Performance of MIMO and Massive MIMO Systems in TWDP Fading Channel

Dissertation submitted in partial fulfillment of the requirements for the award of the degree of

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Submitted by

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CERTIFICATE AND DECLARATION

I, Bhavnika Garg hereby declare that the work which is being presented in the dissertation entitled "**Performance of MIMO and Massive MIMO Systems in TWDP fading channel**", by me in partial fulfillment of the requirement for the award of degree of M.E. in Electronics and Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the guidance of **Dr. Rajesh Khanna** (Professor), Electronics & Communication Engineering Department. The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

Date: 2-7-2015

Bhavnika Garg

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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.

Date: 2-7-2015

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ABSTRACT

Current wireless scenario where directional antennas , wide band signals and narrow band receivers are commonly deployed , give rise to environment which is correctly represented by TWDP (Two Wave Diffuse Power) Fading model other than Rayleigh or Rician Model . TWDP fading has two LOS components in the presence of other diffusely propagating waves. Research shows that when two LOS components are equal in strength and opposite in phase, TWDP fading makes a link which is even poorer than made by Rayleigh Fading. Hence, TWDP fading model should be used to design worst case wireless communication scenario.

Wireless communication systems uses multiple antennas at the transmitter as well as receiver to enhance data rate, throughput, and energy and power efficiency. These systems commonly known as MIMO are employed almost everywhere. The power of MIMO is that it has resilience to combat fading and uses random fading, scattering and multipath propagation in its benefit to enhance capacity. Hence, more faded the environment is more is the capacity that is achieved by MIMO system. TWDP fading scenario which is worst in its properties gives best environment to MIMO and much higher capacity is attained. Also Massive MIMO system which offers many benefits over MIMO systems such as improved data rate, increased directivity , reduced latency due to more degree of freedom when compared in all fading scenario's gives best results for capacity in TWDP fading environment.

The objective of this research work is to analyze the performance of MIMO and Massive MIMO systems in TWDP channel. Upper and Lower Bound of capacity is derived for MIMO system in TWDP fading channel. Performance of Spatially Modulated System which improves BER (Bit error Rate) is studied in TWDP channel.

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LIST OF ACRONYMS

SISO	Single Input Single Output
MIMO	Multiple Input and Multiple Output
TWDP	Two Wave Diffuse Power
LOS	Line Of Sight
PDF	Probability Density Function
SIMO	Single Input Multiple Output
MISO	Multiple Input Single Output
SC	Selection Combining
EGC	Equal Gain Combining
MRC	Maximum Ratio Combining
BER	Bit Error Rate
MATLAB	Matrix Laboratory
BPSK	Binary Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
CSIT	Channel State Information At Transmitter
NCFSK	Non-Coherent Frequency Shift Keying
DPSK	Differential Phase Shift Keying
CF	Characteristic Function
SEP	Symbol Error Probability
QAM	Quadrature Amplitude Modulation
MGF	Moment Generating Function
DF	Decode and Forward Relaying
MPSK	M-ary Phase Shift Keying
MQAM	M-ary Quadrature Amplitude Modulation

MFSK	M-ary Frequency Shift Keying
SSC	Switch and Stay Combining
AF	Amplitude and Forward Relaying
OPRA	Optimal Power and Rate adaptation
TIFR	Truncated Channel Inversion with Fixed Rate
CIFR	Channel Inversion with Fixed Rate
MRT	Maximum Ratio Transmission
EE	Energy Efficiency
SCN	Small Cell Networks
CDF	Cumulative Distributive Function
RQAM	Rectangular Quadrature Amplitude Modulation
XQAM	Cross Quadrature Amplitude Modulation
SQAM	Square Quadrature Amplitude Modulation
ASER	Average Symbol Error Rate
SNR	Signal To Noise Ratio
GTR-U	Generalized Two Ray Fading Model
AF	Amount of Fading
LCR	Level Crossing Rate
RMS	Root Mean Squared
Tx	Transmitter
Rx	Receiver
LSAS	Large Scale Antenna Systems
BS	Base Station
TDD	Time Division Duplexing
STBC	Space Time Block Codes
SM	Spatial Modulation

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CHAPTER 1: INTRODUCTION

Wireless Communication Networks have completely revolutionized the market for data rate, through put, efficiency and performance. Large number of antennas are being used at base station to generate more degree of freedom and hence to achieve higher capacity, more energy efficiency with more directivity. Use of single antenna at transmitter and receiver (SISO-MIMO) has vanished long ago with the arrival of SIMO-MIMO and MISO-MIMO formats. These two formats do provide diversity to compensate fading but need of higher data rate is not met efficiently. Hence, MIMO came as a big advantage. It provides higher throughput, better energy efficiency and has power of using random fading, scattered waves and multipath delay elements in its benefit. Also implementation of Massive MIMO system at the base Station increases capacity drastically with the employment of large number of antennas at the base station as proposed by researchers to meet current capacity requirements.

1.1 BACKGROUND

Fading and interference are main bottleneck in current wireless scenario. These are major performance degrading factors. Hence need is to model and simulate a communication system that can resist fading and improves system's effectiveness. Different propagation environments, produce the fading channels which are diverse and complex. Therefore design of proper fading model that properly characterizes particular propagation channel is essential.

Rayleigh and Rician fading are most commonly used models to characterize propagation environments [1]. However, use of narrow band receiver operation, directional antennas and wide band signals produces a channel which is not correctly characterized by conventional Rayleigh and Rician fading channels [2]. Also recent research shows that some wireless sensor network applications where sensor nodes are deployed in a cavity environment suffer from fading which is more severe than as anticipated by Rayleigh fading and is referred to as TWDP (Two Wave Diffuse Power) fading [3] , [4]. Results given by authors in [5] shows that TWDP fading produces a link poorer than formed by Rayleigh fading , hence should be considered as a worst case scenario in designing a communication system.

In wireless communication, multiple antennas are used both at transmitting as well as receiving end to increase system's performance, hence to enhance capacity or data rate. As already discussed in literature MIMO takes advantage of fading, diversity and delay spread to turn multipath propagation losses into its benefit [6]. TWDP fading which is proved to be most severe form of fading must be an ideal environment for evaluating the performance of MIMO systems and Massive MIMO systems.

1.2 INTRODUCTION TO TWDP FADING

Fading is rapid fluctuation of the amplitude, phases or multiple delays of a radio signal over a short duration of time or travel distances, ignoring large scale path loss effects. It is caused by interference of two or more versions of the transmitted signal which may add destructively or constructively at receiver [1].

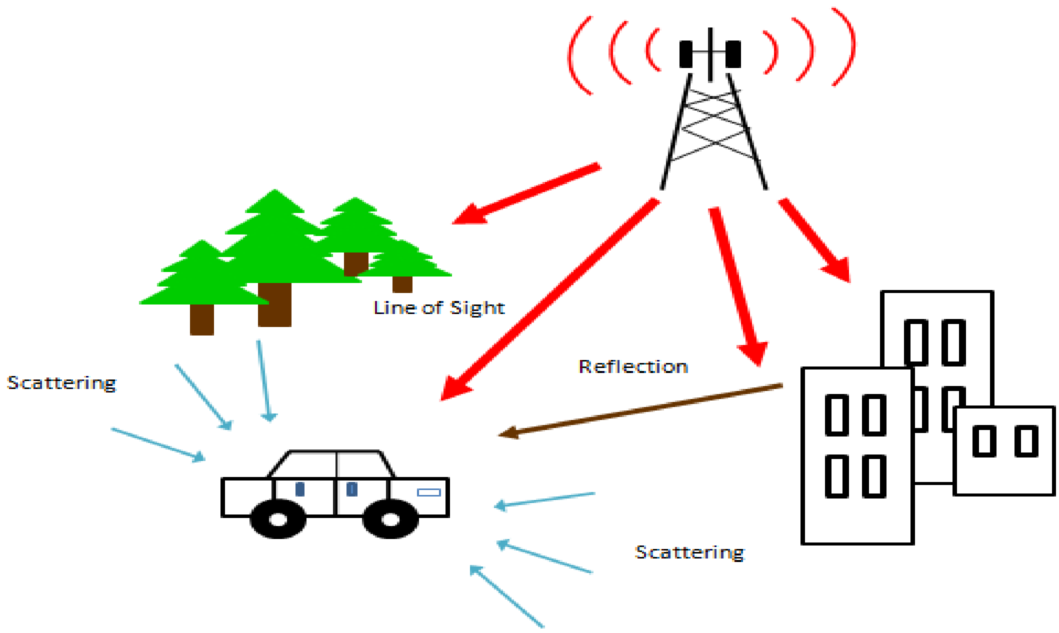

Figure 1.1:- Wireless Communication Scenario [7].

In wireless communication, signal propagates through different paths and arrives at the receiver; hence received signal is combination of multipath waves which are with different phases and amplitudes as given in fig. 1.1. The propagation waves are of two types **Specular** and **Diffuse Components.** Specular waves are characterized by strong LOS (Line of Sight) component plus reflected components while diffuse waves are made up of faint waves with random magnitudes and phases commonly called as scattered components [7]. The resultant signal at the receiver is given by equation (1.1).

$$V_r = \sum_{i=1}^{N} V_i \exp(j\emptyset_i) + \sum_{k=1}^{M} V_k \exp(j\emptyset_k) \,. \quad (1.1)$$

As given in equation (1.1) and represented in fig. 1.2 received signal is made up of N strong components and M diffuse components. A **Specular Component** is a single term $\{V_i \exp(j\emptyset_i)\}$, represents one arriving multipath wave. The phase $\emptyset_i$ of a specular component is random, but the envelope V_i is constant. A **Non- Specular Component/Diffuse Component**, with numerous individual waves carrying power which is negligible to the total average power [2].

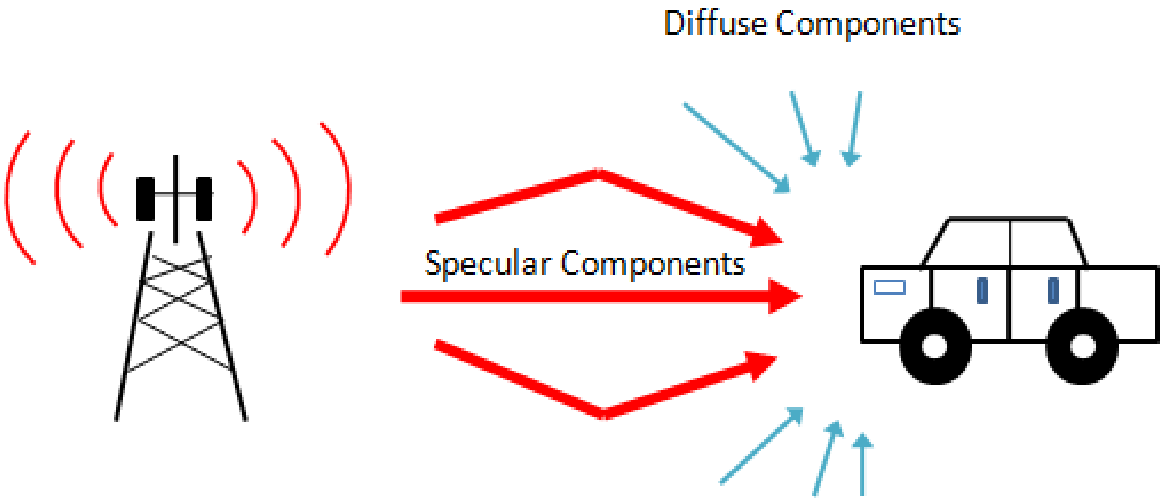

Figure 1.2:-Illustration of Specular and Diffuse Components [7].

TWDP stands for Two Wave Diffuse Power fading and consists of two strong LOS components and many diffuse components. This model has attracted attention since current wireless scenarios are correctly characterized by this fading model. It has two parameters which are K and Δ defined below

$$K=\frac{V_1^2+V_2^2}{2\sigma^2} \qquad \Delta=\frac{2V_1V_2}{V_1^2+V_2^2}.$$

where V_1 and V_2 are voltage amplitude of the two specular waves and $2\sigma^2$ represents the average power of the diffused component. K is the ratio of the specular power to diffused power, while Δ represents the relative power of two specular components [2]. Work done in [8] says that Rician model can be used to study TWDP fading model. When Rician pdf is averaged over phase difference of two LOS components we get TWDP fading pdf. This is elaborately discussed in chapter 3.

1.3 WHY TWDP FADING SCENARIO IS IMPORTANT TO STUDY?

It has been proved in [5] that when two LOS components are equal in magnitude and opposite in phase on reaching receiver, a link is produced which is even worse than Rayleigh fading. Rayleigh fading model has till now been considered to design worst case wireless communication system but this new study has limited the use of Rayleigh model and proposed the use of TWDP fading model to design wireless Communication System. Also use of directional antennas, wideband signals and typical narrowband receiver operations increases the probability of occurrence of TWDP fading [2].

TWDP fading comes into action when power of specular component is much greater than power of diffuse component i.e. value of parameter K is high. Both directional antennas and wide band signal give rise to these conditions. Directional antennas amplifies one multipath waves that is in one particular direction while attenuating the remaining. Even wide band signal reception do the same, it rejects multipath components that arrive with different time delays. Hence, this automatically increases strength of specular component in comparison to diffuse waves [2].

Current wireless systems have made their implementation possible almost everywhere. Wireless Sensor Networks are deployed in cavity environments such as airframes and shipping containers. The propagation environment within these cavities is comparatively static and does not possess capability to fight fades. Hence, new worst case model to correctly characterize this environment space needs to be studied [4].

1.4 ISSUES/GAPS IN TWDP FADING SCENARIO

TWDP fading model offers so many issues to pursue research work. It provides an environment which has not yet been modelled. It is of utmost importance to model and simulate a communication system with this new fading channel to deal with current wireless issues and problems. There is need to improve and testify system’s effectiveness in combating fading conditions. Hence, design of proper and efficient model for particular fading scenario is essential.

First of all, TWDP pdf has complex mathematical representation which is non-convergent and does not have any closed form. Hence it is need of hour to derive an easy expression for TWDP fading statistics .The simple mathematical expression will make the implementation of new systems in TWDP fading easy which will encourage researchers and scholars to readily use this fading model to evaluate the performance of their systems. Although some of authors have given some easy expressions which converges as order increases, but still there is scope for improved expressions.

MIMO which is boon to current wireless communication, has not yet been studied with this fading model. All other formats such as SISO-MIMO , SIMO-MIMO and MISO-MIMO have been applied but the most important configuration in which number of antennas at both the transmitter and receiver is more than one has not been covered in any of the papers . Massive MIMO which is further advancement to MIMO systems with huge number of antennas at the base station to increase capacity, energy efficiency and directivity has been considered in all other fading environments but not in TWDP fading environment. Hence, Performance of MIMO / Massive MIMO systems in TWDP fading scenario needs to be studied.

Various conventional receiver combining techniques such as SC (Selection Combining), MRC (Maximal Ratio Combining) and EGC (Equal Gain Combining) have been applied to this fading model, but Optimal Combining is yet to be seen. Also performance of TWDP fading with coding such as Convolutional Codes and Viterbi has not been studied yet.

Spatial modulation is widely applied now a days to improve system's spectral and energy efficiency. But only conventional fading models have been implemented with Spatially Modulated systems. So TWDP fading model should be made functional with spatial modulation to investigate BER (bit error rate) performance and therefore to study capacity with less/more power applied.

1.5 THESIS SIGNIFICANCE / GOAL

TWDP fading was first proposed by Durgin in 2002. Since then many systems are being studied in the environment given by this fading scenario. Many authors have published their research work in TWDP fading using SISO, SIMO and MISO formats. This research work offers new areas in which TWDP fading model can be applied which are listed as below:-

- MIMO systems are now been implemented in every field due to its ability to attain higher capacity and due to its resilience against fading. All other fading scenarios have been applied to this system, but TWDP has yet not been modelled with MIMO which is main work carried out in this thesis. TWDP has two LOS components in presence of diffuse components. Analytical results are plotted in computer software MATLAB and it is seen how efficiently MIMO works in TWDP fading situation. Also two parameters i.e. K and Δ which characterises TWDP fading are varied in this environment and corresponding effect on capacity of the system is viewed.

- MASSIVE MIMO is replacing many old set ups and now being implemented across the world. Test beds to analyse its performance has been established in some of the prestigious universities of world. Hence, this offers new area of research. Improvement in capacity with increasing antennas at BS (base station) is observed in MATLAB. Although some of the conventional fading scenarios have been implemented with this system. But TWDP fading model is applied to this system in this research work. Again improvement in capacity provided by TWDP fading statistics over Rayleigh and Rician fading is analysed in MATLAB simulations. Again parameters K and Δ are varied and increment – decrement on capacity of MASSIVE MIMO system is observed.
- Modulation schemes such as BPSK and QPSK are applied in TWDP channel and BER is observed. The fact that TWDP fading establishes a link which is worse than the link given by Rayleigh fading is demonstrated with MATLAB Simulations. More BER is observed with TWDP channel and the need to consider this model in designing worst case communication scenario is carried out in thesis. Also various receiver combining techniques i.e. Diversity deployment to enhance systems performance is implemented with TWDP channels. Lastly Spatial Modulation which improves BER performance is applied and results are validated using simulation carried in MATLAB software.
- The objectives defined in this thesis are the following:-

1. Performance analysis of wireless communication systems viz SISO, SIMO, MISO and MIMO in TWDP channel.
2. Analysis of Upper and Lower bounds of capacity of MIMO system in TWDP fading.
3. Performance analysis of Massive MIMO System in TWDP fading.
4. Performance analysis of BPSK and QPSK modulation schemes in TWDP channel with and without receiver diversity.
5. Performance analysis of Spatial Modulated System in TWDP channel.

1.6 THESIS OUTLINE

This thesis has been divided into seven chapters. **Chapter 1** gives introduction to the general Wireless Communication Scenario considering fading, types of wave components that make the channel and various propagation channels. Also it covers introduction of TWDP fading Scenario, main parameters of TWDP fading model, need to study this fading environment, issues / gaps left in this area of research and thesis significance.

Chapter 2 gives an overview of Literature Review where all research work done till now in this field of TWDP fading is presented. All the papers which are published in this field are listed in this chapter chronologically i.e. starting from the first paper published in year 2002, where TWDP fading statistics were first proposed. Recent papers published in year 2014 - 2015 where MGF (Moment Generating Function) is used to derive signal to noise ratio (SNR) in TWDP fading is covered in this chapter.

Chapter 3 focusses on all fading scenarios in detail, their pdf's and plot of their respective pdf's in MATLAB. Also it presents the conditions when TWDP pdf converges to either Rayleigh or Rician pdf. By changing the value of K and Δ, TWDP fading turns into Rayleigh or Rician these conditions are also covered in this chapter.

Chapter 4 considers TWDP channels in all the MIMO formats. SISO, SIMO and MISO all three MIMO formats are discussed before discussing MIMO. The difference in results obtained with SISO and MIMO is discussed. The comparison of three different propagation channels with MIMO system is carried out. Variation of capacity versus SNR in TWDP channel with different values of K and Δ is done. Capacity bounds for MIMO systems in TWDP channels are derived. Complete mathematical analysis is performed to observe upper and lower bound of capacity attained by MIMO system in TWDP channel. Results are plotted in MATLAB.

Chapter 5 starts with introduction to Massive MIMO system. It has been proved mathematically in this chapter that effects of all uncorrelated noise and small – scale fading are removed when number of antennas grow large in number. Comparison of three different propagation channels in MASSIVE MIMO systems is done. Variation of capacity versus SNR in TWDP channel with different values of K and Δ for MASSIVE MIMO systems is covered here.

Chapter 6 compares Rayleigh fading and TWDP fading for BER performance. Also BER improvement provided by Spatial Modulation over conventional modulation techniques is studied, applying TWDP channel.

Chapter 7 concludes the work and presents conclusion with future aspects of TWDP fading.

CHAPTER 2: LITERATURE REVIEW

TWDP fading was first proposed by Durgin in 2002. Before that, conventional fading models Rayleigh and Rician were considered to design wireless communication system. For worst case propagation scenario Rayleigh fading was considered. But current research in area of TWDP fading has proved the fact that when two LOS sight components are equal in amplitude and opposite in phase propagation environment is even worse than that considered with Rayleigh Fading. Also use of directional antennas and narrow band receivers give rise to environment which is not correctly represented by Rayleigh or Rician propagation channels. Hence, analysis of a wireless communication system in TWDP fading is required.

Many papers have been published in this field and lot of research work is being carried by various universities and research departments. This chapter lays emphasis on the work that has been done in chronological order.

In **2002 Durgin et al.**, first proposed TWDP fading. In this, pdf's are used to represent the small scale fading. Pdf's signifies the probability of received signal's strength. The authors for the first time decomposed propagating waves in **Specular** and **Non-Specular** components. Also diffuse components were presented as a non-specular component with many individual waves having power that is negligible in comparison to the strength carried by specular waves. They presented the five closed form analytical pdfs: Rayleigh pdf, One-Wave pdf, Two-Wave pdf, Three- Wave pdf and Rician pdf. The paper described the TWDP fading scenario where there are two specular multipath components in the presence of other diffuse waves. Authors gave the expression of pdf that approximates the TWDP pdf. Order is used to approximate TWDP pdf and by increasing the value of order approximate pdf approaches exact pdf. However , it is also analysed that by using the first few orders accurate representations are made over the most used range of K and Δ [2].

In **2002 Jauhar Ayadi et al.**, showed the upper and lower bounds that channel capacity can attain in presence of Rician fading. They presented averaged Rician channel capacity and showed that it has two contributions, one related to deterministic component i.e. LOS path and other is stochastic part due to random diffusely propagating waves. They first presented general capacity expression and then considered cases to derive upper and lower limits on capacity put by Rician channel. Full matrix calculation was performed on expression of capacity and finally it was deduced that lower bound on capacity is given in the same way as given for Rayleigh channels i.e. considering all diffuse waves with no LOS component . But the upper bound was given as the sum of LOS component as well as diffuse component. Final results were given for two cases i.e. for uncorrelated and correlated antenna elements. For fully correlated antenna elements Rician capacity decreases as K-factor approaches infinity while for uncorrelated antenna elements Rician capacity increases as K-factor increases [9].

In **2003 Michel T. Ivrlac et al.**, investigated fading correlations in wireless MIMO communication systems. They proved that CSIT is important while dealing with fading correlations. If transmitter knows the channel information, correlated fading has proved to be advantageous and provides higher channel capacity than uncorrelated fading. Authors also discussed semi-correlated fading channels and used cut-off analysis to show that semi-correlated fading with linear modulation techniques applied have potential to perform better in good transmit power range , provided that diffident amount of time and frequency diversity exist along with pure space diversity . Authors presented a table in which type of correlation at the transmitter and receiver is given and then the corresponding type of fading that exist in channel is given as in table 2.1 [10].

Table 2.1:-Types of Fading Correlations [10].

Transmitter Side	**Receiver Side**	**Type of Fading**
Uncorrelated	Uncorrelated	Uncorrelated
Correlated	Uncorrelated	Semi-Correlated
Uncorrelated	Correlated	Semi-Correlated type 2
Correlated	Correlated	Fully – Correlated

In **2005 Soon H. Oh et al.**, presented BER performance analysis of an un-coded binary phase shift keying (BPSK) system in TWDP Channels. Results which are derived using MATLAB Simulink are with and without MRC receiver combining technique. Their studies revealed the fact that TWDP fading made a link which was even worse than that of Rayleigh fading when two LOS are equal in strength and have power 6dB greater than Diffused power, Hence, an important result was established which shows that TWDP fading should be considered as worst case model in designing communication system rather than Rayleigh model. The authors presented many tables in which three fading that are Rayleigh, Rician and TWDP are compared on the basis of value of parameters K and Δ. This work for the first time mentioned that when K approaches infinity and Δ approaches one TWDP performs poorer than Rayleigh [5].

In **2007 Wee Sit Lee**, used EGC Receiver Combining Technique with NCFSK and DPSK systems over TWDP channels. Author used method of MGF i.e. Moment Generating Analysis for deriving expression of BER in both NCFSK (Non-Coherent Frequency Shift Keying) and DPSK (Differential Phase Shift Keying) [11].

In **2007 J. Frolik,** modelled a fading channel for wireless sensor networks. The work presented frequency selective data for in-vehicle wireless sensor applications in real world scenario. The fading statistics which makes more severe fading environments than given by Rayleigh fading and hence introduced as Hyper –Rayleigh Fading. Authors even provided empirical fading data for different environments in 2.4GHz band and found that Rayleigh like fading characterizes maximum of fading environments [3]. However, hyper – Rayleigh Fading too constitute 10- 25% of measured cases as given in table 2.2.

Table 2.2:- Empirical Data Collected from Different Environments [3].

ENVIRONMENT	**CASES**	**Rician Channel**	**Rayleigh Channel**	**Hyper-Rayleigh Channel**
Aircraft : MD90	41	22%	52%	22%
Aircraft : 747	44	25%	64%	11%
Bus	100	35%	54%	11%
Wing Aircraft	245	44.9%	30.6%	24.5%

Therefore, two ray, small scale model was introduced as new worst case scenario for the application of wireless sensors [3].

In **2008 Jeff Frolik,** pursued his previous research and presented empirical data showing small scale fading measurements more severe than Rayleigh and named this scenario as hyper- Rayleigh fading. Temporary ever-changing multipath environment is generally represented by Rayleigh fading, which has long been used as the worst – case fading situation. Although Nakagami fading, log normal shadowing and Weil Bull distributions characterize the severe fading model but are unable to do any constructive interference and thus TWDP model with $\Delta \rightarrow 1$ and K ϵ $(0,\infty)$ has been proposed by author for appropriately characterizing hyper Rayleigh channels. Also, wireless sensors are deployed in static environments, which is in fact prone to more severe fading environment and is given by TWDP fading channels [4].

In **2008 Alyssa Magleby et al.**, predicted that wireless sensor networks on aircrafts are prone to environment which is even worse than Rayleigh hence emphasized, that attention should be given on the type of signals used in wireless transmission to overcome severe multipath affects. Therefore, need to analyse TWDP fading channel in MIMO systems was proposed in this work [12].

In **2009 Caijun Zhong et al.**, studied the ergodic capacity limits in MIMO system with generalized fading models. The authors derived several ergodic capacities, upper and lower bounds for Nakagami - m fading channel. The results demonstrated that capacity scaling laws are identical for both Nakagami –m Fading channel and Rayleigh fading channel [13].

In **2010 Lei Sun et al.**, presented precise BER for BPSK system in TWDP channel with co-channel interference environment. Characteristic Function (CF) is used to derive BER expression. Chernoff Bound is used to discuss BER versus SNR. Simulations to compare BER performance with and without co-channel interference in TWDP channel is carried out in this paper [14].

In **2011 Yao Lu et al.**, analysed SEP (Symbol Error Probability) of rectangular QAM for single and multiple channel receptions in TWDP channels. At the combiner output general expression of the MGF of fading power is derived. The SEP expression derived for TWDP channels is implemented on number of diversity branches and considers Rayleigh and Rician channels as special cases [15]. Thus, authors derived novel exact expressions for average SEP in non – diversity and maximal ratio combining (MRC) schemes. And finally performance comparisons have been made in multi-channel QAM systems for TWDP, Rayleigh and Rician channels [15].

In **2011 Yao Lu et al.,** analysed the outage probability of Cooperative relay networks in Two Wave with Diffuse Power Scenario. Authors used sum of MGF of random number of variables distributed by TWDP fading and then used it further. And thus, a closed form expression of Decode and Forward (DF) cooperative relay networks over TWDP fading channels is derived. Finally Monte Carlo simulations validate the obtained results [16].

In **2011 Beng Soon Tan et al.**, showed that both Rayleigh and Rician fading models can be treated as special cases of TWDP fading model. Here, selection combining receiver combining technique is used and improvement in SNR is observed for modulation techniques (such as BPSK, MPSK, MQAM) over TWDP fading channels. MGF approach is used to derive symbol error rate expression in Selection Combining for TWDP fading channels [17].

In **2011 Haghani S. et al.**, studied performance of non-coherent MFSK with L branch signal plus noise (S + N) using Selection Combining Receiver diversity technique. The effect of TWDP fading parameter on performance of (S+N) Selection combining and classical Selection Combining are studied. Monte Carlo simulations were used to validate the theoretical results [18].

In **2011 Haghani S. et al.**, studied performance of non-coherent binary frequency shift keying (BFSK) with dual post- detection switch and stay combining (SSC) in TWDP channels. The performance of post detection SSC is compared to pre-detection and it is found that post detection SSC outperforms Pre detection SSC. Monte Carlo Simulations were carried out to validate obtained results with that of analytical results [19].

In **2012 Yao Lu et al.**, used amplify and forward relaying (AF) in single relay cooperative networks to analyse outage probability and symbol error rate over TWDP systems. The authors found upper bound on received signal to noise ratio and closed form asymptotic expression to approximate outage probability and symbol Error Rate [20].

In **2012 Jiameng Luo et al.,** proposed new opportunistic decode-forward (DF) relaying with beam forming in multiple – input and multiple – output (MIMO) relay networks. The model is set over TWDP fading channels. In this only one relay which has best channel to destination is selected. They demonstrated that diversity order is product of two parameters namely no. of relays and minimum no. of antenna’s at transmitting and receiving end [21].

In **2012 Xiaoxiang Wang et al.**, studied cooperative networks. The Two Wave Diffuse Power fading channels were considered independent and non-identical. The authors used opportunistic amplify and forward (AF) Relaying and finally derived closed form expressions of outage probability and symbol error rate in high signal to noise ratio regime [22].

In **2012 R. Subadar et al.**, obtained expressions of spectral efficiency for optimal and sub optimal adaptive transmission techniques with un-coded MQAM over TWDP fading channels. Authors compared spectral efficiency of TWDP channel in different schemes such as OPRA (Optimal Power and Rate adaptation), TIFR (Truncated channel inversion with fixed rate) and CIFR (Channel inversion with fixed rate) and found that OPRA works best and provides maximum Spectral efficiency. PDF of signal to noise ratio of signal in TWDP channel is derived in this paper [23].

In **2012 Nan Yang et al.,** analysed symbol error rate of selective decode and forward relaying for Two Wave Diffuse Power Fading Channels. They derived exact expressions for M-ary Phase shift keying and M-ary Quadrature amplitude modulation. Asymptotic expression of SER is derived in this paper in terms of diversity order and coding gain. Fact that TWDP fading parameters have no influence on diversity order but do affect coding gain is proved [24].

In **2012 S. Haghani et al.** , studied performance of non-coherent M-ary frequency shift Keying (MFSK) in system which has dual branch post – detection switch and stay combining (SSC) over Two Wave Diffuse Power fading channels. Closed form expression for average bit error Rate (BER) is derived. Monte Carlo Simulations are used to validate theoretical results [25].

In **2012 Huaiyu Dai et al.**, proposed opportunistic Decode and Forward Relaying (DF) with beamforming for multiple networks with N_S antenna's at source and N_d antenna's at destination. In this system, the authors used Maximal ratio transmission (MRT) at source end and Maximal Ratio Combining (MRC) at destination. To view the benefits of proposed scheme, authors derived outage probability for TWDP fading channels [26].

In **2013 Wenjia Liu et al.**, discussed importance of energy efficiency and proposed MASSIVE MIMO as a way to exploit large array gain to provide high EE (energy efficiency). In their analysis they compared SCN (small cell networks) and MASSIVE MIMO systems, demonstrated that when number of cells are large SCN achieves better EE and when number of cells are small MASSIVE MIMO achieves better EE [27].

In **2013 Thomas L. Marzetta et al.**, presented concern over demand of wireless communications which is supposed to increase by factor of 40 in coming years. All advantages of MASSIVE MIMO (large antenna system) are discussed which are as :- orders-of-magnitude improvements in spectral-efficiency , simplest multiplexing pre-coding and de-coding algorithms that can be used to give optimal results, replacement of expensive ultra-linear forty-Watt power amplifiers by many low-power units . Finally authors presented the most distinguishing feature of large number of service-antennas that is possibly hundreds or even thousands – work for a significantly smaller number of active independent (autonomous) terminals [28].

In **2013 Y. Mehmood et al.** , discussed the current need of high throughput wireless communication. This rapid increase in number of wireless applications has put severe limitations on performance of conventional MIMO system, hence urgent need of some new technology like Massive MIMO is proposed. All essential factors of massive MIMO system have been discussed here such as broadcast models, channel estimation and pre-coding procedures [29].

In **2013 R. Subadar et al.**, studied performance of selection combining Receivers over TWDP fading channels with arbitrary and non-identical fading parameters .Also authors' derived expression of CDF and PDF of signal to noise ratio for TWDP fading channels. System performance is studied by varying the no. of branches M and the fading parameters K and Δ. Authors used Monte Carlo simulations to validate the analytical results [30].

In **2013 Sayed Ali Saberali et al.**, gave new expressions for TWDP fading statistics. As pdf for TWDP fading is complex and cannot be expressed in closed form. Hence, the need of simplified expressions always existed. So, authors derived two infinite series expressions for the TWDP fading PDF and CDF and used low complexity algorithm to consider their manipulation. Complementary error function was used to compute TWDP fading PDF. The derived expressions are rapidly shown to converge over practical TWDP fading Parameters. Also authors to implement and validate their technique, plotted BER of a BPSK system using Monte Carlo simulations [31].

In **2013 D. Dixit et al.**, studied performance of QAM signalling over TWDP fading channels. All forms of QAM such as RQAM (Rectangular QAM), SQAM (Square QAM) and XQAM (Cross QAM) are general forms of QAM Signalling. Appell's and Laureicella's hypergeometric functions have been used to express closed –form expressions of ASER(average symbol error rate) also in addition authors gave closed form expression of nth moment of received signal's SNR . Moment Generating Functions are used to analyse closed form expressions of average symbol error rate of general order rectangular QAM and cross QAM [32].

In **2014 Lu Lu et al.** , presented overview of MASSIVE MIMO system, including its benefits and challenges. Paper described information theoretic analysis to illustrate advantage of large antenna system, focussed on main limitation of Massive MIMO which is Pilot Contamination and its potential impact caused by use of Non – orthogonal pilot's sequences by users in adjacent cells. Energy efficiency achieved by massive MIMO systems and degrees of freedom provided by them enables efficient single carrier transmissions. All challenges, options and opportunities associated with implementing Massive MIMO in future wireless Communications Systems are discussed [33]. Fig. 2.1 represents general massive MIMO system.

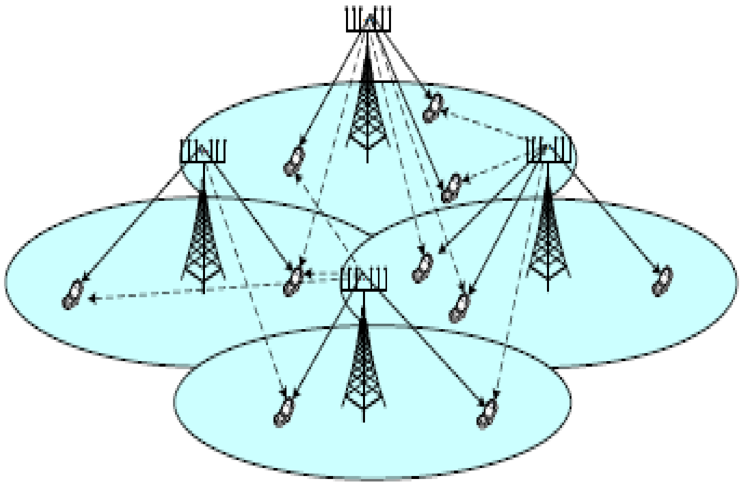

Figure 2.1:-Massive MU-MIMO System [33].

In **2014 Erik G. Larsson et al.**, discussed Massive MIMO as Next Generation Wireless Systems. It included all the advantages of this system. Paper presented massive MIMO as a system to reap all benefits of conventional MIMO but on larger scale. These systems are proposed to be energy efficient, secure and robust. All possible configurations of antenna's in Massive MIMO system was proposed in this paper as shown in fig. 2.2. All the advantages of massive MIMO can be made in to use if extra degrees of freedom provided by the excess of antennas at the BS is properly exploited through use acquisition and synchronization of newly joined terminals [34].

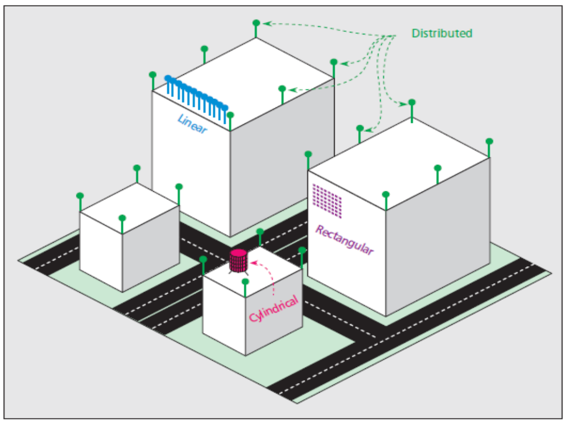

Figure 2.2: - Possible Configurations of Antenna at Massive MIMO BS (Base Station) [34].

All new research work which is being carried out in Massive MIMO has been mentioned in this paper such as The Argos Test-bed which shows the basic functionality of Massive MIMO concept using 64 simultaneously operating antennas. Other test-beds such as Ngara testbed in Australia showing 32 base station array serving 18 user simultaneously are mentioned in this paper [34].

In **2014 Milind Rao et al.**, represented TWDP fading as a model that can characterize a large range of fading behaviour and is presented as two dominant line of sight components in presence of a diffuse component. Also authors studied Amount of fading and Level crossing Rate for TWDP fading [35].

In **2015 Milind Rao et al.**, showed that Generalized Two Ray fading channel can be derived from Rician pdf by replacing K- factor with equivalent K and then averaging phase difference between the LOS components. Authors worked on various statistics of GTR-U model such as PDF, CDF, and Moments of SNR which can be directly obtained by MGF or also can be calculated from the moments of SNR of Rician statistics. They also gave expressions for amount of fading and level crossing rate. They gave the fact that when Two LOS components are equal in strength and opposite in phase makes TWDP fading scenario more probable. Many simulations are included such as capacity versus SNR plots for different values of K and Δ and SEP vs average symbol SNR for 16-QAM [8].

In **2015 A. D. Singh**, studied all digital modulations such as BPSK, M-ary PSK and M- ary QAM over TWDP fading channels. Authors derived expression of characteristic function and outage probability of SNR. ASER (Average Symbol Error Rate) of Coherent and non-coherent systems is studied. Effect of different modulations techniques and fading parameters over TWDP fading channels is studied in this paper. Results are verified using Monte Carlo Simulations. Outage Probability of TWDP channel and error performance of various modulation techniques is analysed in this paper [36].

Final conclusion that can be withdrawn from Literature Survey presented is that TWDP channel has not yet been implemented with MIMO and Massive MIMO systems. Thus, further chapters' analyses performance of MIMO/Massive MIMO systems in TWDP channels. Performance of Spatially Modulated System in TWDP environment is studied.

CHAPTER 3: TYPES OF FADING SCENARIOS

Fading is rapid fluctuation in signal strength caused by destructive interference of two or more versions of transmitted signal. It is the main bottleneck in designing wireless communication model.

3.1 CONVENTIONAL FADING SCENARIOS

Rayleigh and Rician fading models are conventionally used models to properly characterize any fading environment. Hence, these two models are presented before discussing TWDP fading model.

3.1.1 RAYLEIGH FADING SCENARIO

Rayleigh fading scenario consists of many diffuse components with no strong LOS component. It is often considered as worst case fading scenario and thus many practical wireless systems are designed considering this fading scenario. Fig. 3.1 presents Rayleigh fading environment. Also mobile Radio channels often use the Rayleigh distribution to describe statistical time varying nature of received signal [1].

It has many multipath components each with random phase and amplitude. Its pdf is given by

$$f_R(r)=\frac{r}{\sigma^2}\exp\left(\frac{-r^2}{2\sigma^2}\right),\ r\geq 0\ , \tag{3.1}$$

where, r is the fading amplitude, σ is the RMS strength of voltage signal received and σ^2 denotes the average power of received signal before envelope detection [1].

This fading environment is modelled using two random variables such as following

$$\boldsymbol{V_r} = \mathbf{X} + j\mathbf{Y}\ , \tag{3.2}$$

where, **X** and **Y** are two random variables with zero mean and σ^2 variance and thus , the fading amplitude r_i at i-th time instant is given by :-

$$r_i=\sqrt{{x_i}^2+{y_i}^2}\ . \tag{3.3}$$

In eqn. (3.3) x_i and y_i are random variables with zero mean and σ^2 variance.

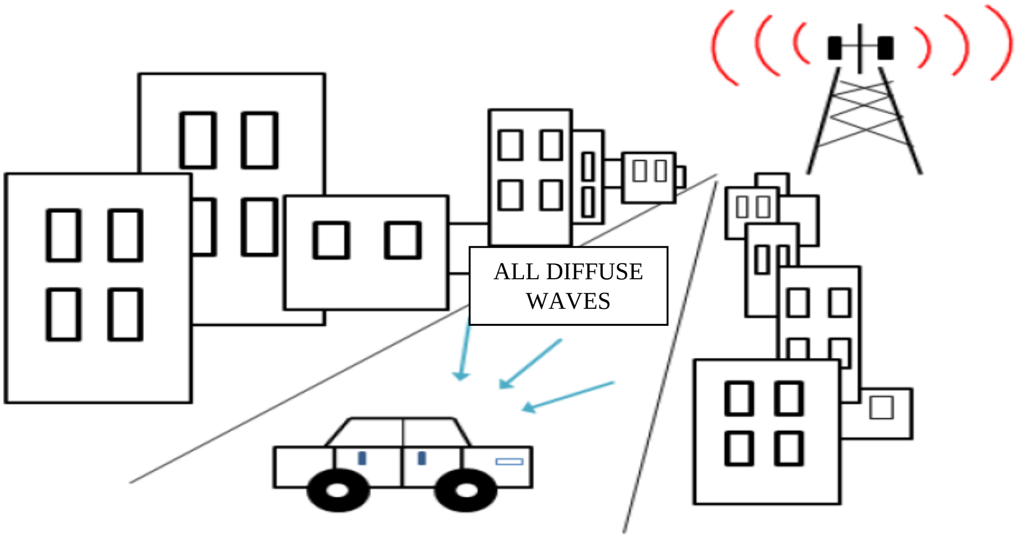

Figure 3.1:- Rayleigh Fading Environment [7].

3.1.2 RICIAN FADING SCENARIO

Rician fading scenario consists of one strong LOS component along with many diffuse components given in fig. 3.2. In such case, diffuse components coming at variable angles are superimposed with that of stationary specular i.e. dominant component. Its pdf is given by

$$f_R(r)= \frac{r}{\sigma^2}\exp\left(-\frac{r^2-V_1^2}{2\sigma^2}\right) I_0\left(\frac{rV_1}{\sigma^2}\right), \quad V_1 \geq 0, r\geq 0 \ , \tag{3.4}$$

where, r denotes the fading amplitude, parameter V_1 is the maximum amplitude of the specular component and I_0 is the modified Bessel function of the first kind and zero order [1].

The fading amplitude r_i at i-th time instant is given by

$$r_i=\sqrt{(x_i + V_i)^2 + {y_i}^2} \quad . \tag{3.5}$$

In eqn. (3.5) V_i is amplitude of specular component and x_i and y_i are random variables with zero mean and σ^2 variance. Rician distribution is commonly analysed using value of parameter K_{Ric}, which is ratio of power of Specular Component to the power of Diffuse Component and is given as $K_{Ric} =\frac{{V_i}^2}{2\sigma^2}$.

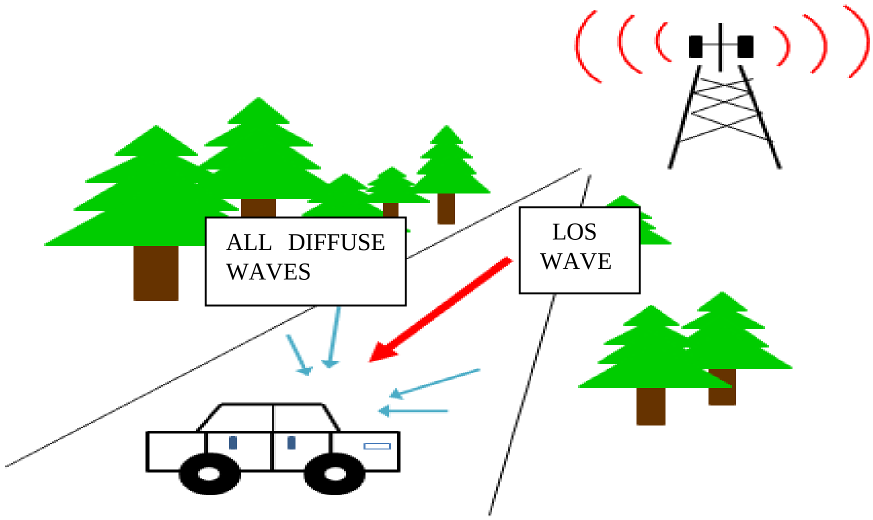

Figure 3.2:- Rician Fading Environment [7].

3.2 TWDP FADING SCENARIO

TWDP fading consists of two strong LOS components and many diffuse components. This model has attracted attention since Current Wireless Scenarios are correctly characterized by this fading model. Fig. 3.3 represents TWDP fading model. Efficient wireless communication requires that transmitter and receiver are well designed which requires knowledge of fading environment. Hence, it is imperative to analyse and design this fading type so that wireless scenario suiting this particular environment is appropriately represented. It has two parameters which are K and Δ.

$$K=\frac{V_1^2+V_2^2}{2\sigma^2} \qquad \Delta=\frac{2V_1V_2}{V_1^2+V_2^2},$$

where, V_1 and V_2 are voltage magnitudes of the two specular waves and $2\sigma^2$ represents the average power of the diffused waves. K is the ratio of the **Specular power** to **Diffused power**, while Δ indicates the relative strength of two **Specular Components** [2].

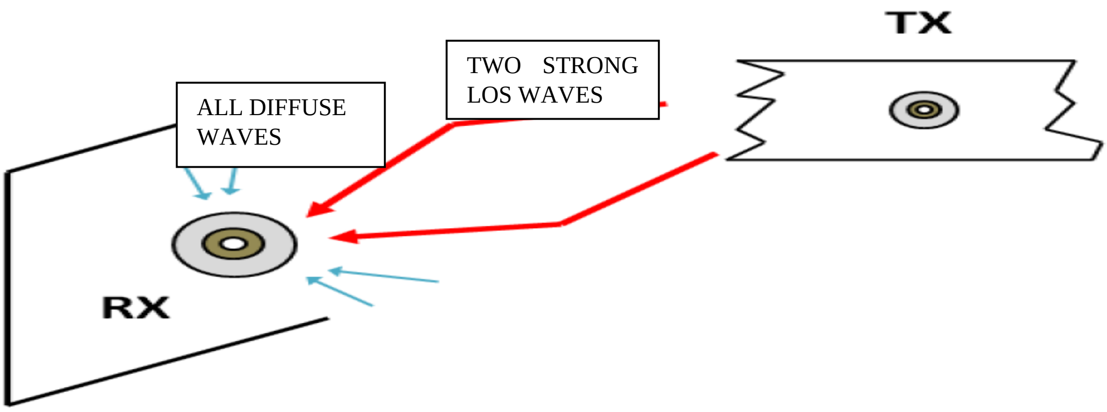

Figure 3.3:- TWDP Fading Scenario [7].

Table 3.1:- Classification of Fading on the Basis of Strengths of Specular Component to Diffuse Component [2].

CASE	1st Specular Voltage V_1	2nd Specular Voltage V_2	Diffuse RMS voltage $\sqrt{2\sigma^2}$	Value Of K	Value of Δ	Type of fading
1	2 μV	2 μV	3 μV	0.89	1	Rayleigh Fading
2	4 μV	2 μV	3 μV	2.22	0.8	Rician Fading
3	4 μV	4 μV	3 μV	3.56	1	TWDP Fading

Table 3.1 classifies three fading scenarios on the basis of strengths carried by Diffuse Component and Specular Component. Table clearly depicts that Value of K is negligible in case of Rayleigh fading and is high for TWDP fading Environment. Also Δ which is 0.8 for Rician fading approaches 1 in TWDP fading Scenario.

Table 3.2:-Categorization of Fading on the Basis of Number of Specular Components.

TYPE OF FADING	NUMBER OF SPECULAR COMPONENTS
Rayleigh Fading	No Specular Component
Rician Fading	One Specular Component
TWDP Fading	Two Specular Components

Table 3.2 classifies fading on the basis of Number of Specular Components. Rayleigh has zero LOS path, while there is one Strong LOS component in Rician fading and Two Strong LOS components in TWDP fading. Rayleigh fading, Rician fading, hyper Rayleigh fading can be considered as the special case of TWDP fading. When K=0 TWDP fading model degenerates to Rayleigh, for Δ=0 Rician fading is approximated and when Δ≅1 and K→ ∞ Hyper Rayleigh fading comes into action. Fig. 3.4 represents specular and diffuse components in TWDP fading.

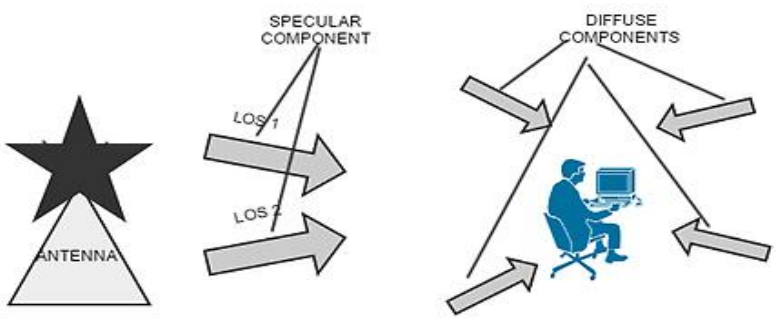

Figure 3.4:-TWDP Environment with Two Specular Components and Many Diffuse Component.

Table 3.3:- Range of Values of K and Δ to Classify the Type of Fading.

Type Of Fading	**Value of K**	**Value of Δ**
Rayleigh Fading	-∞ to 0 dB	Not applicable as no Specular component
Rician Fading	1 to 3 dB	Δ=0 as one Specular Component
TWDP Fading	3 to ∞ dB	Δ=0 to 1

It has a complicated expression of pdf, authors in [2] have proposed pdf for this fading as:

$$f_R(r)=\frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}-K\right)\sum_{i=1}^{M} a_i\, D\left(\frac{r}{\sigma};K;\Delta\cos\frac{\pi(i-1)}{2M-1}\right) \quad , \tag{3.6}$$

where $D(x;K;\alpha)=\frac{1}{2}\exp(\alpha K)I_o(x\sqrt{2K(1-\alpha})+\frac{1}{2}\exp(-\alpha K)I_o(x\sqrt{2K(1+\alpha})$, (3.7)

here, M is the order of the approximate TWDP pdf. Approximate pdf approaches accurate representation by increasing the value of M. The values of first five exact $\{a_i\}$ coefficients is given in[2] and included in table 3.4. The value of order M is defined as Order (M) ≥ $\frac{1}{2}K\Delta$ [2]. The value of product of K and Δ parameters determines the order that should be used while representing TWDP fading.

Table 3.4 :- Exact Coefficients for First Five Orders to Approximate TWDP Fading Pdf [2].

Order	**a_1**				
1	1	**a_2**			
2	$\frac{1}{4}$	$\frac{3}{4}$	**a_3**		
3	$\frac{19}{144}$	$\frac{25}{48}$	$\frac{25}{72}$	**a_4**	
4	$\frac{751}{8640}$	$\frac{3577}{8640}$	$\frac{49}{320}$	$\frac{2989}{860}$	**a_5**
5	$\frac{2857}{44800}$	$\frac{15741}{44800}$	$\frac{27}{1120}$	$\frac{1209}{2800}$	$\frac{2889}{22400}$

TWDP fading model which consists of two specular components and a diffuse component is given in equation 3.8.

$$V_r = V_1 \exp(j\emptyset_1) + V_2 \exp(j\emptyset_2) + \mathbf{X} + j\mathbf{Y} \quad , \qquad (3.8)$$

where, $\boldsymbol{V_r}$ is the received signal, components 1 and 2 are specular components with phases $\emptyset_1, \emptyset_2 \sim \cup\,(0,2\pi)$ and V_1 and V_2 are constant. Diffuse components is given by random variables **X** and **Y**, which are Gaussian distributed with zero mean and σ^2 variance [8].

3.3 FADING MODELS

It is proved in [8], that TWDP pdf can be derived from Rician pdf. PDF can be obtained by integrating α over range of [0:2π]. Here, α denotes the angle of phase difference between two LOS components i.e. $\alpha = \emptyset_1 - \emptyset_2$, where $\emptyset_1$ is the phase of first LOS component or wave and $\emptyset_2$ is the phase of second LOS component.

The equivalent K is used in Rician pdf to derive TWDP pdf.

$$K_{equivalent} = K_{Rician} * (1 + \Delta * \cos(\alpha)) \ . \qquad (3.9)$$

Hence, to derive K_{TWDP} , $K_{equivalent}$ is averaged over range of phase difference α.

3.3.1 RAYLEIGH PDF

When parameter K is close to $-\infty$ dB, i.e. strength of specular component is almost zero compared to diffuse components, the TWDP pdf degenerates to Rayleigh fading as depicted by pdf plot in fig. 3.5. PDF is plotted in MATLAB keeping K= -10 dB. Rayleigh pdf is formed by considering two variables that are randomly distributed with 0 mean and σ^2 variance, which means only diffuse components are present and Line of sight path is absent.

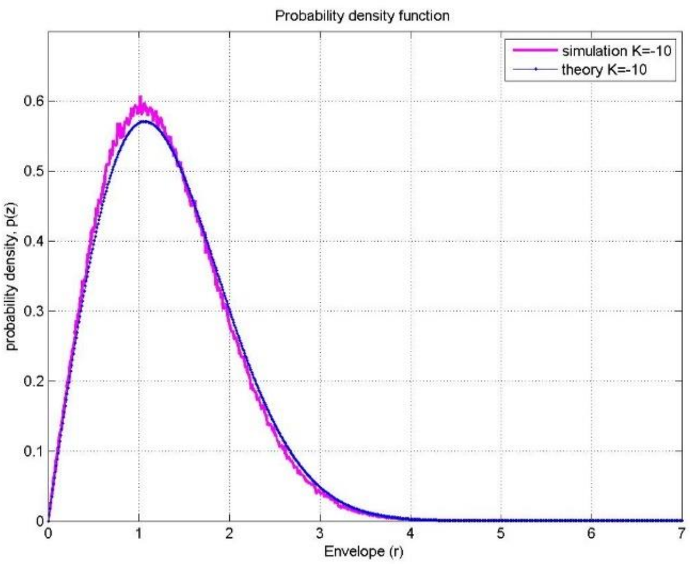

Figure 3.5:-PDF Plot of Rayleigh Fading.

3.3.2 RICIAN PDF

Rician fading has only one LOS component which denotes that value of K exists but is small in value. However, Δ is zero as other LOS component is absent. When K= 2 to 3 dB and Δ=0 then, TWDP pdf assumes shape of Rician pdf as in fig. 3.6.

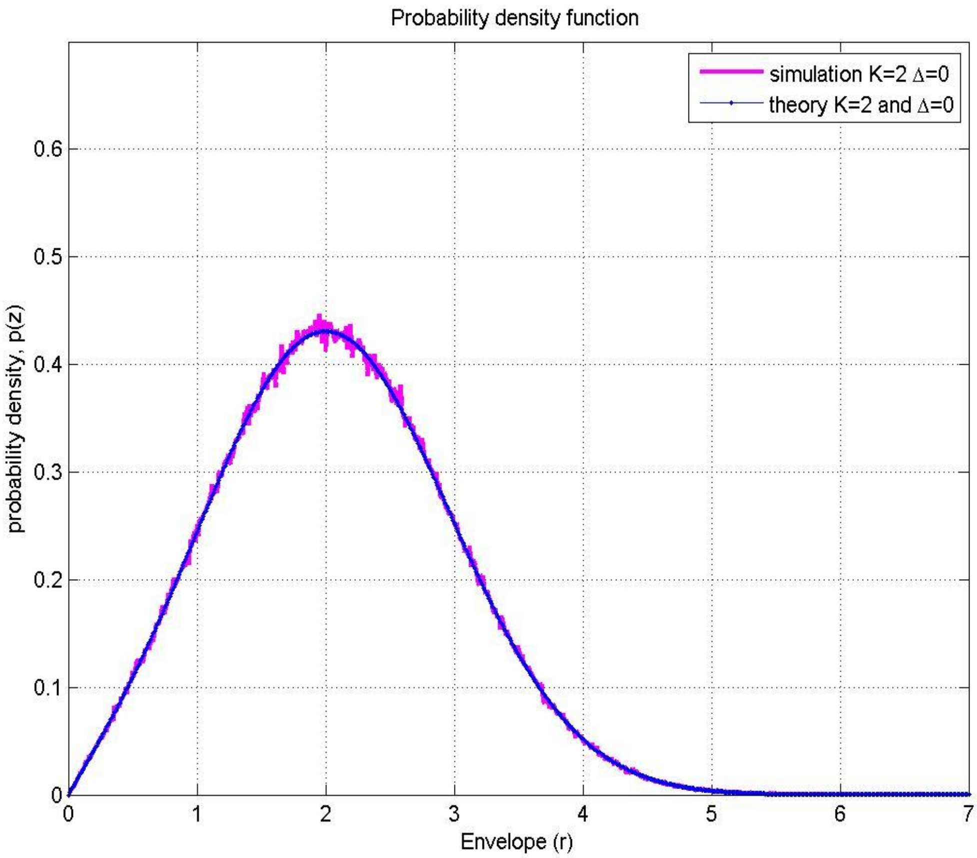

Figure 3.6:- PDF Plot of Rician Fading.

3.3.3 TWDP PDF

In this fading statistics , Value of K (parameter that represents ratio of power of specular component to the power of diffuse component) almost approaches infinity (∞) which means it is very high as compared to that in case of Rayleigh and Rician fading . Δ (parameter that is relative strength of two LOS components) almost approaches 1, as there are two LOS Components in TWDP fading and value of relative strength of these two LOS waves ranges from 0 to 1.

When plotted in MATLAB Computer Software using averaging method as given in equation 10 putting $K\rightarrow \infty$ and $\Delta\rightarrow 1$, TWDP pdf is obtained as in fig. 3.7.

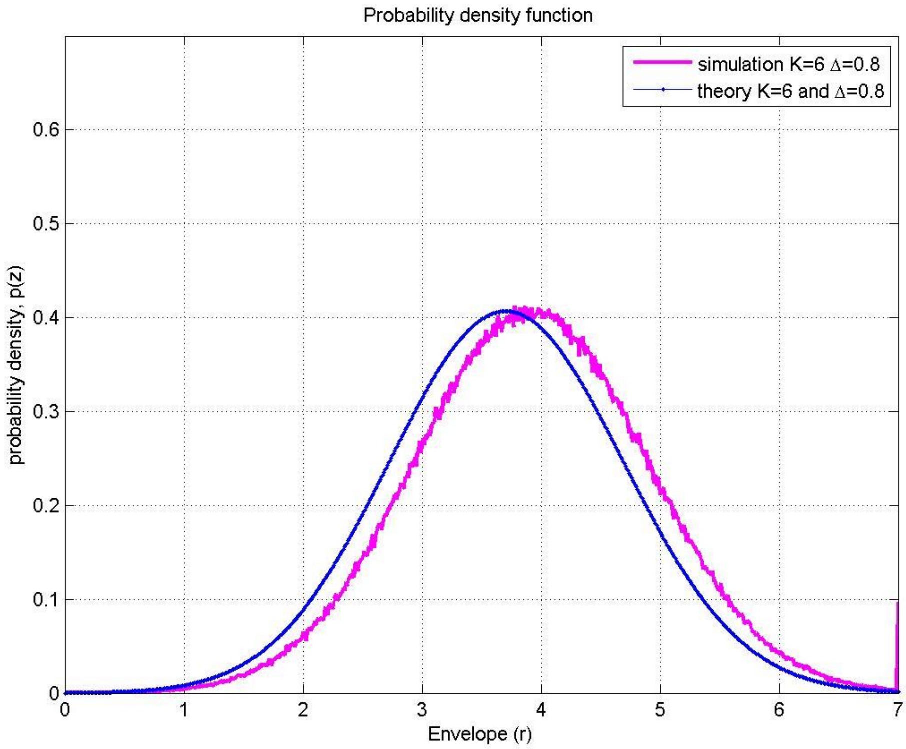

Figure 3.7:-PDF Plot of TWDP Fading.

It can be concluded from this chapter that TWDP fading pdf converges to that of Rayleigh and Rician for some values of K and Δ. The three fading models can be differentiated on the basis of number of specular and diffuse components, strengths of LOS waves and value of K and Δ. In the next chapter performance of wireless communication systems is studied in TWDP fading channel.

CHAPTER 4: PERFORMANCE OF MIMO IN TWDP FADING

MIMO stands for Multiple input and Multiple Output. They have ability to fight fading and use scattering in their own benefit. Hence, performance of MIMO system in TWDP fading environment is very important. This Chapter evaluates the performance of MIMO and all its configurations in TWDP fading.

4.1 MIMO FORMATS

Wireless industry has completely revolutionized Communication. It started with SISO system where one antenna at transmitter transmits and one antenna at receiver receives with no additional processing required. Although SISO being the simplest system is not currently employed due to capacity limitations imposed by Interference and fading.

Figure 4.1:- MIMO-SISO Format [37].

So, SIMO system came for rescue where receiver diversity is present to combat the adverse effects of fading where receiver receives from number of independent sources. SIMO although still easy to implement requires processing at receiver end. Also it offers problems of limited data rate, not enough for current wireless needs where data in form of texts, images and videos needs to be transferred with high speed .

Figure 4.2 :- MIMO-SIMO Format [37].

Some authors, then suggested use of MISO i.e. to employ transmit diversity, where receiver selects optimum signal and no processing is required.

Figure 4.3:-MIMO-MISO Format [37].

But, major problem of limited data rate still existed, which was put to an end with implementation of MIMO (multiple input and multiple output) systems. MIMO provides diversity at both sides i.e. both at transmitter and receiver, hence is able to combat interference and fading in a robust way [37].

Figure 4.4:-MIMO-MIMO Format [37].

4.2 SYSTEM MODEL

Consider a MIMO system with N_t transmit and N_r receive antennas as shown in fig. 4.5. Let $\mathbf{x} \in N_t \times 1$ is transmitted vector, $\mathbf{H} \in C^{N_r \times N_t}$ is channel matrix, $\mathbf{n} \in N_r \times 1$ is noise vector and $\mathbf{y} \in N_r \times 1$ is received vector, then MIMO system can be presented as below in the form of equation 4.1.

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{4.1}$$

Figure 4.5:-System Model.

Capacity of MIMO System is given by

$$C_{MIMO}=\log_2(det(I_{N_r} + \frac{\rho}{N_t}\ \mathbf{H}\boldsymbol{H}^H)). \tag{4.2}$$

However, when TWDP fading exists Elements of **H** are considered to be TWDP faded, and capacity in TWDP fading is given by

$$C_{MIMO-TWDP} = \log_2(det(I_{N_r} + \frac{\rho}{N_t} \boldsymbol{H_{TWDP}} \boldsymbol{H_{TWDP}}^H)) \quad (4.3)$$

All the systems such as SISO, SIMO, MISO and MIMO are studied in TWDP fading considering model given in fig 4.5. All comparisons are made in three fading channels i.e. in Rayleigh, Rician and TWDP fading channel. Rayleigh fading is random fading model, which is modelled in MATLAB using two normal random variables of zero mean and σ^2 variance.

$$\boldsymbol{H_{Rayleigh}} = \text{randn}(N_r, N_t) + j * \text{randn}(N_r, N_t) \quad (4.4)$$

Rician fading has one LOS path , which states that one random variable is non- zero mean while other is zero mean both with σ^2 variance.

$$\boldsymbol{H_{Rician}} = ((\text{randn}(N_r, N_t) * \sigma) + \text{mean}) + j * \text{randn}(N_r, N_t) * \sigma \quad (4.5)$$

TWDP channel is modelled using parameters K and Δ to derive strength of two LOS components as given in equation 4.6.

$$\boldsymbol{V_r} = \underbrace{V_1 \exp(j\emptyset_1) + V_2 \exp(j\emptyset_2)}_{\text{Part1}} + \underbrace{\mathbf{X} + j\mathbf{Y}}_{\text{Part2}} \; ; \quad (4.6)$$

$$V_1 = \frac{\sqrt{(2K\sigma^2)+(2\,\Delta K\sigma^2)} + \sqrt{(2K\sigma^2)-(2\Delta K\sigma^2)}}{2} \quad (4.7)$$

$$V_2 = \frac{\sqrt{(2K\sigma^2)+(2\,\Delta K\sigma^2)} - \sqrt{(2K\sigma^2)-(2\Delta K\sigma^2)}}{2} \quad (4.8)$$

The channel in TWDP fading model is made up of two parts. Part1 constitutes strength of two LOS components V_1 and V_2 with phases $\emptyset_1, \emptyset_2 \sim U(0,2\pi)$ whereas part2 is made up of many diffuse waves modelled by using random variables **X** and **Y** with zero mean and σ^2 variance.

4.3 PERFORMANCE OF SISO SYSTEM IN TWDP FADING

Although this thesis mainly covers MIMO System, but it is wise to discuss SISO once with TWDP channel and analyse its results. It shows results different from that obtained for MIMO system. In presence of fading, SISO system performs the worst. As more severe the fading, less is the capacity attained by SISO system. Hence, performance of SISO System in TWDP channel is included in this thesis work. Also variation in capacity of SISO system with change in value of TWDP parameters (K and Δ) is analysed in MATLAB.

SISO system is modelled by making N_t and N_r equal to 1. For studying capacity of SISO system in three fading environments viz: Rayleigh, Rician and TWDP fading, all three fading environments are modelled by taking their respective number of specular and diffuse components. Method of modelling Rayleigh and Rician fading model has already been discussed in chapter 3. TWDP fading model is discussed above in topic 4.2.

In MATLAB software, performance of SISO system is evaluated in all three fading environments. As, SISO is assumed to perform poorly in worse fading environment, it is performing poorly in TWDP fading environment. In Rayleigh fading environment it performs better than in TWDP scenario, but poorer when compared in Rician fading environment. SISO system performs excellent when any strong LOS component is present.

It performs a way better with Rician fading environment and attains highest capacity there. For e.g. in fig. 4.6 at SNR of 20dB , capacity attained by SISO system in Rician fading is 7.2 bits/sec/hertz, whereas it is only 6.4 bits/sec/hertz in TWDP fading and 7 bits/sec/hertz in Rayleigh fading environment.

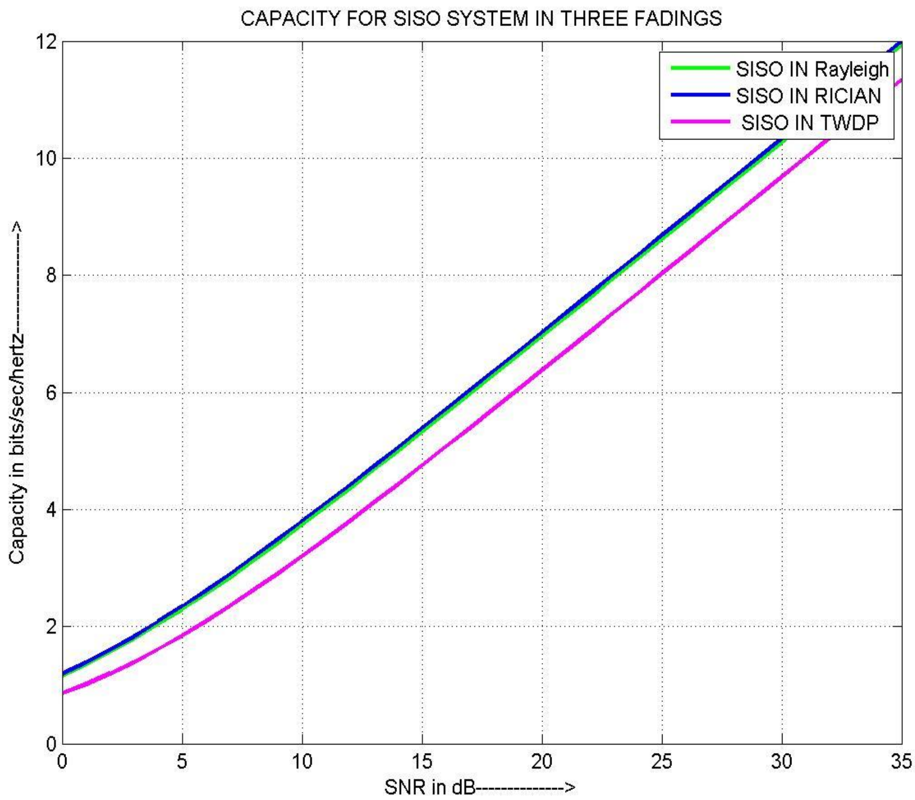

Figure 4.6:- Capacity vs SNR for SISO System in All Three Fading Scenarios.

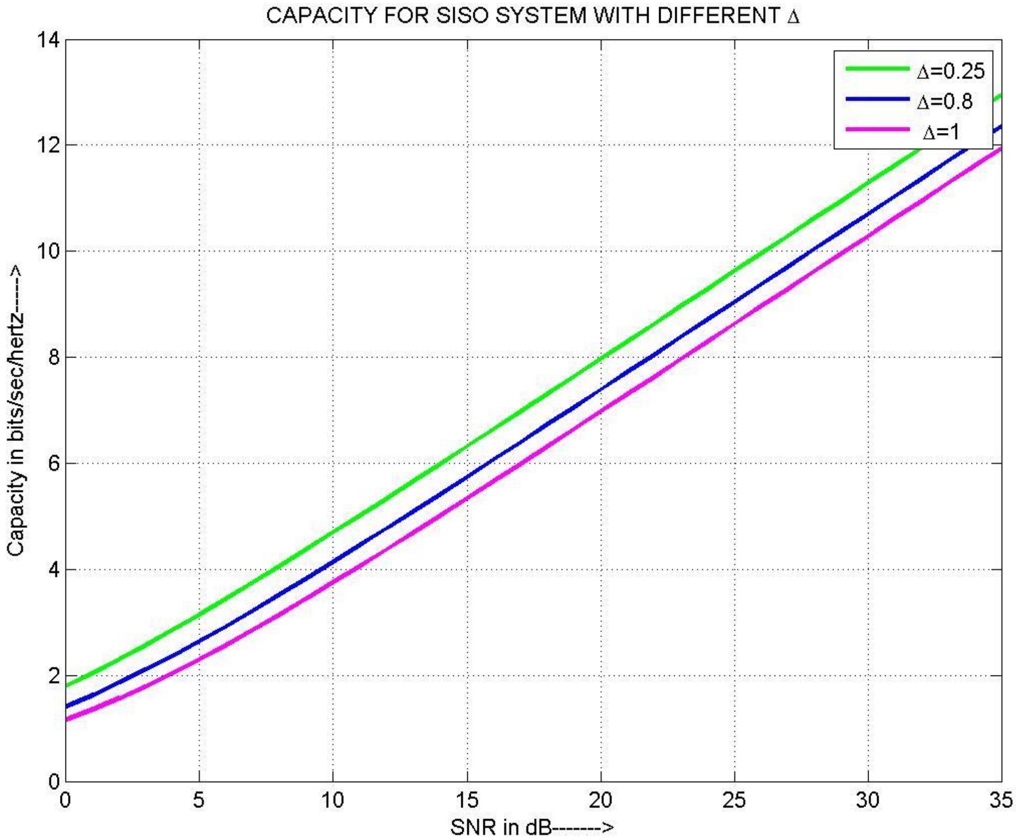

Figure 4.7:-Capacity versus SNR Plot for SISO System with varying Δ and K fixed at 6dB.

Plots in fig.4.7 and 4.8, are capacity versus SNR analytical curves for varying values of K and Δ. In equations 4.3 and 4.4, V_1 and V_2 with corresponding value of K and Δ is derived for calculating strengths of two LOS components. Finally for plotting graphs in MATLAB, channel is made as required for TWDP fading model with two parts. Part1 with LOS components and part2 with diffuse components.

As , the work done by authors in [35] presented the fact that TWDP fading turns more severe when two LOS (Line of Sight) components are equal in strength. Thus, as Δ→1 poor environment conditions turns out for SISO system and they behaves accordingly with increasing Δ in fig. 4.7. In fig. 4.7, at SNR of 20dB 6.8 bits/sec/hertz capacity is attained for $\Delta = 1$. Its is 8 bits/sec/hertz at Δ=0.25 and 7.2 bits/sec/hertz at $\Delta = 0.8$.

However, it is later analysed in this thesis work in MIMO and Massive MIMO systems that as number of branches at transmitter or receiver increases capacity becomes independent of value of Δ i.e. with more no. of antennas almost equal capacity is attained for different values of Δ.

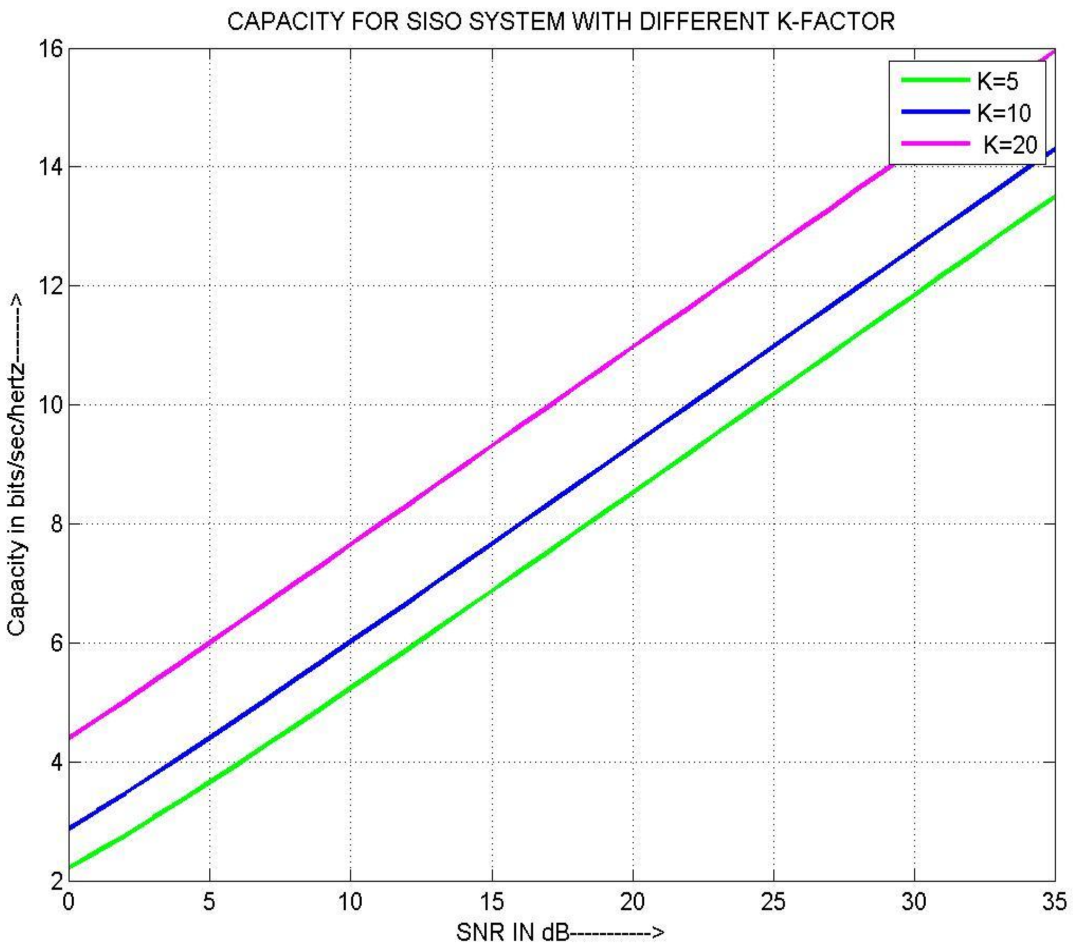

Figure 4.8:-Capacity versus SNR plot in SISO system for different K-factor.

As, it is well known fact that, more is K-factor i.e. line of sight parameter, more capacity SISO system can attain. This is also true for TWDP fading environment which is seen in fig. 4.8. At SNR of 25dB for K=20, capacity as high as 12.6 bits/sec/hertz. It is 11 bits/sec/hertz for K=10 and lowest with K=5 which is 10.1 bits/sec/hertz.

4.4 PERFORMANCE OF SIMO SYSTEM IN TWDP CHANNEL

As number of branches increases either at the transmitter and receiver, diversity is implemented and thus a system appropriate to combat fading is formed. Capacity versus SNR plot for three fading scenario's is compared with/without diversity techniques and TWDP fading scenario is established as fading which forms worst link and thus performs better when large number of branches are available at transmitter or receiver .

4.4.1 SIMO SYSTEM WITHOUT DIVERSITY TECHNIQUES

TWDP channel model is created in the same way as was for SISO system with one antenna at the transmitter and two antennas at receiver.

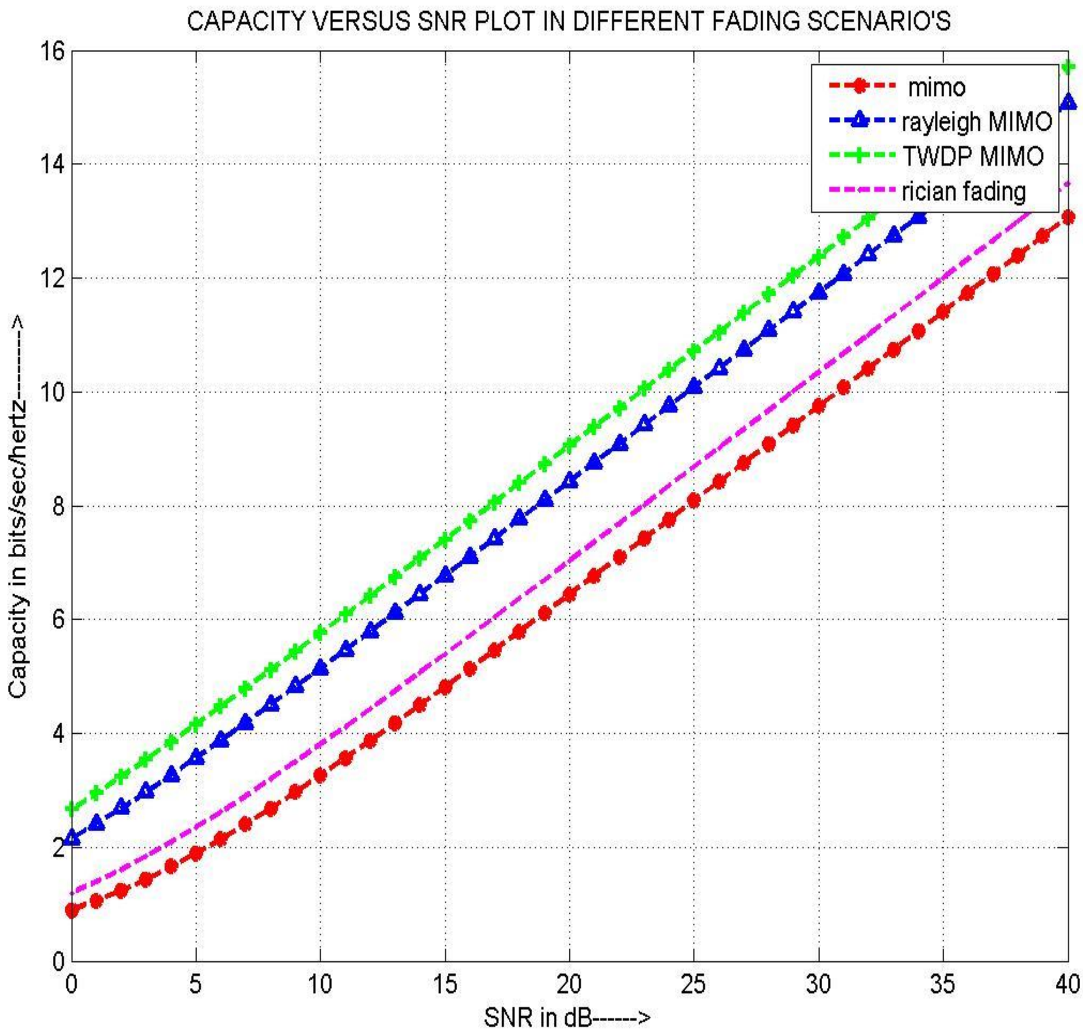

Figure 4.9:-Capacity versus SNR for SIMO system in all fading channels.

Fig. 4.9 is MATLAB plot which compares capacity of SIMO system with $N_t = 1$ and N_r =2 in three fading scenario's. In this matrix **H** is generated for all channels as per procedure explained in section 4.2. As, it is clearly depicted in fig. 4.9 capacity is maximum in TWDP fading channel and poorer in Rician fading channel. At 25dB, capacity with TWDP channel is 10.8 bits/sec/hertz and is 10 bits/sec/hertz with Rayleigh channel and achieves lowest capacity with Rician channel which is 8.8 bits/sec/hertz.

Value of Δ, has a strong impact on the variation of capacity with respect to SNR. As Δ→1, TWDP fading turns more severe. But diversity branches add resilience to combat fading and fading is used in its favour by the system. In Fig. 4.10, it is clearly visible that at 20 dB, capacity attained when Δ=0.25 is lowest which is about 11 bits/sec/hertz. Capacity is Increasing as Δ is approaching 1 and attains the value of 11.8 bits/sec/hertz when Δ=0.8 and 11.9 bits /sec/hertz when Δ=1.

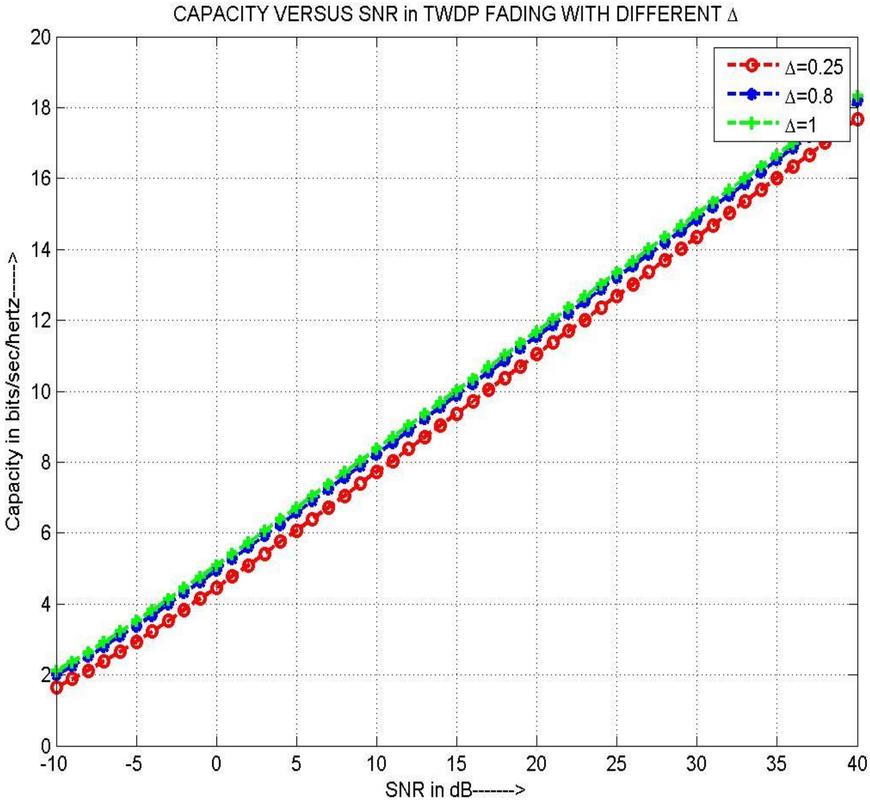

Figure 4.10:- Capacity vs SNR in TWDP fading with different Δ For K fixed at 6 dB.

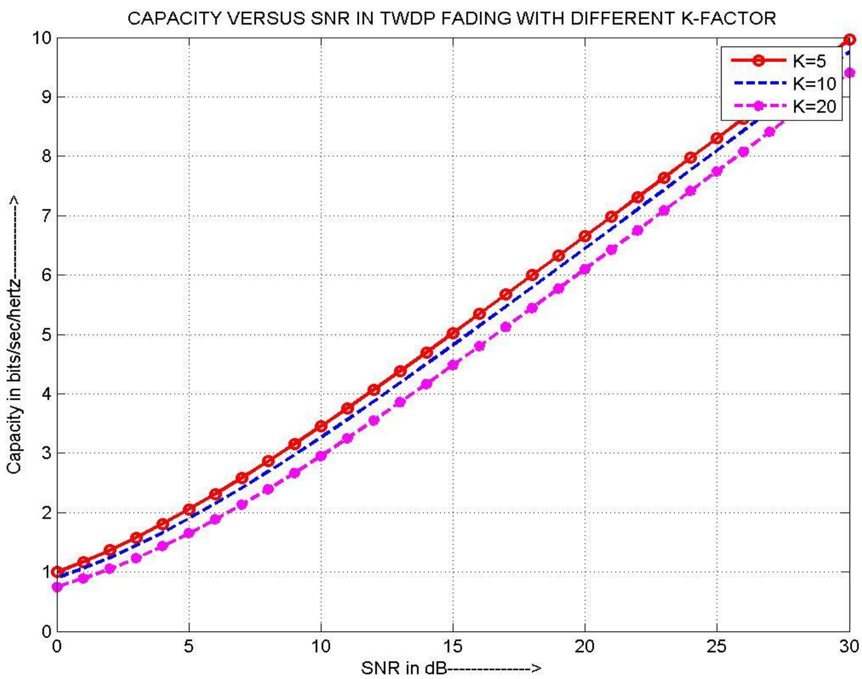

Figure 4.11:-Capacity vs SNR in TWDP fading with different K-factor and Δ fixed at 1.

LOS component achieves higher capacity when there is only one transmitter and one receiver, however when number of branches are increased to combat or compensate fading LOS path adds disadvantage and deteriorates system's performance by decreasing capacity. K-factor which denotes strength of LOS component or of specular components attains lower value of capacity when more number of branches are available either at the transmitter or receiver. Fig. 4.11, clearly depicts the performance of SIMO system with varying K-factor. At SNR of 20 dB, with K-factor 5 capacity is 6.8 bits/sec/hertz. It is 6.5 bits /sec/hertz with K-factor 10 and 6 bits /sec/hertz with K-factor 20.

4.4.2 SIMO SYSTEM WITH DIVERSITY TECHNIQUES

DIVERSITY: - It is a receiver combining technique that provides reliable wireless link at comparatively low cost. It requires no training overhead as required in equalization. There are many receiver diversity techniques which are being used. SC (Selection Combining), EGC (Equal Gain Combining) and MRC (Maximal Ratio Combining) are commonly deployed.

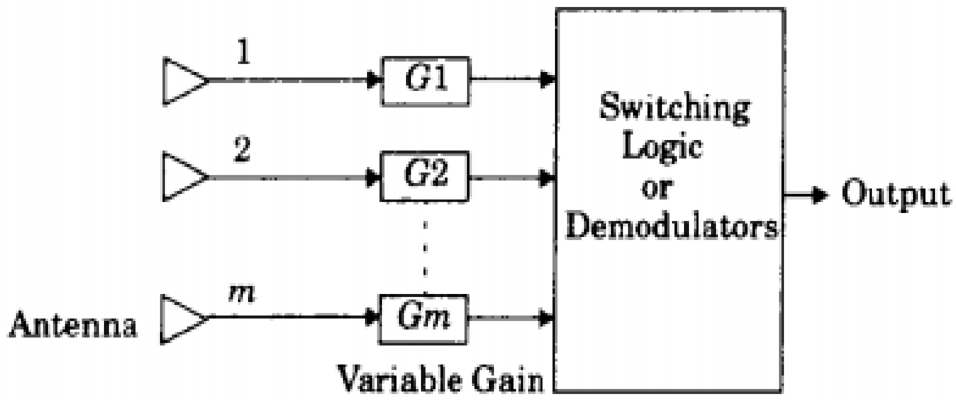

Figure 4.12:-Block Diagram for Space Diversity [1].

SC (Selection Combining) is the simplest diversity technique. In this technique, receiver branch having the maximum instantaneous SNR is passed on to the demodulator. A block diagram is given in fig. 4.12 to illustrate the functioning of SC technique.

MRC (Maximum Ratio Combining):- Gives the output SNR equal to total of individual SNR's. As shown in fig. 4.13, there are M branches and thus M corresponding gains. The value of gain is in accordance of SNR present on the branch link. This is best form of diversity implementation but requires complex circuitry i.e. individual receiver and phasing circuit for each branch.

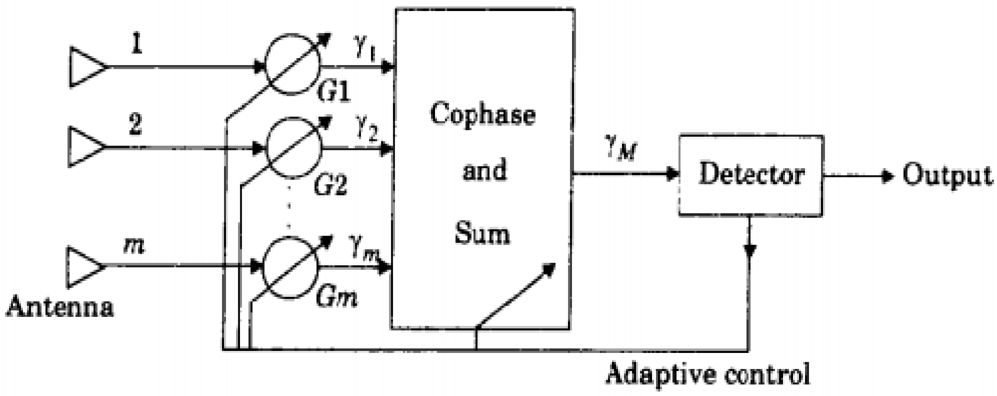

Figure 4.13:-Maximum Ratio Combiner [1].

Equal Gain Combining (EGC):- Although MRC provides efficient results but the variable gains makes circuit complex**.** Hence in EGC, signal from all the M branches is co-phased and weights on them are set to one. Performance of EGC is better than SC but slightly poorer than MRC.

Hence performance of all three receiver combining techniques in TWDP channel applying BPSK modulation is observed in fig.4.14-4.16. As well as all three receiver combining techniques are compared in fig. 4.17.In fig. 4.14, Selection Combining technique is used at receiver end with TWDP channel. It is well demonstrated in MATLAB simulation, that when no. of receive antennas increase, BER decreases. At SNR of 10 dB, BER with 1 receive antenna is about 10^{-3} , whereas it is about 10^{-5} with 2 receive antennas. Hence, BER has reduced drastically.

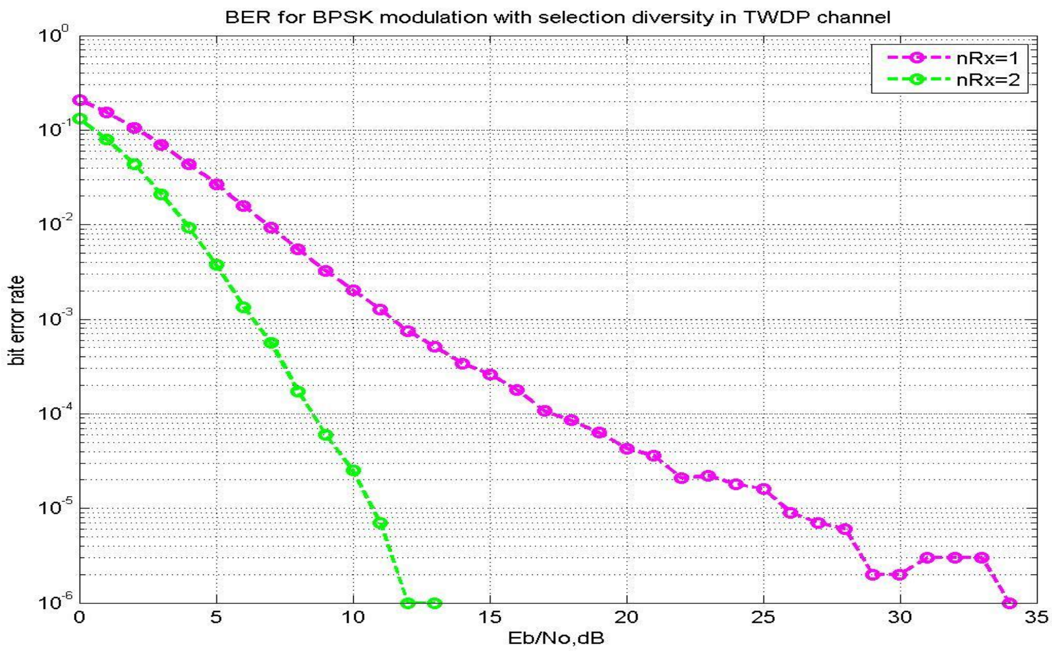

Figure 4.14:-BER for BPSK with SC in TWDP channel with K=5dB and Δ=1.

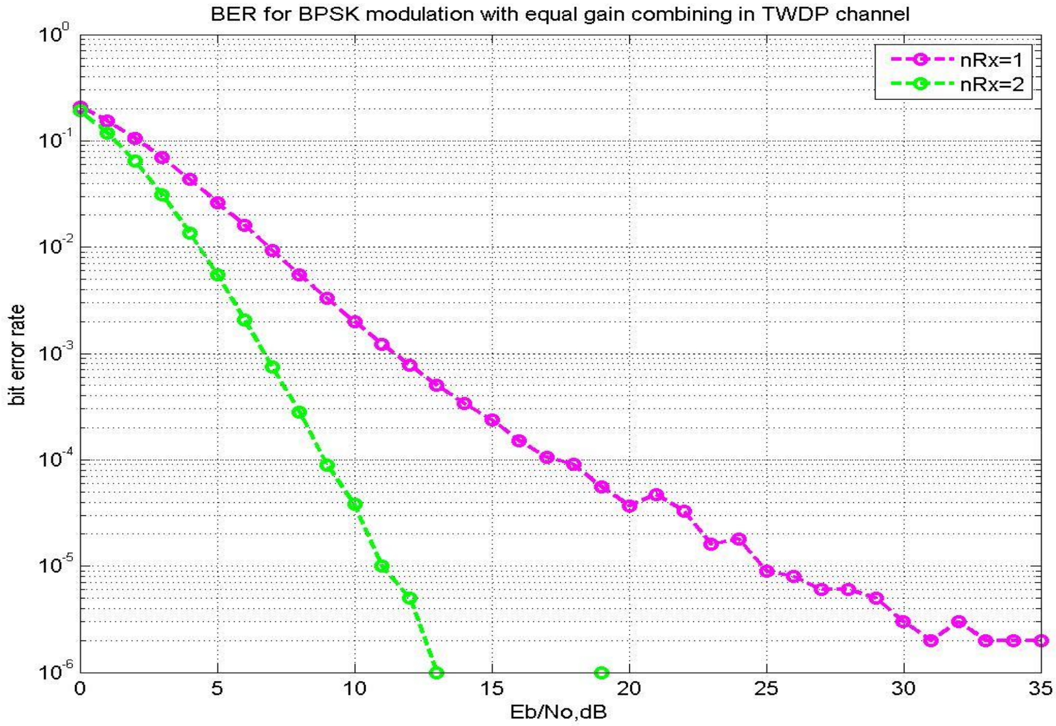

Figure 4.15:- BER for BPSK with EGC in TWDP channel with K=5dB and Δ=1.

EGC (equal gain combining) receiver technique is applied in fig. 4.15. MATLAB simulation validates the result that BER decreases on increasing no. of receive antennas. At SNR of 15 dB, 0 BER is observed for N_r=2 and about 10^{-4} BER is obtained for N_r=1.

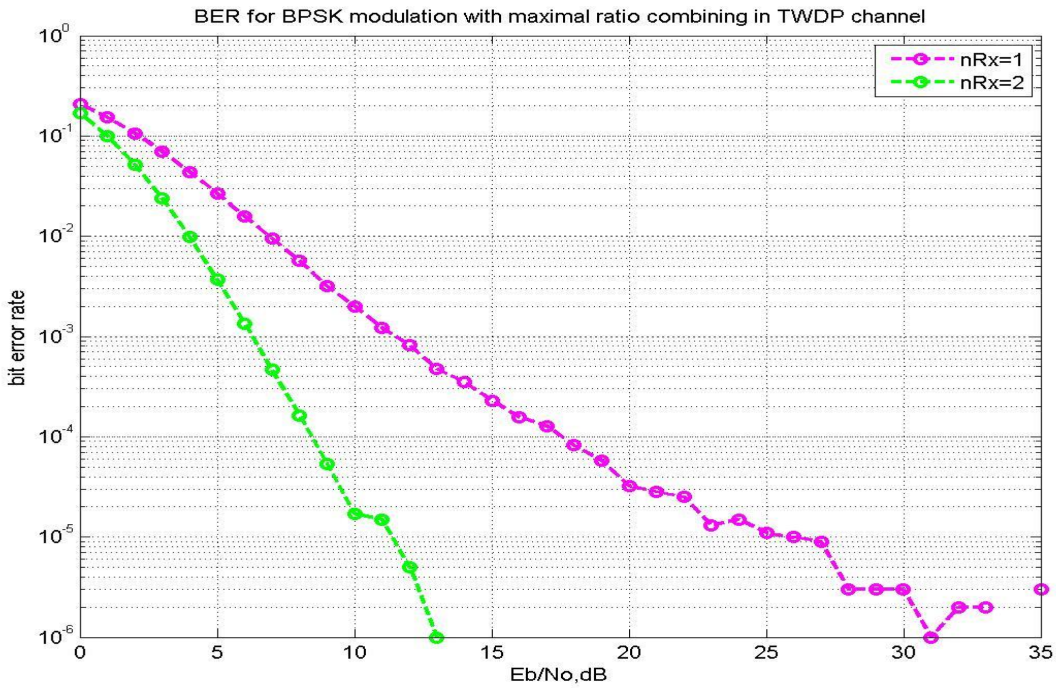

Figure 4.16:-BER for BPSK with MRC in TWDP channel with K=5dB and Δ=1.

Here, in fig. 4.16 MRC (Maximal Ratio Combining) again, BER decreases on increasingN_R. At 15 dB, BER is 0 for $N_r = 2$ and is 10^{-4} for $N_r = 1$. Fig. 4.17 compares all receiver combining techniques viz: SC, EGC and MRC in TWDP fading environment. As MRC is known as best receiver combining technique, it is same for TWDP channel also. MRC attains lowest BER, then comes EGC and last is SC which has maximum BER in TWDP channel amongst all combining techniques. MRC therefore being best is used when precise results are required. But most commonly employed technique is EGC which is easy to deploy and gives feasible results as well. Table 4.1 lists the results obtained in this MATLAB simulation. It compares three diversity combining techniques for signal to noise ratio, to attain 10^{-3} BER.

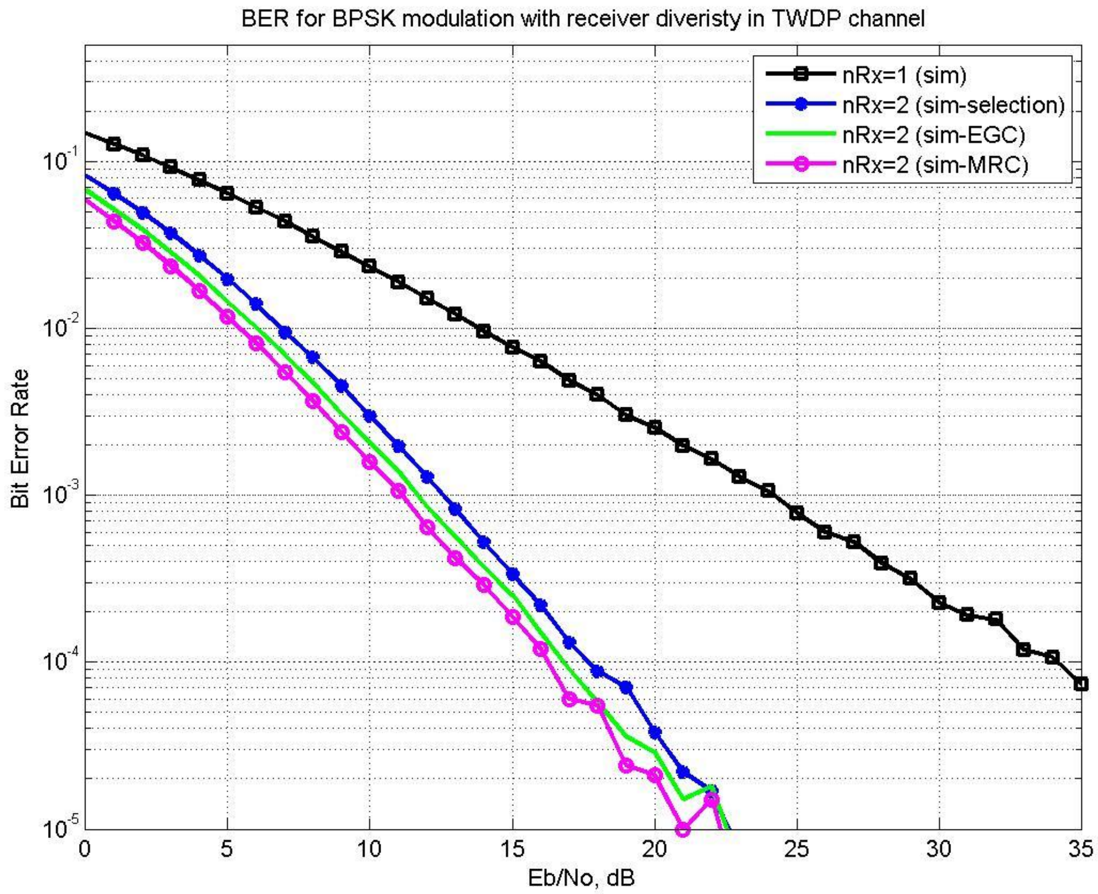

Figure 4.17:- BER for BPSK with all receiver combining techniques in TWDP channel.

Table 4.1:- Performance of Diversity Techniques in TWDP channel.

Name of Diversity Technique	Bit Error Rate(BER)	SNR Required
SC	10^{-3}	13 dB
EGC	10^{-3}	12 dB
MRC	10^{-3}	11 dB

4.5 PERFORMANCE OF MISO SYSTEM IN TWDP FADING

MISO also provides diversity to combat and fight fading with more antennas at the transmitter. Here, in this system two antennas are taken at transmitter and one at receiver. MISO although provides transmit diversity, but no coherent combining of signal is available which decreases coding gain and hence lower capacity is attained which is quite visible in MATLAB plot in fig. 4.18. Here 2 bits/sec/hertz lower capacity than compared to SIMO system is attained. But, the other result that capacity in maximum in TWDP channel is correctly demonstrated. At 25dB capacity obtained with TWDP channel is 8.8 bits/sec/hertz whereas it is between 6-8bits/sec/hertz for other channels such as Rayleigh and Rician.

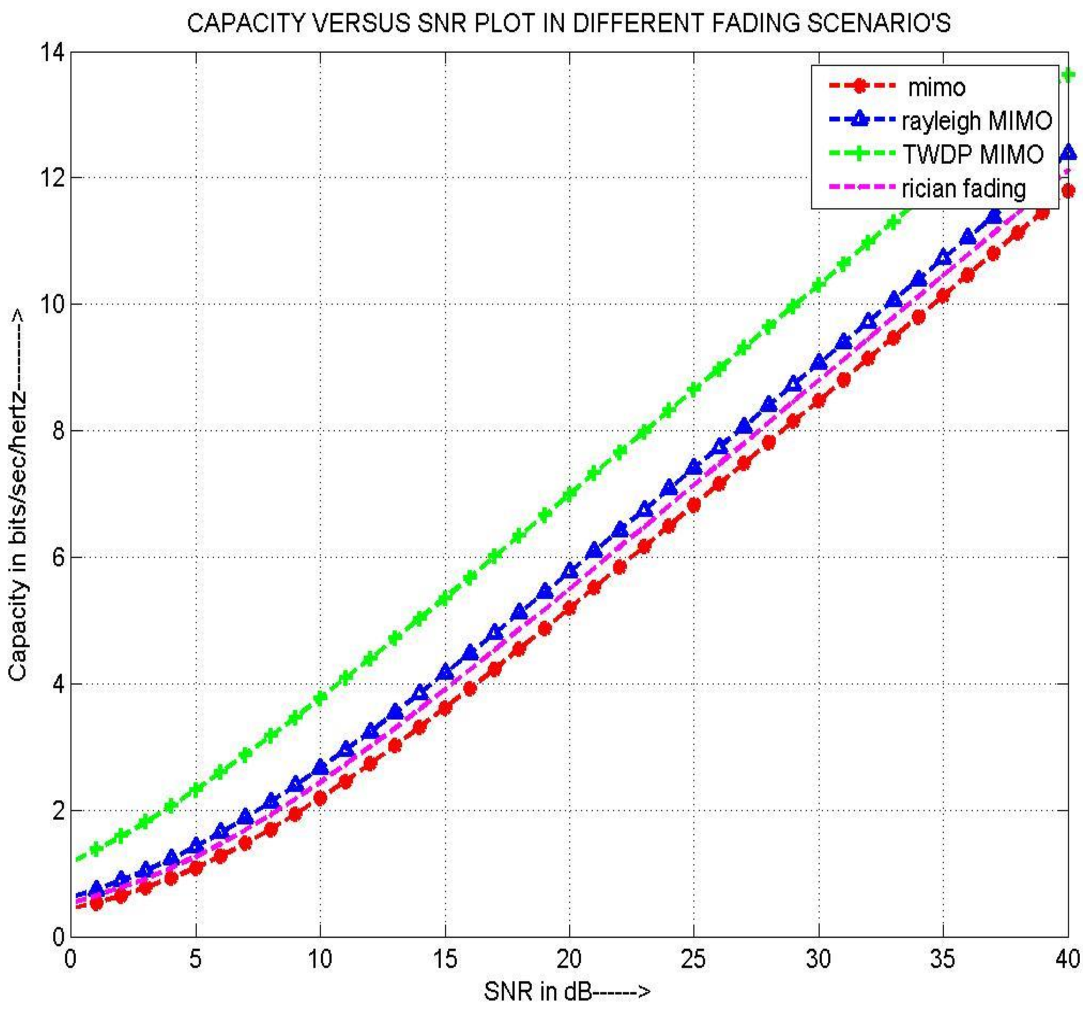

Figure 4.18:-Capacity versus SNR for MISO system in TWDP channel.

In next figures parameters K and Δ are varied in MISO format with TWDP fading applied. Fading parameters has strong impact on the performance of particular system which is demonstrated in these MATLAB results.

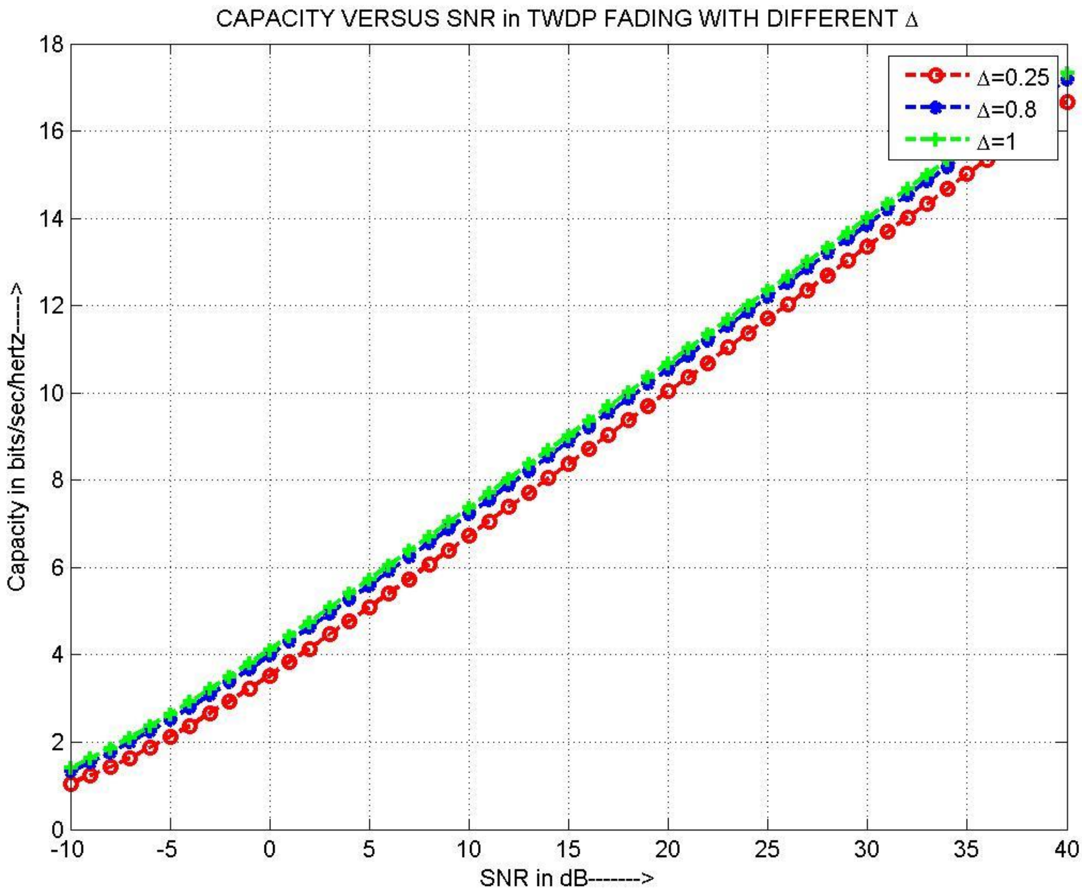

Figure 4.19:-Capacity vs SNR in TWDP fading with different Δ and K fixed at 6 dB.

Fig 4.19 is MATLAB plot for MISO (2×1) format. Results are very much similar to that of SIMO Format. Capacity is higher for larger value of Δ. At SNR of 20 dB, it is 10 bits/sec/hertz for Δ=0.25, 10.2 bits/sec/hertz for Δ=0.8 and is 10.3 bits/sec/hertz for Δ=1.

Result shows that there only marginal increase in capacity for Δ changing from 0.8 to 1, which shows that data rate becomes independent of parameter Δ when branches are more.

K-factor always puts lower bounds on capacity attained when there are more than one antenna at receiver or transmitter. MISO system also shows same results. Fig. 4.20 is capacity versus SNR plot with different values of K (5 10 15) and results show that capacity is more when K-Factor is less. At SNR of 20 dB, capacity is 7.2 bits/sec/hertz when K=20, 7.9 bits/sec/hertz when K=10 and highest at K=5, which is 8 bits/sec/hertz.

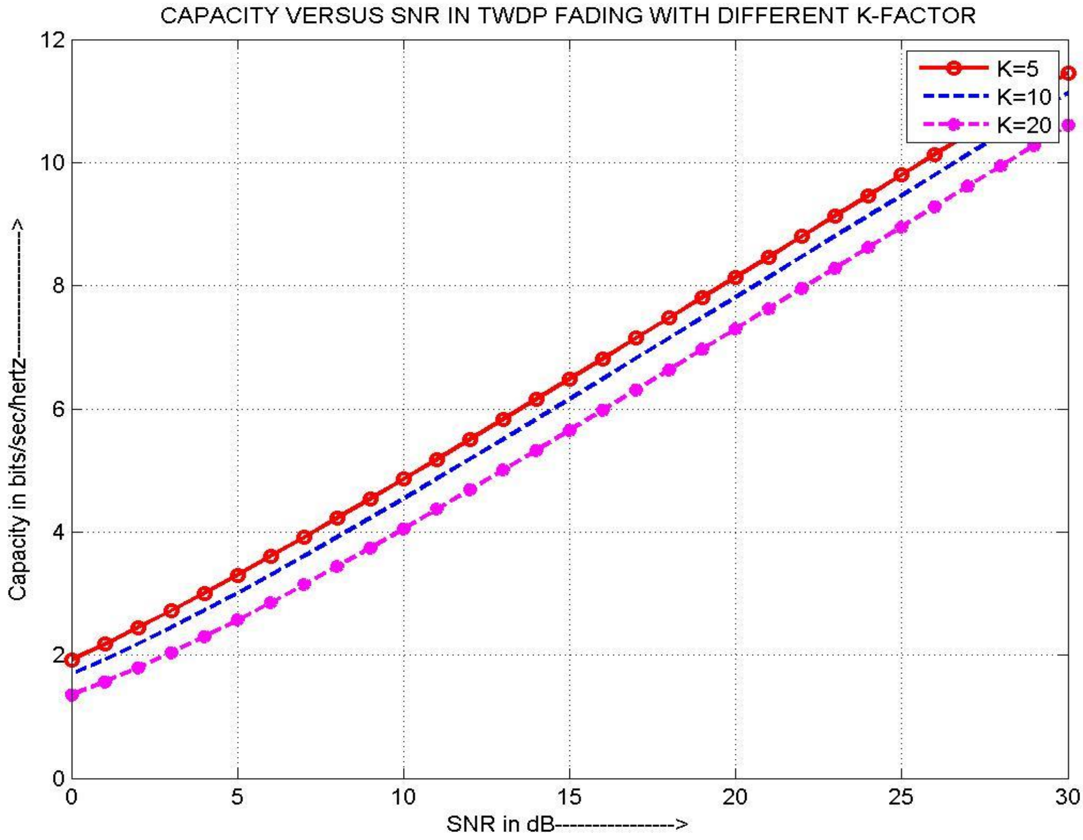

Figure 4.20:-Capacity vs SNR in TWDP fading with different K-factor and Δ=1.

4.6 PERFORANCE OF MIMO SYSTEM IN TWDP FADING

In wireless communication, MIMO systems are widely studied to increase system performance. However, in practical scenario's transmitted signal has to experience diverse effects such as interference and fading. Thus, there lies challenge in designing a wireless system that is effective in providing better services with limited resources [38]. However, it is given in [39] that MIMO take benefit of random fading and uses this as its advantage to increase channel capacity. MIMO makes a difference and turns multipath propagation losses into an advantage.

Till now, Rayleigh fading has been considered as the worst case fading model. But, it has already been discussed that, when two LOS components are equal in magnitude and opposite in phase fading called TWDP fading originates which is more severe than Rayleigh. Hence, there is more multipath propagation losses and random fades in TWDP fading, which gives the fact that MIMO should perform best in TWDP fading environment. Rayleigh has only random components present with no LOS component, hence it also gives good results with MIMO system but TWDP environment where two LOS components cancel each other in presence of only diffuse wave gives best results in MIMO system. Rician due to presence of LOS component gives worst results in MIMO system.

Also, two main parameters K and Δ put influence on the capacity attained by system. As K is the LOS factor more the value of K less is the capacity attained by MIMO system. Also when, Δ is increased more capacity is attained by MIMO system due to severe form of TWDP fading.

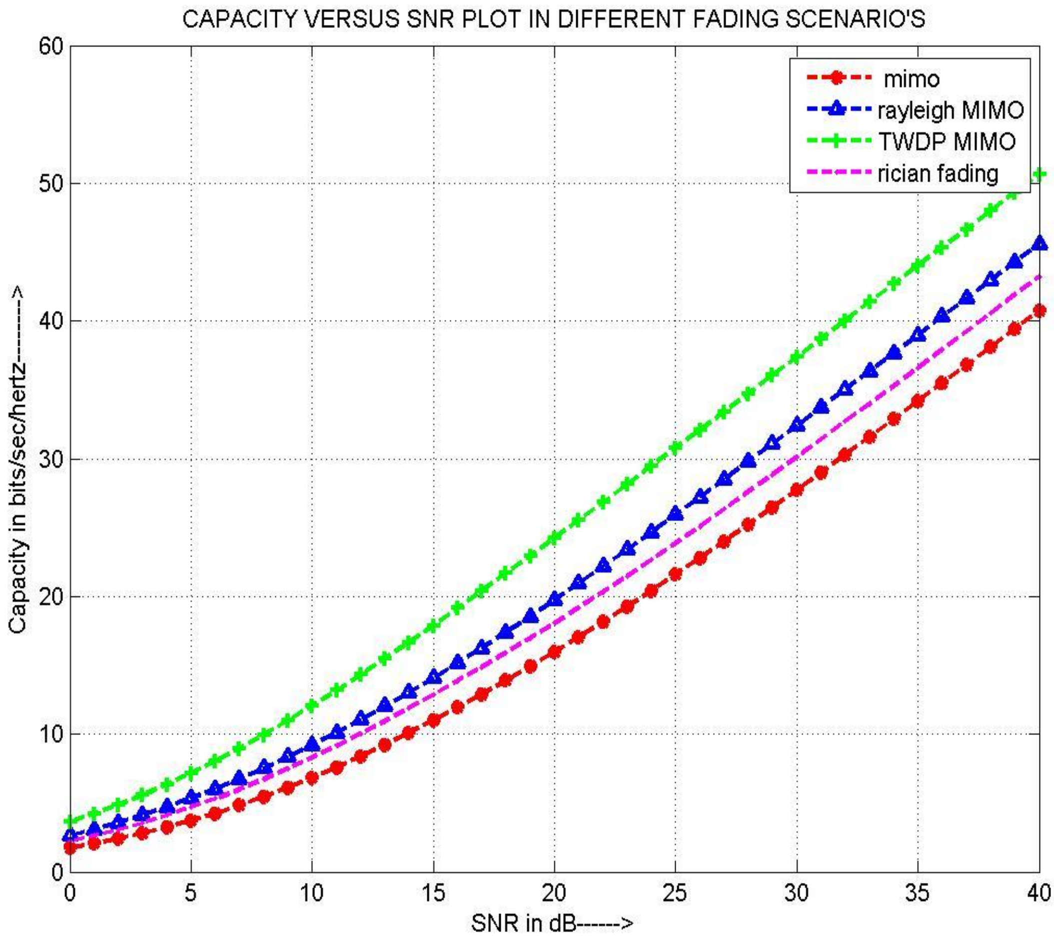

Figure 4.21:-Capacity versus SNR for MIMO system in all fading channels.

Fig. 4.21 validate the findings and MIMO system performs best in TWDP fading channel followed by Rayleigh fading channel and then in Rician fading channel. MIMO as already discussed, turns random fading in its benefit and thus attains higher capacity in more scattered environment. TWDP fading environment is highly scattered due to two equal and opposite LOS components in many diffusely propagating waves turning best surroundings for MIMO system.

This fact is also well demonstrated by the results of plots done in computer software MATLAB. In MIMO system with N_t and N_r is equal to 4. Analytical capacity is plotted with matrix **H** generated by method explained in section 4.2. MIMO performs excellently in TWDP channel due to most severe form of fading. Capacity versus SNR curve is plotted in MATLAB and results as expected are obtained. In fig. 4.21 at SNR of 25 dB, TWDP channel attains highest capacity of 30 bits/sec/hertz whereas it is 26 bits/sec/hertz for Rayleigh channel and 24 bits/sec/hertz for Rician channel.

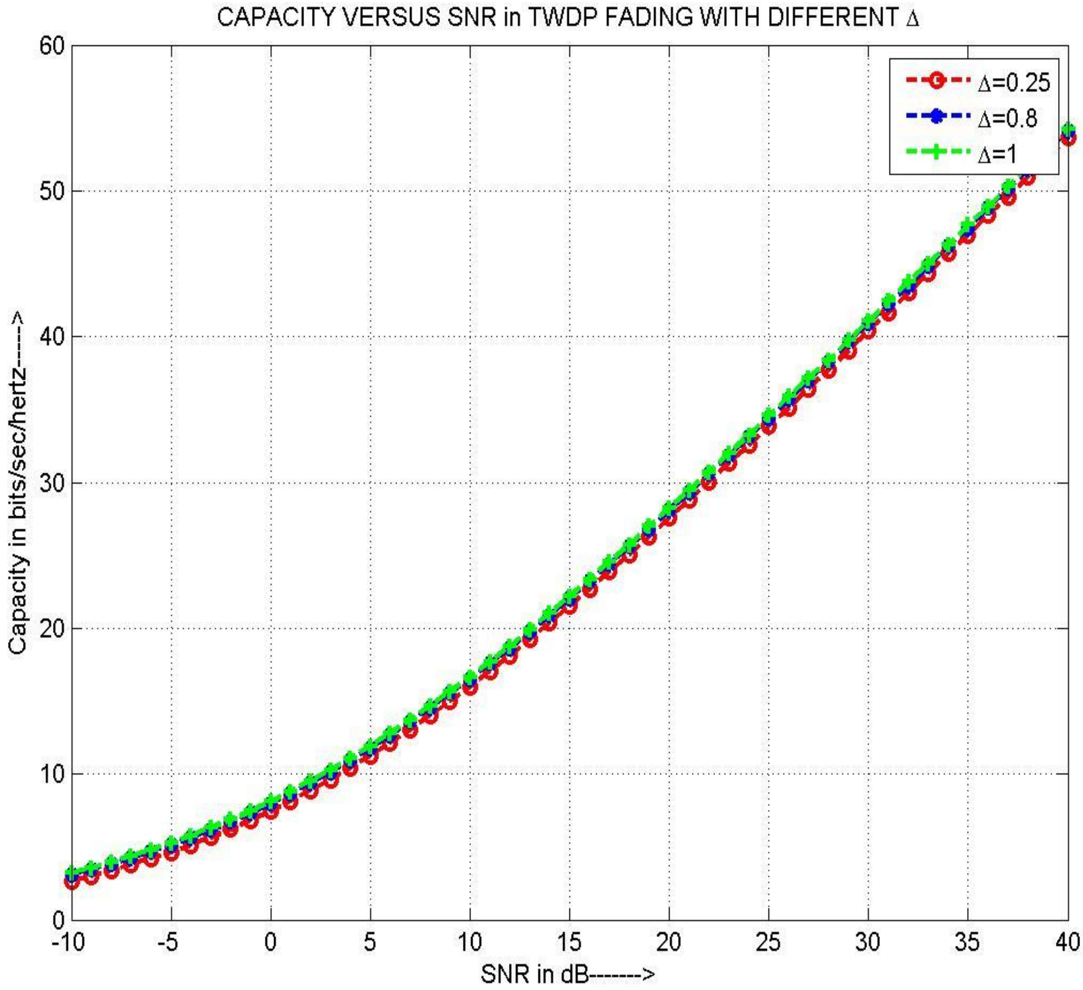

Figure 4.22:-Capacity versus SNR in TWDP fading with different Δ and K=6 dB.

In fig. 4.22 however, variation of capacity on increasing Δ is same as attained by SIMO or MISO formats , but capacity in all three cases is closer to one another. For e.g. at SNR of 20 dB, capacity when Δ=1 is 28 bits/sec/hertz, when Δ=0.8 capacity is 27 bits/sec/hertz and for Δ= 0.25 , it is 26 bits/sec/hertz.

The fact that as no. of transmit and receive antennas increase in number, variation of capacity becomes independent of Δ is demonstrated in this fig. Also in next topic, when Massive MIMO system comes into action, this variation is more clearly visible.

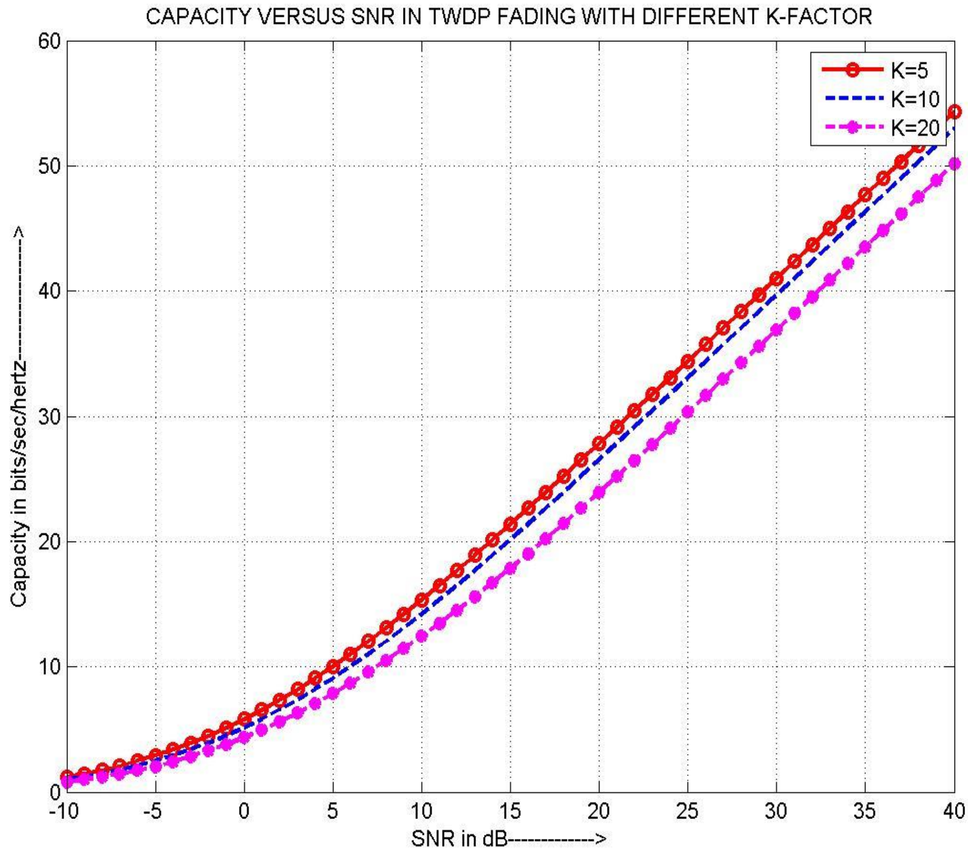

Figure 4.23:-Capacity versus SNR in TWDP fading for different K-Factor and Δ fixed at 1.

As K- factor increases capacity increases in SISO system, but this is somewhat different when MIMO system is considered. In MIMO more scattered the environment is, the better the system performs. Hence LOS component puts negative effect on MIMO system which is clearly seen in fig. 4.23. At SNR of 20 dB when K=20, capacity is 24 bits/sec/hertz and it increases to 28 bits/sec/hertz when K =5.

4.7 CAPACITY UPPER AND LOWER BOUNDS FOR MIMO IN TWDP FADING

In a TWDP channel, there are three components. Two components are deterministic and one is stochastic. Hence, channel matrix in this case is given as:-

$$\boldsymbol{H_{TWDP}} = \mathrm{a}\boldsymbol{H1_{LOS}} + \mathrm{b}\boldsymbol{H2_{LOS}} + \mathrm{c}\boldsymbol{H_{Ray}} \quad ; \qquad (4.9)$$

where, again a, b and c are scalars (a and b are power of two LOS components and c is power of stochastic component). Hence in TWDP fading K –factor can be expressed as: $K_{TWDP} = \frac{a^2+b^2}{c^2}$

and Δ which is relative strength of two LOS components is given as: $\Delta_{TWDP} = \frac{2ab}{a^2+b^2}$

K→0 channel is pure Rayleigh

K→ ∞ and $\Delta = 0$ channel is Rician

K→ ∞ and $\Delta \to 1$ channel is TWDP

Exact Capacity Formula:-

The capacity expression of the TWDP channel matrix depends on the Eigen values of the Hermitian matrix $\boldsymbol{H_{TWDP}}\,\boldsymbol{H_{TWDP}^{H}}$. Consider λ_i , i=1….., n are Eigen values of $\boldsymbol{H_{TWDP}}\,\boldsymbol{H_{TWDP}^{H}}$.

$$C_{TWDP} = \sum_{i=1}^{N_t} \log_2\left(1 + \frac{\rho}{N_t}\lambda_i\right) \quad . \tag{4.10}$$

Lower capacity bound in TWDP fading:-

As TWDP system is made of three components, two LOS and one stochastic. Lower bound is achieved when both LOS parts being anti-phase cancel each other and only random part exists, which turns out to be same as Rayleigh. Hence, in this case Rayleigh model is considered, in which elements of channel matrix $\boldsymbol{H_{Ray}}$ are random and hence all entries are taken as random variables. Then it can be shown [40] that for large N and large value of SNR, ρ a capacity lower bound is given by:-

Assume that, N_t and $N_r = N$

$$C_{Lower-Bound} = \mathrm{N} * \log_2\left(\frac{\rho}{e}\right) \quad . \tag{4.11}$$

Component (given by Rayleigh channel contribution)

Upper bound on Capacity Formula in TWDP fading:-

Here, in this section a way of deriving TWDP's upper bound channel capacity. To begin consider the TWDP channel matrix expression in terms of LOS and Rayleigh channel matrices. The product of

$$\boldsymbol{H_{TWDP}}\,\boldsymbol{H_{TWDP}^{H}} = (\mathrm{a}\boldsymbol{H1_{LOS}} + \mathrm{b}\boldsymbol{H2_{LOS}} + \mathrm{c}\boldsymbol{H_{Ray}}) * (\mathrm{a}\boldsymbol{H1_{LOS}} + \mathrm{b}\boldsymbol{H2_{LOS}} + \mathrm{c}\boldsymbol{H_{Ray}})^H$$
$$= a^2\boldsymbol{H1_{LOS}}\,\boldsymbol{H1_{LOS}^{H}} + b^2\boldsymbol{H2_{LOS}}\,\boldsymbol{H2_{LOS}^{H}} + c^2\boldsymbol{H_{Ray}}\,\boldsymbol{H_{Ray}^{H}} + \mathrm{ab}\boldsymbol{H1_{LOS}}\,\boldsymbol{H2_{LOS}^{H}} +$$
$$ba\boldsymbol{H2_{LOS}}\,\boldsymbol{H1_{LOS}^{H}} + \mathrm{ac}\,(\boldsymbol{H_{Ray}}\,\boldsymbol{H1_{LOS}^{H}} + \boldsymbol{H1_{LOS}}\,\boldsymbol{H_{Ray}^{H}}) + \mathrm{bc}\,(\boldsymbol{H_{Ray}}\,\boldsymbol{H2_{LOS}^{H}} + \boldsymbol{H2_{LOS}}\,\boldsymbol{H_{Ray}^{H}}). \tag{4.12}$$

From the expression given in equation (4.12), it is clear that capacity is sum of six components: - Pure LOS 1, Pure LOS 2, Pure Rayleigh term and three hybrid contributions where, term with coefficient ab has two LOS components contributing jointly and terms containing coefficients ac and bc have both the LOS and Rayleigh components contributing together.

Hence, taking statistical expectation of terms with ac and bc coefficients.

E {ac($\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H1}_{\boldsymbol{LOS}}^{H}$ + $\boldsymbol{H1}_{\boldsymbol{LOS}}\ \boldsymbol{H}_{\boldsymbol{Ray}}^{H}$)+bc($\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H2}_{\boldsymbol{LOS}}^{H}$ + $\boldsymbol{H2}_{\boldsymbol{LOS}}\ \boldsymbol{H}_{\boldsymbol{Ray}}^{H}$)}

= E {ac($\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H1}_{\boldsymbol{LOS}}^{H}$ + $\boldsymbol{H1}_{\boldsymbol{LOS}}\ \boldsymbol{H}_{\boldsymbol{Ray}}^{H}$)}+E{bc($\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H2}_{\boldsymbol{LOS}}^{H}$ + $\boldsymbol{H2}_{\boldsymbol{LOS}}\ \boldsymbol{H}_{\boldsymbol{Ray}}^{H}$)}

= 0

Now, equation (4.12) reduces to:-

$$\boldsymbol{H}_{\boldsymbol{TWDP}}\,\boldsymbol{H}_{\boldsymbol{TWDP}}^{H} = a^2\boldsymbol{H1}_{\boldsymbol{LOS}}\,\boldsymbol{H1}_{\boldsymbol{LOS}}^{H} + b^2\boldsymbol{H2}_{\boldsymbol{LOS}}\,\boldsymbol{H2}_{\boldsymbol{LOS}}^{H} + c^2\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H}_{\boldsymbol{Ray}}^{H} + \mathrm{ab}\boldsymbol{H1}_{\boldsymbol{LOS}}\,\boldsymbol{H2}_{\boldsymbol{LOS}}^{H} + ba\boldsymbol{H2}_{\boldsymbol{LOS}}\ \boldsymbol{H1}_{\boldsymbol{LOS}}^{H}\ . \tag{4.13}$$

Considering, the two LOS components to be fully uncorrelated, hence putting ab and ba term to zero.

$$\boldsymbol{H}_{\boldsymbol{TWDP}}\,\boldsymbol{H}_{\boldsymbol{TWDP}}^{H} = a^2\boldsymbol{H1}_{\boldsymbol{LOS}}\ \boldsymbol{H1}_{\boldsymbol{LOS}}^{H} + b^2\boldsymbol{H2}_{\boldsymbol{LOS}}\ \boldsymbol{H2}_{\boldsymbol{LOS}}^{H} + c^2\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H}_{\boldsymbol{Ray}}^{H}\,. \tag{4.14}$$

Thus, hybrid term's contribution is neglected and pure LOS and pure random component is considered in capacity expression.

$$C_{TWDP} = \log_2\det(\boldsymbol{I}_{\boldsymbol{N}} + \frac{\rho}{N}a^2\boldsymbol{H1}_{\boldsymbol{LOS}}\,\boldsymbol{H1}_{\boldsymbol{LOS}}^{H} + \frac{\rho}{N}b^2\boldsymbol{H2}_{\boldsymbol{LOS}}\,\boldsymbol{H2}_{\boldsymbol{LOS}}^{H} + c^2\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H}_{\boldsymbol{Ray}}^{H})$$

$$= \sum_{i=1}^{N}\log_2(1 + \frac{\rho}{N}\lambda_i), \tag{4.15}$$

here λ_i are Eigen values of $a^2\boldsymbol{H1}_{\boldsymbol{LOS}}\,\boldsymbol{H1}_{\boldsymbol{LOS}}^{H} + b^2\boldsymbol{H2}_{\boldsymbol{LOS}}\,\boldsymbol{H2}_{\boldsymbol{LOS}}^{H} + c^2\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H}_{\boldsymbol{Ray}}^{H}$.

Determinant term in capacity expression can be written as:-

$$\det(\boldsymbol{I}_{\boldsymbol{N}} + \frac{\rho}{N}a^2\boldsymbol{H1}_{\boldsymbol{LOS}}\,\boldsymbol{H1}_{\boldsymbol{LOS}}^{H} + \frac{\rho}{N}b^2\boldsymbol{H2}_{\boldsymbol{LOS}}\,\boldsymbol{H2}_{\boldsymbol{LOS}}^{H} + \frac{\rho}{N}c^2\boldsymbol{H}_{\boldsymbol{Ray}}\,\boldsymbol{H}_{\boldsymbol{Ray}}^{H})\,. \tag{4.16}$$

Using property of matrices, if **A** and **B** are respectively N×M and M×N matrices,

Then det{$\boldsymbol{I}_{\boldsymbol{N}}$ **+ AB}** =det {$\boldsymbol{I}_{\boldsymbol{M}}$ **+ BA**}

$$= \det\left\{\boldsymbol{I}_{\boldsymbol{N}} + \left[\sqrt{\frac{\rho}{N}}a\boldsymbol{H1}_{\boldsymbol{LOS}}\quad \sqrt{\frac{\rho}{N}}b\boldsymbol{H2}_{\boldsymbol{LOS}}\ \sqrt{\frac{\rho}{N}}c\boldsymbol{H}_{\boldsymbol{Ray}}\right]\begin{bmatrix}\sqrt{\frac{\rho}{N}}a\boldsymbol{H1}_{\boldsymbol{LOS}}^{\boldsymbol{H}}\\ \sqrt{\frac{\rho}{N}}b\boldsymbol{H2}_{\boldsymbol{LOS}}^{\boldsymbol{H}}\\ \sqrt{\frac{\rho}{N}}c\boldsymbol{H}_{\boldsymbol{Ray}}^{\boldsymbol{H}}\end{bmatrix}\right\} \tag{4.17}$$

$$=\det\left\{\boldsymbol{I_{3N}}+\begin{bmatrix}\sqrt{\frac{\rho}{N}}a\boldsymbol{H1_{LOS}^H}\\ \sqrt{\frac{\rho}{N}}b\boldsymbol{H2_{LOS}^H}\\ \sqrt{\frac{\rho}{N}}c\boldsymbol{H_{Ray}^H}\end{bmatrix}\begin{bmatrix}\sqrt{\frac{\rho}{N}}a\boldsymbol{H1_{LOS}} & \sqrt{\frac{\rho}{N}}b\boldsymbol{H2_{LOS}} & \sqrt{\frac{\rho}{N}}c\boldsymbol{H_{Ray}}\end{bmatrix}\right\} \quad (4.18)$$

$$=\det\left\{\begin{bmatrix}\boldsymbol{I_N}+\frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}} & \frac{\rho}{N}ab\boldsymbol{H1_{LOS}^H H2_{LOS}} & \frac{\rho}{N}ac\boldsymbol{H1_{LOS}^H H_{Ray}}\\ \frac{\rho}{N}ba\boldsymbol{H2_{LOS}^H H1_{LOS}} & \boldsymbol{I_N}+\frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}} & \frac{\rho}{N}bc\boldsymbol{H2_{LOS}^H H_{Ray}}\\ \frac{\rho}{N}ca\boldsymbol{H_{Ray}^H H1_{LOS}} & \frac{\rho}{N}cb\boldsymbol{H_{Ray}^H H2_{LOS}} & \boldsymbol{I_N}+\frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}}\end{bmatrix}\right\} \quad (4.19)$$

Now, terms with coefficients ab and ba can be put to zero as there is no correlation among the two LOS components.

$$\det\left\{\begin{bmatrix}\boldsymbol{I_N}+\frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}} & 0 & \frac{\rho}{N}ac\boldsymbol{H1_{LOS}^H H_{Ray}}\\ 0 & \boldsymbol{I_N}+\frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}} & \frac{\rho}{N}bc\boldsymbol{H2_{LOS}^H H_{Ray}}\\ \frac{\rho}{N}ca\boldsymbol{H_{Ray}^H H1_{LOS}} & \frac{\rho}{N}cb\boldsymbol{H_{Ray}^H H2_{LOS}} & \boldsymbol{I_N}+\frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}}\end{bmatrix}\right\} \quad (4.20)$$

Now, the matrix is Hermitian and can be factorized using block lower – Diagonal –Upper (LDU)

$$\begin{bmatrix}\boldsymbol{I_N} & 0 & 0\\ 0 & \boldsymbol{I_N} & 0\\ \frac{\rho}{N}ac\boldsymbol{H_{Ray}^H H1_{LOS}}\left(\boldsymbol{I_N}+\frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1} & \frac{\rho}{N}bc\boldsymbol{H_{Ray}^H H2_{LOS}}\left(\boldsymbol{I_N}+\frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1} & \boldsymbol{I_N}\end{bmatrix}\times$$

$$\boldsymbol{D}\times\begin{bmatrix}\boldsymbol{I_N} & 0 & \left(I_N+\frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1}\frac{\rho}{N}ac\boldsymbol{H1_{LOS}^H H_{Ray}}\\ 0 & \boldsymbol{I_N} & \left(I_N+\frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1}\frac{\rho}{N}bc\boldsymbol{H2_{LOS}^H H_{Ray}}\\ 0 & 0 & \boldsymbol{I_N}\end{bmatrix} \quad (4.21)$$

D can be written as

$$\begin{bmatrix}\boldsymbol{I_N}+\frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}} & 0 & 0\\ 0 & \boldsymbol{I_N}+\frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}} & 0\\ 0 & 0 & X\end{bmatrix} \quad (4.22)$$

Term, X is large and can be given as

$$X =\left\{\boldsymbol{I_N}+\frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}}-\left(\frac{\rho}{N}\right)^2 a^2c^2\boldsymbol{H_{Ray}^H H1_{LOS}}\left(\boldsymbol{I_N}+\frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1}\boldsymbol{H1_{LOS}^H H_{Ray}}-\left(\frac{\rho}{N}\right)^2 b^2c^2\boldsymbol{H_{Ray}^H H2_{LOS}}\left(\boldsymbol{I_N}+\frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1}\boldsymbol{H2_{LOS}^H H_{Ray}}\right\} \quad (4.23)$$

Using, property of the determinant of a product of matrices and since the determinant of a block diagonal is the product of the determinants of the diagonal blocks:-

$\det\left\{\begin{bmatrix} \boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}} & 0 & \frac{\rho}{N}ac\boldsymbol{H1_{LOS}^H H_{Ray}} \\ 0 & \boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}} & \frac{\rho}{N}bc\boldsymbol{H2_{LOS}^H H_{Ray}} \\ \frac{\rho}{N}ca\boldsymbol{H_{Ray}^H H1_{LOS}} & \frac{\rho}{N}cb\boldsymbol{H_{Ray}^H H2_{LOS}} & I_N + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}} \end{bmatrix}\right\}$ can be reduced to :

$= 1\times\det\{\mathbf{D}\}\times 1$

$$= \det\left\{\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right\}\times\det\left\{\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right\}\times\det\{X\} \quad (4.24)$$

Now, X can be resolved as following

$$X=\left\{\boldsymbol{I_N} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}} - \left(\frac{\rho}{N}\right)^2 a^2c^2\boldsymbol{H_{Ray}^H H1_{LOS}}\left(\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1}\boldsymbol{H1_{LOS}^H H_{Ray}} - \left(\frac{\rho}{N}\right)^2 b^2c^2\boldsymbol{H_{Ray}^H H2_{LOS}}\left(\boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1}\boldsymbol{H2_{LOS}^H H_{Ray}}\right\}$$

$$= \boldsymbol{I_N} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H}\left[\boldsymbol{I_N} - \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\left(\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1}\boldsymbol{H1_{LOS}^H}\right]\boldsymbol{H_{Ray}} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H}\left[\boldsymbol{I_N} - \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}}\left(\boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1}\boldsymbol{H2_{LOS}^H}\right]\boldsymbol{H_{Ray}} \quad (4.25)$$

Using the inversion matrix lemma it can be shown that

$[\boldsymbol{A} + \boldsymbol{BCD}]^{-1} = \boldsymbol{A}^{-1} - \boldsymbol{A}^{-1}\boldsymbol{B}[\mathbf{D}\boldsymbol{A}^{-1}\mathbf{B} + \boldsymbol{C}^{-1}]\,\mathbf{D}\boldsymbol{A}^{-1}$

$$\boldsymbol{I_N} - \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\left(\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1}\boldsymbol{H1_{LOS}^H} = \left(\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1} \quad (4.26)$$

$$\boldsymbol{I_N} - \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}}\left(\boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1}\boldsymbol{H2_{LOS}^H} = \left(\boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1} \quad (4.27)$$

Hence expression can be further reduced to

$$\boldsymbol{I_N} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H}\left(\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1}\boldsymbol{H_{Ray}} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H}\left(\boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1}\boldsymbol{H_{Ray}} \quad (4.28)$$

Since, $\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}} > 0$

$\boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}} > 0$

and $\frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}} > 0$

Then we have,

$$\boldsymbol{I_N} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H}\left(\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right)^{-1}\boldsymbol{H_{Ray}} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H}\left(\boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}}\right)^{-1}\boldsymbol{H_{Ray}}$$

$$\leq \boldsymbol{I_N} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}} \quad (4.29)$$

Hence, determinant expression can be given as:-

$$\text{Det}\{X\} \leq \det\left\{\boldsymbol{I_N} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}}\right\} \quad (4.30)$$

Now, finally upper bound on the determinant expression can be given as:-

$$\det\left\{\begin{bmatrix} \boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}} & 0 & \frac{\rho}{N}ac\boldsymbol{H1_{LOS}^H H_{Ray}} \\ 0 & \boldsymbol{I_N} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}^H H2_{LOS}} & \frac{\rho}{N}bc\boldsymbol{H2_{LOS}^H H_{Ray}} \\ \frac{\rho}{N}ca\boldsymbol{H_{Ray}^H H1_{LOS}} & \frac{\rho}{N}cb\boldsymbol{H_{Ray}^H H2_{LOS}} & \boldsymbol{I_N} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}} \end{bmatrix}\right\}$$

$$= \det\left\{\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right\} \times \det\left\{\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right\} \times \det\{X\}$$

$$\leq \det\left\{\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right\} \times \det\left\{\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}^H H1_{LOS}}\right\} \times \det\left\{\boldsymbol{I_N} + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}^H H_{Ray}}\right\} \quad (4.31)$$

Determinant in capacity expression can be given as:-

$$\det(I_N + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\,\boldsymbol{H1_{LOS}^H} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}}\,\boldsymbol{H2_{LOS}^H} + c^2\boldsymbol{H_{Ray}}\,\boldsymbol{H_{Ray}^H})$$

$$\leq \det(I_N + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\,\boldsymbol{H1_{LOS}^H}) \times \det(I_N + \frac{\rho}{N}\boldsymbol{b^2 H2_{LOS}}\,\boldsymbol{H2_{LOS}^H}) \times \det(I_N + \frac{\rho}{N}\boldsymbol{H_{Ray}}\,\boldsymbol{H_{Ray}^H}) \quad (4.32)$$

According to work done by authors in [9], an upper bound on determinant expression can be put as

$$\det(\boldsymbol{I_N} + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\,\boldsymbol{H1_{LOS}^H} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}}\,\boldsymbol{H2_{LOS}^H} + c^2\boldsymbol{H_{Ray}}\,\boldsymbol{H_{Ray}^H})$$

$$\leq \det(I_N + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\,\boldsymbol{H1_{LOS}^H}) \times \det(I_N + \frac{\rho}{N}\boldsymbol{b^2 H2_{LOS}}\,\boldsymbol{H2_{LOS}^H}) \times \det(I_N + \frac{\rho}{N}\boldsymbol{H_{Ray}}\,\boldsymbol{H_{Ray}^H}) \quad (4.33)$$

Since f(x) $=\log_2(x)$ is strictly increasing function, applying this function on determinant inequality given above generates:-

$$\log_2 \det(I_N + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\,\boldsymbol{H1_{LOS}^H} + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}}\,\boldsymbol{H2_{LOS}^H} + c^2\boldsymbol{H_{Ray}}\,\boldsymbol{H_{Ray}^H})$$

$$\leq \log_2\det(I_N + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\,\boldsymbol{H1_{LOS}^H}) \times \det(I_N + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}}\,\boldsymbol{H2_{LOS}^H}) \times \det(I_N + \frac{\rho}{N}\boldsymbol{H_{Ray}}\,\boldsymbol{H_{Ray}^H})$$

$$= \log_2 \det(I_N + \frac{\rho}{N}a^2\boldsymbol{H1_{LOS}}\,\boldsymbol{H1_{LOS}^H}) + \log_2 \det(I_N + \frac{\rho}{N}b^2\boldsymbol{H2_{LOS}}\,\boldsymbol{H2_{LOS}^H}) +$$

$$\log_2 \det(I_N + \frac{\rho}{N}c^2\boldsymbol{H_{Ray}}\,\boldsymbol{H_{Ray}^H}) \;. \quad (4.34)$$

Hence, upper bound on capacity of TWDP channel can be given as:-

$$C_{TWDP} \leq C_{LOS1}+C_{LOS2}+C_{Ray} \quad . \tag{4.35}$$

Hence, from equations 4.11 and 4.35 capacity bounds of MIMO system in TWDP channel can be given as below:

$$\text{N}* \log_2(\frac{\rho}{e}) \leq C_{TWDP} \leq C_{LOS1}+C_{LOS2}+C_{Ray} \quad . \tag{4.36}$$

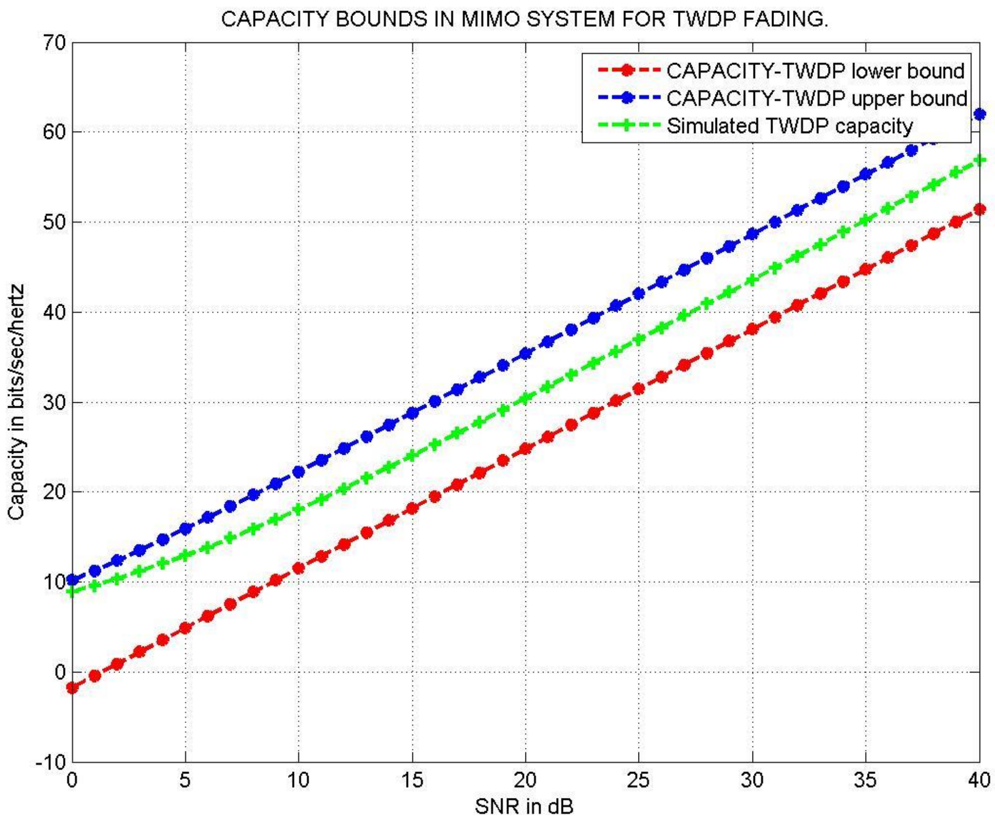

Figure 4.24:- Capacity versus SNR in TWDP channel for considering bounds in MIMO.

Fig. 4.24, gives bounds i.e. lower and upper bound in TWDP channel for MIMO system with N_t and N_r equal to 4. At 40 dB, maximum capacity attained is 64 bits/sec/hertz and lowest capacity that MIMO system can attain with TWDP channel is 51 bits/sec/hertz. Model Simulated in MATLAB to analyse capacity lies in between the upper and lower bound.

In this chapter performance of wireless communication systems viz SISO, SIMO, MISO and MIMO is studied in TWDP fading channel. SISO performs poorer in TWDP channel whereas multiple antenna systems SIMO, MISO and MIMO performed excellently, due to their ability to combat fading. In next chapter Massive MIMO system is studied and its performance in TWDP fading channel is analysed.

CHAPTER 5: MASSIVE MIMO SYSTEM AND ITS PERFORMANCE IN TWDP FADING

Multi–user MIMO offers many merits over traditional point to point MIMO viz: it does not require rich scattering environment and works with low cost single-antenna terminals consuming less power. So, originally conceived multi–user MIMO, with almost equal number of transmitting/receiving antennas is not a scalable technology. Recently in order to achieve more vivid gains as well as to streamline the required signal processing, massive MIMO (also known as large scale antenna systems(LSAS) , very large MIMO , full dimension MIMO, hyper MIMO, and ARGOS have been proposed in [33],[34] ,where base station(BS) is designed with large number of antennas e.g. 100 or more .

5.1 INTRODUCTION TO MASSIVE MIMO SYSTEM

In Massive MIMO system each BS is having large number of antennas as compared to the number of users. This eliminates fading and interference in hardware in a friendly way by offering huge number of degrees of freedom [33]. Massive MIMO gives benefits over current practice of multi-user MIMO through implementation of plenty of service antennas over operating terminals and time division duplex (TDD) operation. Excess of antennas at BS helps in focussing energy into even smaller regions in space.

Massive MIMO provides improvement in capacity of the order of 10 or more and can improve energy efficiency of the order of 100 or more [34]. Simple multiplexing, de-coding and pre-coding algorithms can give best results, many low-power units can replace expensive ultra-linear high power amplifiers, and the constructive action of the law of large numbers can greatly enable power-control and resource-allocation [28]. When number of antennas becomes very large or tends to infinity, the effect of fast fading and noise vanish and intra cell interference can be controlled using simple linear pre-coding and detection schemes.

Fig. 5.1, represents general Massive MIMO system in which there are 100 of antennas at the base station and only tens of users. Thus, N_t-N_r=90 giving rise to large degree of freedom and low power units can be employed exploiting all these advantages of Massive MIMO system.

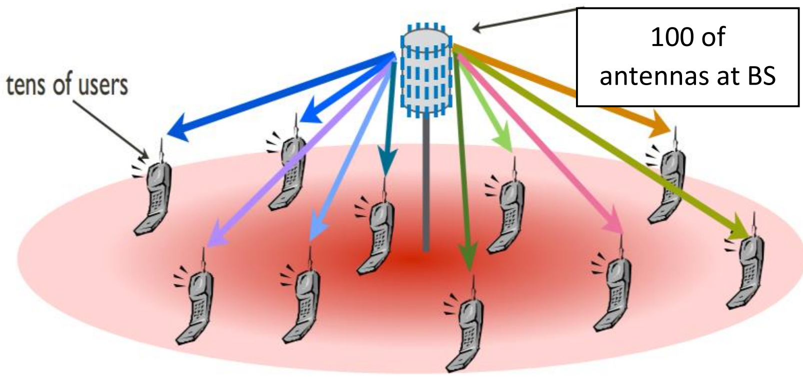

Figure 5.1 :- Illustration of Massive MIMO System [41].

5.2 MATHEMATICAL MODEL OF MASSIVE MIMO SYSTEM

Consider a point to point MIMO transmission where the transmitter and the receiver are equipped with N_t and N_r antennas respectively. Also consider a narrow band time invariant channel with a deterministic and constant channel matrix **H** $\epsilon\, C^{N_r \times N_t}$.

The received signal vector, **y** $\in C^{N_r \times 1}$ can be expressed **as**:-

$$\mathbf{y} = \sqrt{\rho}\mathbf{H}\mathbf{x} + \mathbf{n} \quad ; \tag{5.1}$$

where, **x** $\epsilon\ C^{N_t \times 1}$ is transmit signal vector and n $\epsilon\ C^{N_r \times 1}$ represents noise and interference. Total power of transmit signal is normalised i.e. E $\{||x||^2\} = 1$ and the noise is zero mean circularly symmetric complex Gaussian with an identity covariance matrix **I**. The scalar ρ is the transmit power. The instantaneous achievable rate can be expressed as:

$$C = \log_2 \det(\mathbf{I} + \frac{\rho}{N_t}\mathbf{H}\mathbf{H}^{\mathrm{H}}) \text{ bits/sec/hertz .} \tag{5.2}$$

Also effects of noise and fading are removed when no. of antenna's increase in number.

$$\frac{\mathbf{H}\mathbf{H}^{\mathrm{H}}}{N_t} = \begin{bmatrix} \beta_1 \frac{||h_1||^2}{N_t} & \sqrt{\beta_1}\sqrt{\beta_2}\frac{h_1^H h_2}{N_t} \ldots.. & \sqrt{\beta_1}\sqrt{\beta_k}\frac{h_1^H h_k}{N_t} \\ \sqrt{\beta_2}\sqrt{\beta_1}\frac{h_1^H h_2}{N_t} & \beta_1 \frac{||h_2||^2}{N_t} \ldots\ldots & \sqrt{\beta_2}\sqrt{\beta_k}\frac{h_1^H h_2}{N_t} \\ \sqrt{\beta_k}\sqrt{\beta_1}\frac{h_1^H h_2}{N_t} & \sqrt{\beta_1}\sqrt{\beta_2}\frac{h_1^H h_2}{N_t} \ldots.. & \beta_1 \frac{||h_k||^2}{N_t} \end{bmatrix} \tag{5.3}$$

As N_t approaches infinity all diagonal elements become 1 and non – diagonal elements becomes 0. $\frac{h_1^H h_k}{N_t}$-------→0, $\frac{||h_k||^2}{N_t} - -\!-\!\!\rightarrow 1$

$$\text{Matrix } \frac{\mathbf{H}\mathbf{H}^{\mathbf{H}}}{N_t} \text{ decomposes into } = \begin{bmatrix} \beta_1 & 0 & 0 \\ 0 & \beta_2 & 0 \\ 0 & 0 & \beta_k \end{bmatrix} \quad ; \tag{5.4}$$

where, β_k represents fading coefficient.

When matched filter is used at the output, received signal is decoded as given below:-

$\boldsymbol{H^H}$y=$\sqrt{P}\boldsymbol{H^H H x} + \boldsymbol{H^H n}$. (5.5)

As N_t approaches infinity $\boldsymbol{H^H n}$ --------→0.

This whole mathematical explanation demonstrates that the interference and noise automatically vanishes when number of antenna's grow large in number.

As N_t approaches infinity (or large) $\frac{\mathbf{HH}^{\mathrm{H}}}{\boldsymbol{N_t}}$ approaches $\mathbf{I}_{\boldsymbol{N_r}}$ hence capacity or rate achieved becomes

C=$\log_2$det ($\mathbf{I}_{\boldsymbol{N_r}} + \frac{\rho}{\boldsymbol{N_t}}\mathbf{I}_{\boldsymbol{N_r}}$) bits/sec/hertz. (5.6)

It can be further solved into

C= $N_r * \log_2(1 + \rho)$ bits/sec/hertz. (5.7)

Which is N_r is times of the SISO capacity providing large increase in capacity over conventional MIMO systems. Fig 5.2 is MATLAB plot which depicts clearly that capacity increases manifolds as number of transmitting antenna increases. In this N_t is being increased and corresponding increase in capacity is attained.

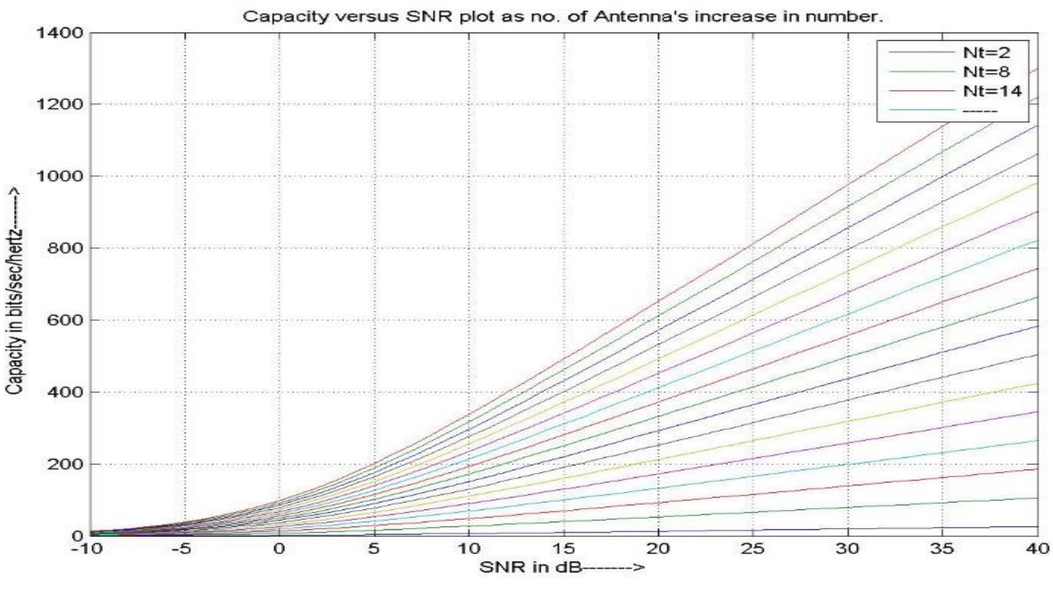

Figure 5.2:-Capacity versus SNR with increasing Transmit antennas and N_r fixed.

5.3 PERFORMANCE OF MASSIVE MIMO SYSTEM IN TWDP FADING

As in massive MIMO systems number of base station antennas are very large as compared to number of antennas that are with users. We have simulated the capacity using equation (5.2). Here H is generated as per procedure described in Chapter 4. In all the plots N_t=100 and N_r=10.

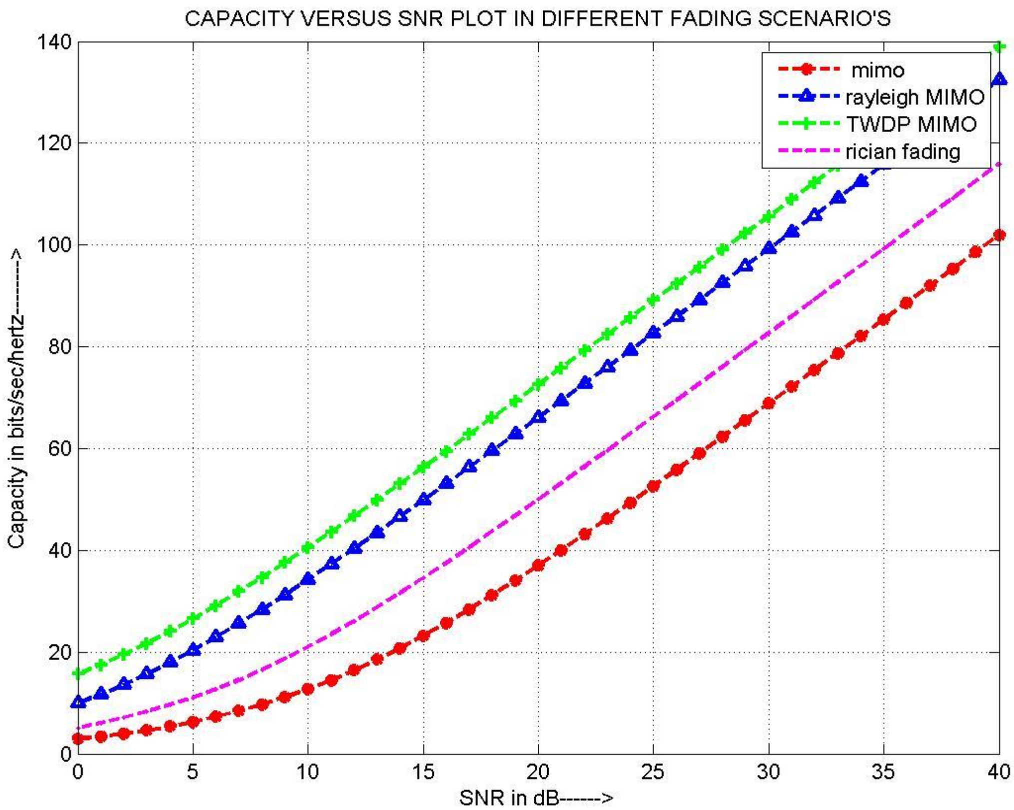

Figure 5.3:-Capacity versus SNR plot in Massive MIMO system in all fading channel.

Fig. 5.3 shows capacity versus SNR plot of Massive MIMO system. Here, even higher capacity is attained in all fading scenarios. At SNR of 25 dB Massive MIMO system in TWDP channel obtains capacity as higher as 88 bits/sec/hertz, which is much greater than that was attained for 4×4 MIMO system. Capacity in Rayleigh channel is 81 bits/sec/hertz. Rician channel which has one LOS component gives poorer environmental conditions to Massive MIMO system and low value of capacity which is 64 bits/sec/hertz is attained.

The capacity of massive MIMO system is plotted for various values of K and Δ. TWDP parameter Δ gives almost same variation as was obtained in MIMO. But the main difference is at higher SNR, capacity becomes independent of value of Δ. For e.g. in fig. 5.4 at SNR of 35 dB 120 bits/sec/hertz capacity is obtained for all three values $\Delta = 0.25$, $\Delta = 0.8$ and $\Delta = 1$. Thus increasing the number of antennas, the system becomes independent of value of Δ. K- Factor which denotes the LOS component strength is showing similar results with Massive MIMO system too. With Increasing K-factor, capacity decreases. In fig. 5.5 at SNR of 30 dB , for K=5 capacity of 158 bits/sec/hertz is attained which keeps decreasing as K increases to 10 and 20. At K= 10, capacity is 150 bits/sec/hertz and at K=20, capacity is 146 bits/sec/hertz is obtained.

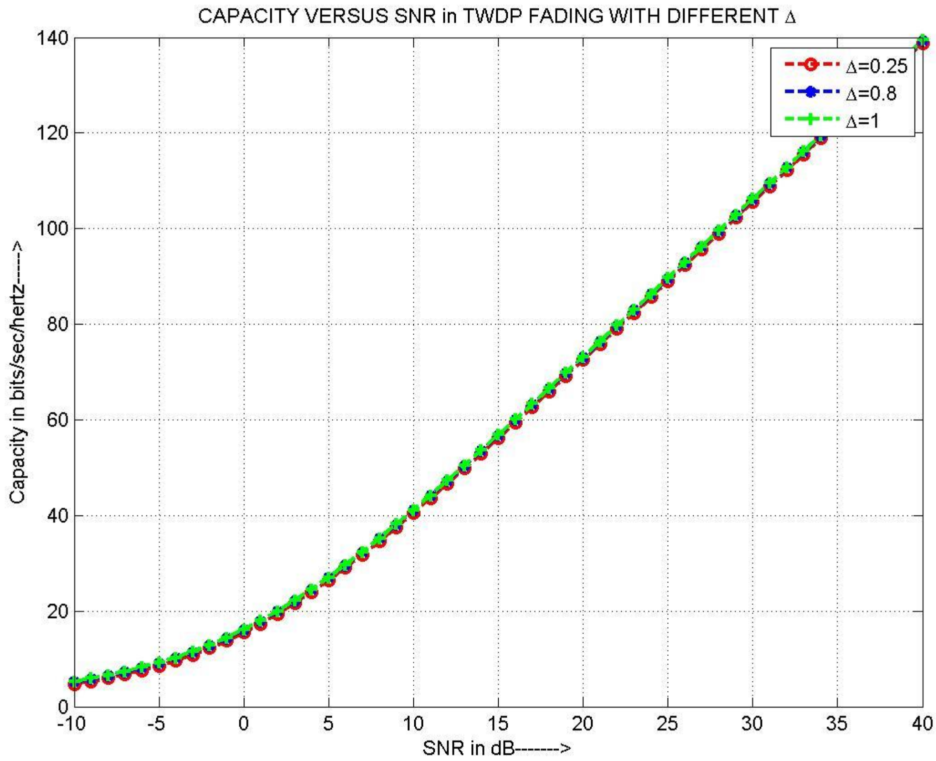

Figure 5.4:-Capacity versus SNR in TWDP channel with different Δ and K= 6 dB.

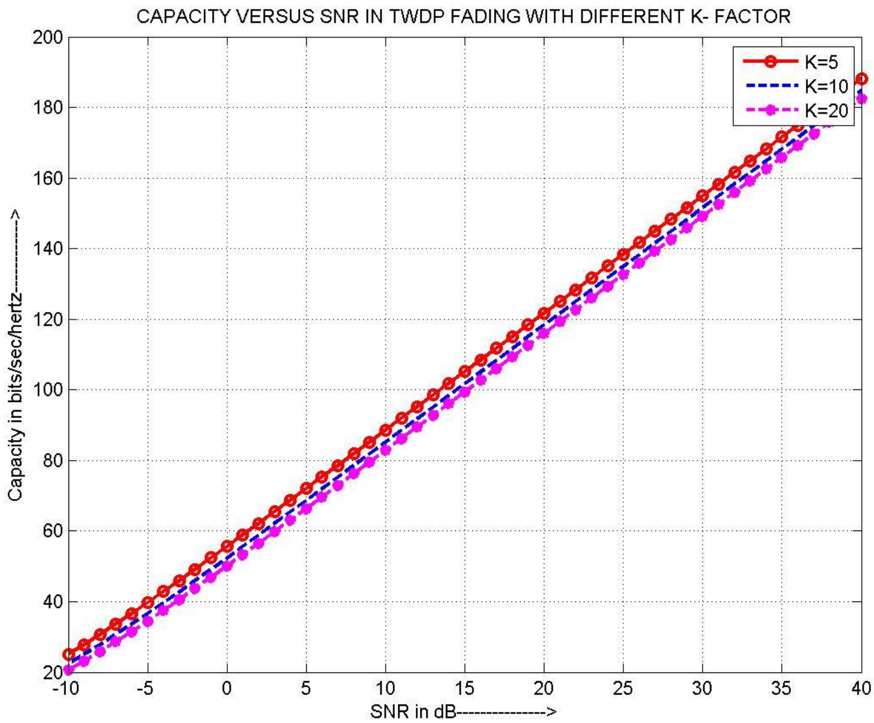

Figure 5.5:-Capacity versus SNR in TWDP channel with different K-Factor for Δ fixed at 1.

CHAPTER 6: PERFORMANCE OF VARIOUS MODULATION TECHNIQUES IN TWDP FADING

Modulation: - It is practise in which fast varying carrier signal is varied according to message signal. Analog and digital are the two types of modulations but, digital is preferred over Analog for better quality and efficient communication.

Binary phase shift keying (BPSK):- It is a modulation technique where there are two symbols and one bit is transmitted at a time. It has one phase for one symbol and then the phase changes by 180° for the other symbol. Fig. 6.1 is constellation diagram of BPSK where there are two symbols at 180° phase shift.

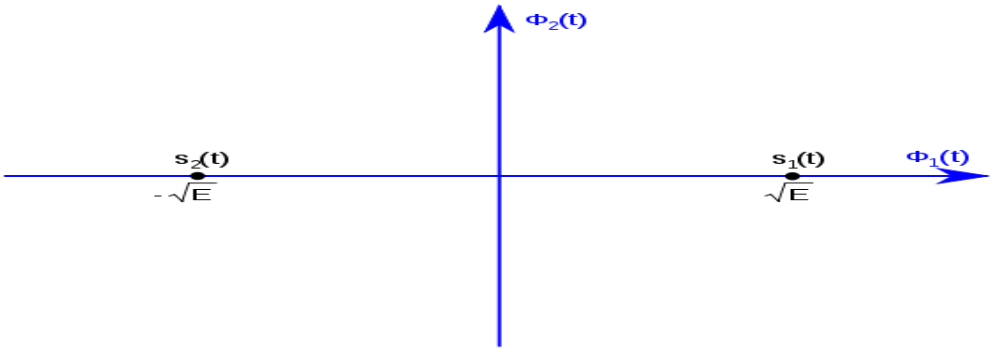

Figure 6.1:-BPSK Constellation Diagram [42].

QPSK MODULATION: - QPSK is Quadrature phase shift Keying. There are two basis functions which are used to define four symbols in space. To maintain good Euclidean distance Gray coding is used. Fig. 6.2 is signal space representation of QPSK.

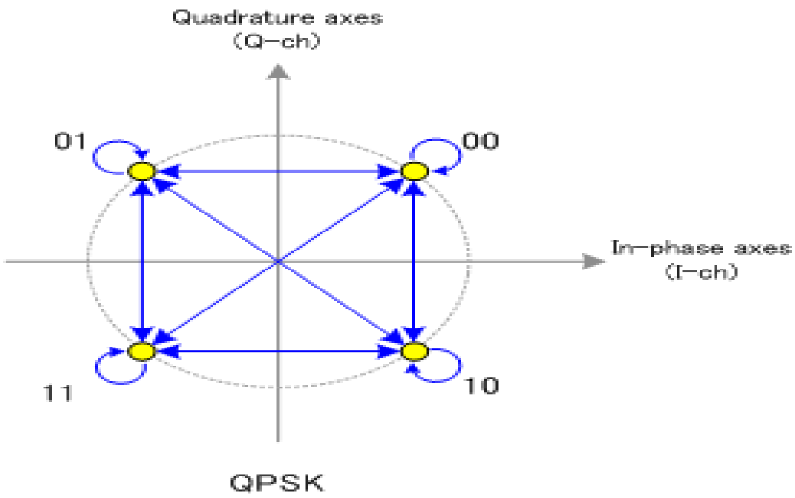

Figure 6.2:-QPSK Constellation Diagram [43].

6.1 PERFORMANCE OF CONVENTIONAL MODULATION TECHNIQUES IN TWDP FADING CHANNELS

BER is observed for conventional modulation techniques in TWDP fading environment. In BPSK modulation, BER observed is higher with TWDP channel than with Rayleigh channel which establishes the fact that TWDP channel produces the link which is worse than Rayleigh channel.

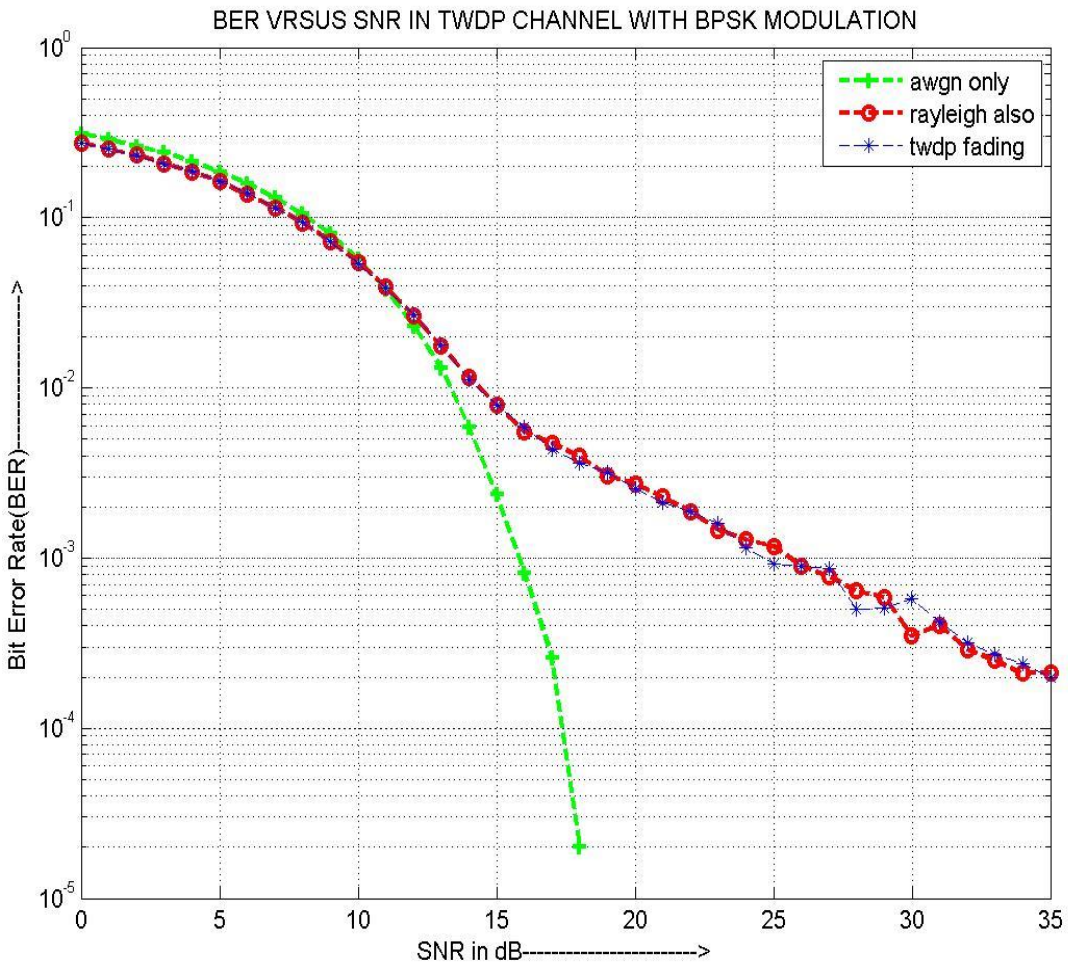

Figure 6.3:-BER versus SNR in TWDP channel for BPSK modulation.

When SNR is varied from 0 to 35 dB, higher BER is achieved for TWDP fading than for Rayleigh fading. In fig. 6.3 as at SNR of 30 dB, Rayleigh fading environment has BER of 5×10^{-4} and in TWDP fading environment BER is 8×10^{-4}.

It is known fact, that when number of bits to be transmitted in a symbol are more, BER increases. Hence, QPSK has more BER rate than BPSK as in QPSK two bits are transmitted per symbol. This is exactly obtained in MATLAB simulation and is shown in fig. 6.4.

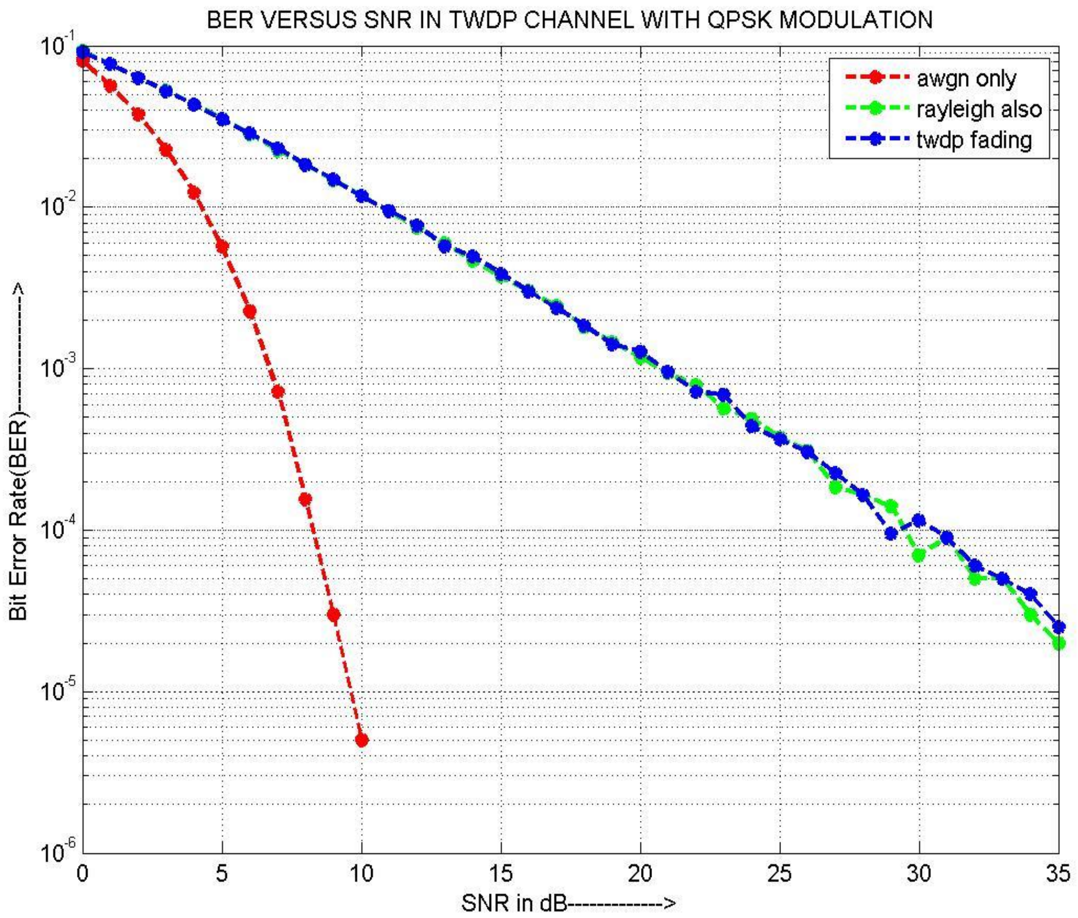

Figure 6.4:-BER versus SNR in TWDP channel with QPSK modulation.

Fig. 6.4 shows that TWDP channel forms a link worse than formed by Rayleigh channel with QPSK modulation technique as well. As at SNR of 30 dB TWDP channel has BER of 2 $\times 10^{-4}$ and Rayleigh channel has BER of 8×10^{-5}. Hence, it establishes the need of designing models in TWDP fading channels for worst case wireless communication scenario.

6.2 PERFORMANCE OF SPATIAL MODULATION IN TWDP FADING

Spatial Modulation, a novel concept is alternative to MIMO's general techniques of STBC (space time block codes) and spatial multiplexing. Current wireless communication requires that both energy and spectral needs are met efficiently. SM uses single radio frequency chain and provides attractive compromise between wireless network's area energy and spectral efficiency. Its basic idea is an extension of two dimensional signal constellation (such as M-PSK and M-QAM) to spatial dimension which is third one [44].

Fig. 6.5 plots BER versus SNR curve for 4-QAM modulation in TWDP channel. This is without spatial modulation. However, when this novel technique is applied BER improves significantly which is seen in next figure.

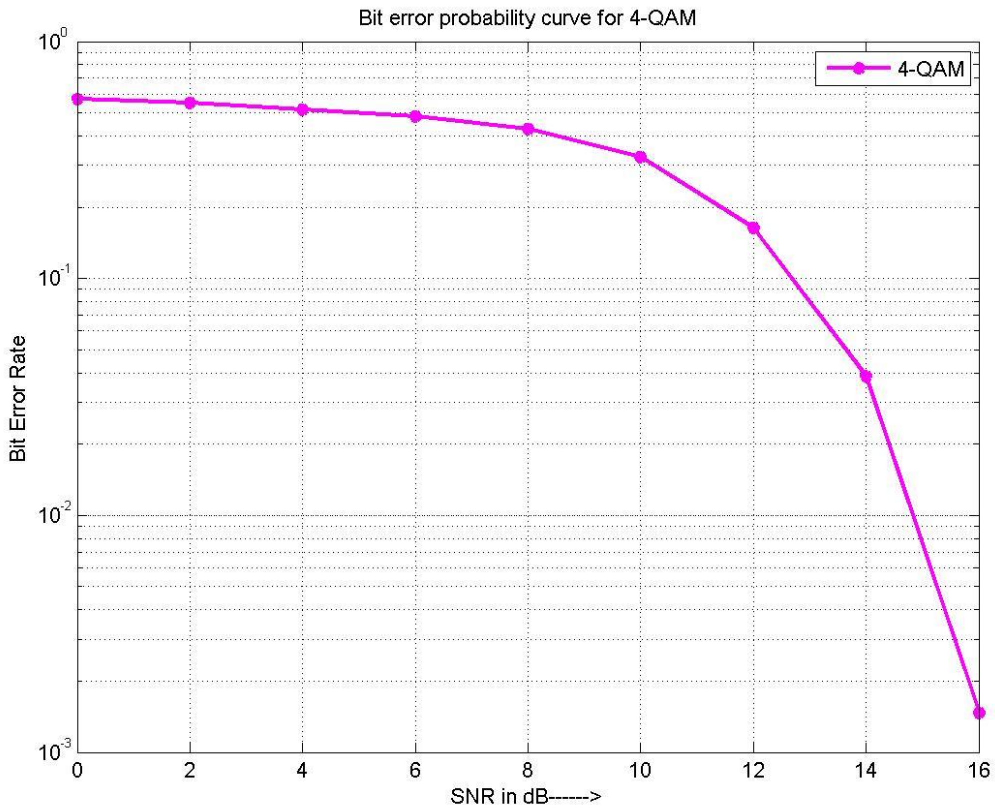

Figure 6.5:-BER vs SNR for 4-QAM modulation in TWDP channel.

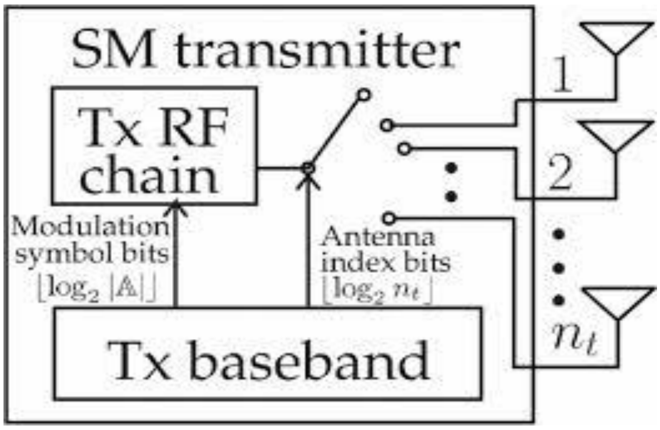

Figure 6.6:-SPATIAL MODULATION [45].

This technique is supposed to increase spectral efficiency as well as power efficiency, because of its antenna selection capability. SM mapper is used to map the bits from transmitting end to receiving end. Number of RF chains being used is reduced, hence power utilized is also reduced. It has got many advantages such as diversity, higher data rate, simpler receiver as well as transmitter design, low transmit power supply and better efficiency of the power amplifiers [46]. Fig. 6.6 shows block diagram of SM with Tx RF chain and Tx baseband.Tx baseband sends the modulation symbol bits to RF chain. Antenna index bits selects the antenna unit which is to be employed for transmission. In fig. 6.7 N_t is number of transmitting antennas and M is modulation index.

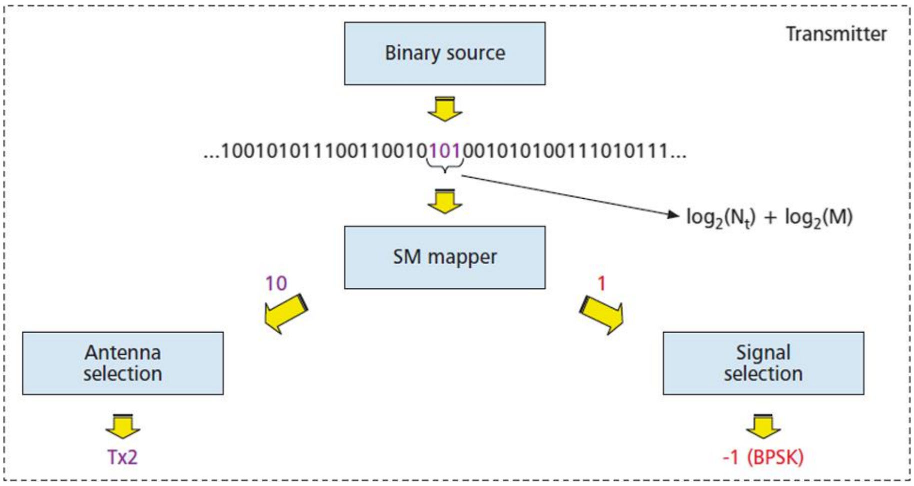

Figure 6.7:-Showing Potential of SM with Antenna and Signal Selection [46].

Fig. 6.7 explains the methodology that is followed in spatial modulation with N_t =4 and M=2. SM mapper has parts: Antenna Selection unit and Signal Selection unit. Now, let '101' be the three bits that are present at the input of SM modulator. As $\log_2 N_t$=2 and $\log_2 M$=1. Thus, first two bits in '101' selects the antenna and third bit denotes the bit to be transmitted in BPSK modulation (where 0 means '+1' and 1 means '-1').

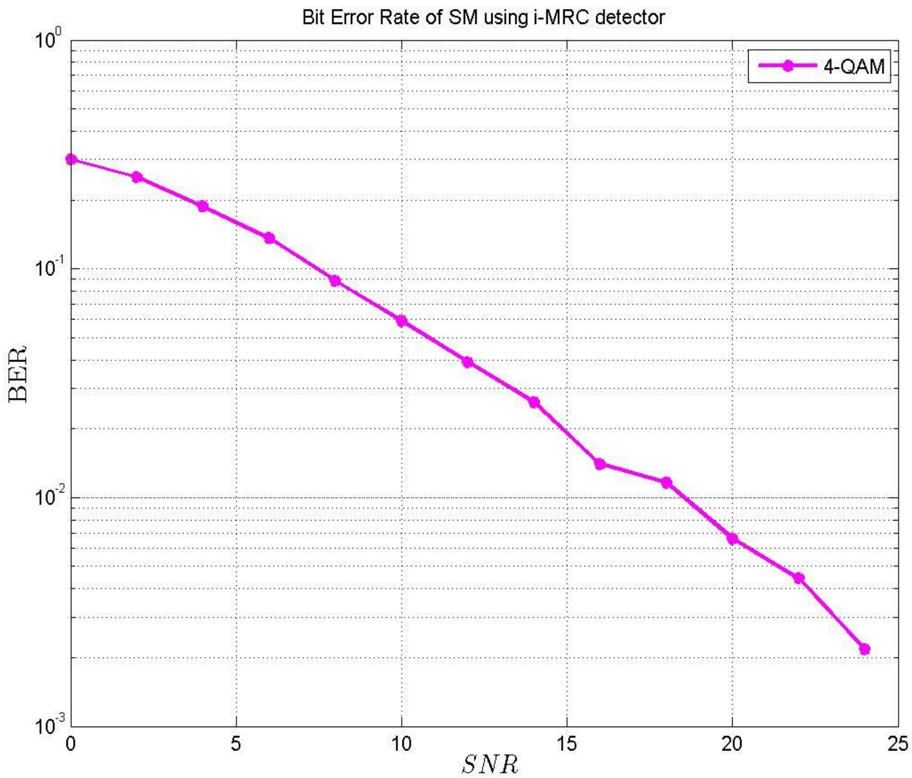

Figure 6.8:-BER versus SNR with SM and 4-QAM in TWDP Channel.

Fig. 6.8 shows BER with Spatial modulation in 4-QAM modulation. It is clearly seen that when compared with fig 6.5, BER has decreased with SM. At, BER of 10^{-1} 4-QAM SM in TWDP channel needs SNR of 7 dB while a system without SM needs SNR of 13 dB . Thus SM gives an additional gain of 6dB, with less number of chains.

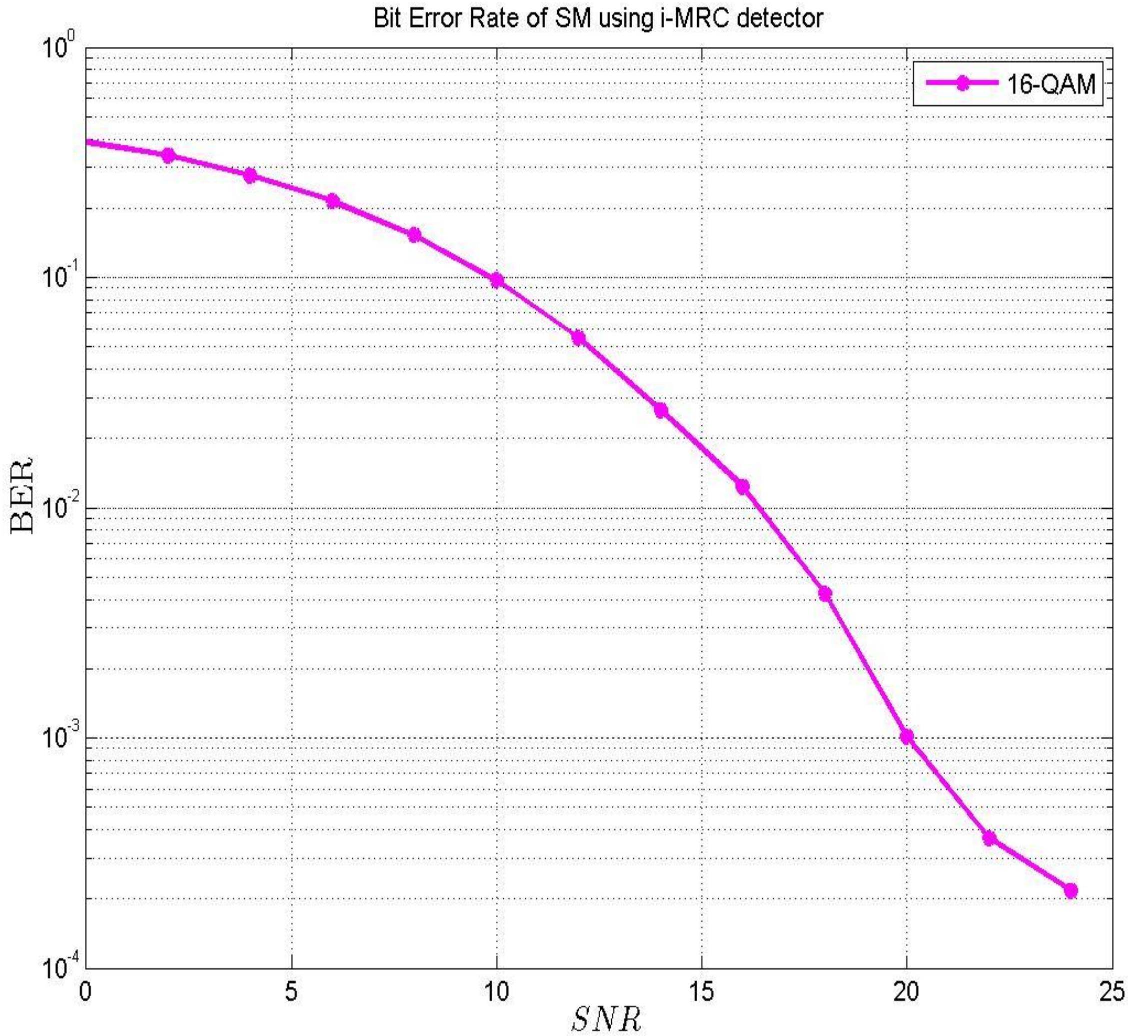

Figure 6.9:-BER versus SNR with SM and 16-QAM over TWDP channel.

Fig. 6.9, shows that when modulation index increases in 16-QAM BER also increases as more number of bits are being transferred in one symbol. Fig. 6.10 is BER versus SNR for SM 64-QAM over TWDP channel. Here, as number of bits in a symbol are 8, hence more BER is observed. For e.g. at SNR of 15 dB BER in 64-QAM is 8×10^{-2} which is just 2×10^{-2} in 16-QAM as seen in fig. 6.9.

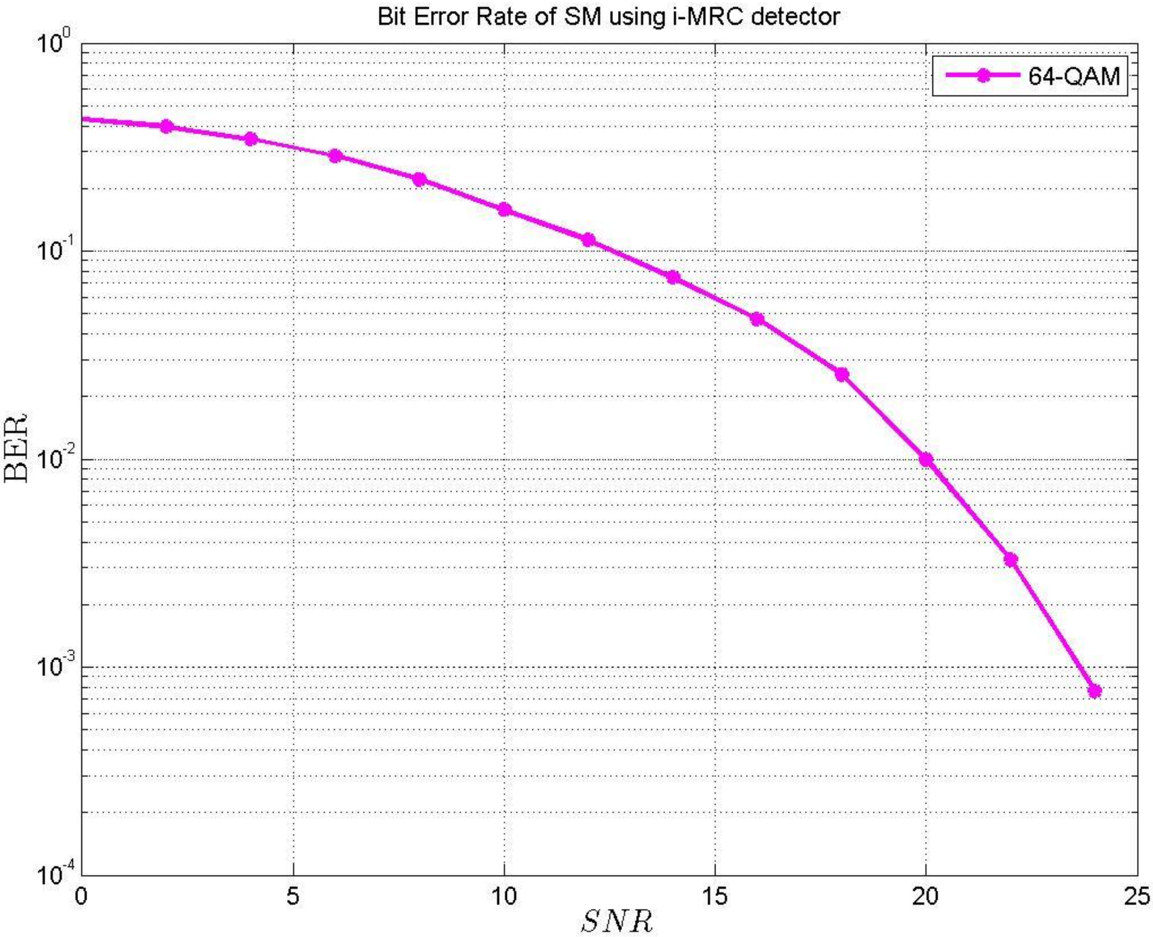

Figure 6.10:-BER versus SNR with SM and 64 QAM over TWDP channel.

In this chapter, BER performance of BPSK and QPSK modulation techniques is studied in TWDP fading channel and Rayleigh fading channel. TWDP fading produces more BER and is represented as worst case communication model. Spatial modulation systems is studied with TWDP channel where BER has reduced drastically, which suggests the use of this system with TWDP channel.

CHAPTER 7: CONCLUSION AND FUTURE SCOPE

7.1 CONCLUSION

Thesis proves that TWDP model makes a link which is even worse than made by Rayleigh fading. Hence, TWDP model should be considered as worst case fading scenario and should be used in designing worst case wireless communication models.

Modulation techniques such as BPSK / QPSK, when applied in both Rayleigh and TWDP fading environment, depicted the fact that more BER is observed with TWDP fading hence, link worse than Rayleigh is established. SISO system performed best with Rician fading environment due to strong LOS component present and worst with TWDP fading environment due to cancellation of two LOS components. When receiver diversity techniques are applied, it shows that BER decreases on increasing the No. of Receive antenna's as greater ability and resilience is added to combat fading and interference.

MIMO which uses scattering , diffraction and fading in its advantage and attains higher data rate in more faded environment Hence, it has been shown to achieve more capacity in TWDP fading environment rather than Rayleigh or Rician fading environment . Also, Massive MIMO which is implemented these days to meet high data rate demands, performs better in TWDP fading environment. The two parameters of TWDP fading K and Δ performed accordingly with MIMO and Massive MIMO. On increasing K capacity decreases and on increasing Δ capacity increases. Results obtained for all systems are included in table 7.1.

Table 7.1:-Comparison of Results Obtained for Different Systems in TWDP channel.

Name of Communication System	Capacity attained at 30 dB SNR	Effect of parameter K on Capacity	Effect of parameter Δ on Capacity
SISO	9.8 bits/sec/hertz	Capacity increases as K increases	Capacity decreases as Δ increases
SIMO	12.2 bits/sec/hertz	Capacity decreases as K increases	Capacity increases as Δ increases
MISO	10.2 bits/sec/hertz	Capacity decreases as K increases	Capacity increases as Δ increases

MIMO	38 bits/sec/hertz	Capacity decreases as K increases	Capacity increases as Δ increases
Massive MIMO	105 bits/sec/hertz	Capacity decreases as K increases	Capacity increases as Δ increases

Spatial modulation which improves energy efficiency has been discussed with TWDP channel and results show that lesser BER and enhanced performance is attained.

7.2 FUTURE SCOPE

TWDP FADING models offers new areas of research. Current wireless needs, implementation of wireless sensors for security and maintenance, requires that this model is correctly modelled and represented.

First and foremost is its easy mathematical representation. Its pdf as discussed in chapter 3, has no closed form expression which makes its implementation difficult, hence easy mathematical representation solves lot of problems which due to limited time was out of scope of this thesis work. Also other receiver combining techniques such as, optimal combining has yet not been implemented with TWDP channels. Coding techniques such as Convolutional Codes and Viterbi algorithm, which improves BER needs to be investigated with this fading.

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