag{95}$$

$$n'(k) = \left[n_1'(k), n_2'(k), ..., nn_R'(k)\right]^T \tag{96}$$

$$H'(k) = \begin{pmatrix} H_{11}'(k) & \dots & H_{1nT}'(k) \\ \vdots & \ddots & \vdots \\ H_{nr_1}'(k) & \cdots & H_{nr_nT}'(k) \end{pmatrix} \tag{97}$$

where $r'(k), x'(k), n'(k)$ represents output signal, signal given as input and noise of the sub-channel present in MIMO-OFDM system, for transmitting antennas n_T' and receiving antennas n_R' , channel matrix of k sub-channels is given by $H'(k)$, mathematical expression is given by:

$$r'(k) = h'(k)x'(k) + n'(k) \tag{98}$$

Relationship between input and output is linear, which same as that in a flat fading channel. Block diagram for this is given by figure 3.13.

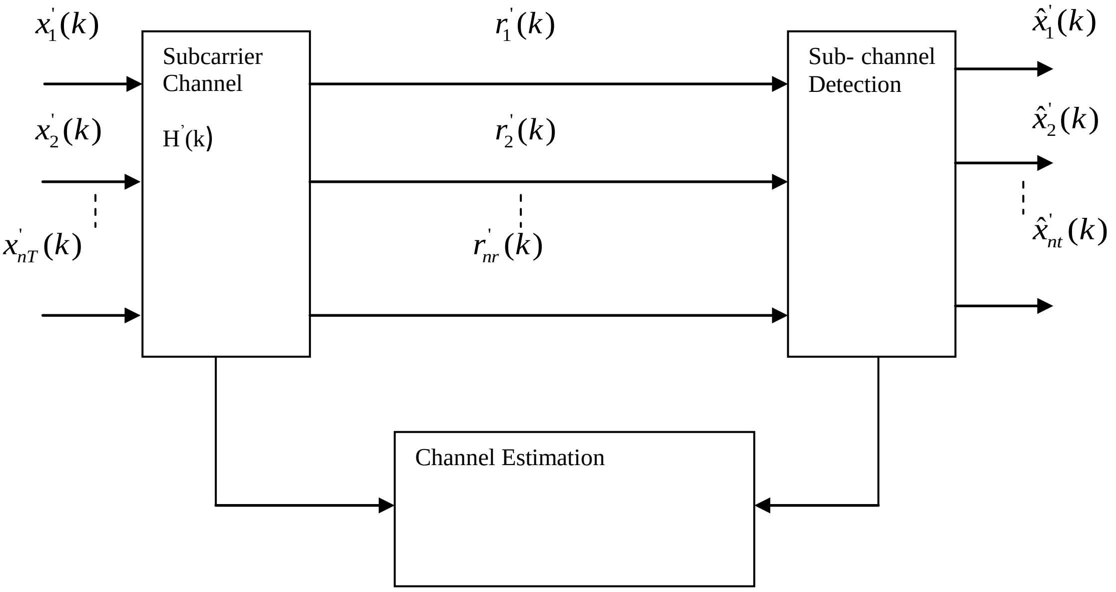

Figure 3.12: MIMO-OFDM Subcarrier Channel Model

Zero-forcing technique used for MIMO systems is most basic and simple algorithm, main idea behind Zero- forcing technique is to eliminate interference that occur in MIMO systems, that is obtained by multiplying the inverse of the received signal with the received signal itself. Zero- forcing algorithm for MIMO-OFDM systems can be given as follows:

$$\hat{x}_{ZF}^{'} = E(x_{ZF}^{'}) \tag{99}$$

CHAPTER 4: RESULTS AND DISCUSSIONS

Behaviour of MIMO-OFDM in terms of SNR vs. BER curves have been presented in this research work. The results have been obtained for both Rayleigh and rician channels. The MIMO-OFDM system discussed above is designed by using STBC coding. Coherent zero-forcing technique has been used to decode the STBC coded data that has been received at the receiver end. Antenna configuration used in here is 2x2.

4.1 BER Analysis of STBC MIMO-OFDM System

Here in this section, SNR vs. BER curve for simple STBC MIMO OFDM system with higher order modulation techniques for different fading channels namely Rayleigh and rician is given. Starting is done with MPSK modulation for Rayleigh channel and then it is followed by Rician channel.

4.1.1 M-PSK over Rayleigh Fading Channel

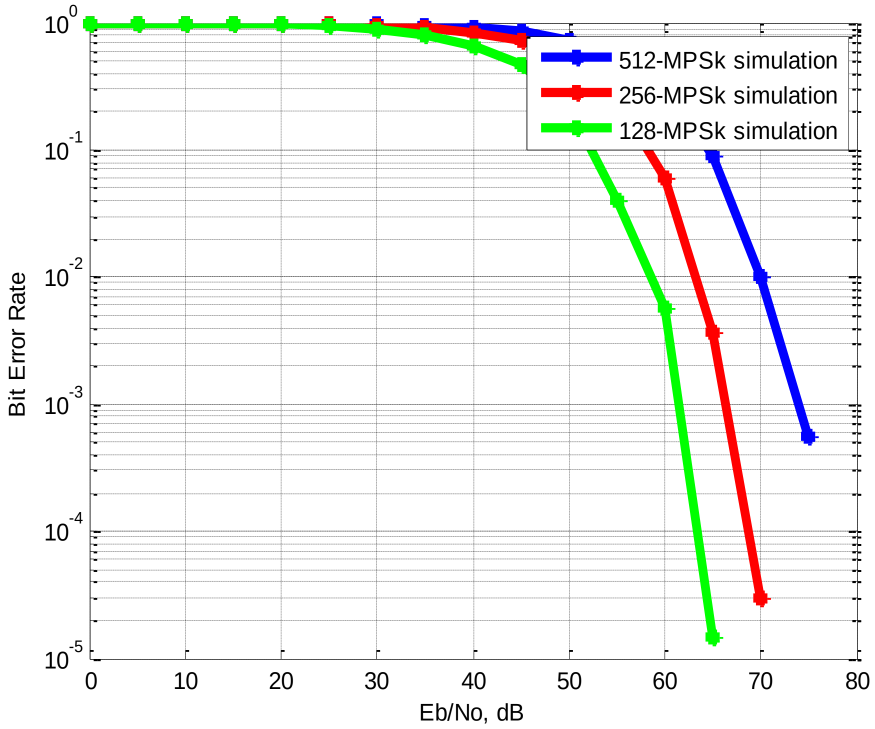

Figure 4.1: SNR vs. BER Curve over Rayleigh Fading Channel

Here in the above shown simulation results BER performance of generalized STBC MIMO-OFDM for different modulation rates have been given for Rayleigh channel, modulation rates used 512,256 and 128 M-PSK modulation. It has been observed that as the modulation order increases BER increases but we know that the bandwidth efficiency increases. SNR of 58dB occurred at BER of 10^{-2} for 128 PSK modulation, and SNR of 63 dB occurs at BER of 10^{-2} for 256 PSK modulation and SNR of 70 dB occurs at BER of 10^{-2} for 512 PSK modulation.

4.1.2 M-PSK over Rician Fading Channel

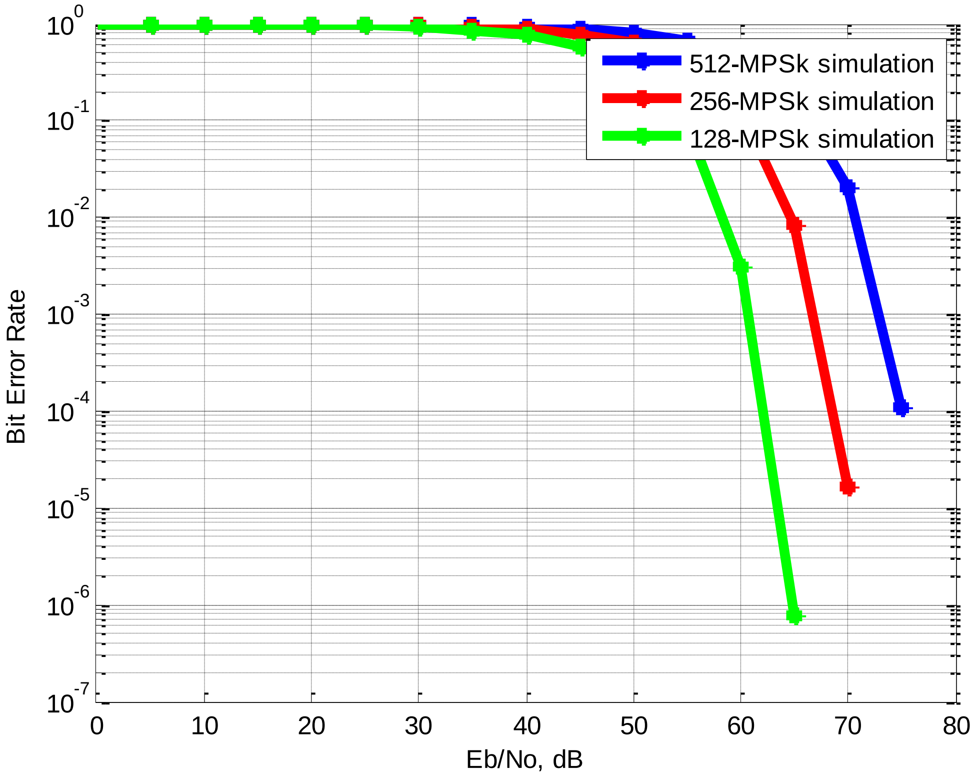

Figure 4.2: SNR vs. BER Curve over Rician Fading Channel

Here in the above shown simulation results BER performance of generalized STBC MIMO-OFDM for different modulation rates have been given for Rician channel, modulation rates used 512,256 and 128 M-PSK modulation. It has been observed that as the modulation order increases BER increases but we know that the bandwidth efficiency increases. SNR of 58dB occurred at BER of 10^{-2} for 128 PSK modulation, and SNR of 65 dB occurs at BER of 10^{-2} for 256 PSK modulation and SNR of 71 dB occurs at BER of 10^{-2} for 512 PSK modulation.

By above results it has been clear that as the modulation order increases, BER increases but because of the spectral efficiency that has been provided by higher order modulation schemes we use higher modulation techniques. Rest on the basis of application a trade-off has been obtained between bandwidth and BER.

4.2 BER Analysis of STBC MIMO OFDM System using ICI Self Cancellation Technique

Sensitivity to synchronization errors has been considered as a major disadvantage of OFDM systems. At receiver end there occur sampling clock errors, carrier-frequency offset and symbol timing offset. The orthogonality has been destroyed by inappropriate estimation of carrier frequency offset. Further it causes ICI in the system model. All these offsets introduced should be estimated and compensated just before the FFT of the signal. Mostly the timing errors and frequency offset are more prominent in an OFDM system. So the simulation that has been done here consider the effect of ICI that has been caused by CFO. In order to mitigate the ICI, ICI self cancellation technique has been used and the simulation results for the same are also given. Basically the comparison between STBC MIMO-OFDM without ISI and with ICI has been drawn. Modulation technique used here is BPSK, number of symbols used are 10 and FFT used is 512 length of CP is 3 and various values of normalized CFO used are .3 and .15, antenna configuration used is 2x2.

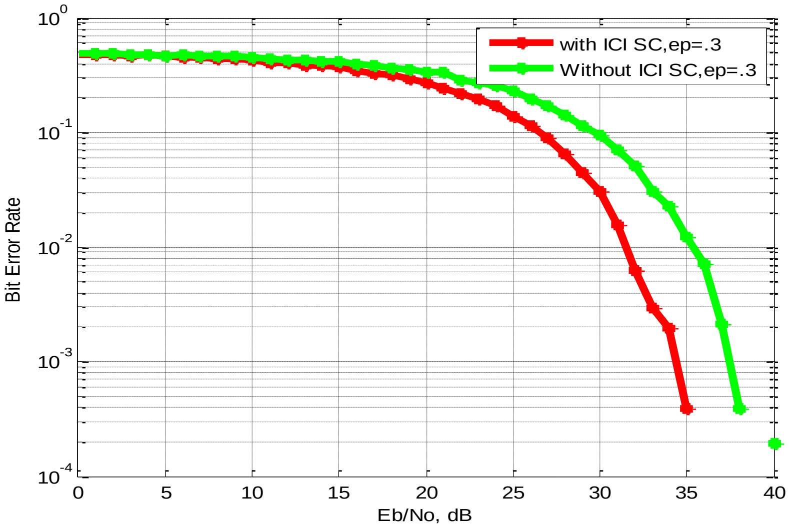

Figure 4.3: SNR vs. BER Curve for STBC MIMO OFDM System using ISI Self Cancellation Technique with normalized CFO of .3

It has been clearly shown by the simulation results that by using ICI self cancellation technique for normalized CFO of .3 there has been improvement of 3dB. Further elaborating it can be said that BER of $10^{-3.7}$ has been obtained at 38dB if no ICI self cancellation technique has been applied but if we apply the ICI self cancellation technique the same BER is obtained at 35 dB

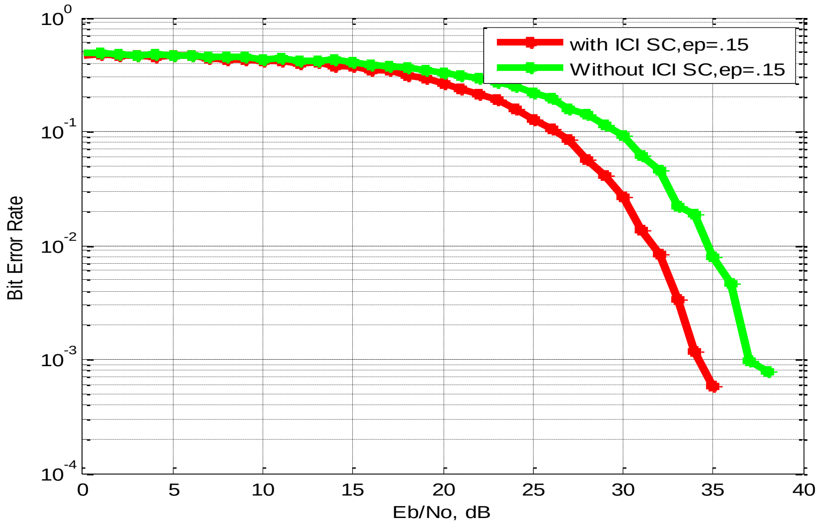

Figure 4.4: SNR vs. BER Curve for STBC MIMO OFDM System using ISI Self Cancellation Technique with normalized CFO of .15

It has been clearly shown by the simulation results that by using ICI self cancellation technique for normalized CFO of .15 there has been improvement of 3dB. Further elaborating it can be said that BER of 10^{-3} has been obtained at 37dB if no ICI self cancellation technique has been applied but if we apply the ICI self cancellation technique the same BER is obtained at 34 dB.

4.3 BER Analysis of STBC MIMO-OFDM using Cooperative Diversity

Here in this section SNR vs. BER performance analysis of STBC MIMO-OFDM system using cooperative diversity done. Simulation has been done using the assumption that the three stations present are at equal distance from each other so there occurs same average SNR is assumed and path loss is also considered same. Amplify and forward technique has been used for by the relay station and combining technique used is MRC. Figures below compares the SNR vs. BER curve for STBC MIMO-OFDM system without Cooperative diversity and with cooperative diversity. it has been concluded that the system with cooperative diversity outperforms the system without cooperative Diversity for both Rayleigh and rician channel.

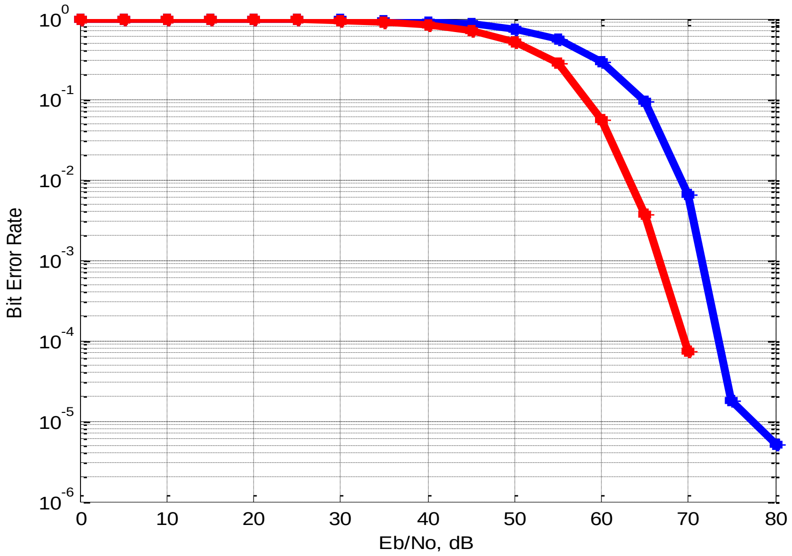

Figure 4.5: SNR vs. BER Curve for STBC MIMO OFDM System using Cooperative Diversity over Rayleigh Fading Channel

From the curve shown above it is clear that SNR of 70dB is obtained at BER of $10^{-2.5}$ in case of STBC MIMO-OFDM system without cooperative diversity but bu using cooperative diversity same BER is obtained at 63 dB in case of Rayleigh channel. So there is an improvement of 7dB.

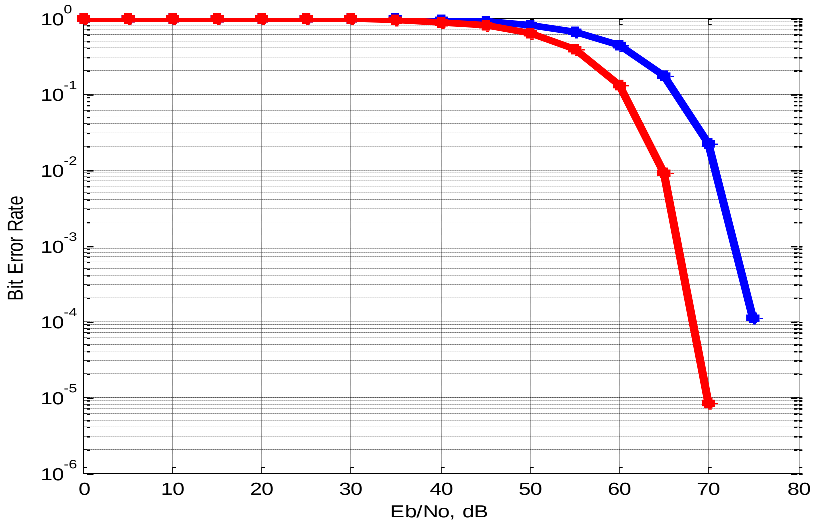

Figure 4.6: SNR vs. BER Curve for STBC MIMO OFDM System using Cooperative Diversity over Rician Fading Channel

From the curve shown above it is clear that SNR of 72dB is obtained at BER of $10^{-2.5}$ for the case of STBC MIMO-OFDM system without cooperative diversity but by using cooperative diversity same BER is obtained at 65 dB in case of Rician channel. So there is an improvement of 7dB.

It has been concluded that by using STBC-MIMO OFDM system with 512-PSK modulation and FFT size of 256 for Rayleigh channel BER of 10^{-2} occurs at SNR of 69 dB but by using Cooperative diversity same BER is obtained at SNR of 62 dB. So, there occurs an improvement of 7dB in SNR by using Cooperative diversity. For rician channel SNR of 72 dB has been obtained at BER of 10^{-2} in case of STBC MIMO-OFDM system but by using STBC MIMO-OFDM with cooperative diversity SNR of 65 dB has been obtained at same BER so here is also an improvement of 7 dB.

By taking into consideration the issue of ICI occurring in STBC MIMO-OFDM system SNR vs. BER curve shows the performance as concluded in few lines given below. Modulation technique used here is BPSK modulation and FFT size used is 512. It has been concluded from the results obtained that by using ICI self cancellation technique for CFO of .3 there is an improvement of 3dB in SNR. It can be elaborated as SNR of 38dB is obtained at BER of $10^{-3.7}$ for the case of STBC MIMO-OFDM system without ICI cancellation and by using ICI cancellation BER of 35 dB has been obtained at same BER value. Further for the case of normalized CFO of .15 there is an improvement of 3 dB by employing ICI self Cancellation technique. It can be elaborated as if no ICI self cancellation technique has been employed than the BER of 10^{-3} has been obtained at 37 dB SNR but by employing ICI self Cancellation technique the same BER is obtained at 34 dB.

CHAPTER 5: CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

In the work done, performance analysis of STBC MIMO-OFDM system has been done at higher level modulation techniques and for various channels. Higher order modulations have been applied to STBC MIMO-OFDM systems for achieving large data capacity. But it is well known fact that as the modulation order increases BER also increases. The reason for this is as we keep on increasing the modulation order the decision area of the demodulator in corresponding constellation diagram decreases, due to this demodulator leads to errors in the result obtained as output of demodulator. The signal has been distorted by the channel more severely at SNR values. Resulting distortions leads to shifting of constellation points that further causes the degraded results at the output of demodulator. But with increase in SNR the distortions introduced by channel also affect the signal to a lower extent, and this result in decrease in BER of the system. So it has been concluded that by using higher order modulation techniques large data capacity can be achieved, one thing that has to be taken care of is the extent upto which the value of SNR can be increased. Data capacity varies in direct proportion with SNR.

In this research work 512-PSK modulation technique has been used for analysis of STBC MIMO-OFDM system along with cooperative diversity. Also for better system performance in terms of BER for proposed system; ICI a self cancellation technique has been deployed. The system performance has been measured under Rayleigh and Rician fading channels. By applying cooperative diversity to STBC MIMO-OFDM system there is an improvement of 7dB in SNR at BER of $10^{-2.5}$ as compared non cooperative diversity based system. Further STBC MIMO-OFDM system with ICI self cancellation technique provides an improvement of 3 dB in SNR at BER of $10^{-3.7}$ for normalized CFO of 0.3 in comparison to the system with non ICI self cancellation.

5.2 Future Scope

In future the work can be done by using any other source coding techniques for MIMO-OFDM systems, such as LD coding, SFBC coding STFBC coding. Moreover the analysis can be done for higher order antenna configurations like as 8x8, 6X6 and 4X4.

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