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STUDY OF ENHANCEMENT OF SPECTRAL EFFICIENCY OF WIRELESS FADING CHANNEL USING MIMO TECHNIQUES

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ABSTRACT

Wireless communication has become one of the most widely used communication technologies in today's era. Mobile communication, Bluetooth, Wi-Fi, Wi-MAX, 4G, 3GPP LTE systems, HSPA+ etc. are all wireless communication technologies that we use in our day to day life. But the most important challenge in the wireless communication is to overcome the barriers of the propagation loss in the wireless channel in order to obtain the higher data rate. At present single antenna systems at both transmitter and receiver are deployed widely in wireless communication systems but it has not become an optimal technique to mitigate the problems of loss due to channel fading. Thus researchers have developed Multiple Input and Multiple Output (MIMO) techniques which uses multiple antennas both at transmitter and receiver in which different diversity techniques are used to overcome the channel barriers and mitigate the fading characteristics of the channel. This paper leads to the study of enhancement of spectral efficiency of wireless fading channel using MIMO techniques by developing MIMO models of different size using MATLAB and computes statistical data for increase of BER and Capacity with increase in SNR of the received signal and compares them with various MIMO sizes.

Keywords: Channel capacity, Diversity, Maximum Ratio Combining, Multipath fading, Rayleigh fading channel.

I. INTRODUCTION

In wireless communication it is very important for one to understand the phenomenon's occurring in a wireless medium which defines the characteristics of the wireless channel. ***Fading*** is the phenomenon that causes change in the signal attenuation over a certain propagation medium in wireless communication. The presence of reflectors in the environment surrounding the transmitter and receiver causes the reflection of the transmitted signals resulting in multiple reflective paths. Due to this the receiver receives a superposition of multiple copies of transmitted signal, each travelling in a different path. Each signal copy will experience different attenuation, delay and phase shift while travelling from source to the receiver. This can result in either constructive or destructive interference, thereby amplifying or attenuating the signal power seen at the receiver. Strong destructive interference is often known as ***deep fade***. Hence this can result in a complete failure of communication. Hence, fading can cause poor performance in a communication system because it can result in a loss of signal power without reducing the power of noise, i.e., the bit error rate increases with the drop in signal to noise ratio (SNR). In a wireless mobile communication system, a signal travels from transmitter to the receiver over multiple reflective paths, this phenomenon is known as ***multipath propagation***. It causes fluctuations in the signal amplitude, phase and the angle of reception of the signal resulting in ***Multipath fading***.

When a signal is transmitted over the communication channel then one may undergo two types of fading they are:

a) Large scale fading
b) Small scale fading.

We will discuss these two topics in details in the latter sections. Small scale fading is also known as ***Rayleigh Fading,*** if there are multiple reflective paths in large number and if there is no line of sight signal component, then the envelope of such a received signal is statistically described by Rayleigh pdf. Hence to overcome this problem of signal degradation due to multipath fading researchers have developed a new technique known as the Multiple Input Multiple Output (MIMO) system. **MIMO** is a multi antenna technique both at transmitter and receiver which uses different *diversity* and *channel coding techniques* to exploit the Fading channel characteristics. Previously many research have been done on MIMO by exploiting the various channel characteristics of the wireless fading channel in order to improve the Signal to Noise Ratio (SNR) of the received signal with reduced Bit Error Rate (BER). This has led to the improvement of received signal quality and also increase the channel capacity of the wireless communication system. Further researches are going on in order to improve the spectral efficiency of the wireless communication system in order to deploy the system commercially.

As we know that the bandwidth is a very limited resource in the communication systems hence, it is very important for us to implement such a system by which these scarce resources can be used in a very efficient manner in order to improve the capacity and the spectral efficiency. This paper leads to the study of enhancement of spectral efficiency of wireless fading channel using MIMO techniques by developing MIMO models of different size using MATLAB and computes statistical data for increase of BER and Capacity with increase in SNR of the received signal and compares them with various MIMO sizes. From this paper we can understand the wireless channel characteristics and its behaviour and select appropriate modulation and diversity techniques to efficiently exploit the channel characteristic in order to obtain higher data rate with reduced BER.

II. CLASSIFICATION OF FADING

2.1 Large Scale Fading

Large Scale Fading results in the average signal power attenuation or path loss due to motion of transmitter or receiver over a large area. This phenomenon occurs due to the signal scattering caused by prominent terrain contours (for example, forest, hills, tall buildings, lamp posts, etc.) between the transmitter (Tx) and the receiver (Rx).

Generally for both outdoor and indoor radio channels the propagation model indicates that the mean loss $\overline{L_p(d)}$, as a function of distance '**d**' relative to a reference distance '**d_0**', hence, mean path loss is:

$$\overline{L_p(d)} \propto \left(\frac{d}{d_0}\right)^n \qquad (1)$$

Hence in decibel form path loss is:

$$\overline{L_p(d)}\,(dB) = L_s(d_0)\,(dB) + 10n\log\left(\frac{d}{d_0}\right) \qquad (2)$$

Where,

$\overline{L_p(d)}$ = Mean or average path loss in (dB)

$L_s(d_0)$ = A path loss component w.r.t reference distance d_0 in (dB)

$\overline{L_p(d)}$ when plotted on a log-log scale, then the graph of $\overline{L_p(d)}$ vs. 'd' (for $d>d_0$) yields a straight line with a slope equal to10n dB/decade. Where 'n' depends upon frequency, antenna height and propagation environment. [1]

2.2 Small Scale Fading

Small scale fading refers to a rapid change in the signal amplitude and phase that occurs as a result of small changes in the ***spatial positioning*** (as small as half wavelength) between the transmitter and the receiver.

Small scale fading occurs in two mechanisms, they are:-

1. Time spreading of signal (signal dispersion).
2. Time variance of the channel (propagation path changes due to motion).

Small scale fading is also known as ***Rayleigh Fading*** if there are multiple reflective paths in large number and if there is no line of sight signal component, then the envelope of such a received signal is statistically described by Rayleigh pdf. [1]

2.2.1. Classification of small scale fading

There are different types of small scale fading they are *Frequency Selective* and *Frequency Non-selective Fading* classified under Time spreading of signals and *Fast Fading* and *Slow Fading* classified under Time variance of channel. This is shown below in Fig 2.1.

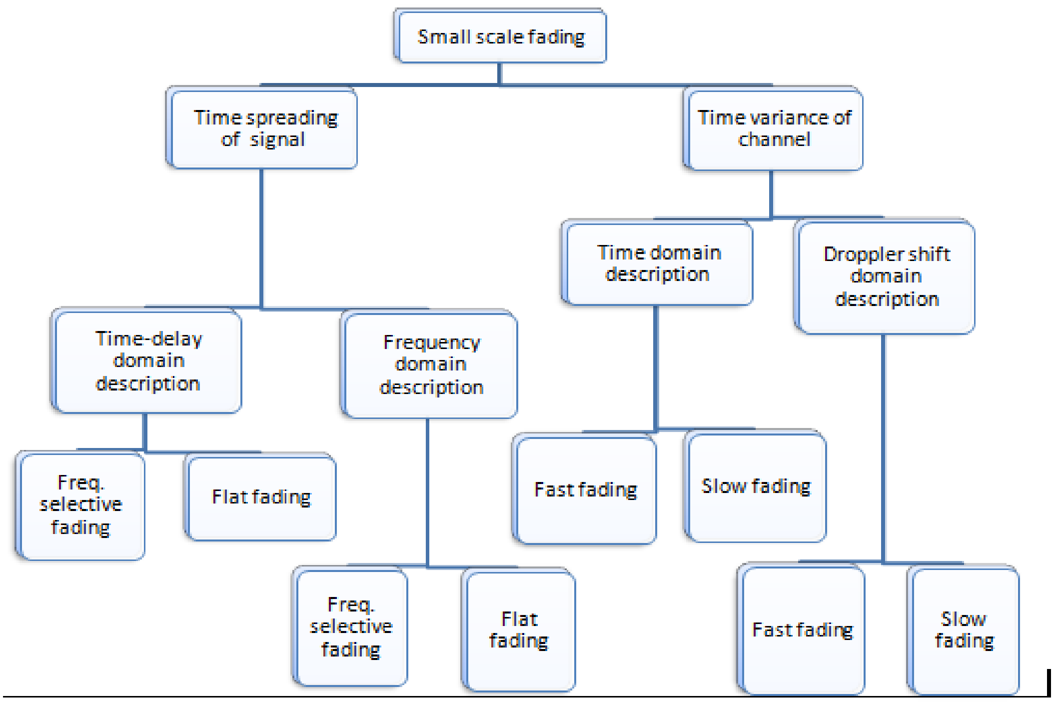

Fig 2.1: Classification of Small Scale Fading

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2.2.2. Delay Spread and Coherence Bandwidth

Delay spread is a measure of ***multipath richness*** of a communication channel. It can be interpreted as the difference between the time of arrival of the earliest significant multipath component (i.e., the line of sight component) and the time of arrival of the latest multipath component. It is mostly used to characterize the wireless channels. The importance of delay spread is that how it effect the ***Inter Symbol Interference (ISI).*** If the symbol duration is big enough compared to the delay spread (typically 10 times big would be good enough) then one can expect an equivalent ISI free channel. The correspondence with the frequency domain is the notation of **coherence bandwidth (CB)**, which is the bandwidth over which the channel can be assumed flat. [2]

Coherence Bandwidth is inversely related to the delay spread. Hence, shorter the delay spread, larger is the coherence bandwidth. If the multipath time delay spread equals '**D**' seconds, then the coherence bandwidth 'W_c' in rad/sec is given approximately by the equation:

$$W_c \approx \frac{2\pi}{D} \qquad (3)$$

Also, coherence bandwidth 'B_C' in Hertz is given approximately by the equation:

$$B_c \approx \frac{1}{D} \qquad (4)$$

For a Rayleigh-fading channel with an exponential delay profile, one finds coherence bandwidth as:

$$B_c = \frac{1}{2p\, T_{rms}} \qquad (5)$$

Where, T_{rms} is the rms delay spread. [1][2]

2.2.3. Frequency Selective Fading

A channel is said to exhibit frequency selective fading if $T_m > T_s$, where 'T_m' is the maximum excess delay spread and 'T_s' is the symbol time duration. Also when if $f_0 < \frac{1}{T} \approx W$, where the symbol rate $\frac{1}{T}$ is nominally taken to be equal to the signaling rate or signal bandwidth 'W'. This leads to pulse broadening and hence results in an ISI distortion also known as channel induced ISI.[1]

2.2.4. Flat Fading

The channel is said to exhibit flat fading under the condition $T_m < T_s$. In this condition, all of the multipath components of a symbol arrive within the symbol time duration. It also occurs if the coherence bandwidth 'f_0' is greater than the signal bandwidth 'W'. i.e., $f_0 > W$

Where:

$$W \approx \frac{1}{T_s} \qquad (6)$$

In flat fading there won't be any introduction of channel-induced ISI distortion but performance degradation may still be expected due to the loss in SNR due to fading.

2.2.5. Fast Fading

Fast fading is used to describe channels in which $T_0 < T_s$ which means coherence time < signal time duration or symbol time. It also occurs when channel fading rate > symbol rate, $f_d > W$. it results in high Doppler, PLL failure, irreducible BER. This results in channel induced ISI.

2.2.6. Slow Fading

A channel introduces slow fading only when, $T_0 > T_s$. Here, the time duration in which the channel behaves in a correlated manner is long compared to the time duration of the transmitted symbol. Hence the channel state remains virtually unchanged during the time in which the symbol is transmitted. It occurs when channel fading rate < symbol rate, $f_d < W$. It results in low Doppler, loss in SNR. There is no channel induced **ISI** but degradation in signal occurs due to loss in SNR. [1]

2.3. Performance over a Slow and Fast fading Rayleigh channel

It has been observed that by applying different Rayleigh fading channel, the plots of bit error rate versus $\frac{E_b}{N_0}$ (SNR) for the various signalling schemes each manifests the classical exponential relationship (a waterfall-shape associated with AWGN performance). This is shown in the Section 3 of this report.

III. MITIGATION OF THE DEGRADATION EFFECTS OF FADING

The three major performance categories in terms of bit-error probability 'P_B' versus $\frac{E_b}{N_0}$ are:

(a) The Good.
(b) The Bad.
(c) The Awful.

This is described below and shown in Fig 3.1:

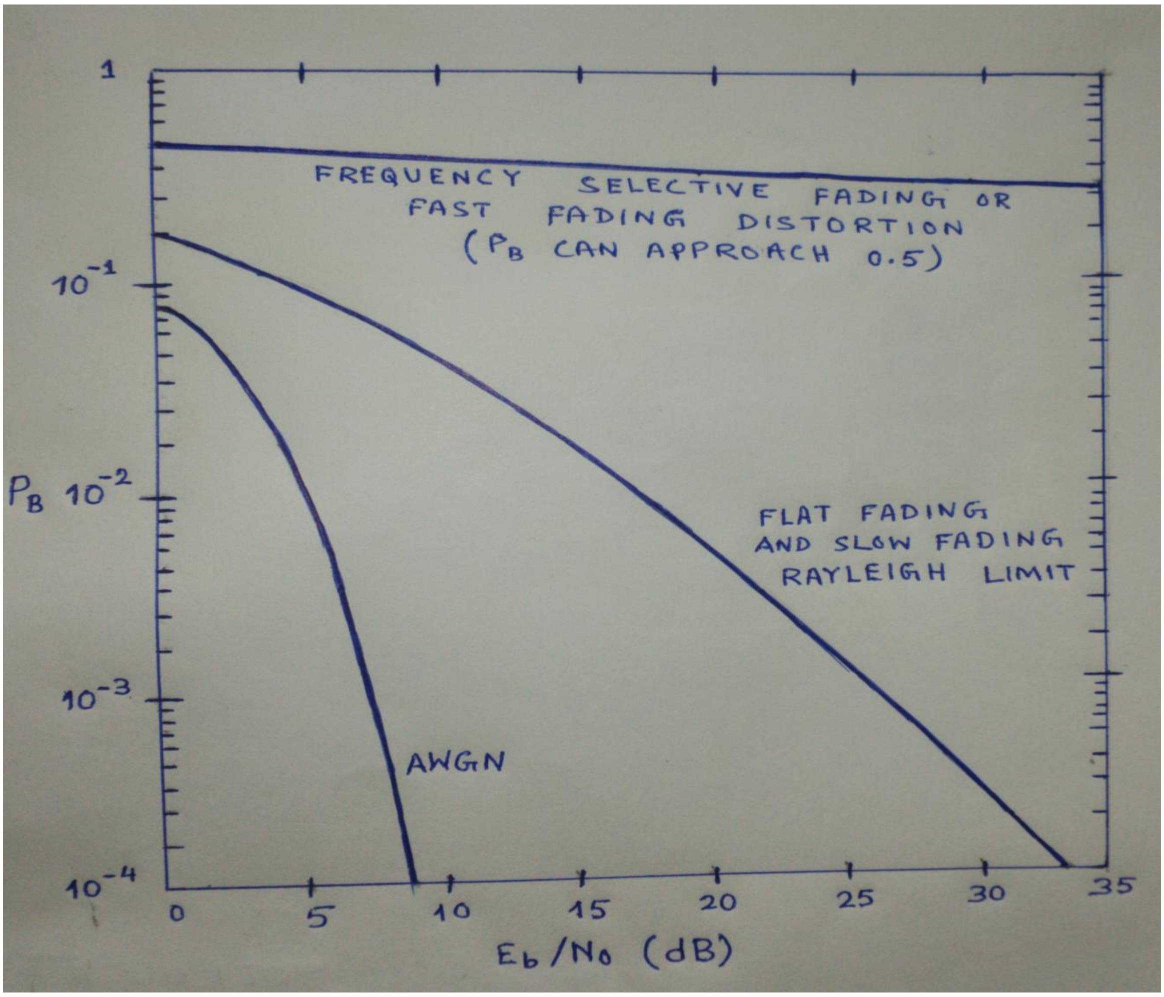

Fig 3.1: the Good Channel, the Bad Channel and the Awful Channel Characteristic. [1]

3.1 The Good

The left most exponential curve in Fig.3.1 highlights the performance that can be expected when using any modulation scheme in AWGN interference. Here good performance can be expected. [1]

3.2 The Bad

The middle curve in Fig.3.1 refers to the Rayleigh limit, shows the performance degradation resulting from the $\frac{E_b}{N_0}$ loss which is a characteristics of flat fading or slow fading when there is no line-of-sight component present. The curve is a function of reciprocal of $\frac{E_b}{N_0}$ (an inverse linear function), so the practical values of $\frac{E_b}{N_0}$ performance will be bad. [1]

3.3 The Awful

The curve that reaches the irreducible error rate level, sometimes called as error floor, represents awful performance shown in Fig.3.1, where bit error rate probability can level off at the values nearly equal to 0.5. This shows severe performance degradation resulting from frequency selective fading or fast fading. [1]

Hence, once signal distortion is mitigated then the P_B versus $\frac{E_b}{N_0}$ performance can make a transition from "***Awful***" category to merely "***Bad***", i.e., ***Rayleigh limit curve.*** Then it is further possible to overcome the effects of fading and strive to approach the ***AWGN*** system performance by using some ***diversity techniques*** *and by using a powerful* ***error correction coding technique***. [1]

MIMO is a multi antenna technique both at transmitter and receiver which uses different *diversity* and *channel coding techniques* to exploit the Fading channel characteristics. This is described in the following sections.

IV. MIMO TECHNIQUES AND DIVERSITY

In mobile radio communication Multiple-Input and Multiple-Output or MIMO uses the multiple antennas at both the transmitter and receiver to improve communication performance.

Multiple antennas are used to perform ***smart antenna*** functions such as spreading the total transmit power over the antennas to achieve an array gain that increases the spectral efficiency i.e., (more bits per second per hertz of bandwidth) or to achieve a diversity gain that improves the link reliability (reduce fading) or both.

However the term MIMO usually refers to a method for multiplying the capacity of a radio link by exploiting multipath propagation. This MIMO technology is an essential element of the wireless communication standards such as IEEE 802.11n (Wi-Fi), IEEE 802.ac, 4G, 3GPP Long Term Evolution, Wi-MAX and HSPA+.

4.1 MIMO Basics

A channel may be affected by fading which will impact the signal to noise ratio. This in turn affects the error rate when digital data is being transmitted. The principle of diversity is to provide multiple versions or copies of the same signal at the receiver. If these copies of the signal are made to be affected in the different ways by the signal paths, the probability that all the copies will be affected at the same time is considerably reduced. Hence diversity technique helps to stabilize a link and improves performance by reducing the bit error rate.

MIMO wireless systems, characterized by multiple antenna elements at the transmitter and receiver, have demonstrated the potential for increased capacity in rich multipath environments. Such systems operate by exploiting the spatial properties of the multipath channel, thereby offering a new dimension which can be used to enable enhanced communication performance. While coding and signal processing are key elements to successful implementation of a MIMO system, the propagation channel and antenna design represent major parameters that ultimately impact system performance.

Like the Simple multipath propagation environment showing two paths between transmit and receive. The arrays are capable of resolving the individual multipath, enabling increased data throughput shown in Fig 4.1.

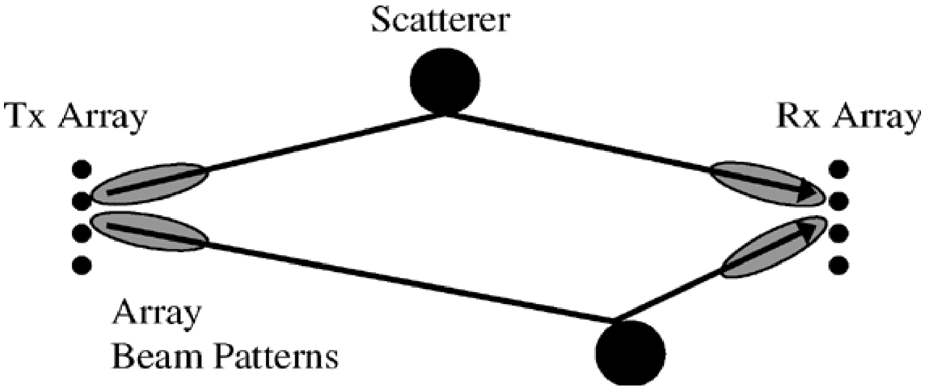

Fig 4.1: Simple Multipath Propagation Model.

For linear channel elements, the MIMO channel input–output relationship may be written as:

$$\underset{N_R\times1}{y(\omega)} = \underset{N_R\times N_T}{H(\omega)}\ \underset{N_T\times1}{x(\omega)} + \underset{N_R\times1}{\eta(\omega)} \quad (7)$$

Where, $\eta(\omega)$ is additive noise produced by the channel (interference plus noise from the RF front end), $x(\omega)$ is the source vector and $y(\omega)$ is the receive vector and the matrix dimensions are as specified in the equation 7. A simple MIMO model is shown in the Fig. 4.2.

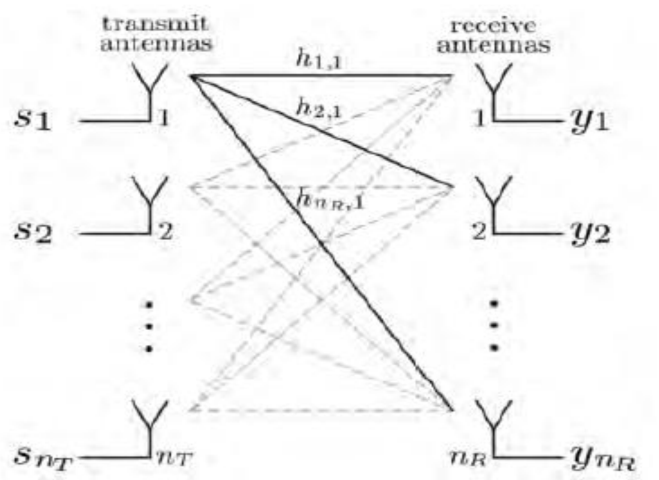

Fig 4.2: the MIMO Channel with n_T Transmit and n_R Receive Antennas.

Each element $H_{i,j}(\omega)$ represents the transfer function between the ith transmit and jth receive antenna. Since the transmit vector is projected into $\mathbf{H}(\omega)$, the number of independent data streams (Q) that can be supported must be at most equal to the rank of $\mathbf{H}(\omega)$.

Where,

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$$H(\tau, t) = \begin{bmatrix} h_{11}(\tau,t) & \cdots & h_{1n_t}(\tau,t) \\ \vdots & \ddots & \vdots \\ h_{n_r1}(\tau,t) & \cdots & h_{n_rn_t}(\tau,t) \end{bmatrix} \qquad (8)$$

This is a ***MIMO channel matrix*** for a ***Rayleigh fading channel*** with complex random elements. In frequency domain the channel is approximated by a complex matrix having independent identically distributed (iid) entries with zero mean and unit variance.[4]

4.2 Different Diversity Techniques

There are different diversity techniques that can be used in MIMO are:

1. Time diversity.
2. Frequency diversity.
3. Antenna diversity.
4. Spatial diversity.
5. Polarization diversity.

In ***Time diversity*** repeatedly transmits information at time spacing that exceeds the coherence time of the channel, so that multiple repetitions of the signal will be received with independent fading conditions thereby providing for diversity. It is used in RAKE receiver for spread spectrum in CDMA. In ***Frequency diversity*** information is transmitted on more than one carrier frequency. Under this technique the frequencies separated by more than the coherence bandwidth of the channel then the channels will be uncorrelated and will thus not experience the same fade. There are many other diversity techniques mentioned above but the widely used diversity technique is ***Space diversity*** which is used in MIMO technology. The most optimum form of space diversity is ***Maximum Ratio Combining***.

4.2.1 .Maximal Ratio Combining

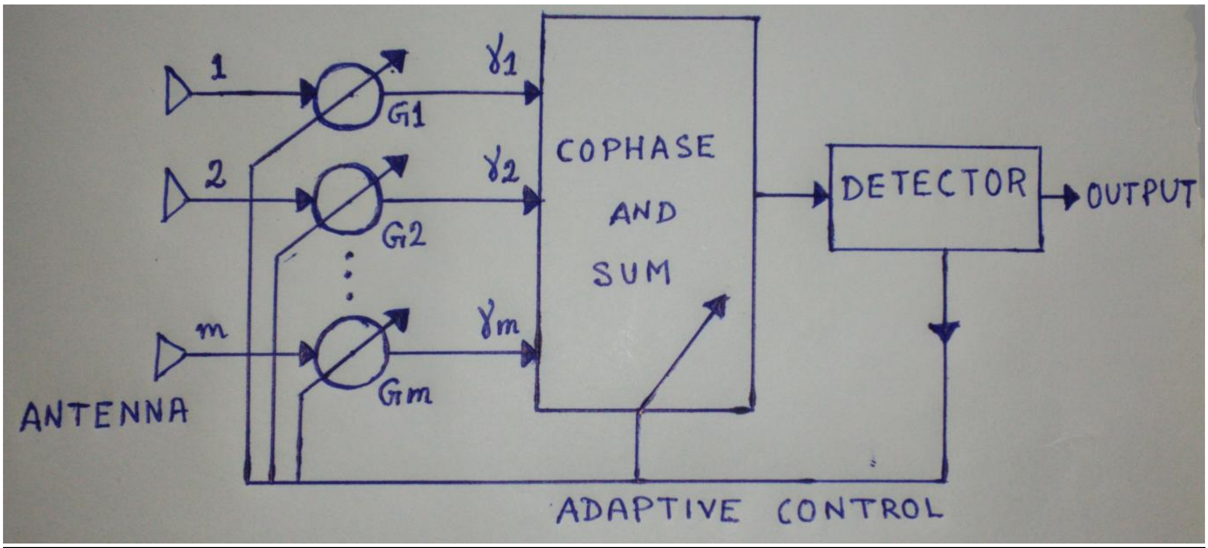

Fig 4.3: Block Diagram of MRC.

In this method the signal from all of the ***'M'*** branches are weighted according to their individual signal voltage-to-noise ratio (**SNR's**) and then summed together. Hence the individual signals must be ***co-phased*** before being

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summed up (unlike selection diversity) which generally requires an individual receiver and phasing circuit for each antenna element. This is shown in the Fig 4.3.

Hence, Maximum Ratio Combining produces an output SNR which is equal to the sum of the individual SNR's. Thus it has an advantage of producing an output with an acceptable SNR even when none of the individual signals are themselves acceptable. This technique gives the best statistical reduction of fading of any known linear diversity combiner [3]. Hence, this technique is used in this project.

V. MIMO CHANNEL CAPACITY

To see how parallel spatial channels can increase capacity, consider the simple case of Q uncoupled transmission lines. If only one transmission line is used to send data, the Shannon channel capacity will be:

$$C_1 = \log_2(1+\rho) \tag{9}$$

Where 'ρ' is the receiver SNR. If the transmit power is instead equally divided among the lines, the capacity becomes:

$$C_Q = \sum_{q=1}^{Q} \log_2\left(1+\frac{\rho}{Q}\right) = Q\log_2\left(1+\frac{\rho}{Q}\right) \tag{10}$$

Where, we have assumed equal receiver noise.

A generalized ***MIMO capacity*** formula for any **(n_r, n_t)** MIMO system is:

$$C = \log_2\left(\det\left[I_{n_r} + \left(\frac{\rho}{n_t}\right) HH^H\right]\right) \text{ b/s/Hz} \qquad (11)\ [4][5]$$

Where,

det = Determinant of matrix.

I_{n_r} = $(n_r \times n_t)$ Identity matrix.

H = channel matrix of MIMO system of the order $(n_r \times n_t)$ given in equation (8).

H^H = Hermitian matrix of **H**.

ρ = Signal to noise ratio (SNR).

5.1. Uninformed Transmit Capacity

If the channel is unknown to the transmitter then for the MIMO system, given by the equation:

$$y = \sqrt{\frac{E_s}{N_T}} Hs + n \qquad (12)\ [4]$$

With the covariance matrix of 'S' is given by:

$$R_x = E\{SS^H\} \tag{13}$$

The vector '**S**' in this case may be chosen such that $R_{ss} = I_{Nt}$. This means that the signals at the transmit antennas are independent and of equal power. The total transmit power is divided equally amongst ***'Nt'*** transmit antennas to form ***'Nt'*** independent streams given by: [4]

$$R_x = \left(\frac{P_T}{N_T}\right) I \tag{14}$$

Hence, Channel capacity,

$$C_{UT} = \log_2\left|I_{n_r} + \left(\frac{\rho}{n_t}\right) HH^H\right| \tag{15}$$

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Hence, the channel is considered as a ***full rank MIMO channel*** with $\mathbf{N_t = N_r = N}$ so that the rank of channel $\boldsymbol{r = N}$. The maximum capacity is achieved when H is an orthogonal matrix, i.e.,:

$$HH^H = H^H H. \qquad (16) \quad [4]\,[5]$$

VI. PROJECT WORK AND OBSERVATIONS

From the survey of previous research findings on the capacity enhancement of the Rayleigh fading channel using MIMO technology we have come to know that in a mobile wireless communication system the two important resources ***Signal power 'P'*** and ***Bandwidth 'B'*** are the limited quantities and the signal transmitted over the wireless link undergoes multipath reflections, diffraction and refractions from the multiple ***Interacting Objects (IO's)*** present in the communication environment resulting in a signal loss, attenuation and fading.

Hence, we have used MIMO technology and designed the channel matrix for the Rayleigh Fading Channel using the ***Maximum Ratio Combining Technique*** and ***Alamouti techniques***. By applying the channel capacity formula for ***uninformed channel capacity*** shown in equation (9) and designing the Rayleigh fading MIMO channel matrix '**H**' by using the **MATLAB** programming we have designed a (***2×2) MIMO*** transmitter and receiver model with ***BPSK*** *modulation* and *demodulation* technique along with different diversity techniques for a ***Rayleigh fading channel***. Then we have transmitted data streams using this **MIMO** system and have computed and plotted the ***SNR vs BER*** curve for (**1×1**), (**1×2**) and (**2×2**) MIMO models. We have also computed and plotted *the* ***Capacity vs SNR*** graph for (**2×2**) MIMO, (**4×4**) MIMO, (**6×6**) MIMO, (**8×8**) MIMO and (**10×10**) MIMO models. Observations are shown below in Fig 6.1 and Fig 6.2.

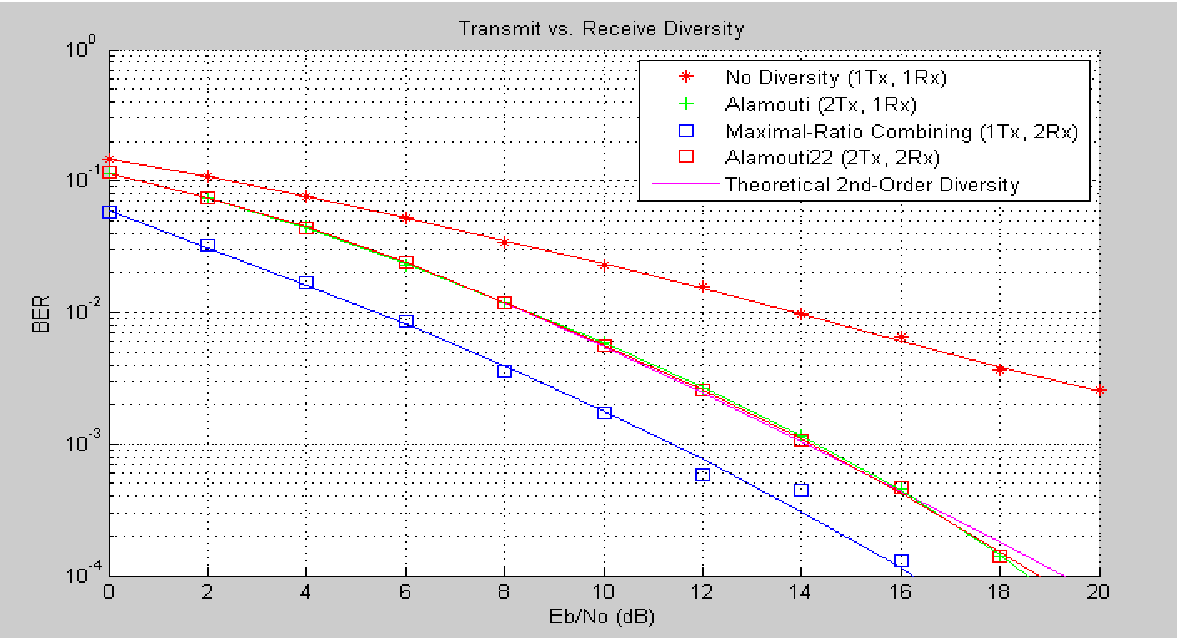

Fig 6.1: E_b/N_o vs BER Plot for MIMO System.

From the above plot of ***E_b/N_o Vs BER*** for a MIMO system (Fig. 6.1) we can see that the BER reduces with the increase in no. of transmit and receive antennas for different diversity techniques. From the graph we can also see that the BER gradually reduces with the increase in SNR value (**E_b/N_o**) and from the plot we can also see that implementation of diversity techniques have reduced the BER to a great extent compared to the no diversity technique but by studying this output plot we can see that Maximum Ratio Combining (MRC) diversity

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technique is the most optimum technique as it reduces the BER to a very low extent with increase in SNR which is depicted by the blue colour curve in the graph which approaches towards 'The Good' i.e., the AWGN region from 'The Bad' i.e., the Rayleigh fading region of the waterfall model shown in Fig. 3.1. This shows that MIMO systems improves the quality of received signals and hence the efficiency of the system in a Rayleigh fading channel and maximum Ratio Combining technique comes out to be the optimal diversity technique to be implemented in the communication system to achieve higher data rate.

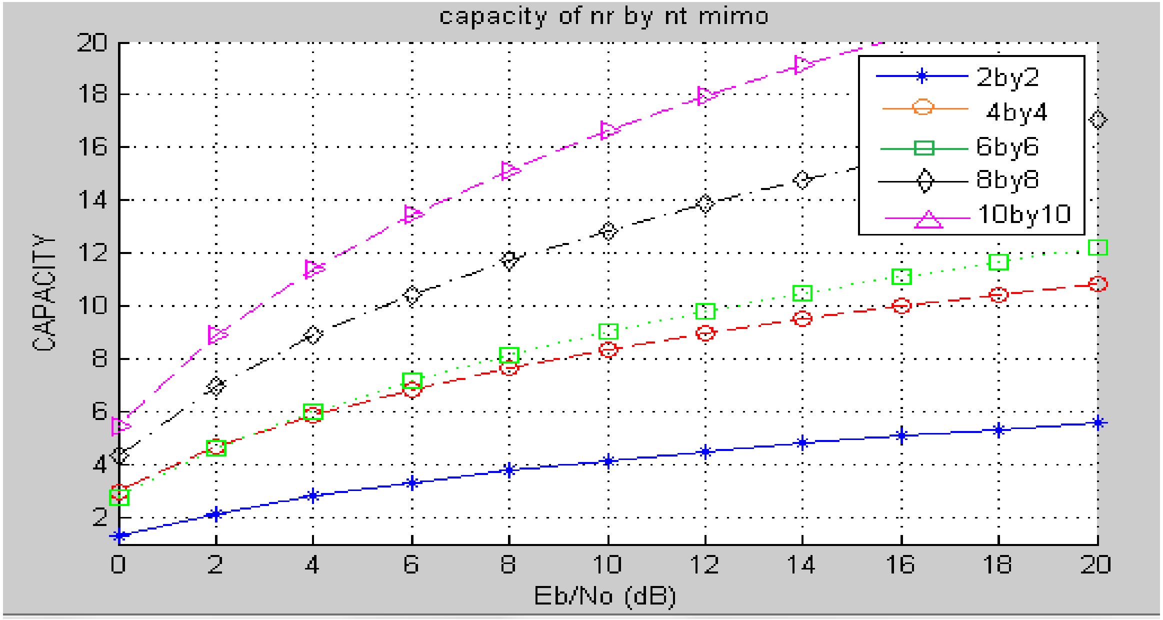

Fig. 6.2: Capacity Vs SNR Output Plot for MIMO System of Different Size.

The above observation (Fig. 6.2) we can see the Capacity vs SNR plot for various MIMO sizes starting from (**2×2**) to (**10×10**) MIMO models gradually in increasing order. From this output graph it is clearly seen that channel capacity goes on increasing as we increase the MIMO sizes. Hence we can conclude that the channel capacity and hence the channel efficiency of the Rayleigh fading channel using MIMO technique increases as we go on increasing the number of transmit and receive antennas of a MIMO system.

VII. CONCLUSION

Wireless communication systems employing multiple transmit and receive antennas have potentially greater capacity than their single antenna system on the same bandwidth. Understanding the gains that are possible with such systems requires detailed knowledge of the MIMO channel transfer matrix. This paper provides a tutorial on the operation of MIMO wireless communication systems and illustrates how multiple antennas can lead to increased system capacity for multipath communication channels. From the survey and study of different researches and from the observations of the project model shown in Fig.6.1 and Fig.6.2, it has been found that signal quality at the receiver increases with the implementation of different diversity techniques in MIMO systems. This results in the reduction of the BER with increase in Signal to Noise Ratio (SNR) which will led to the increase in high data rate. However there are lots of different diversity as well as modulation techniques amongst which we have used MRC and Alamouti techniques along with BPSK modulation and demodulation techniques. We also found that the channel capacity also increases with the increase in SNR. Hence, the channel efficiency of the Rayleigh fading channel increases greatly using MIMO system. This paper will provide a clear understanding of the Rayleigh fading channel and ways to exploit the fading channel characteristics and implement this techniques to further develop new communication technologies and can be applied in different existing communication technologies like *Wi-Fi, Wi-MAX, 4G, 3GPP LTE systems, HSPA+, etc* in order to achieve much higher data rate and spectral efficiency than that we have achieved. Further research can be done based on this paper using a combination of different other diversity as well as modulation and demodulation techniques and compare the output results with the observations of the project given in this paper.

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