PERFORMANCE ANALYSIS OF SISO & MIMO FREE-SPACE OPTICAL SYSTEMS THROUGH THIN CLOUD

Submitted to

Dr. Satya Prasad Majumder

Professor, Department of EEE

Bangladesh University of Engineering and Technology

Submitted by

Mahdy Khan Rifat

(0906082)

&

Mohammad Rafat

(0906125)

Department of Electrical and Electronic Engineering

Bangladesh University of Engineering and Technology

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Declaration

I hereby declare that this thesis report has been written based only on the works and results found by us. Material of the works or research or thesis by other researchers are mentioned by their references. This thesis, neither in whole nor in part, has been previously submitted for any degree.

Thesis Supervisor

Dr. Satya Prasad Majumder

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Authors

Mahdy Khan Rifat

…………………………..

Mohammad Rafat

…………………………..

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Abstract

Free space optical communication (FSO) is one of the sprouting technologies in optical communication systems domain. It is a cost effective and high bandwidth access technique, which has been receiving growing attention with recent commercialization successes; thus it can be employed as an alternative for the conventional radio frequency (RF) links to work out the current limitations in communication systems. But, FSO from satellite and ground or air to air consists of cloud as part of the communication channel. Cloud causes pulse broadening in time domain and attenuation in radiant pulse power. So, the bit error rate (BER) performance decreases with thickness of cloud. Spatial diversity, which involves the use of multiple laser transmitters or receivers or both, can be used over FSO links to mitigate cloud-induced complications with fading channels. Here, we have employed multiple-input multiple-output (MIMO) technique to improve the BER performance of an FSO system. We have analyzed BER of single-input single-output (SISO) system with MIMO system undergoing cloud channels of different thickness using binary phase shift keying (BPSK) signaling technique. Significant improvement in receiver performance is obtained by simulating the systems under same conditions.

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List of Acronyms

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
FSO	Free-Space Optics
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
QPSK	Quadrature Phase Shift Keying
SIMO	Single Input Multiple Output
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio

Chapter 1

Introduction to FSO

1.1 Introduction

Free-space optics (FSO), also called free-space photonics (FSP), refers to the transmission of modulated visible or infrared (IR) beams through the atmosphere to obtain broadband communications. Most frequently, laser beams are used, although non-lasing sources such as light-emitting diodes (LEDs) or IR-emitting diodes (IREDs) will serve the purpose. The theory of FSO is essentially the same as that for fiber optic transmission. The difference is that the energy beam is collimated and sent through clear air or space from the source to the destination, rather than guided through an optical fiber. If the energy source does not produce a sufficiently parallel beam to travel the required distance, collimation can be done with lenses. At the source, the visible or IR energy is modulated with the data to be transmitted. At the destination, the beam is intercepted by a photo-detector, the data is extracted from the visible or IR beam (demodulated), and the resulting signal is amplified and sent to the hardware.

FSO systems can function over distances of several kilometers. As long as there is a clear line of sight between the source and the destination, communication is theoretically possible. Even if there is no direct line of sight, strategically positioned mirrors can be used to reflect the energy. The beams can pass through glass windows with little or no attenuation.

Although FSO systems can be a good solution for some broadband networking needs, there are limitations. Most significant is the fact that cloud, rain, dust, snow, fog or smog can block the transmission path and shut down the network. Our work is on increasing the performance through thin clouds by using space diversity.

1.2 Free-space optical communication (FSO)

Free-space optical communication (FSO) using intensity modulation and direct detection (IM/DD), is a cost-effective and high bandwidth access technique, which has recently received significant attention and commercial interest for a variety of applications. Optical wireless communication systems are rapidly gaining popularity as effective means of transferring data at high rates over short distances due to the necessity of a cost-effective, license-free, and high-bandwidth access communication technique. These systems facilitate rapidly deployable, lightweight, high-capacity communication without licensing fees and tariffs. Terrestrial FSO is not free of challenges though. A major impairment over FSO links is the atmospheric turbulence, caused by the variations in the refractive index because of inhomogeneities in temperature and pressure changes. In clear weather conditions, the atmospheric turbulence results in fluctuations at the intensity of the received signal, i.e., signal fading, also known as scintillation in optical communication terminology. Turbulence is caused by inhomogeneities of both temperature and pressure in the atmosphere and can severely degrade the link performance, particularly over link distances of 1 km or longer. The performance of this technology depends strongly on the atmospheric conditions between the transmitter and the receiver and the parameters of the link such as the length and the operation wavelength. Effects of fog, rain, cloud, atmospheric gases, and aerosols also result in beam attenuation due to photon absorption and scattering.

The performance of FSO systems over turbulence channels has been addressed in many previous works. Representative examples can be found in [1] and the references therein. The results presented in these papers have demonstrated that the performance of single-input single-output (SISO) FSO links is severely degraded from cloud. More specifically, the average bit error probability of such systems is far away from satisfying the typical targets for FSO applications within practical ranges of signal-to-noise ratio (SNR). To circumvent this problem, powerful fading mitigation techniques have to be deployed. In the open technical literature on FSO communication, the two most popular existing techniques for mitigation of the degrading effects of atmospheric turbulence are error control coding in conjunction with interleaving and maximum likelihood sequence detection (MLSD). However, for most scenarios the first one requires large-size interleavers to achieve the promised coding gains. On the other hand, MLSD requires complicated multidimensional integrations and suffers from excessive computational complexity.

Another promising solution is the use of diversity techniques and the most popular scheme is the spatial diversity, i.e., the employment of multiple transmit/receive apertures, a well-known diversity technique in Radio-Frequency (RF) systems [2]. By using multiple apertures at the transmitter and/or the receiver, the inherent redundancy of spatial diversity has the potential to significantly enhance the performance. Moreover, the possibility for temporal blockage of the laser beams by obstructions is further reduced and longer distances can be covered through heavier weather conditions [3]. Concerning the performance analysis of FSO systems employing spatial diversity, the technical literature is rather rich.

On the other hand, various statistical models, e.g. the log-normal, the gamma-gamma (G-G), the I-K, the K, the negative exponential and the Rician log-normal distribution, have been used in order to describe the optical channel characteristics with respect to the atmospheric turbulence strength.

1.2.1 Technical Advantages

This technology is useful where the physical connections are impractical due to high costs or other considerations.

- Ease of deployment
- Can be used to power devices
- License-free long-range operation (in contrast with radio communication)
- High bit rates
- Low bit error rates
- Immunity to electromagnetic interference
- Full duplex operation
- Protocol transparency
- Increased security when working with narrow beam(s)
- No Fresnel zone necessary

1.2.2 Range Limiting Factors

For terrestrial applications, the principal limiting factors are:

- Fog
- Cloud
- Beam dispersion
- Atmospheric absorption
- Rain
- Snow
- Terrestrial scintillation
- Interference from background light sources (including the Sun)
- Shadowing
- Pointing stability in wind
- Pollution / smog

These factors cause an attenuated receiver signal and lead to higher bit error ratio (BER). To overcome these issues, vendors found some solutions, like multi-beam or multi-path architectures, which use more than one sender and more than one receiver. Some state-of-the-art devices also have larger fade margin (extra power, reserved for rain, smog, fog). To keep an eye-safe environment, good FSO systems have a limited laser power density and support laser classes 1 or 1M. Atmospheric and fog attenuation, which are exponential in nature, limit practical range of FSO devices to several kilometers.

1.3 Multipath Propagation

In wireless telecommunications, multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from water bodies and terrestrial objects such as mountains and buildings. The effects of multipath include constructive and destructive interference, and phase shifting of the signal.

In digital radio communications (such as GSM) multipath can cause errors and affect the quality of communications. We discuss all the related issues in this chapter.

1.3.1 Multipath & Small-Scale Fading

When the delay differences among various distinct propagation paths are very small compared with the symbol interval in digital transmission, the multipath components are almost indistinguishable at the receiver. Those multipath components can add constructively or destructively, depending on the carrier frequency and delay differences. As the mobile station moves, the position of each scattered with respect to the transmitter and receiver may change. The overall effect is that the received signal level fluctuates with time, a phenomenon called fading.

Multipath signals are received in a terrestrial environment, i.e., where different forms of propagation are present and the signals arrive at the receiver from transmitter via a variety of paths. Therefore there would be multipath interference, causing multi-path fading. Adding the effect of movement of either TX or RX or the surrounding clutter to it, the received overall signal amplitude or phase changes over a small amount of time. Mainly this causes the fading.

The term fading, or, small-scale fading, means rapid fluctuations of the amplitudes, phases, or multipath delays of a radio signal over a short period or short travel distance. This might be so severe that large scale radio propagation loss effects might be ignored.

1.3.2 Multipath Fading Effects

In principle, the following are the main multipath effects:

- Rapid changes in signal strength over a small travel distance or time interval.
- Random frequency modulation for varying Doppler shifts on different-path signals.
- Time dispersion or echoes caused by multipath propagation delays.

1.3.3 Factors Influencing Fading

The following physical factors influence small-scale fading in the radio propagation channel:

- Multipath propagation – Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. The effects of multipath include constructive and destructive interference, and phase shifting of the signal.
- Speed of the mobile – The relative motion between the base station and the mobile results in random frequency modulation due to different Doppler shifts on each of the multipath components.
- Speed of surrounding objects – If objects in the radio channel are in motion, they induce a time varying Doppler shift on multipath components. If the surrounding objects move at a greater rate than the mobile, then this effect dominates fading.
- Transmission Bandwidth of the signal – If the transmitted radio signal bandwidth is greater than the "bandwidth" of the multipath channel (quantified by coherence bandwidth), the received signal will be distorted.

1.4 Diversity

Diversity improves transmission performance by making use of more than one independently faded version of the transmitted signal. If several replicas of the signal, carrying the same information, are received over multiple channels the chances that all the independently faded signal components experience deep fading simultaneously are greatly reduced. That will significantly improve transmission accuracy as transmission errors are most likely to happen when SNR (signal to noise ratio) is low during deep fading period. So diversity is a common used technique in wireless system to combat channel fading. Different types of diversity uses Frequency, Time, Space, Polarization, Antenna and Angel as the source of diversity, which are discusses later.

1.5 Objective of Our Thesis

In our thesis, we have tried to implement MIMO technique to the existing SISO system configuration for propagation through thin cloud in the atmosphere. Here we have also considered Rayleigh fading which occurs due to multipath propagation in FSO channel. Whether the performance of the in MIMO system is better than that of a usual SISO system, or not, is to be determined in this thesis via simulations in various conditions. We have used different thicknesses of clouds; also fading and non-fading channels are used along with AWGN channel.

Chapter 2

Background Knowledge on FSO

2.1 Transmission through free space

Block diagram of our usual transmission system looks like the figure below. At first, input data stream is taken in and is modulated using a higher frequency via Binary Phase Shift Keying (BPSK) technique. Other forms of modulation are QPSK (Quadrature Phase Shift Keying), M-PSK (M-ary Phase Shift Keying), M-PAM (M-ary Pulse Amplitude Modulation) etc. Then the signal is transmitted through a single transmitter. This signal travels through channel, mainly consisting of air, to the destined receiver. Noise are added in this part of the channel. The receiver uses a Band Pass Filter (BPF) to clear out unnecessary bandwidth. Then it is demodulated using the same frequency used in modulation. A Low Pass Filter (LPF), and an integrator is used before sampling. The threshold voltage is zero volt for BPSK transmission.

2.2 Atmospheric turbulence

The refractive index of the atmosphere in the area between the transmitter and the receiver of a wireless optical link fluctuates randomly due to the atmospheric turbulence [3]. These fluctuations are induced mainly due to temperature oscillations among the atmosphere, the ground and the oceans. More specifically atmospheric turbulence is a phenomenon belonging to different spatial and temporal scales. In the Planetary Boundary Layer (PBL), where human activities take place, it is generated by the wind's interaction with the earth's surface, which is said to be in a state of turbulent motion [4]. Turbulence is responsible for the transfer of heat, matter, and momentum within the PBL. However, it is random in nature and remains a complicated phenomenon with many unsolved aspects. The scientific community relies on the combination of experiments, theory, and computer models to understand it. Turbulence is created by thermal convection, wind shear and by the wind flowing over ground obstacles. Within the PBL, turbulence has a diurnal variation reaching a maximum about midday when the solar radiation is at a maximum. Solar radiation heats the surface which, in turn radiates heat to the air above it that becomes warmer and more buoyant and rises while cooler, denser air descends to displace it. The resulting vertical movement of air, together with flow disturbances around surface obstacles, makes low-level winds extremely irregular thus turbulent. The turbulence intensity depends primarily on the temperature lapse rate, i.e. $\lambda = dT/dH$, which is essentially the rate of temperature increase or decrease with increasing height. Under unstable conditions the temperature decreases with height and a hypothetical parcel of air which is warmer than its surrounding air would tend to rise. Turbulence in the atmosphere is carried by rotational-like motions called eddies, which exist in different length scales characterized by different velocity and time scales. The larger eddies are unstable and break up into smaller ones with the subsequent transfer of the kinetic energy of the initial large eddy. The smaller eddies in turn break up into even smaller eddies and the energy is passed on to the new smaller ones. The energy is passed down from the larger scales to the smaller ones until the viscosity of the fluid (in this case air) can dissipate the Performance Analysis of SISO and MIMO FSO Communication Systems Over Turbulent Channels kinetic energy into internal energy (or thermal energy). This is called the energy cascade and it is one of the main characteristics of turbulent motion. Other important features of turbulence are irregularity (or chaotic), diffusivity (mixing), turbulent diffusion (molecular diffusivity), rotationality (always three dimensional, the mechanism that aids the energy cascade), dissipation (the transfer of energy from larger to smaller eddies), length scales of turbulent eddies. The size of eddies spans from the order of a few millimeters to meters, namely the inner and outer scales, respectively [5]. This inner and outer scales is the main phenomenon for the choice of the appropriate distribution for turbulence's mathematical representation. It is commonly known that in turbulent flow the actual flow velocity is broken into the mean velocity U plus the fluctuating turbulent velocity component u, in the three directions, respectively. Thus, in the x-axis the instantaneous flow velocity is $Ux + ux$. The values of the turbulent components namely ux, uy and uz may not be expressed as functions of time but a statistical description is only possible. Turbulence within the PBL can degrade the performance of free-space optical links, particularly over ranges of the order of 1 km or longer. This phenomenon is not caused by the turbulent eddies which possess different velocities but only by the parcels of air with different temperatures (and thus different densities) rising or descending that cross the path of the FSO links. They cause inhomogeneities in the temperature and pressure profiles of the atmosphere and lead to variations of the refractive index along the transmission path. Based on the fluctuations of the air density, the scientific community has developed the refractive index structure parameter C_n^2 (related to the temperature structure one, i.e. CT_2) which takes different values depending on the strength of turbulence. The parameter C_n^2 may be measured experimentally of computed theoretically if one knows the outer scale of turbulence (i.e., the large eddy size scale) and the potential refractive. Additionally, as we will demonstrate below, there are many mathematical models for the estimation of the C_n^2 value. Thus, these variation of the refraction index in the free space area that the beam of the optical link propagates and causes deflections of the light beam into and mostly out of the transmit path. This random radiation of the laser beam results in fluctuations of the optical signal's irradiance at the receiver's side. This phenomenon is the so-called scintillation [6]. The influence of scintillation in the performance of the wireless optical communication systems is very strong for the terrestrial links because induces fading of the signal arriving at the receiver in a random way. Thus, in order to estimate the optical signal arriving at the receiver it is necessary to study the appropriate statistical distribution which describes the fading statistics of each area. Many statistical models have been proposed for the simulation of these fading statistics caused by the atmospheric turbulence effect. Some of them have been arising from experimental results, while, others, from theoretical studies. It is obvious that each location has irregularities, depending on the ground's morphology, the weather conditions, the time of the day and the turbulence strength. The proposed statistical models concern weak, moderate, strong or very strong turbulence conditions and the turbulence strength can be estimated through the turbulence parameter C_n^2, which depends on many parameters of the weather conditions. One of the statistical parameters that we are using for the practical estimation of scintillation influence at the wireless optical links' performance, is the scintillation index which is given by the following mathematical expression:

$$\sigma_I^2 = \frac{< I^2 > - < I >^2}{< I >^2} \tag{2.1}$$

with I being the optical signal's irradiance at the receiver and <> represents the ensemble average value. In the weak scintillation theory, under the assumption of plane wave propagation, the scintillation index is proportional to the Rytov variance and is given as:

$$\sigma_{I,R}^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \tag{2.2}$$

where C_n^2 is the parameter of turbulence, $k = 2\pi/\lambda$ is the optical wavenumber, while L is the link's length.

If we assume spherical wave propagation, σI, R can be expressed as:

$$\sigma_{I,R}^2 = 0.5C_n^2 k^{7/6} L^{11/6} \quad (2.3)$$

2.3 Details on Multipath Fading

2.3.1 Types of Small-Scale Fading

The type of fading experienced by the signal through a mobile channel depends on the relation between the signal parameters (bandwidth, symbol period) and the channel parameters (rms-delay spread and Doppler spread). Hence we have four different types of fading. There are two types of fading due to the time dispersive nature of the channel.

2.3.1.1 Fading Effects due to Multipath Time Delay Spread

Flat Fading:

Such types of fading occurs when the bandwidth of the transmitted signal is less than the coherence bandwidth of the channel. Equivalently if the symbol period of the signal is more than the rms delay spread of the channel, then the fading is flat fading.

So we can say that flat fading occurs when

$$B_S < B_C \quad (2.4)$$

where B_S is the signal bandwidth and B_C is the coherence bandwidth. Also

$$T_S > \sigma_\tau \quad (2.5)$$

where T_S is the symbol period and σ_τ is the rms-delay spread. And in such a case, mobile channel has a constant gain and linear phase response over its bandwidth.

Frequency Selective Fading:

Frequency selective fading occurs when the signal bandwidth is more than the coherence bandwidth of the mobile radio channel or equivalently the symbols duration of the signal is less than the rms- delay spread.

$$B_S > B_C \quad (2.6)$$

and

$$T_S > \sigma_\tau \quad (2.7)$$

At the receiver, we obtain multiple copies of the transmitted signal, all attenuated and delayed in time.

2.3.1.2 Fading Effects due to Doppler Spread

Fast Fading

In a fast fading channel, the channel impulse response changes rapidly within the symbol duration of the signal. Due to Doppler spreading, signal undergoes frequency dispersion leading to distortion. Therefore a signal undergoes fast fading if

$$T_S > T_C \quad (2.8)$$

where T_C is the coherence time and

$$B_S < B_D \quad (2.9)$$

where B_D is the Doppler spread. Transmission involving very low data rates suffer from fast fading.

Slow Fading

In such a channel, the rate of the change of the channel impulse response is much less than the transmitted signal. We can consider a slow faded channel a channel in which channel is almost constant over at least one symbol duration. Hence

$$T_S < T_C \quad (2.10)$$

and

$$B_S > B_D \quad (2.11)$$

We observe that the velocity of the user plays an important role in deciding whether the signal experiences fast or slow fading.

2.3.2 Doppler Shift

The Doppler effect (or Doppler shift) is the change in frequency of a wave for an observer moving relative to the source of the wave. In classical physics (waves in a medium), the relationship between the observed frequency f and the emitted frequency f_o is given by:

$$f = \left(\frac{v \pm v_r}{v \pm v_s}\right) f_0 \tag{2.12}$$

where v is the velocity of waves in the medium, v_s is the velocity of the source relative to the medium and v_r is the velocity of the receiver relative to the medium.

In mobile communication, the above equation can be slightly changed according to our convenience since the source (BS) is fixed and located at a remote elevated level from ground. The expected Doppler shift of the EM wave then comes out to be $\pm v_c{}^r f_o$ or, $\pm v_\lambda{}^r$. As the BS is located at an elevated place, a cos φ factor would also be multiplied with this.

Consider a mobile moving at a constant velocity v, along a path segment length d between points A and B, while it receives signals from a remote BS source S. The difference in path lengths traveled by the wave from source S to the mobile at points A and B is $\Delta l = d \cos\theta = v\Delta t \cos\theta$, where Δt is the time required for the mobile to travel from A to B, and θ is assumed to be the same at points A and B since the source is assumed to be very far away. The phase change in the received signal due to the difference in path lengths is therefore

$$\Delta\varphi = \frac{2\pi\Delta l}{\lambda} = \frac{2\pi v\Delta t}{\lambda}\cos\theta \tag{2.13}$$

and hence the apparent change in frequency, or Doppler shift (f_d) is

$$f_d = \frac{1}{2\pi}.\frac{\Delta\varphi}{\Delta t} = \frac{v}{\lambda}.\cos\theta. \tag{2.14}$$

2.3.3 Time Dispersion Parameters

These parameters include the mean excess delay, rms-delay spread and excess delay spread. The mean excess delay is the first moment of the power delay profile and is defined as

$$\bar{\tau} = \frac{\sum a_k^2 \tau_k}{\sum a_k^2} = \frac{\sum P(\tau_k)\tau_k}{\sum P(\tau_k)} \tag{2.15}$$

where a_k is the amplitude, τ_k is the excess delay and $P_{(\tau k)}$ is the power of the individual multipath signals.

The mean square excess delay spread is defined as

$$\bar{\tau^2} = \frac{\sum P(\tau_k)\tau_k^2}{\sum P(\tau_k)} \tag{2.16}$$

Since the rms delay spread is the square root of the second central moment of the power delay profile, it can be written as

$$\sigma_\tau = \sqrt{\bar{\tau^2} - (\bar{\tau})^2} \tag{2.17}$$

As a rule of thumb, for a channel to be flat fading the following condition must be satisfied

$$\frac{\sigma_\tau}{T_S} \leq 0.1 \tag{2.18}$$

where T_S is the symbol duration. For this case, no equalizer is required at the receiver.

2.4 Various Fading Models

2.4.1 Rayleigh Fading Model

Let there be two multipath signals S_1 and S_2 received at two different time instants due to the presence of obstacles as shown in Figure 5.6. Now there can either be constructive or destructive interference between the two signals.

Let E_n be the electric field and θ_n be the relative phase of the various multipath signals. So we have

$$\tilde{E} = \sum_{n=1}^{N} E_n e^{j\theta_n} \tag{2.19}$$

Now if $N \to \infty$ (i.e. are sufficiently large number of multipath) and all the E_n are i.i.d. distributed, then by Central Limit Theorem we have,

$$R = Z_i^2 + Z_r^2 \tag{2.20}$$

And,

$$\Phi = \tan^{-1} \frac{Zi}{Zr} \tag{2.21}$$

For all practical purposes we assume that the relative phase θ_n is uniformly distributed.

$$E[e^{j\theta_n}] = \frac{1}{2\pi} \int_0^{2\pi} e^{j\theta} d\theta = 0 \tag{2.22}$$

It can be seen that E_n and θ_n are independent. So,

$$E[\tilde{E}] = E[\sum E_n e^{j\theta_n}] = 0$$

$$E[\left|\tilde{E}\right|^2] = E[\sum E_n e^{j\theta_n} \sum E_n^* e^{-j\theta_n}] = E[\sum_m \sum_n E_n E_m e^{j(\theta_n - \theta_m)}] = \sum_{n=1}^{N} E_n^2 = P_0 \tag{2.23}$$

where P_0 is the total power obtained. To find the Cumulative Distribution Function (CDF) of R, we proceed as follows,

$$F_R(r) = P_r(R \leq r) = \iint\limits_A f_{Z_i,Z_r}(z_i, z_r) dz_i dz_r \tag{2.24}$$

where A is determined by the values taken by the dummy variable r. Let Z_i and Z_r be zero mean Gaussian RVs. Hence the CDF can be written as

$$F_R(r) = \iint\limits_A \frac{1}{\sqrt{2\pi}\sigma^2} e^{\frac{-(Z_r^2+Z_i^2)}{2\sigma^2}} dZ_i dZ_r \tag{2.25}$$

Let, $r = p \cos \theta_n$ and $Z_i = p \sin \theta_n$. So we have

$$\begin{aligned} F_R(r) &= \int_0^{2\pi}\int_0^{2\pi} \frac{1}{\sqrt{2\pi}\sigma^2} e^{\frac{-p^2}{2\sigma^2}} p dp d\theta \\ &= 1 - e^{\frac{-r^2}{2\sigma^2}} \end{aligned} \tag{2.26}$$

Above equation is valid for all $r \geq 0$. The pdf can be written as

$$f_R(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} \tag{2.27}$$

and is shown in Figure 5.7 with different σ values. This equation too is valid for all $r \geq 0$. Above distribution is known as Rayleigh distribution and it has been derived for slow fading.

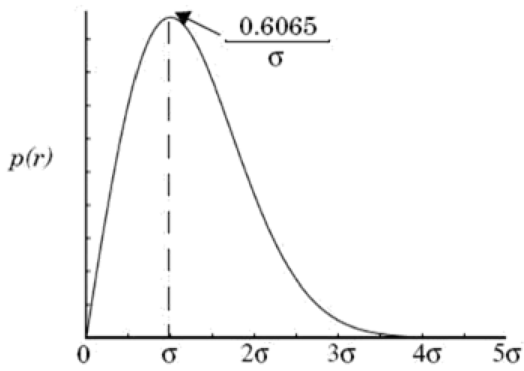

Figure 2.1: Rayleigh probability density function.

However, if f_D < 1 Hz, we call it as Quasi-stationary Rayleigh fading. We observe the following:

$$E[R] = \sqrt{\frac{\pi}{2}}\sigma$$
$$E[R^2] = 2\sigma^2$$
$$\mathrm{var}[R] = (2 - \frac{\pi}{2})\sigma^2$$
$$median[R] = 1.77\sigma. \qquad (2.28)$$

2.4.2 Rician Fading Model

Rician Fading is the addition to all the normal multipath in direct LOS path.

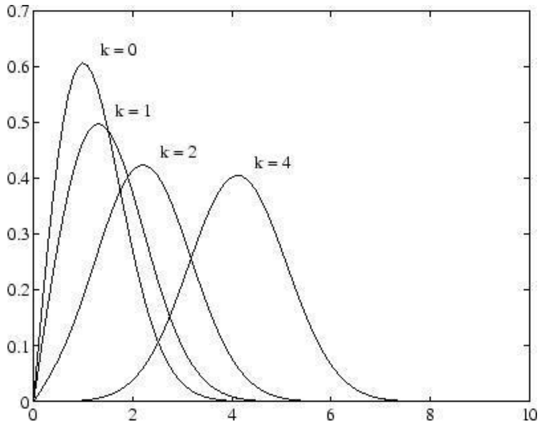

Figure 2.2: Rician probability density function

$$f_R(r) = \frac{r}{\sigma^2} e^{\frac{-(r^2+A^2)}{2\sigma^2}} I_0(\frac{A_r}{\sigma^2}) \qquad (2.29)$$

for all $A \geq 0$ and $r \geq 0$. Here A is the peak amplitude of the dominant signal and $I_0(.)$ is the modified Bessel function of the first kind and zero-th order. A factor K is defined as

$$K_{dB} = 10 \log \frac{A^2}{2\sigma^2} \qquad (2.30)$$

As A $\rightarrow$ 0 then $K_{dB} \rightarrow \infty$.

2.4.3 Generalized Model: Nakagami Distribution

A generalization of the Rayleigh and Rician fading is the Nakagami distribution.

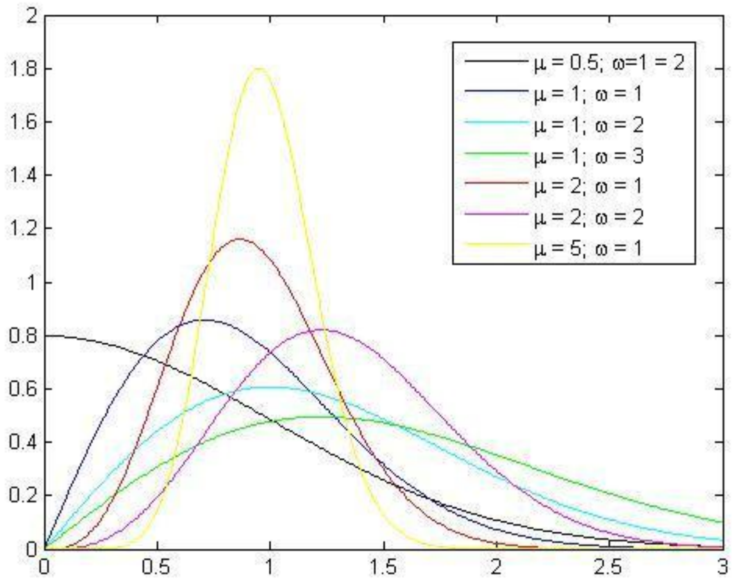

Figure 3.3: Nakagami probability density function.

Its pdf is given as,

$$f_R(r) = \frac{2r^{m-1}}{\Gamma(m)}\left(\frac{m^m}{\Omega^m}\right)e^{\frac{-mr^2}{\Omega}} \tag{2.31}$$

$\Gamma(m)$ = gamma function

Ω = average signal power and

m = fading factor. It is always greater than or equal to 0.5.

When m=1, Nakagami model is the Rayleigh model.

When,
$$m = \frac{(M+1)^2}{2M+1} \tag{2.32}$$

where
$$M = \frac{A}{2\sigma} \tag{2.33}$$

then, Nakagami fading is the Rician fading.

As m $\rightarrow \infty$ Nakagami fading is the impulse channel and no fading occurs.

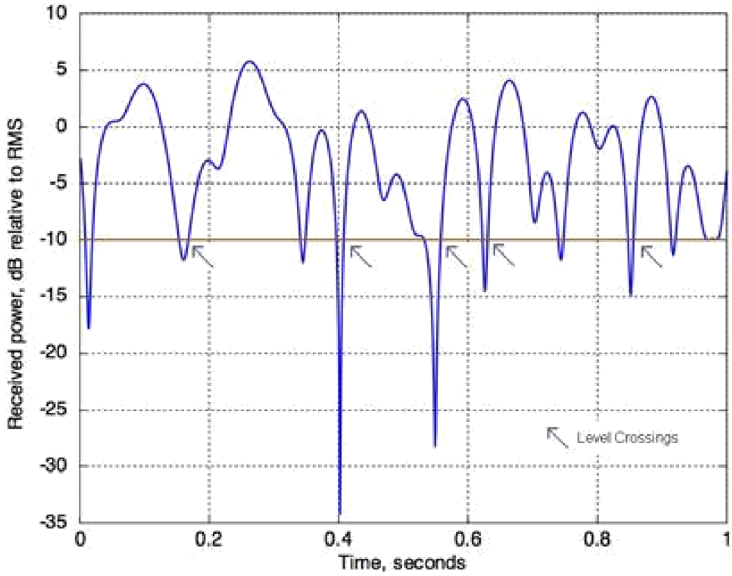

Figure 2.4: Schematic representation of level crossing with a Rayleigh fading envelope at 10 Hz Doppler spread.

2.4.4 Gamma-Gamma (GG) Fading

In the Gamma-Gamma (GG) fading pdf model, the fading pdf is modeled as the modulation of two statistically independent Gamma distributed process $p_1(x)$ and $p_2(y)$ where $I = xy$ [37], [42]. Hence

$$p(I)=\frac{2}{\Gamma(\alpha)\Gamma(\beta)I}(\alpha\beta I)^{(\alpha+\beta)/2}K_{\alpha-\beta}(2\,\alpha\beta\, I),\ I > 0 \qquad (2.34)$$

where I is the normalized received laser beam power, $\Gamma(x)$ is the gamma function, and $K_v(z)$ is the modified Bessel function of the second kind.

In the GG fading pdf model, parameters α and β are regarded to represent the effective numbers of large-scale and small-scale scatters of the turbulence channel
where

$$E[I^2]=(1+\frac{1}{\alpha})\ (1+\frac{1}{\beta}) \qquad (2.35)$$

As $I = xy$,

$$E[I^2] = E[x^2]E[y^2] = (1+\sigma_x^2)(1+\sigma_y^2) \tag{2.36}$$

where σ_x^2 and σ_y^2 are the normalized variance of the large-scale and small-scale scatters respectively. Hence

$$\sigma = \frac{1}{\sigma_x^2} = \frac{1}{\exp(\sigma_{lnx}^2)-1} \tag{2.37}$$

$$\beta = \frac{1}{\sigma_y^2} = \frac{1}{\exp\left(\sigma_{lny}^2\right)-1} \tag{2.38}$$

and

$$\sigma_I^2 = \exp(\sigma_{\ln x}^2 + \sigma_{\ln y}^2) - 1 \tag{2.39}$$

2.5 Types of Diversity

The following sections describe the various ways of obtaining independently faded signals

2.5.1 Frequency Diversity

The desired message is transmitted simultaneously over several frequency slots. The separation between adjacent frequency slots should be larger than the channel coherence bandwidth such that channel fading over each slot is independent of that in any other slot. By using redundant signal transmission, this diversity improves link transmission quality at the cost of extra frequency bandwidth.

2.5.2 Time Diversity

The desired message is transmitted repeatedly over several time periods. The time separation between adjacent transmissions should be larger than the channel coherence time such that the channel fading experienced by each transmission is independent of the channel fading experienced by all of the other transmission. In addition to extra system capacity (in terms of transmission time) due to the redundant transmission, this diversity introduces a significant signal processing delay, especially when the channel coherence time is large. In practice, time diversity is more frequently exploited through interleaving, forward-error correction, and automatic retransmission request (ARQ).

2.5.3 Space diversity

The desired message is transmitted by using multiple transmitting antennas and receiving antennas. The space separation between adjacent antennas should be large enough to ensure that the signals from different antennas are independently faded. In a Rayleigh fading environment, it can be shown that, if two antennas are separated by half of the carrier wavelength, the corresponding two signals experience independent fading. Taking into account the shadowing effect, usually a separation of at least 10 carrier wavelengths is required between two adjacent antennas. This diversity does not require extra system capacity; however, the cost is the extra antennas needed.

2.5.4 Angle Diversity

The desired message is received simultaneously by several directive antennas pointing in widely different directions. The received signals consist of waves coming from all directions. It has been observed that the scattered signals associated with the different (non-overlapping) directions are uncorrelated. Angle diversity can be viewed as a special case of space diversity since it also requires multiple antennas.

2.5.5 Path Diversity

In CDMA cellular networks, the use of direct sequence spread spectrum modulation techniques permits the desired signal to be transmitted over a frequency bandwidth much larger than the channel coherence bandwidth. The spread spectrum signal can resolve multipath signal components as long as the path delays are separated by at least one cheap period. A rake receiver can separate the received signal components from different propagation paths by using code correlation and can then combine the signal components constructively. In CDMA, exploiting the path diversity reduces the transmitted power needed and increases the system capacity

2.5.6 Polarization Diversity

The horizontal and vertical polarization components transmitted by two polarized antennas at the base station and received by two polarized antennas at the mobile station can provide two uncorrelated fading signals. Polarization diversity results in 3dB power reduction at the transmitting site since the power must be split into two different polarized antennas.

2.5.7 Antenna diversity:

Antenna diversity techniques are commonly utilized at the base stations due to less constraint on both antenna space and power. In addition, it is more economical to add more complex equipment to the base stations rather than at the remote units. To increase the quality of the transmission and reduce multipath fading at the remote unit, it would be beneficial if space diversity also could be utilized at the remote units.

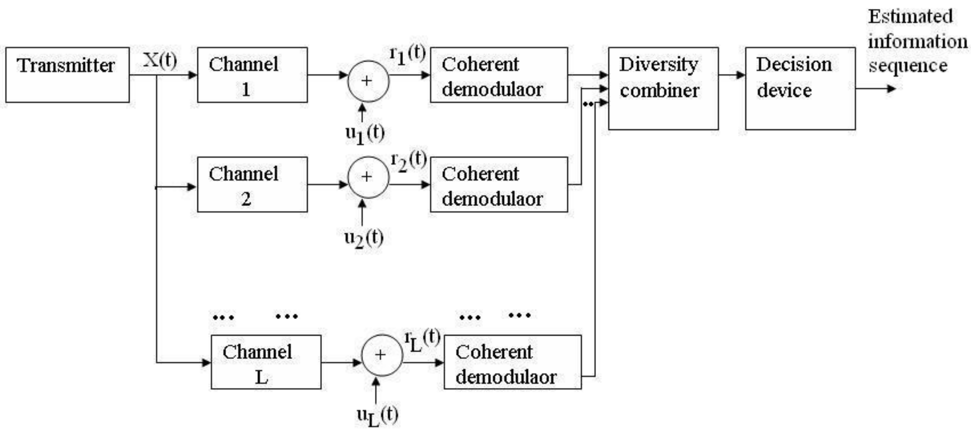

Figure 2.5: Diversity with coherent demodulator

2.6 SISO, SIMO, MISO, MIMO Terminology

To minimize fading effect there are a number of different Multiple-Input Multiple-Output (MIMO) configurations or formats that can be used. These are termed SISO, SIMO, MISO and MIMO. These different MIMO formats offer different advantages and disadvantages; these can be balanced to provide the optimum solution for any given application. The different MIMO formats - SISO, SIMO, MISO and MIMO require different numbers of antennas as well as having different levels of complexity. Also dependent upon the format, processing may be needed at one end of the link. There are many formats of MIMO that can be used from SISO, through SIMO and MISO to the full MIMO systems. These are all able to provide significant improvements of performance, but generally at the cost of additional processing and the number of antennas used. Balances of performance against costs, size, processing available and the resulting battery life need to be made when choosing the correct option.

2.6.1 SISO

The simplest form of radio link can be defined in MIMO terms as SISO - Single Input Single Output. This is effectively a standard radio channel - this transmitter operates with one antenna as does the receiver. There is no diversity and no additional processing required.

Fig 2.6: SISO - Single Input Single Output

The advantage of a SISO system is its simplicity. SISO requires no processing in terms of the various forms of diversity that may be used. However the SISO channel is limited in its performance. Interference and fading will impact the system more than a MIMO system using some form of diversity, and the channel bandwidth is limited by Shannon's law - the throughput being dependent upon the channel bandwidth and the signal to noise ratio.

2.6.2 SIMO

The SIMO or Single Input Multiple Output version of MIMO occurs where the transmitter has a single antenna and the receiver has multiple antennas. This is also known as receive diversity. It is often used to enable a receiver system that receives signals from a number of independent sources to combat the effects of fading. It has been used for many years with short wave listening / receiving stations to combat the effects of ionospheric fading and interference.

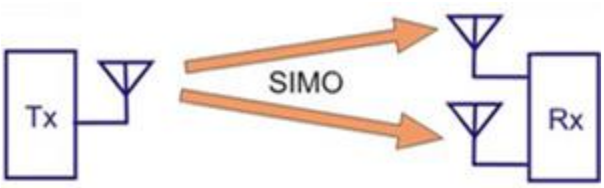

Fig 2.7: SIMO - Single Input Multiple Output

SIMO has the advantage that it is relatively easy to implement although it does have some disadvantages in that the processing is required in the receiver. The use of SIMO may be quite acceptable in many applications, but where the receiver is located in a mobile device such as a cellphone handset, the levels of processing may be limited by size, cost and battery drain.

There are two forms of SIMO that can be used:

- Switched Diversity SIMO: looks for the strongest signal and switches to that antenna.
- Maximum Ratio Combining SIMO**:** takes both signals and combines them so the signals from both antennas contribute to the overall signal.

2.6.3 MISO

MISO is also termed transmit diversity. In this case, the same data is transmitted redundantly from the two transmitter antennas. The receiver is then able to receive the optimum signal which it can then use to receive extract the required data.

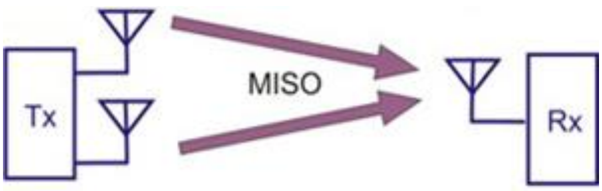

Fig 2.8: MISO - Multiple Input Single Output

The advantage of using MISO is that the multiple antennas and the redundancy coding / processing is moved from the receiver to the transmitter. In instances such as cellphone UEs, this can be a significant advantage in terms of space for the antennas and reducing the level of processing required in the receiver for the redundancy coding. This has a positive impact on size, cost and battery life as the lower level of processing requires less battery consumption.

2.6.4 MIMO

Where there are more than one antenna at either end of the radio link, this is termed MIMO - Multiple Input Multiple Output. MIMO can be used to provide improvements in both channel robustness as well as channel throughput.

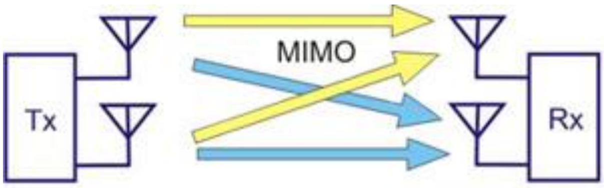

Fig 2.9: MIMO - Multiple Input Multiple Output

In order to be able to benefit from MIMO fully it is necessary to be able to utilize coding on the channels to separate the data from the different paths. This requires processing, but provides additional channel robustness / data throughput capacity.

2.7 Details on MIMO

2.7.1 MIMO Spatial Multiplexing

In any case for MIMO spatial multiplexing the number of receive antennas must be equal to or greater than the number of transmit antennas. To take advantage of the additional throughput offered, MIMO wireless systems utilize a matrix mathematical approach.[7] Data streams t1, t2, … tn can be transmitted from antennas 1, 2, … n. Then there are a variety of paths that can be used with each path having different channel properties. To enable the receiver to be able to differentiate between the different data streams it is necessary to use. These can be represented by the properties h_{12}, travelling from transmit antenna 2 to receive antenna 1 and so forth. In this way for a three transmit, three receive antenna system a matrix can be set up:

$$\begin{aligned} r_1 &= h_{11}\, t_1 + h_{12}\, t_2 + h_{13}\, t_3 \\ r_2 &= h_{21}\, t_1 + h_{22}\, t_2 + h_{23}\, t_3 \\ r_3 &= h_{31}\, t_1 + h_{32}\, t_2 + h_{33}\, t_3 \end{aligned} \tag{2.40}$$

where r_1 is the received signal at antenna 1 and so on. In matrix format this can be represented as:

$$[R] = [H] \times [T] \tag{2.41}$$

To recover the transmitted data-stream at the receiver it is necessary to perform a considerable amount of signal processing. First the MIMO system decoder must estimate the individual channel transfer characteristic h_{ij} to determine the channel transfer matrix. Once all of this has been estimated, then the matrix [H] has been produced and the transmitted data streams can be reconstructed by multiplying the received vector with the inverse of the transfer matrix.

$$[T] = [H]^{-1} \times [R] \tag{2.42}$$

This process can be likened to the solving of a set of N linear simultaneous equations to reveal the values of N variables.

The MIMO antenna technologies used are key to the overall MIMO performance. Additionally MIMO beam-forming is an option that is coming to the fore.
As various forms of technology improve the MIMO antenna technology can be pushed further allowing techniques like MIMO beam-forming to be considered.

2.7.2 MIMO Antenna & MIMO Beam-Forming Development

For many years antenna technology has been used to improve the performance of systems. Directive antennas have been used for very many years to improve signal levels and reduce interference. Directive antenna systems have, for example, been used to improve the capacity of cellular telecommunications systems. By splitting a cell site into sector where each antenna illuminates 60° or 120° the capacity can be greatly increased - tripled when using 120° antennas. With the development of more adaptive systems and greater levels of processing power, it is possible to utilize antenna beam-forming techniques with systems such as MIMO.

2.7.3 MIMO Beam-Forming Smart Antennas

Beam-forming techniques can be used with any antenna system - not just on MIMO systems. They are used to create a certain required antenna directive pattern to give the required performance under the given conditions [8].

Smart antennas are normally used - these are antennas that can be controlled automatically according the required performance and the prevailing conditions. Smart antennas can be divided into two groups:

- Phased Array Systems: they are switched and have a number of pre-defined patterns - the required one being switched according to the direction required.

- Adaptive Array Systems (AAS): This type of antenna uses what is termed adaptive beam-forming and it has an infinite number of patterns and can be adjusted to the requirements in real time.

MIMO beam-forming using phased array systems requires the overall system to determine the direction of arrival of the incoming signal and then switch in the most appropriate beam. This is something of a compromise because the fixed beam is unlikely to exactly match the required direction.

Adaptive array systems are able to direct the beam in the exact direction needed, and also move the beam in real time - this is a particular advantage for moving systems - a factor that often happens with mobile telecommunications. However the cost is the considerable extra complexity required.

2.8 Linear Combining

At the receiver end there are three types of linear combining techniques to decide what data were sent by the transmitter. They are described here.

2.8.1 Maximal Ratio Combining

In this combining technique the receiver is able to accurately estimate the amplitude fading and carrier phase distortion for each diversity channel. With the complex channel gains, the receiver coherently demodulates the received signal from each branch. The phase distortion is removed from the L^{th} branch by multiplying the signal component with complex term. The coherently detected signal is then weighted by the corresponding amplitude gain. The weighted received signals from all the L branches are then summed together and applied to the decision device. Maximal ratio combining achieves the best performance.

2.8.2 Equal Gain Combining

The maximal ratio combining approach an accurate estimate of the channel amplitude gain, which increases the receiver complexity. An alternative approach is to weight all the signals equally after coherent detection, which removes the phase distortion. The coherently detected signals from all the L branches are simply added and applied to the decision device. As the receiver does not need to estimate the amplitude fading, its complexity is reduced as compared with that of maximal ratio combining.

2.8.3 Selective Combining

In this scheme, the receiver monitors the SNR value of each diversity channel and chooses the one with the maximum SNR value for signal detection. Compared with the preceding two schemes, selective diversity is much easier to implement without much performance degradation, especially located in different base stations, which would make it difficult to use maximal ratio combining or equal gain combining.

Among the three combining schemes, selective combining is easier to implement without much performance degradation. But MRC achieves the best performance.

2.9 SNR, SINR & SIR

2.9.1 Signal to Noise Ratio

The ratio of the amplitude of a desired signal at any point to the amplitude of noise signals at that same point; often expressed in decibels; the peak value is usually used for pulse noise, while the root-mean-square (rms) value is used for random noise. It is abbreviated as S/N or SNR, the quantity that measures the relationship between the strength of an information carrying signal in an electrical communications system and the random fluctuations in amplitude, phase, and frequency superimposed on that signal and collectively referred to as noise. For analog signals, the ratio, denoted S/N, is usually stated in terms of the relative amounts of electrical power contained in the signal and noise. For digital signals the ratio is defined as the amount of energy in the signal per bit of information carried by the signal, relative to the amount of noise power per hertz of signal bandwidth (the noise power spectral density), and is denoted E_b/N_0. Since both signal and noise fluctuate randomly with time, S/N and E_b/N_0 are specified in terms of statistical or time averages of these quantities. The magnitude of the signal noise ratio in a communications systems is an important factor in how well a receiver can recover the information carrying signal from its corrupted version and hence how reliably information can be communicated. Generally speaking, for a given value of S/N the performance depends on how the information quantities are encoded into the signal parameters and on the method of recovering them from the received signal. The more complex encoding methods such as phase-shift keying or quadrature amplitude shift keying usually result in better performance than simpler schemes such as amplitude or frequency shift keying. As an example, a digital communication system operating at a bit error rate of 10^{-5} requires as much as 7 dB less for E_b/N_0 when employing binary phase-shift-keying as when using binary amplitude-shift keying.

The signal to noise ratio is the ratio between the wanted signal and the unwanted background noise.

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{2.43}$$

It is more usual to see a signal to noise ratio expressed in a logarithmic basis using decibels:

$$SNR_{dB} = 10 \log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \tag{2.44}$$

If all levels are expressed in decibels, then the formula can be simplified to:

$$SNR_{dB} = P_{signal_{dB}} - P_{noise_{dB}} \tag{2.45}$$

The power levels may be expressed in levels such as dBm (decibels relative to a mill-watt) or to some other standard by which the levels can be compared.

2.9.2 SINR and SIR

In information theory and telecommunication engineering, the signal-to-interference-plus-noise ratio is a quantity used to give theoretical upper bounds on channel capacity (or the rate of information transfer) in wireless communication systems such as networks. Analogous to the SNR used often in wired communications systems, the SINR is defined as the power of a certain signal of interest divided by the sum of the interference power (from all the other interfering signals) and the power of some background noise. If the power of noise term is zero, then the SINR reduces to the signal-to-interference ratio (SIR). Conversely, zero interference reduces the SINR to the signal-to-noise ratio (SNR), which is used less often when developing mathematical models of wireless networks such as cellular networks.

2.10 BER

In telecommunication transmission, the bit error rate (BER) is the percentage of bits that have errors relative to the total number of bits received in a transmission, usually expressed as ten to a negative power. For example, a transmission might have a BER of 10^{-6}, meaning that, out of 1,000,000 bits transmitted, one bit was in error. The BER is an indication of how often a packet or other data unit has to be retransmitted because of an error. Too high a BER may indicate that a slower data rate would actually improve overall transmission time for a given amount of transmitted data since the BER might be reduced, lowering the number of packets that had to be resent.

2.10.1 Factor Affecting the BER

In a communication system, the receiver side BER may be affected by transmission channel noise, interference, distortion, bit synchronization problems, attenuation, wireless multipath fading, etc.

The BER may be improved by choosing a strong signal strength (unless this causes cross-talk and more bit errors), by choosing a slow and robust modulation scheme or line coding scheme, and by applying channel coding schemes such as redundant forward error correction codes.

The transmission BER is the number of detected bits that are incorrect before error correction, divided by the total number of transferred bits (including redundant error codes). The information BER, approximately equal to the decoding error probability, is the number of decoded bits that remain incorrect after the error correction, divided by the total number of decoded bits (the useful information). Normally the transmission BER is larger than the information BER. The information BER is affected by the strength of the forward error correction code.

2.10.2 BER Calculation

For the theoretical equation for bit error rate (BER) with Binary Phase Shift Keying (BPSK) modulation scheme in Additive White Gaussian Noise (AWGN) channel. The BER results obtained using Matlab/Octave simulation scripts show good agreement with the derived theoretical results.

With Binary Phase Shift Keying (BPSK), the binary digits 1 and 0 maybe represented by the analog levels $+\sqrt{E_b}$ and $-\sqrt{E_b}$ respectively. The system model is as shown in the Figure below.

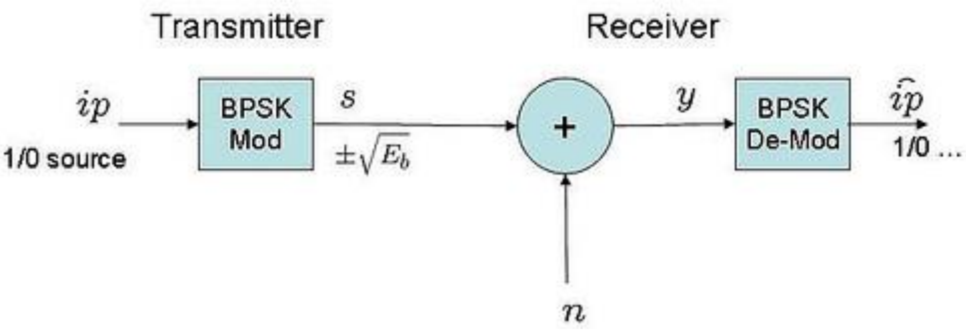

Fig 2.10: Simplified block diagram with BPSK transmitter-receiver

The transmitted waveform gets corrupted by noise n, typically referred to as Additive White Gaussian Noise (AWGN) where,

- Additive: As the noise gets 'added' (and not multiplied) to the received signal
- White: The spectrum of the noise if flat for all frequencies.
- Gaussian: The values of the noise n follows the Gaussian probability distribution function.

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{2.46}$$

with $\mu = 0$ and $\sigma^2 = \frac{N_0}{2}$.

The received signal is
$y = s_1 + n$, when bit 1 is transmitted and
$y = s_1 + n$, when bit 0 is transmitted.

The conditional probability distribution function (PDF) of y for the two cases are:

$$p(y|s_0) = \frac{1}{\sqrt{\pi N_0}} e^{\frac{-(y+\sqrt{E_b})^2}{N_0}}$$

$$p(y|s_1) = \frac{1}{\sqrt{\pi N_0}} e^{\frac{-(y-\sqrt{E_b})^2}{N_0}} \tag{2.47}$$

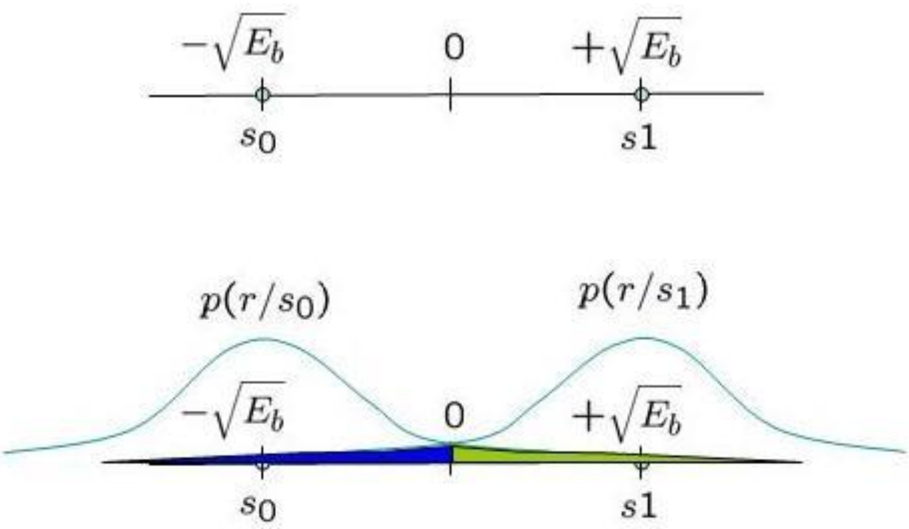

Fig 2.11: Conditional probability density function with BPSK modulation

Assuming that s_1 and s_0 are equally probable i.e. p(s_1)=p(s_0)=0.5, the threshold forms the optimal decision boundary:

$$y>0 \Rightarrow s_1 \qquad \text{and} \qquad y \leq 0 \Rightarrow s_0 \tag{2.48}$$

Total probability of bit error

$$P_b = p(s_1)p(e|s_1) + p(s_0)p(e|s_0) \tag{2.49}$$

With this threshold, the probability of error given s_1 is transmitted is the area in blue region. Similarly the probability of error given s_0 is transmitted is the area in green region.

If the complementary error function is,

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-x^2} dx \tag{2.50}$$

Then

$$P_b = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{2.51}$$

Chapter 3

System Model & Analysis of FSO Links

3.1 Effect of Thin Cloud

Space optical communication is generally considered to have great potential. The conspicuous advantages of optical communication are: large information bandwidth, low transmitter power, greater directionality, and immunity to jamming. In some situations, part of the optical channel travels through the atmosphere that occasionally contains water clouds. Clouds as part of the communication channel cause signal power attenuation and temporal widening. This effect limits the maximum system bandwidth and increases the bit error rate (BER). The use of optical communication in space is generally described from the point of view of technological aspects, and only brief treatments of the effects of the environment on the performance of the communication are given. The [9] includes the effects of background radiant power on the signal-to-noise ratio in the space data link. In previous research authors derived the impulse response function of atmospheric clouds for optical pulses. [10] The temporal impulse response function of atmospheric cloud is modeled as a double gamma function. Based on the impulse response of the atmospheric cloud channel a mathematical model of an optical communication system was derived. The changes in the parameters of the channel can be measured and the communication system can be adapted to these changes. The communication system includes a receiver and transmitter and also receives information about the channel conditions. The transmitter can be adapted to changes in channel conditions through adaptation of the bit error rate. The receiver can be adapted to such changes in channel conditions by adaptation of detector and filter parameters. Although the high information rate capability of optical communication would be limited under adverse conditions, it would be only temporary until channel conditions improved. We here we deal with the effect of atmospheric cloud on optical pulse propagation, which is that of time domain widening. It is hoped that this contribution of an adaptive optical communication system for the atmospheric cloud channel will lead to improved performance of optical communication and generate deeper insight into the effects of clouds on optical communication.

3.1.1 Channel Description

To analyze the effects of atmospheric clouds on optical pulses here use a multi-scattering Monte Carlo simulation. The cloud is the communication channel. From the results of the simulation from paper [11] derived the impulse response, attenuation, and temporal widening of the optical pulse. The impulse response of the cloud channel is defined by a double gamma function,

$$h(t) = \frac{\pi {D_R}^2}{4}[k_1 \exp(-tk_2) + k_3 \exp(-tk_4)]u(t)t, \tag{3.1}$$

where t is time, k_i are the parameters from measurement or simulation, D_R is the diameter of the receiver telescope, and u(t) is a step function. The transmission function of the channel cloud is the Fourier transform of the impulse response is

$$H(f) = \frac{\pi {D_R}^2}{4}\left[\frac{k_1}{(k_2 + j2\pi f)^2} + \frac{k_3}{(k_4 + j2\pi f)^2}\right] \tag{3.2}$$

where f is the frequency.

Here, the Double Gamma Function Constants are:

	Physical Thickness (m)				
Constant	200	225	250	275	300
k_1	120.1	34.1	12.4	5.1	2.4
k_2	1.9×10^7	1.9×10^7	1.1×10^7	0.8×10^7	1.7×10^7
k_3	1.55	1.6	0.66	0.28	0.19
k_4	3×10^6	3×10^6	2.4×10^6	1.8×10^6	1.6×10^6

Fig. 3.1: Parameters of thin cloud

The parameters k_i describe cloud characteristics for optical pulses and the geometry of the system. To probe the cloud characteristics one can use lidar. One can perform probing by measuring the laser beam backscatter with the atmospheric cloud. It is important to emphasize that, for high values of optical thickness, lidar measurement may not be so accurate because of multi-scattering. A new method for probing the cloud characteristics is the electro-optic oscillator, whose oscillation frequency is a function of cloud transmission. When the cloud characteristics change the cloud transmission function also changes, which alters the oscillation frequency. The oscillation frequency thus characterizes cloud characteristics. The advantage of this system is the direct measurement of cloud channel characteristics and the ability to work with high values of optical thickness

3.2 SISO

Block diagram of our usual transmission system looks like the figure below. At first, input data stream is taken in and is modulated using a higher frequency via Binary Phase Shift Keying (BPSK) technique. Other forms of modulation are QPSK (Quadrature Phase Shift Keying), M-PSK (M-ary Phase Shift Keying), M-PAM (M-ary Pulse Amplitude Modulation) etc. Then the signal is transmitted through a single transmitter. This signal travels through channel, mainly consisting of air, to the destined receiver. Noise are added in this part of the channel. The receiver uses a Band Pass Filter (BPF) to clear out unnecessary bandwidth. Then it is demodulated using the same frequency used in modulation. A Low Pass Filter (LPF), and an integrator is used before sampling. The threshold voltage is zero volt for BPSK transmission.

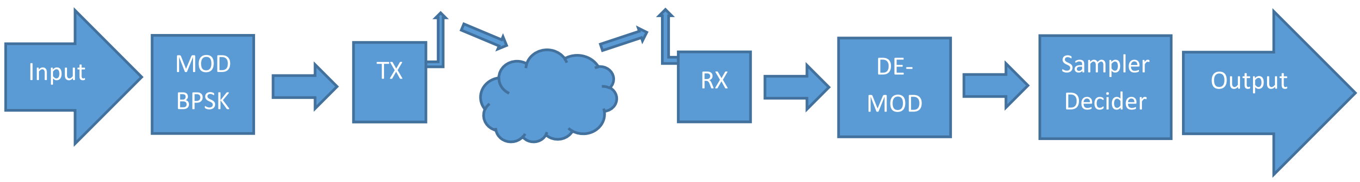

Fig 3.2: Block diagram of SISO through Cloud

3.3 MIMO

Now days, MIMO technology has attracted more attention in case of wireless communication systems because of some efficient improvement in error performances, spectral efficiency, bandwidth utilization, higher throughput, etc.. Because of these improvements in wireless communication systems and cellular systems, it is used in many of the well-known cellular technologies such as LTE (Long Term Evolution), 3GPP-LTE, CDMA-2000, Mobile Wi-MAX, WIBRO (Wireless Broadband Internet) WLAN and some of the video broadcasting techniques such as DVB, DAB, DVB-T, etc.

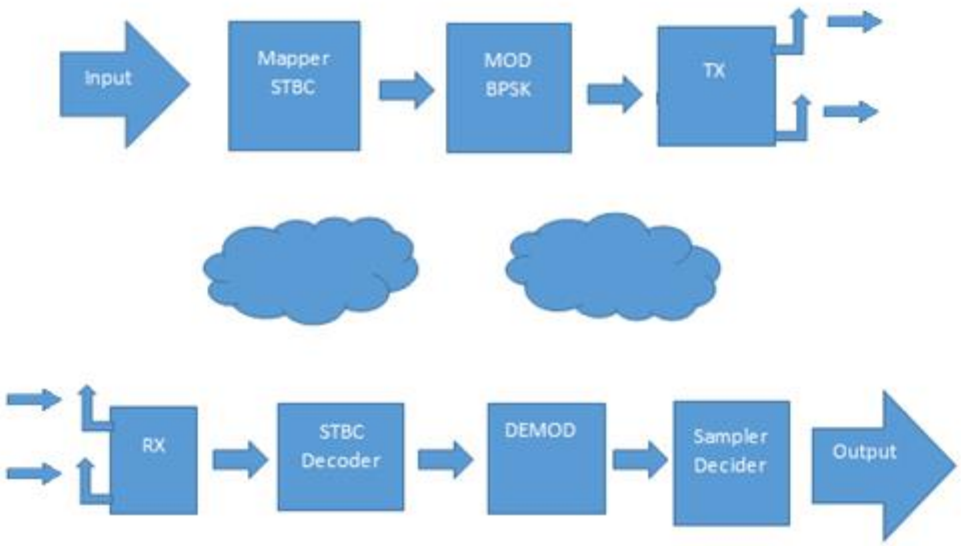

Fig. 3.3: Block diagram of MIMO through Cloud

In order to remove the effect of fading some of the interleaved coding schemes are used such as space-block codes based on transmit, receiver and transmit-receiver diversity schemes for MISO, SIMO and MIMO systems, respectively. One of the well-known receiver diversity scheme is MRRC (Maximal Receiver Ratio Combining) scheme of the diversity order 1XM. Then in order to remove its disadvantages and in order to improve its performance two new schemes were developed by Sivash M. Alamouti which was then become one of the well-known space time diversity scheme known as Alamouti scheme.

3.2.1 MIMO Channel Model

MIMO wireless communication channel is the major and critical topic in wireless communication system. Main reason behind it is that wireless communication channel is more dynamic as compared to wired communication channel.[12] If we want to represent any MIMO communication channel, than we need to represent it in matrix form as shown in below equation. First of all consider the MIMO channel example shown in figure

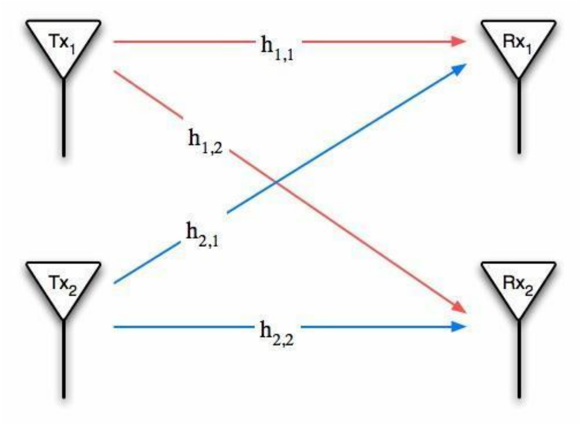

Fig. 3.4: 2x2 MIMO Channel

Now, in above equation each of the matrix elements $h_{i,j}$, shows the impedence parameter of the channel between i^{th} transmitting antenna and j^{th} receiving antenna. So, the value of this $h_{i,j}$ parameter changes according to the value of LOS (Line Of Sight) parameter and fading distribution and fading effect according to the different channels.

3.3.1 Different types of Fading in MIMO

In most of the mobile or cellular systems, the height of the mobile antenna may be smaller than the surrounding structures. Thus, the existence of a direct or line-of-sight path between the transmitter and the receiver is highly unlikely. [13]In such a case, propagation is mainly due to reflection and scattering from the buildings and by diffraction over and/or around them. So, in practice, the transmitted signal arrives at the receiver via several paths with different time delays creating a multi-path situation. At the receiver, these multi-path waves with randomly distributed amplitudes and phases combine to give a resultant signal that fluctuates in time and space. Therefore, a receiver at one location may have a signal that is much different from the signal at another location, only a short distance away, because of the change in the phase relationship among the incoming radio waves. This causes significant fluctuations in the signal amplitude. This phenomenon of random fluctuations in the received signal level is termed as fading.

Based on the fading distribution, variety of fading models is there, which are well-known in wireless communication system as a wireless communication channel. There are mainly four models: - AWGN, Rayleigh, Rician and Nakagami fading channel models.

3.4 AWGN Channel

Additive white Gaussian noise (AWGN) channel is a universal channel model for analyzing any new scheme. In this model, the channel does nothing but add a white Gaussian noise to the signal passing through it. Fading does not exist or if exists than it is of very less amount. The only distortion is introduced by the AWGN. AWGN channel is a theoretical channel used for analysis purpose only. So, if s(t) is transmitted symbol then the received symbol is given as

$$r(t)=s(t)+n(t) \tag{3.3}$$

where n(t) is the Additive White Gaussian Noise (AWGN).

3.5 Rayleigh Channel

Rayleigh fading is statistical channel model for the representation of the effect of multi-path propagation environment over transmission symbols or radio signals. When the transmitted signal passed through the channel will vary randomly or fade according to the Rayleigh distribution then that channel termed as RAYLEIGH channel. Rayleigh fading is mostly applicable only when there is no Line-Of-Sight between transmitter and receiver. So,

$$r(t)=s(t)*h(t)+n(t) \tag{3.4}$$

where r(t) is distributed by using Rayleigh distribution function.

3.3 Alamouti Scheme

Alamouti scheme for 2 transmitting antennas is illustrated in figure. Here all the transmitting symbols those are two s_1 and s_2 are generally coded as shown in figure and then these coded symbols are generally interleaved in particularly two time-slots with the code rate of 2 symbols per second. [14] It means two symbols s_1 and s_2 is transmitted during first time slot and another two coded symbols such as $-s_2^*$ and s_1^* is transmitted during second time slot.

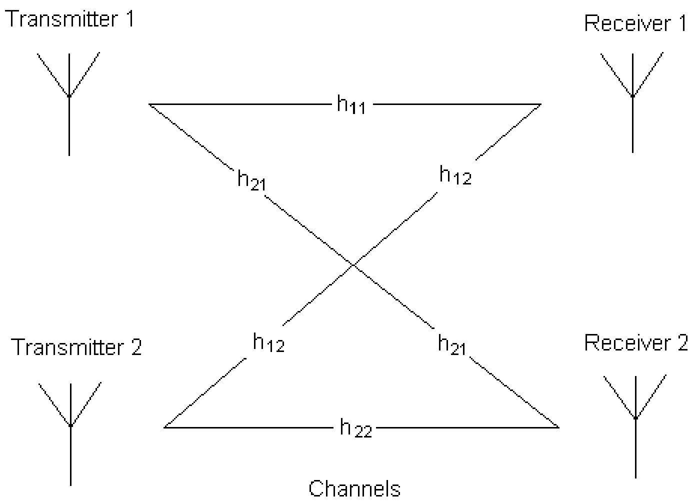

Fig 3.5: 2x2 MIMO Channel (Alternative)

Here, x_1 and x_2 are modulated signal.

The received vector after the first time slot is

$$\begin{bmatrix} y_{11} \\ y_{12} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{12} \end{bmatrix} \qquad (3.6)$$

The received vector after the second time slot is

$$\begin{bmatrix} y_{21} \\ y_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} -x_2^* \\ x_1^* \end{bmatrix} + \begin{bmatrix} n_{21} \\ n_{22} \end{bmatrix} \qquad (3.7)$$

Where $[y_{11}, y_{12}]^T$ denotes the received vector in the first time slot by antennas 1 and 2 respectively.

$[y_{21}, y_{22}]^T$ denotes the received vector in the second time slot by antennas 1 and 2 respectively.

h_{ij} denotes Channel impulse response from j^{th} transmit antenna to i^{th} receive antenna which remains constant during the two time slots as discussed. $[n_{11}, n_{12}]^T$ denotes the AWGN noise vector during time slot 1 and $[n_{21}, n_{22}]^T$ denotes the AWGN noise vector during time slot 2.

Let us define $Y = HX + N$ where $Y = [y_{11} \quad y_{12} \quad y^*_{21} \quad y^*_{22}]^T$

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h^*_{12} & -h^*_{11} \\ h^*_{22} & -h^*_{21} \end{bmatrix} \tag{3.8}$$

H is an orthogonal matrix.

$X = [x_1 \quad x_2]^T$ and $N = [n_{11} \quad n_{12} \quad n^*_{21} \quad n^*_{22}]^T$

Now we combine this equation in a single matrix equation,

$$\begin{bmatrix} y_{11} \\ y_{12} \\ y^*_{21} \\ y^*_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h^*_{12} & -h^*_{11} \\ h^*_{22} & -h^*_{21} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{12} \\ n^*_{21} \\ n^*_{22} \end{bmatrix} \tag{3.9}$$

From this equations, we can get the [X] matrix via MMSE or ZF equalizer.

3.7 Simulation Process

We have used a software called Matlab to simulate the systems. We have randomly taken 100,000 data as input to the modulator. Then we try two different types of transmission system SISO and MIMO passing through thin cloud as an atmospheric turbulence. Both of these systems also pass through a fading channel following the Rayleigh distribution. After using demodulator, sampler and decider we get the output data and compare it to obtain BER for various E_b/N_o.

Chapter 4

Observation and Results

4.1 SISO through Cloud without Fading

The obtained bit error rate (BER) curve for different values of E_b/N_o looks alike for different thicknesses of cloud with having some power penalty as thickness of cloud increases. This system has no fading in it; so, only the effect of cloud is shown in the figure.

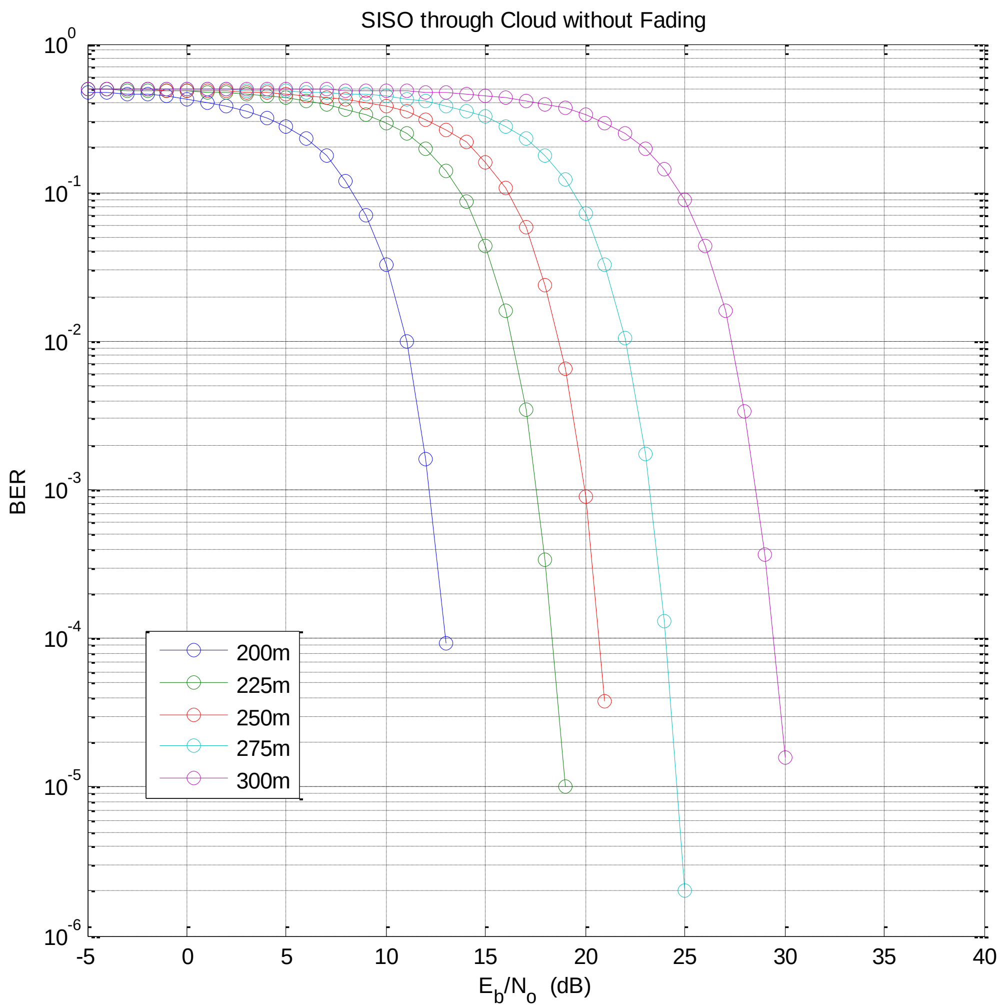

Fig. 4.1: SISO with cloud and no fading

4.2 SISO through Cloud with Fading

For random input of 100,000 bits we have obtained the bit error rate (BER) for different values of E_b/N_o in a system fitted with SISO through thin cloud undergoing Rayleigh fading. For obtaining the same BER for same thickness of cloud, the E_b/N_o for fading channel is far greater than the E_b/N_o for non-fading channel; so fading causes huge power penalty.

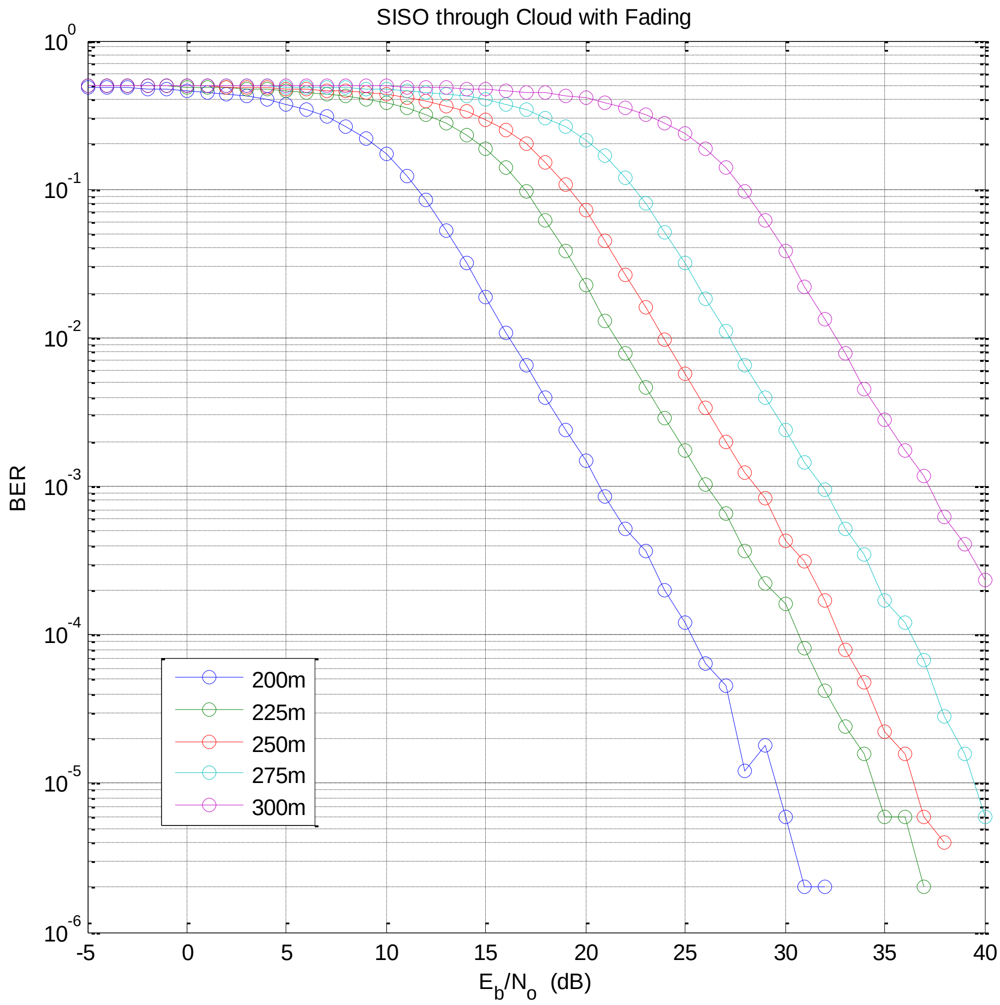

Fig. 4.2: SISO with cloud and with fading

4.3 MIMO through Cloud without Fading

For 2 transmitter and 2 receiver antenna, we have obtained the bit error rate (BER) for different values of E_b/N_o in a system fitted with MIMO through thin cloud. For obtaining the same BER, we need lesser E_b/N_o than what was needed in SISO through thin cloud (non-fading channel).

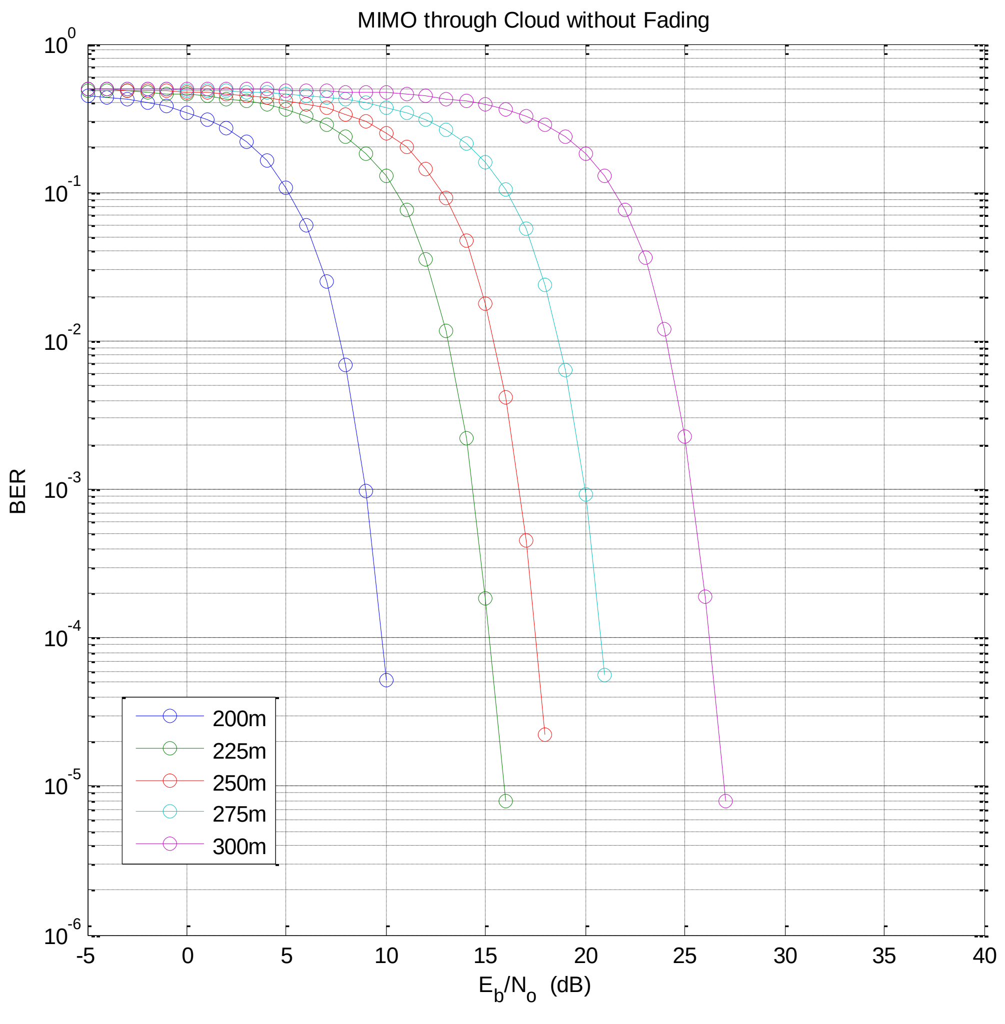

Fig. 4.3: MIMO with cloud and no fading

4.4 MIMO through Cloud with Fading

For the same system in previous section, we have obtained the bit error rate (BER) for different values of E_b/N_o with adding Rayleigh fading channel. For obtaining the same BER, we have to take greater E_b/N_o for thicker cloud; but it is less than what was needed in SISO through thin cloud with fading channel.

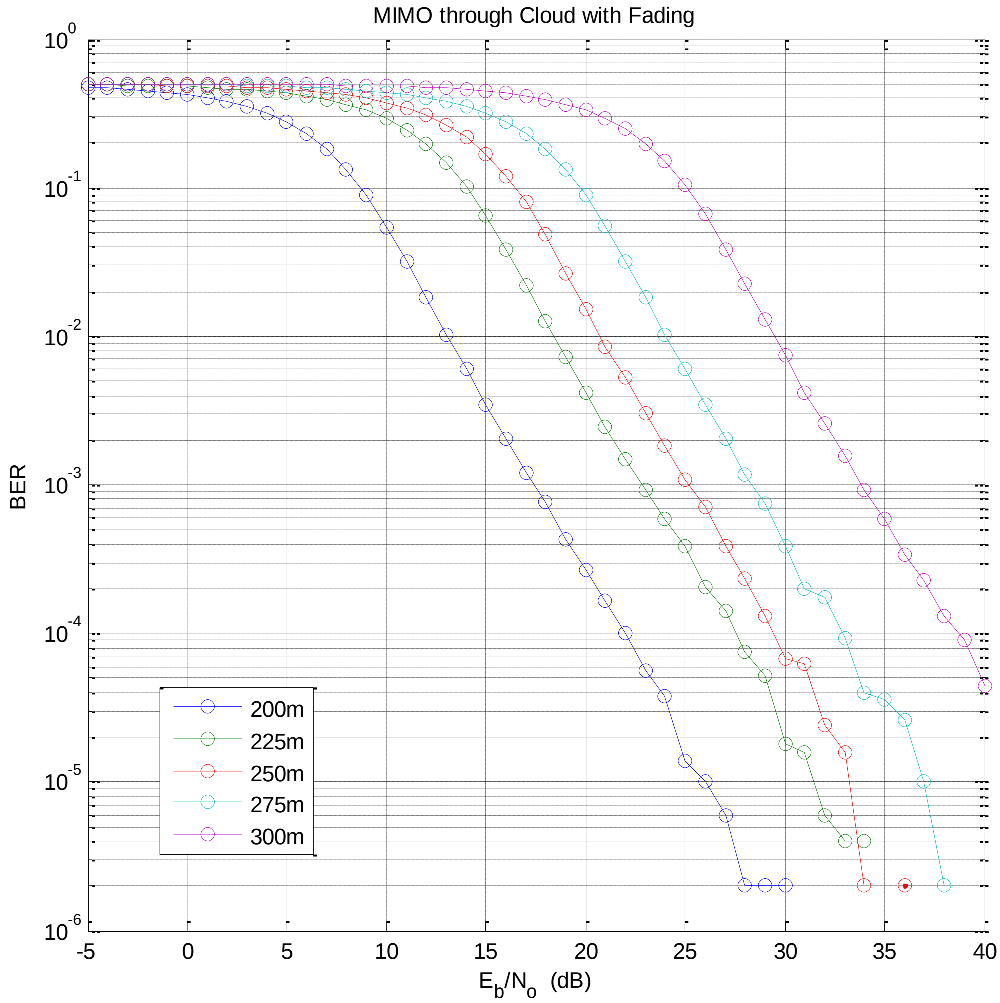

Fig. 4.4: MIMO with cloud and with fading

4.5 Power Penalty at BER of 10^{-3}

From the curves in the previous sections we see that MIMO has much improved the performance of the system by minimizing power penalty of 8~10dB. Also, the amount of power penalty for fading and non-fading channel is increasing with thickness of cloud.

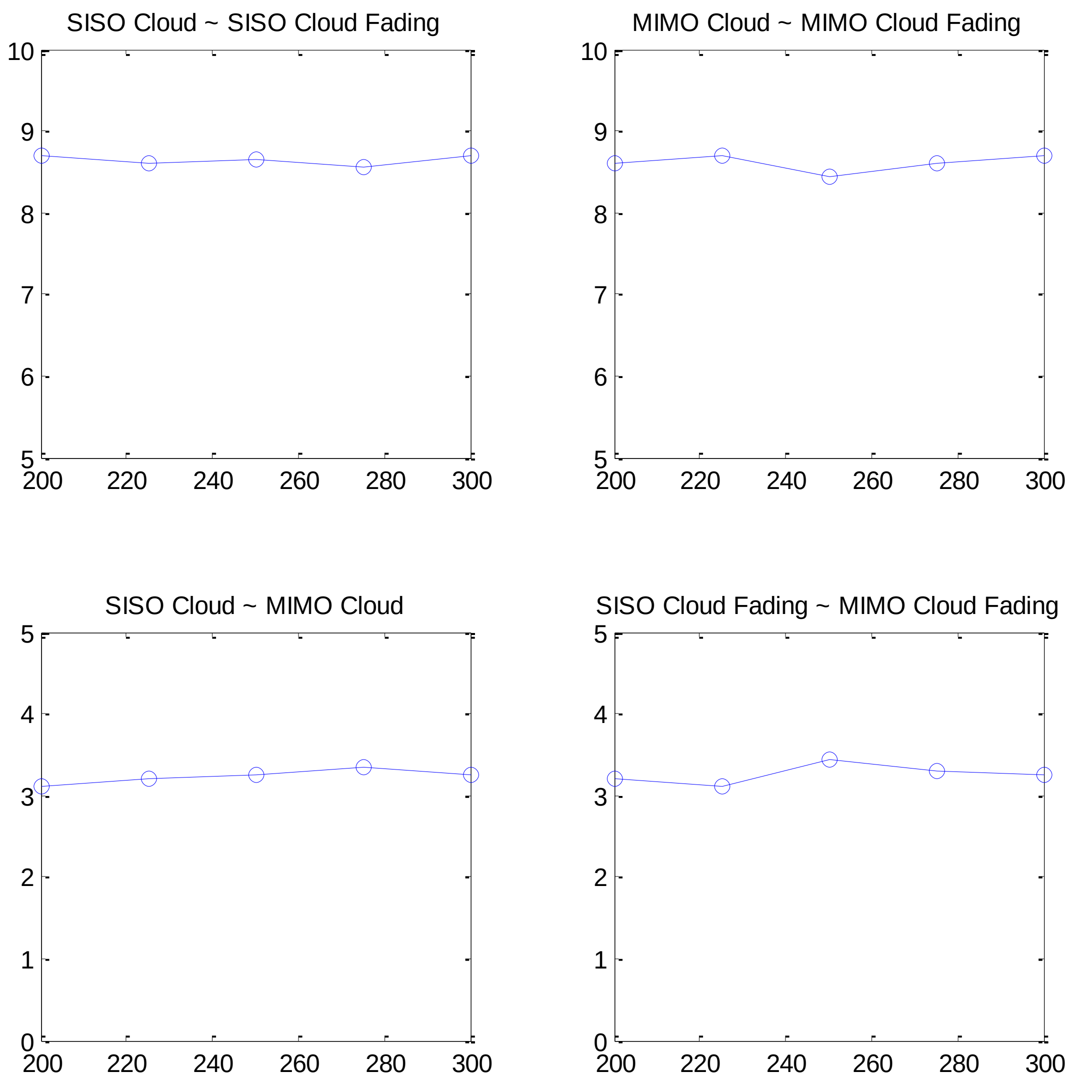

Fig. 4.5: Various power penalties

4.6 Performance for Same E_b/N_o

Through thin cloud, MIMO with fading performs close to the ideal SISO without fading for smaller thickness of the cloud. Also the MIMO system performs much better in both fading and non-fading channels than the SISO systems respectively.

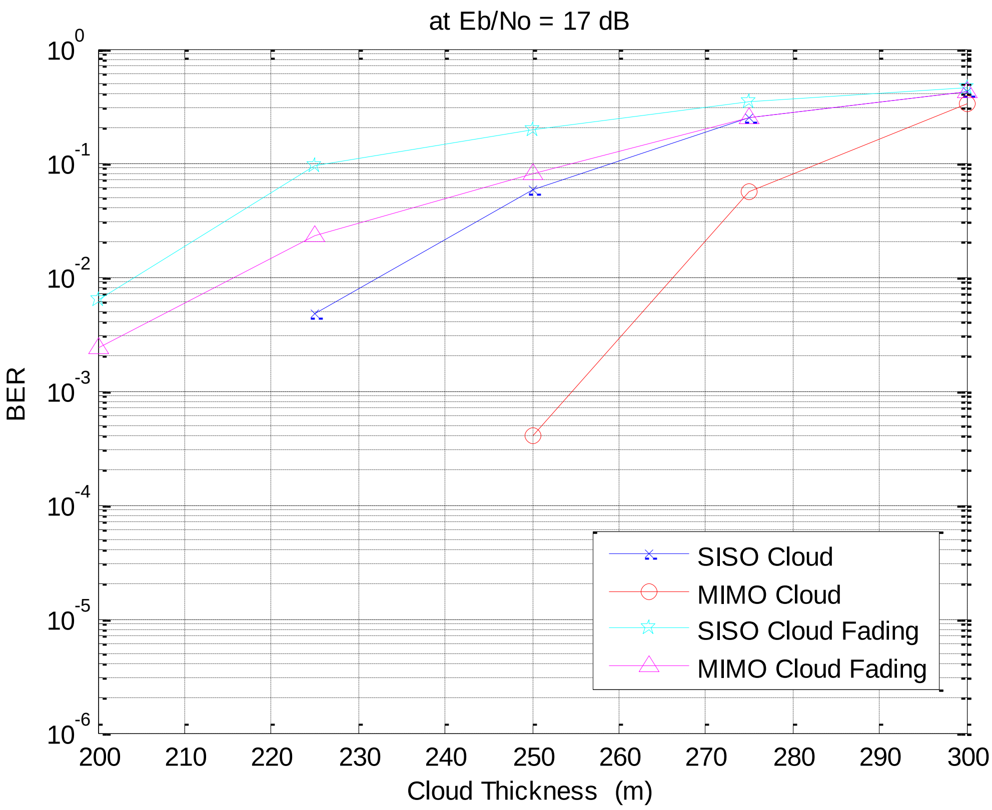

Fig. 4.6: BER vs. Cloud Thickness

Chapter 5

Conclusion and Future Works

5.1 Conclusion

From the simulations, for propagation through cloud and fading channel, MIMO system is better than the SISO system for both fading and non-fading transmission. For obtaining same BER, we have to use a large power penalty in systems with fading. This power penalty can be reduced a lot by employing MIMO technique. Also, clouds can be very harmful to the performance of an FSO communication system. For the low SINR values the performance of the system through cloud is not good; and fading makes it worse. As cloud thickens all the systems are prone to massive error; but for thin cloud around 200~225m the error is minimum. BER performance in MIMO with Fading is almost similar to SISO without Fading in the presence of Cloud. So, from the results of the simulations in this thesis paper, it can clearly be seen that MIMO performs much better through atmospheric cloud and fading than SISO system.

5.2 Future work

In this thesis paper, we have implemented 2-transmitter 2 receiver (2x2) MIMO transmission system to improve BER performance. Different number of transmitters and receivers can result differently. So, the optimal number of transmitter and receiver has to be determined via more simulations.

Also, the modulation technique can be changed. Here, we have considered thin cloud's effect on BPSK modulated system. QPSK and M-PSK modulated systems will result in different values for same range of SNR.

References

[1] S. Arnon, D. Sadot, and N. S. Kopeika, “Analysis of optical pulse distortion through clouds for satellite to earth adaptive optical communication,” J. Mod. Opt. 41, 1591–1605 ~1994.

[2] S. Arnon and N. S. Kopeika, “Free space optical communication: detector array aperture for optical communication through thin clouds,” Opt. Eng. 34, 511–516 ~1955

[3] E. J. Shin and V. W. S. Chan, “Optical communication over the turbulent atmospheric channel using spatial diversity,” *IEEE Globecom*, Nov.2002, pp. 2055-2060.

[4] X. Zhu and J. M. Kahn, “Free-space optical communication through atmospheric turbulence channels,” *IEEE Trans. Commun.*, vol. 50, no. 8, pp. 1293-1300, Aug. 2002.

[5] X. Zhu and J. M. Kahn, “Performance bounds for coded free-space optical communications through atmospheric turbulence channels,” *IEEE Trans. Commun.,* vol. 51, no. 8, pp. 1233-1239, Aug. 2003.

[6] L. C. Andrews, R. L. Phillips, and P. T. Yu, “Optical scintillations and fade statistics for a satellite-communication system,” Appl. Opt. 34, 7742–7751 ~1995.

[7] S. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE Journal on selected areas in communications*, vol. 16, no. 8, pp. 1451–1458, 1998

[8] I. Kim, H. Hakakha, P. Adhikari, and E. J. Korevaar, “Scintillation reduction using multiple transmitters,” in *Proc. SPIE*, Feb. 1997, vol.2990.

[9] R. A. Elliott, “Multiple scattering of optical pulses in scale model clouds,” Appl. Opt. 22, 2670 –2681 ~1983.

[10] G. C. Mooradian and M. Geller, “Temporal and angular spreading of blue-green pulses in clouds,” Appl. Opt. 21, 1572– 1577 ~1982.

[11] S. Arnon and N. S. Kopeika “Adaptive optical transmitter and receiver for space communication through thin clouds “Appl Opt 36 pp. 1987-1993 (1997

[12] M. M. Kamruzzaman ,”Performance of Decode and Forward MIMO Relaying using STBC for Wireless Uplink” *IEEE* VOL. 9, pp 3200-3206 ,DECEMBER 2014

[13] S. Mohammad Navidpour, Murat Uysal, Mohsen Kavehrad, “BER Performance of Free-Space Optical Transmission with Spatial Diversity’”. *IEEE* Vol. 6, NO. 8, AUGUST 2007

[14] M. N. Rindani 1, A. A. Bavarva ,”BER performance comparison of 4x4 extended Alamouti scheme for different fading channels.” pp Vol. 2, Issue 3, March 2013