ANALYTICAL EVALUATION OF THE EFFECT OF CROSS-POLARIZATION IN A POLARIZATION DIVERSITY MIMO SATELLITE TO GROUND LINK

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APPROVAL CERTIFICATE

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DEDICATION

To My Parents and Family

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This thesis is the most significant accomplishment in my life. I would like to thank my parents and wife for their continuous encouragement and sacrifice throughout the period.

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ABSTRACT

Any communication link that uses an artificial satellite in its propagation path is referred to as satellite communication. In today's world, satellite communications are critical. Over 2000 artificial satellites are currently in use. They are utilized for traditional point-to-point communications, mobile applications, and the distribution of TV and radio programming and can be found in geostationary, Molniya, elliptical, and low Earth orbits. The polarization orthogonal to the desired polarity is known as cross polarization. For example, if an antenna's fields are intended to be horizontally polarized, the cross-polarization in this case is vertical. As a result, most antenna radiation patterns are provided. Polarization diversity is one of the most important techniques to increase the capacity of a Multiple Input Multiple Output (MIMO) antenna system from satellite to ground link. However, such link is highly degraded to cross-polarization effect. MIMO technique may provide better performance of such system. So attempt is made to evaluate the cross-polarization induced crosstalk in a MIMO satellite link using polarization diversity. Analysis is developed to find the interference due to cross-polarization in a 2×2 MIMO and 4×4 MIMO satellite link. The expression of signal to interference plus noise ratio (SINR) is developed. The Bit-Error-Rates (BER) performance results are evaluated for different environments like Open area, Sub-urban area, Urban area and Aeronautical/Marin area. The power penalty for LOS component of 4×4 MIMO satellite to ground communication system. 0.1dB, 1.5 dB, 2.5dB and 4.0 dB power penalty are measured for open, sub-urban, urban and aeronautical/marine area which are slightly higher than 2×2 MIMO system. So, 4×4 MIMO system gives better output with low power penalty. The power penalty is compared for three different channel components like LOS components (β), Reflection components (ξ) and Diffused components (α). The LOS component gives the higher power penalty which 0.5 dB to 0.9 dB than other diffused component is 0.1 dB to 0.5 dB and reflection component is less than 0.1dB to 0.3dB. It is found the satellite to ground link suffers power penalty due to cross-polarization which is significant for A/M area and least penalty for Open area environment.

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LIST OF ABBREVIATIONS

A/MA	Aeronautical/ Marine Area
BER	Bit Error Rate
C/XPI	Carrier to Cross-Polarization Interference
CDMA	Code Division Multiple Access
CNIR	Carrier to Noise plus Interference Ratio
GEO	Geostationary Earth Orbit/Group on Earth Observation
GHz	Giga Hertz
LOS	Line of Sight
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
NFV	Network Function Virtualization
OA	Open Area
OFDM	Orthogonal Frequency Division Multiplexing
PDF	Probability Distribution Function
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
SDN	Software Defined Networking
SINR	Signal to Interference Plus Noise Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SQPSK	Quadriphase Shift King
STBC	Space Time Block Coding
STC	Space Time Coding
XPD	Cross-Polarization Discrimination

LIST OF SYMBOLS

$\mathbf{C_n}$	Refracting index
D(t)	Diffuse signal
E_b	Signal power
H	Channel matrix
H_{11}	Co-polar component
H_{12}	Cross-polarization coefficient
H_{21}	Cross-polarization component
H_{22}	Co-polar component
K	K-factors
L	Path length through the turbulence area
L(t)	Line-of-Sight signal
N_0	Noise power
P(x)	Probability density function of amplitude fading
R	Receive signal
V	Noise vector
α	Reflected signal component
λ	Wavelength
ξ	Diffused signal component
σ	Variance

CHAPTER 1

INTRODUCTION

1.1 Introduction

Satellite communication is a man-made communication method that uses the transponder to communicate. It establishes a communication link between two transmitters and receivers located anywhere on the planet. Satellites play a crucial part in current telecommunications systems, such as weather forecasts, mobile applications, TV broadcasts, military applications, and other practical relevance [1].

People benefit from a variety of services provided by satellite, but it also has lots of disadvantages, like as interference, altitude, power, and lifetime. The Geostationary Earth Orbit (GEO) satellite uses high-frequency communication and is influenced by atmospheric turbulence. The spot dancing, signal distortion, scintillation of receive intensities are caused by atmospheric turbulence. In addition, bandwidth is another limitation in satellite communication [2]. Dual polarization is the solution to overcome this bandwidth problem. It simultaneously transmits two different data streams over the same frequency [3].

1.2 Multiple Antenna Systems in Satellite Communications

It has been demonstrated, both theory and practice, that multiple-input multiple-output (MIMO) systems offer the maximum capacity, high spectral efficiency, and high gains by exploiting space-time processing techniques in different propagation environments [4]. The combination of the radio channels and independent uncorrelated channels performs this superior performance. The channel diversion can be achieved by using additional time and frequency dimensions. The advantages are obtained by MIMO channels are highly dependent on the orientations of scattering and the correlations among signal carriers which limit the performance of MIMO systems. The antenna separation, in terms of the wavelength of the operating frequency, has a significant impact on the spatial correlation. To achieve uncorrelated fading paths adequate antenna spacing along with a rich scattering environment is necessary. An alternative solution to achieve low fading correlation is to use antenna arrays with cross polarizations, i.e., antenna arrays with polarizations in orthogonal or near orthogonal orientations without increasing the bandwidth and in particular, the concept of three-dimensional (3D) polarization has a significant role in achieving diversity by polarization. It has been shown in recent research that it is possible to attain even more channels by using the benefits of the combined spatial and polarization diversity in rich scattering environments. Satellite communication systems are not immune from this wave of innovation. However, due to differences in the propagation conditions in satellite and terrestrial links, the applicability and designs of MIMO systems are different as well [5]. Due to very large path lengths, transmit or receive antennas must be placed at appropriate distances from each other to realize diverse paths. To achieve this, the possible diversity sources, i.e., satellite diversity and site diversity can be exploited in forming the MIMO channels for satellites. In the case of satellite diversity, the satellites are far apart from each other to achieve diversity and as a result, the path lengths and the time of arrival of signals can vary.

1.3 Limitations of Satellite Links

1.3.1 Turbulence

In electromagnetic wave propagation through the earth's atmosphere like satellite communications, it is known that a random fluctuation of the dielectric constant of the atmosphere affects propagation characteristics of electromagnetic waves [6]. The random fluctuation, called atmospheric turbulence, causes waveform distortion, scintillations of the received intensity, the reduction in the spatial coherence of wave beams, etc. These effects make the received power decrease and result in the degradation in the performance of satellite communication links. The effects of atmospheric turbulence are not negligible in satellite communications in high carrier frequencies at low elevation angles. For example, tropospheric scintillation, caused by turbulence in the lowest layer of the atmosphere, has been observed in satellite communications in Ku-band at low elevation angles. Therefore, it becomes important to consider the effects of atmospheric turbulence appropriately in the design of such satellite communication systems [7]. However, because a carrier frequency becomes higher according to the increase in the required channel capacity of satellite communication links in the next generation, the analysis of the effects of atmospheric turbulence should be done at the higher carrier frequencies such as Ka-band, a millimeter-wave, and an optical wave.

1.3.2 Cross-polarization

Polarization is an important factor for RF antennas and radio communications that offers a freedom of diversity, multiplexing and accuracy [8]. For the electromagnetic wave the polarization is effectively the plane in which the electric wave vibrates. This is important when looking at antennas because they are sensitive to polarization, and generally while receive or transmit a signal with a particular polarization. For most antennas it is very easy to determine the polarization parameters and angle by using the three orthogonal projection of radio vector [9]. It is simply in the same plane as the elements of the antenna. So a vertical antenna (i.e. one with vertical elements) will receive vertically polarized signals best and similarly a horizontal antenna will receive

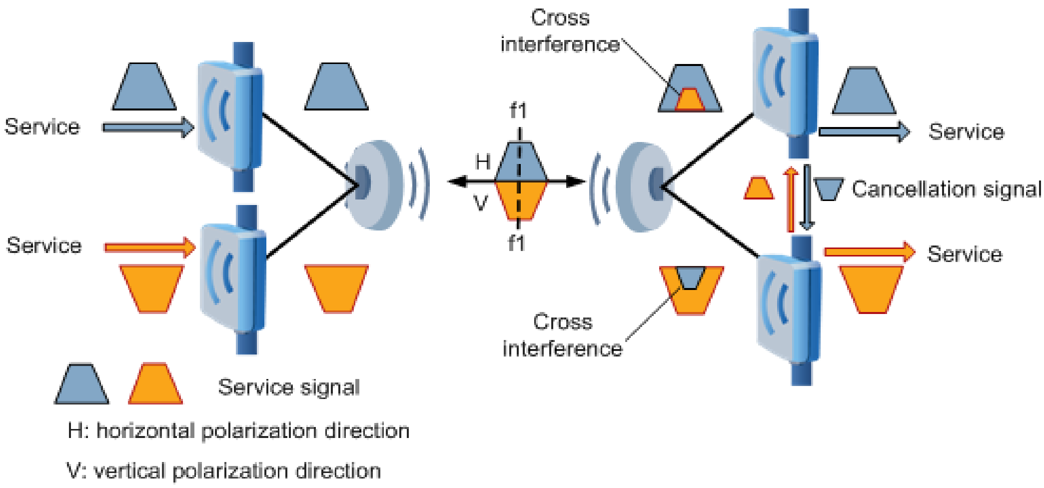

Fig. 1.1: Cross-polarization at the receiver [9].

horizontally polarized signals. During propagation the atmospheric channel cause coupling of electromagnetic waves for vertical to horizontal polarization and introduce cross-polarization electric field at the receiver end which shown in Fig.1.1.

1.3.3 Fading

In wireless communications, fading is the attenuation of signal with several variables over certain propagation media. The fading may vary with time, geographical position or radio frequency, and is often modeled as a random process [10]. In wireless systems, fading can caused due to multipath propagation, referred to as multipath induced fading or because of shadowing from obstacles affecting the wave propagation, sometimes referred to as shadow fading. The presence of reflectors in the environment surrounding a transmitter and receiver create multiple paths which a transmitted signal can traverse. As a result, the receiver sees the superposition of multiple copies of the transmitted signal, each traversing a different path. Each signal copy will experience differences in attenuation, delay and phase shift while travelling from the source to the receiver. This can result in either constructive or destructive interference [11], amplifying or

attenuating the signal power seen at the receiver. Strong destructive interference is frequently referred to as a deep fade and may result in temporary failure of communication due to a severe drop in the channel signal-to-noise ratio. A common example of deep fade is the experience of stopping at a traffic light and hearing an FM broadcast degenerate into static, while the signal is re-acquired if the vehicle moves only a fraction of a meter. The loss of the broadcast is caused by the vehicle stopping at a point where the signal experienced severe destructive interference. Cellular phones can also exhibit similar momentary fades. Fading channel models are often used to model the effects of electromagnetic transmission of information over the air in cellular networks and broadcast communication. Fading channel models are also used in acoustic communications to model the distortion caused by the water.

1.3.4 Interference

In communication system, interference is an unwanted signal which irritates or make barrier to reach the actual signal to the destination [12]. Interference occurs into the channel between transmitter and receiver for a system. There are various types of interference such as Electromagnetic Interference (EMI), Co-channel Interference (CCI) is also called crosstalk, Adjacent Channel Interference (ACI), Inter Symbol Interference (ISI) and Common Mode Interference (CMI). It is not always destructive sometimes noise can be used effectively to transmit the signal. Interference cost for satellite communication is millions of dollars each year. Solutions such as sophisticated, cost effective tools are now available that allow operators to plug leaks that cost the loss of revenue as a result of interference. Today’s satellites are designed interference free brand as possible to minimize this huge amount of cost [13]. The Satellite Users Interference Reduction Group (SUIRG) categorizes satellite communication interference into five main groups, these are: User Error, Human Error, Equipment Failure, Cross-polarization Leakage, Adjacent Satellites, Terrestrial Services, Deliberate Interference.

1.4 Literature Review

In this literature review I present the overview of MIMO diversity scheme with the effect of cross-polarization. The related published article also summarized and tried to find out it's importance, drawbacks and research gaps.

A key strategy for increasing the throughput of a satellite communication system is polarization diversity [14]. However, cross-polarization caused by atmospheric effects limits such devices. The employment of numerous antennas with space-time block code (STBC) to boost performance and overcome channel effects is a valuable strategy. The efficiency of such multiple-input multiple-output (MIMO) systems is impressive with polarization diversity is represented with antenna code [15]. MIMO with orthogonal frequency division multiplexing (OFDM) using dual polarization is also found to be promising in wireless communication [16]. Using MIMO techniques, the performance of a ka-band satellite to earth link is also recently reported considering single polarization [17]. Using dual polarized receivers, the performance of a satellite link with circular polarization are also reported considering the coupling between the antenna ports which result in cross-polarization effect [18].

A novel technique to compensate for the cross-polarization effect is reported for a polarization division multiplexed systems using non-linear polarization crosstalk cancelled [19]. The dual polarized group on earth observation (GEO) satellite systems are also investigated to long term evolution (LTE) systems using minimum mean square case estimation [20]. More recently, maximal ratio combining techniques is applied to a land mobile satellite channel with shadowed rician fading [21] with imperfect channel state information. It is essential to develop analytical approach to quantify the bit error rate (BER) performance of a MIMO satellite to ground link with polarization diversity in different atmospheric conditions taking into account the effect of cross-polarization. In satellite communication research are going on tremendously to improve each part like quality of service, hat shaped dielectric antenna [22], wireless backhaul, and network i.e. SDN and NFV are the new research outcome. Higher frequency band for example ku and ka-band, cross-layer approach, and modern strategies observing satellite constellation [23] are also using. The different satellite are using for different purpose such as Nano-satellite trying to give everyone access to the space and LEO satellite [24] fixed for a certain country with speed synchronization. Now it is very challenges to minimize the BER because of huge barrier on the space like electromagnetic interferences [25] and liquid water content in the atmosphere [26] for four dimensional constant with dual polarization [27]. The axially symmetric refractor antennas, can be reduced to zero cross-polarization by the use of special feeds like the Huygens source [28]. When the satellite system operates under the dual polarization mode, due to the rain attenuation depolarization, the system is interfered by the terrestrial microwave link [29]. If the dual polarization can be used properly then communication capacity will double of the system [30]. A general and unified MIMO model which very effective in both mobile satellite system and ancillary terrestrial component [31]. It is also calculated with the higher frequency band that dual polarization brings the better output in the sea surface [32] Constellation of earth observation satellite is important and combination as well as satellite to earth link availability to minimize the BER. The resource allocation information of satellite link and sessions with the help of TCP congestion window also contributes in the BER performances. The CS-3 beacon signal investigates the cross polarization discrimination on Ka-band satellite to ground path [33]. We know that ice crystals in rain cloud as well as rain drop are the reasons of depolarization of microwaves and millimetre waves on satellite to ground path. In a second or less, thunder storm can change the cross-polarization and cross-polarization phase [34]. The data is compared, after analysis of dual polarization and attenuation, three ways and result is concluded that mean and median safely comparable but equiporable result treated with cautions [35]. In wireless radio communication system rain induced cross-polarization is a major factor. Differential phase shift is become below 10 GHz when frequency is increased differential attenuation also increased. It is estimated 1.5 dB power gain using dual polarized antennas in high regime SNR [36]. To fulfil the demand of modern era higher technology and reliable design and also higher frequency is being used parallel interference is increased. To predict and compensate the carrier-to-noise-plus-interference (CNIDR) triple site diversity scheme is being used. It is also possible a zero cross-polarization mode through the rain when orthogonally polarized signal are transmitted canting angle is assume zero and raindrops are treated random variable. The personal satellite communication system, the

satellite-to-mobile link of personal mobile, are employing to control the power direct sequence code-division multiple access (DS-CDMA) and analysis is compared with conventional communication system which gests the better result. An experimental terrestrial link was set up using dual polarization frequency reuse system for the purpose of very-high-date rate. Two 3.2 Gb/s signals were used with quadri phase shift keying (SQPSK) transmitted on opposite sense of circular polarization over 7 km path located in cane rain region. The antenna should carefully control for the system if such techniques are to be employed in satellite to space link. The transmission capacity can be doubled using orthogonally polarized quadrature amplitude modulated (QAM) carrier in microwave radio communication but it suffers degradation because of carrier-to-cross-polarization interference (C/XPI). This interference can be mitigate with employing diagonalizer, LMS, and bootstrapped cancellers.

1.5 Research Gap

A research gap is a field of study that is either undiscovered or under-explored and has room for more investigation. It's a previously unexplored territory that your research aims to investigate. It refers to a question that hasn't gotten enough attention or hasn't gotten any attention at all. Some study areas are listed below:

Satellite engineers interested in signal degradations such as fading-outages (attenuation) and cross-polarisation will find these two techniques challenging due to the more difficult propagation conditions at higher frequencies [37]. In satellite communications at high carrier frequencies and low elevation angles, the effects of air turbulence are not negligible. For example, tropospheric scintillation has been seen in Ku-band satellite communications at low elevation angles, which is generated by turbulence in the lowest layer of the atmosphere. It's crucial to factor in the impacts of air turbulence when designing satellite communication systems like this [38]. Signal power penalty is caused for different reasons like signal reflection, signal diffused and line of sight signal.

Besides several environmental conditions like rainy, foggy, dusty condition caused power penalty for signal from satellite to ground link.

1.6 Research Motivations

Satellite technology is the most powerful technology that ever invented. Some natural phenomenon can be created by using satellite i.e. hurricanes, floods, droughts and it also be controlled to save the human lives. Other useful application like weather forecasting, satellite communication which is very effective for the telecommunication in worldwide. Research is continuing for further improvement like signal power, low costing, noise reduction etc. In this thesis a system model is constructed with the effect of cross-polarization in polarization diversity MIMO satellite to ground link. MIMO diversity is used to cover the ability to distinguish transmission over multiple paths, it is possible to encode the signal more efficiently if the effect of those paths is considered. Cross-polarization in MIMO system is bad affect to BER because undesired polarization is present at the receiver. BPSK modulation is used in this system because it is most robust modulation technique due the fact that binary 1 and 0 are separated by 180-degree phase shift of the carrier. Due to this property, BPSK modulated data can travel longer distances when transmitted from base station or subscriber station. Hence BPSK modulation is employed in pilot carrier as well as in preamble sequences. BPSK is power efficient modulation technique as less power is needed to transmit the carrier with less number of bits. Power penalty is needed to measure because it is more expected in telecommunication engineering.

1.7 Objectives of this Thesis

The objectives of the thesis are:

(i) Development of an analytical model of a MIMO satellite to ground link with polarization diversity.

(ii) To carryout analysis of signal to interference and noise ratio (SINR) and bit error rate with the effect of cross-polarization due to atmospheric effect in a MIMO satellite to ground link.

(iii) To evaluate the BER performances results with different environmental parameters for the satellite to ground MIMO link;

(iv) To evaluate the power penalty due to cross-polarization in various environmental conditions and system parameters in MIMO satellite link.

The possible outcome of this thesis work will be the useful and more efficient to implement satellite to ground link data transmission using polarization diversity with MIMO.

1.8 Organization of the Thesis

This thesis consists of five chapters presenting background and reviews of the relevant literature, performance analysis of a (2×2) & (4×4) MIMO system model from satellite to ground link with effect of cross-polarization, varying few environmental parameters find expected results, summary of the key findings and potential future research opportunities.

The thesis chapter is organized as followings;

Chapter 2 describes a (2×2) MIMO system model and performance analysis is presented for asatellite to ground link with cross-polarization. Here (2×2) MIMO system model is presented, polarizarion diversity transmitter antenna and receiver antenna are shown with proper analysis.

Chapter 3 describes the theoretical analysis of a (4×4) MIMO system model from satellite to ground link with effect of cross-polarization. SINR and BER equation is derived with related coefficient and component. A block diagram of transmitter and receiver antenna data stream also illustrate briefly.

Chapter 4 discusse the results and discussion on effect of cross-polarization on a (2×2) and (4×4) MIMO system for a satellite to ground link. After the changing different parameters numerical value like LOS components (β), diffused components (α) and reflection components (ξ), SINR is measured and power penalty is compared for a satellite to ground link

Chapter 5 concludes the thesis by summarizing the major findings, as well as indentifying several potential research opportunities for the improvements.

CHAPTER2

PERFORMANCE ANALYSIS OF A (2×2) MIMO SYSTEM MODEL FROM SATELLITE TO GROUND LINK WITH EFFECT OF CROSS-POLARIZATION

2.1 Introduction

2x2 MIMO, also known as 2T2R, employs two antennas to establish up to two data streams with the receiving device. When compared to single-antenna networks, 2x2 delivers a throughput boost of up to 100%. The data payload is divided across both antennas and broadcast over the same frequency band once two spatial streams have been formed. The antennas must be well segregated and designed to give a low correlation coefficient for spatial multiplexing to work. Using orthogonal polarizations, such as one vertically polarized antenna and one horizontally polarized antenna, is typically the most effective technique to produce low correlation in a 2x2 system.

Polarization diversity is an essential scheme to increase the throughput of a satellite communication system. However, such system is limited by a cross-polarization induced by atmospheric effect [39]. The use of multiple antennas signalling with a useful technique to increase the throughput and overcoming the channel effects. The performance of such MIMO systems with polarization diversity is represented with antenna code. More recently, maximal ratio combining techniques is applied to a land mobile satellite channel with shadowed rician fading with imperfect channel state information. In this paper, we provide an analytical approach to evaluate the cross-polarization effect on the bit error rate performance of a satellite to ground link considering 2×2 MIMO technique.

The BER results are evaluated with the effect of cross-polarization for different environmental condition such as urban area, sub-urban area, open area and aero/marine area. In each area certain parameter is set to specify the fixed region and SINR and BER performance is compared after the matlab simulation. Satellite communication is very much important for next generation communication systems and networks due to its high reliability and matured technology. However, performance of satellite to ground links are very much deteriorated due to atmospheric turbulence effects specially at carrier frequency higher than 30 GHz.

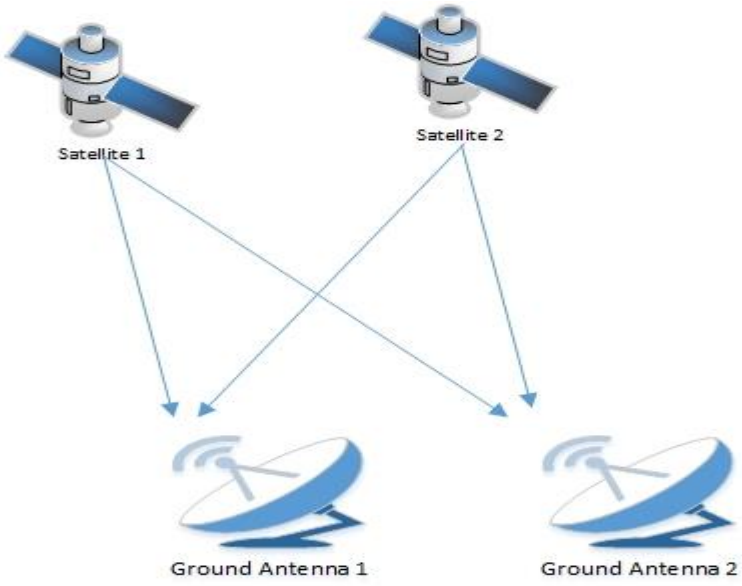

Fig. 2.1: Geometry of a possible intra-system interference of cross-polarization for a satellite to ground link.

Significant research works are reported on the effect of atmosphere turbulence on broadband communications operating near 10 GHZ [38]. Analytical performance of satellite to earth link is investigated considering the effect of atmospheric turbulence for various modulations formats. Some simulation results are also available on the effect of turbulence on satellite to earth link [40]. Performance analysis with diversity in transmit and receive are also recently respected in presence of turbulence effects for satellite to earth and earth to satellite link. MIMO satellite to earth link is developed using Gaussian and log-Normal [41] channel models for turbulence induced fading. Simulation results are recently respected on satellite to earth SISO and MIMO links user Log-Normal. Besides, channel capacity [42] is more important in satellite communication. In this paper, we present an analytical approach to evaluate the bit error rate (BER) performance of a satellite to earth link at 30 GHZ taking into account the effect of turbulence induced fading which is considered to have log-normal distribution results are evaluated numerically for several atmospheric turbulence condition and compared to simulation results respected easier. Power penalty due to turbulence induced fading of a given BER of 10^{-5} are also evaluated.

2.2 System Model

A system model describes that how the processes interact and what operations these processes perform, but it does not go into details as to how this processes are implemented. Figure 2.2 depicts a block diagram of a satellite-to-ground mobile communication system, in which data is first entered into a polarization diversity transmitter block, after which the signal is sent via the atmosphere and received by the receiver. Un-shadowed propagation (when the land receiver has an unobstructed LOS route to the satellite); shadowed propagation (LOS to the satellite is partially or completely obstructed).

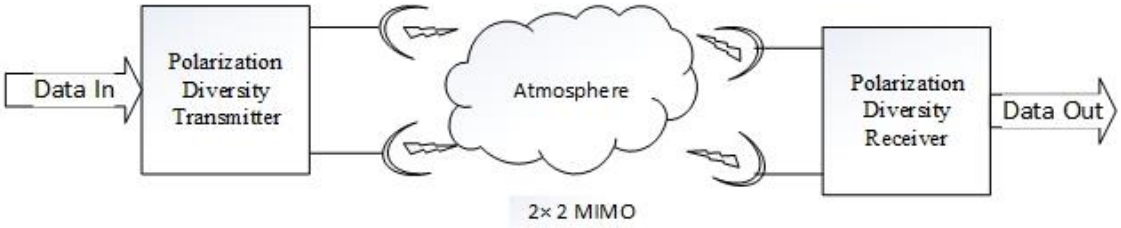

Fig.2.2: Block diagram of a satellite to ground link.

The symbol stream is split into two sub-streams that are sent across two orthogonal polarized channels at the same time. The signal is received as co-polar and cross-polar components from the transmitter in a 2×2 cross-polarization system. The satellite land model may be divided into four categories of places based on the degree of Line-of-Sight obstruction: Open, Suburban, and Urban, Areo/Marine Areas. By using appropriate K-factor in open area unobstructed direct components and diffuse components are present.

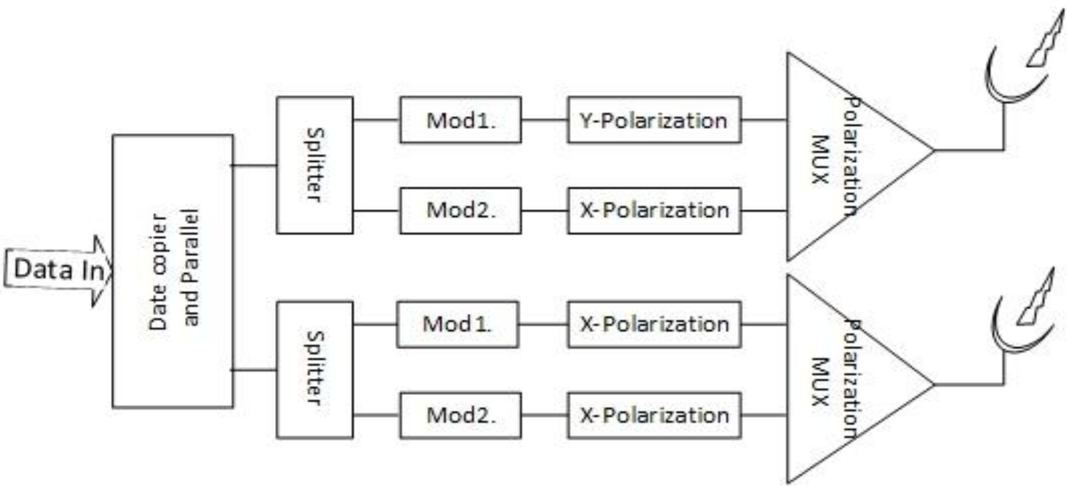

Fig. 2.3: Block diagram of polarization diversity transmitter.

A transmitter on a communications satellite is known as a satellite transmitter. A communications satellite is a man-made satellite that sends and receives signals from Earth and orbits in a geostationary orbit. A sender, or transmitter, is a device that broadcasts radio or television signals. The input data stream is given to a data copier and parallel block and output is copied and splitted through spliter with separate branch of transmitting antenna. Splitted signal is modulated X and Y components separately. The combine signal is fed to the transmitting antenna.

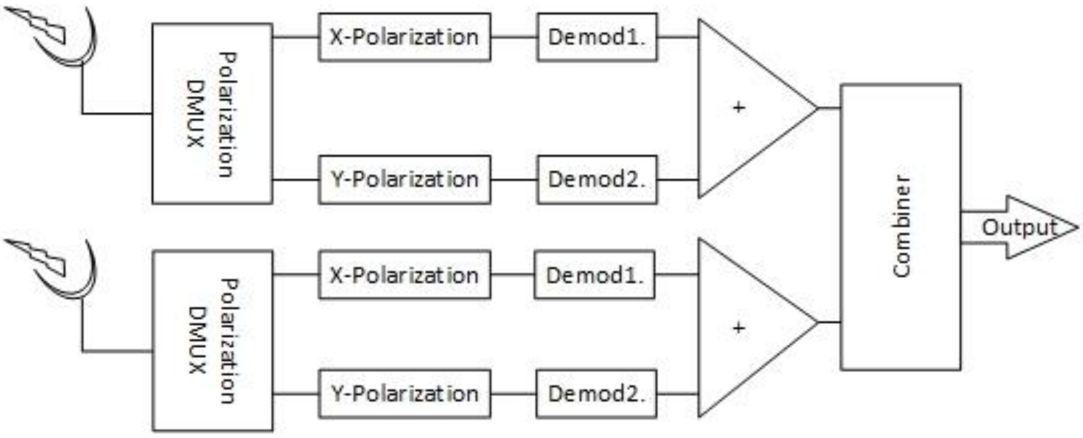

Fig. 2.4: Block diagram of polarization diversity receiver.

The block diagram of the (2×2) MIMO polarization diversity receiver is shown in Fig.2.4. The receive signals is demultiplexed by a polarization dimultiplexer to get X and Y components and pass to coherent BPSK demodulators. Outputs of the coherent modulators are combined and sent to the second stage combiner.

The Rician K-factor (Ratio of signal power in the line-of-sight component to the scattered power) for direct component 200 and specular component zero. The signals cross correlation values are in the range of 0.1 - 0.5. In sub-urban area the channel is described by a shadowed line of sight component and diffuse components. The Rician K-factor for direct component 60 and specular component 0 in suburban area. The signals cross correlation values are in the range $0.1 - 0.5$. In urban area the channel has only a diffuse component. The typical K-factor for direct component 50 and specular component 0 in urban area. The signals cross correlation values are in the range $0.1 - 0.5$. In Aero/Marine area the channel has specular and diffuse components. The typical K-factor for direct component 40 and specular component 0. The signals cross correlation values are in the range $0.1 - 0.5$.

2.3 Theoretical Analysis on a (2×2) MIMO Satellite to Ground Link with Cross-polarization

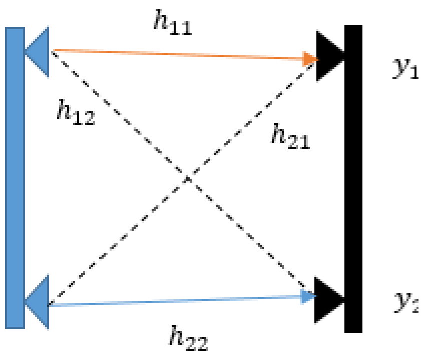

Fig. 2.5: 2×2 Alamouti STBC system.

The 2×2 Alamouti STBC system is shown in figure 2.5 where we use 2 antenna at the transmitter and 2 antenna at the receiver. Each transmitter antenna transmit diversity signal and receiver also receive the diversity signal. In a narrowband polarization multiplexing system, the received signal can be written from the above the figure is

$$y = Ha + b \quad (2.1)$$

Where,

H is the $(N_R \times N_T)$ complex channel matrix.

a= $[a_1, a_2]$ is the complex vector for the transmitted signal.

y= $[y_1, y_2]$ is the complex vector for the received signal.

b= $[b_1, b_2]$ is the complex vector for the additive zero mean complex Gaussian noise vector signal

The signal propagates to receiver through the different channel. The 2×2 polarization channel matrix given by

$$H = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix} \quad (2.2)$$

The h_{11} and h_{22} coefficients are the gains between the co-polar components, and the coefficients h_{21} and h_{12} are the cross-couplings from one polarization to the other. The effect of the cross polarization are highly dependent on the polarization scattering matrix which, in turn, depends on the physical limitations of the wireless environment and the antenna's ability to separate the orthogonal polarization. The geometry of a possible intra system interference of a cross-polarized satellite-earth communications link is shown in Figure 2.1, where the interference signal occur because of cross polarized antenna and polarization changes occur due to the reflection and diffuse components.

The propagation from satellite to earth station can be divided in three types as either un shadowed (when land receiver has a clear LOS path to the satellite); shadowed (LOS to the satellite is partially obstructed); blocked (LOS is completely obstructed); The un shadowed LOS propagation is described by a Rician distribution with a specific K-factor. When the earth receiver has LOS propagation from a satellite, the un shadowed signal received at the land receiver has three components: a LOS signal *L (t),* a specular coherently reflected signal *S(t),* and a diffuse signal *D (t)*

The received signal y *(t)* by a earth station can expressed with multiplying the Rician K-factors as;

$$y(t) = \sqrt{\frac{k_1}{k_2+k_1+1}}L(t) + \sqrt{\frac{k_2}{k_2+k_1+1}}S(t) + \sqrt{\frac{1}{k_2+k_1+1}}D(t) + v(t) \quad [43] \qquad (2.3)$$

Where *v(t)* is Gaussian noise and k_1 and k_2 are k-factors of LOS and specular signals respectively. Following equation (2.1), (2.2) and (2.3), we represent the polarization channel in satellite to ground communication by using the matrices representing LOS (L), specular (*S*), and diffuse (*D*) component is,

Where, $L = \begin{bmatrix} l_{11} & l_{21} \\ l_{12} & l_{22} \end{bmatrix}$, $S = \begin{bmatrix} s_{11} & s_{21} \\ s_{12} & s_{22} \end{bmatrix}$ and $D = \begin{bmatrix} d_{11} & d_{21} \\ d_{12} & d_{22} \end{bmatrix}$ respectively.

The total channel matrix can be represent as

$$H = \begin{bmatrix} l_{11} & l_{21} \\ l_{12} & l_{22} \end{bmatrix} \begin{bmatrix} \sqrt{\frac{k_{11}}{k_{11}+k_{12}+1}} & 0 \\ 0 & \sqrt{\frac{k_{21}}{k_{21}+k_{22}+1}} \end{bmatrix} + \begin{bmatrix} s_{11} & s_{21} \\ s_{12} & s_{22} \end{bmatrix} \begin{bmatrix} \sqrt{\frac{k_{12}}{k_{11}+k_{12}+1}} & 0 \\ 0 & \sqrt{\frac{k_{22}}{k_{21}+k_{22}+1}} \end{bmatrix} + \begin{bmatrix} d_{11} & d_{21} \\ d_{12} & d_{22} \end{bmatrix} \begin{bmatrix} \sqrt{\frac{1}{k_{11}+k_{12}+1}} & 0 \\ 0 & \sqrt{\frac{1}{k_{21}+k_{22}+1}} \end{bmatrix} \qquad (2.4)$$

It is noted the following;

a) k_{11}, k_{21} and k_{12}, k_{22} are the K-factors of the direct and specular polarized channel components respectively. We define different k-factors for different polarizations.
i) Vertical polarization (k_{11} and k_{12}).
ii) Horizontal polarization (k_{21} and k_{22})
The elements of the matrix L, which are denoted as $l_{i,j}$ (i,j =1,2) are fixed complex numbers, satisfying

$$\varepsilon\|l_{11}\|^2 = 1-\beta_1,\ \varepsilon\|l_{12}\|^2 = \beta_1,\ \varepsilon\|l_{22}\|^2 = \beta_2,\ \varepsilon\|l_{21}\|^2 = 1-\beta_2 \quad [44] \qquad (2.5)$$

Where, β_1 and β_2 are the LOS component and signal strength. The parameters $0\le \beta_1 \le 0.5$ and $0\le \beta_2 \le 0.5$ are directly related to the XPD of the fixed channel matrix part, and are a function of the antenna's ability to separate the orthogonal polarization. The XPD is defined as the power ratio of the received portions of the co-polarized transmitted signal to the cross-polarized transmitted signal.

Typically, the elements of LOS matrix can be written as;

$$l_{11} = \sqrt{1-\beta_1}(\cos\phi_{11} + i\sin\phi_{11}),\quad l_{22} = \sqrt{1-\beta_2}(\cos\phi_{22} + i\sin\phi_{22}) \qquad (2.6)$$

$$l_{12} = \sqrt{1-\beta_1}(\cos\phi_{12} + i\sin\phi_{12}),\ l_{21} = \sqrt{1-\beta_2}(\cos\phi_{21} + i\sin\phi_{21}) \quad [45] \qquad (2.7)$$

Where the distributions of $\emptyset_{11}$, $\emptyset_{12}$, $\emptyset_{21}$ and $\emptyset_{22}$ are uniform over the interval [0, 2π].
Here, we assume equal path lengths of the horizontal and vertical polarized channels.
Thus, $\emptyset_{21}$=$\emptyset_{11}$=$\emptyset_{12}$=$\emptyset_{22}$.

The elements of the specular component S, which are denoted as $s_{i,j}$ (i,j=1,2) are also fixed complex numbers satisfying

$$\varepsilon\|s_{11}\|^2 = 1-\xi_1,\ \varepsilon\|s_{12}\|^2 = \xi_1,\quad \varepsilon\|s_{22}\|^2 = 1-\xi_2,\ \varepsilon\|s_{21}\|^2 = \xi_2 \qquad (2.8)$$

Where, ξ_1 and ξ_2 are specular component. The parameters $0\le \xi_1 \le 0.5$ and $0\le \xi_2 \le 0.5$ are related to reflection component and incident angle. A problem that can occur with specular components is that at low elevation angles, a significant portion of the multi path is likely to experience a reversal of polarization upon reflection, and the majority of the signal power will be received in the opposite polarization in circular polarization. On this case, the XPD parameters satisfy 0.5≤ ξ_1 ≤1 and 0≤ ξ_2 ≤0.5

The elements of the diffuse matrix D are modelled as zero mean, complex Gaussian random variables. The variances of elements of matrix D depends on the propagation conditions. In general, we set

$$\varepsilon\|d_{11}\|^2 = 1-\alpha_1,\ \varepsilon\|d_{12}\|^2 = \alpha_1,\ \varepsilon\|d_{22}\|^2 = 1-\alpha_2,\ \varepsilon\|d_{21}\|^2 = \alpha_2 \text{ [46]} \quad (2.9)$$

Where, α_1 and α_2 are directly related to the XPD of the diffuse signals and signal quality, hich are affected not only by the antennas ability to separate the orthogonal polarization, but also by the propagation environment. Signal cross-correlation is the other major parameter that characterizes the polarization channel.

Following the equation 2.3 and 2.4, 2.7, 2.8. To minimize the equation, we take only LOS signal part, where LOS channel matrix is multiplied with the Rician K-factor matrix to find the amplitude of the LOS signal.

$$H_{LOS} = \begin{bmatrix} l_{11} & l_{21} \\ l_{12} & l_{22} \end{bmatrix} \begin{bmatrix} \sqrt{\frac{k_{11}}{k_{11}+k_{12}+1}} & 0 \\ 0 & \sqrt{\frac{k_{21}}{k_{21}+k_{22}+1}} \end{bmatrix}$$

$$= \begin{bmatrix} l_{11}\sqrt{\frac{k_{11}}{k_{11}+k_{12}+1}} & 0 \\ 0 & l_{22}\sqrt{\frac{k_{21}}{k_{21}+k_{22}+1}} \end{bmatrix}$$

$$= \begin{bmatrix} \sqrt{1-\beta_1}\cos\phi_{11} + i\sin\phi_{11}\sqrt{\frac{k_{11}}{k_{11}+k_{12}+1}} & 0 \\ 0 & \sqrt{1-\beta_2}\cos\phi_{22} + i\sin\phi_{22}\sqrt{\frac{k_{21}}{k_{21}+k_{22}+1}} \end{bmatrix}$$

$$= \begin{bmatrix} H_{11} & 0 \\ 0 & H_{22} \end{bmatrix} \tag{2.10}$$

Where, $l_{11} = \sqrt{1-\beta_1}(\cos\phi_{11} + i\sin\phi_{11})$, $l_{22} = \sqrt{1-\beta_1}(\cos\phi_{22} + i\sin\phi_{22})$ and

$$H_{11} = \sqrt{1-\beta_2}\cos\phi_{11} + i\sin\phi_{11}\sqrt{\frac{k_{11}}{k_{11}+k_{12}+1}}, H_{22} = \sqrt{1-\beta_2}\cos\phi_{22} + i\sin\phi_{22}\sqrt{\frac{k_{22}}{k_{21}+k_{22}+1}}$$

H_{11}, H_{22} are the first and second co-polar channel component of two antennas.

The amplitude of LOS signal for H_{11} channel component as follows;

$$H_{11} = \sqrt{1-\beta_1}\sqrt{\frac{k_{11}}{k_{11}+k_{12}+1}}(\cos\phi_{11} + i\sin\phi_{11}) = \sqrt{1-\beta_1}\sqrt{\frac{k_{11}}{k_{11}+k_{12}+1}}e^{i\phi_{11}} \tag{2.11}$$

Where, amplitude $|H_{11}| = \sqrt{1-\beta_1}\sqrt{\frac{k_{11}}{k_{11}+k_{12}+1}}$, Phase: $\angle H_{11} = \emptyset_{11}$

Here, phase is neglected only amplitude is considered as a signal power. The another channel component H_{22}, the amplitude is found as followes;

$$H_{22} = \sqrt{1-\beta_2}\cos\phi_{22} + i\sin\phi_{22}\sqrt{\frac{k_{21}}{k_{21}+k_{22}+1}}$$

$$= \sqrt{\frac{k_{21}(1-\beta_2)}{k_{21}+k_{22}+1}}(\cos\phi_{22} + i\sin\phi_{22}) = \sqrt{\frac{k_{21}(1-\beta_2)}{k_{21}+k_{22}+1}}e^{i\varphi_{22}} \tag{2.12}$$

Where, amplitude $|H_{22}| = \sqrt{1-\beta_2}\sqrt{\frac{k_{21}}{k_{21}+k_{22}+1}}$, Phase: $\angle H_{22} = \emptyset_{22}$

For the reflected signal channel components, which will use as an interference signal power:

Reflected signal: $H_{11} = \sqrt{1-\xi_1}\sqrt{\frac{k_{12}}{k_{11}+k_{12}+1}}(\cos\phi_{11} + i\sin\phi_{11})$ (2.13)

Amplitude, $|H_{11}| = \sqrt{1-\xi_1}\sqrt{\frac{k_{12}}{k_{11}+k_{12}+1}}$ (2.14)

Diffuse signal channel components, which will use as an interference signal power:

$$H_{11} = \sqrt{1-\alpha_1}\sqrt{\frac{1}{k_{11}+k_{12}+1}}(\cos\phi_{11} + i\sin\phi_{11}) = \sqrt{1-\alpha_1}\sqrt{\frac{1}{k_{11}+k_{12}+1}}(e^{j\phi_{11}}) \quad (2.15)$$

Amplitude, $\left|H_{11}\right| = \sqrt{1-\alpha_1}\sqrt{\frac{1}{k_{11}+k_{12}+1}}$ (2.16)

We know that,

SINR (Signal to Interference plus Noise Ratio) $=\frac{\text{Signal Power}}{\text{Inferference Power+Noise Power}}$

The power of the signal comes from amplitude of LOS and The power of interference come from amplitude of reflection and diffused signals.

$$BER = \frac{1}{2}erfc\sqrt{\frac{SINR}{2}} \quad (2.17)$$

Following the equation of (2.11), (2.14) and (2.16) we get the SINR for the channel components H_{11}:

$$SINR = \frac{\left(\sqrt{\frac{k_{11}(1-\beta_1)}{k_{11}+k_{12}+1}}\right)^2}{\left[\left(\sqrt{\frac{k_{12}(1-\xi_1)}{k_{11}+k_{12}+1}}\right)^2+\left(\sqrt{\frac{1-\alpha_1}{k_{11}+k_{12}+1}}\right)^2\right]+\sigma_n^2} = \frac{\frac{k_{11}\left(1-\beta_1\left(\frac{E_b}{N_0}\right)\right)}{k_{11}+k_{12}+1}}{2\frac{E_b}{N_0}\left(\frac{k_{12}(1-\xi_1)+(1-\alpha_1)}{k_{11}+k_{12}+1}\right)+2} \quad (2.18)$$

Here, $\left(\sqrt{\frac{k_{11}(1-\beta_1)}{k_{11}+k_{12}+1}}\right)^2$ is the signal power from LOS signal,

$\left[\left(\sqrt{\frac{k_{12}(1-\xi_1)}{k_{11}+k_{12}+1}}\right)^2 + \left(\sqrt{\frac{1-\alpha_1}{k_{11}+k_{12}+1}}\right)^2\right]$ is the interference power combination of reflected and diffused signal and σ_n^2 is the noise power.Putting the equation of SINR we get the BER;

$$BER = \frac{1}{2} erfc \sqrt{\frac{SINR}{2}} = \frac{1}{2} erfc \sqrt{\frac{\frac{k_{11}(1-\beta_1)\frac{E_b}{N_0}}{k_{11}+k_{12}+1}}{\frac{4E_b}{N_0}\left(\frac{k_{11}(1-\xi_1)+(1-\alpha_1)}{k_{11}+k_{12}+1}\right)+4}}$$

(2.19)

Following the equation of (2.12), (2.14) and (2.17) we get the SINR for the channel components H_{22}:

$$SINR = \frac{\left(\sqrt{\frac{k_{22}(1-\beta_2)}{k_{21}+k_{22}+1}}\right)^2 P_{sig}}{\left[\left(\sqrt{\frac{k_{22}(1-\xi_2)}{k_{21}+k_{22}+1}}\right)^2 + \left(\sqrt{\frac{1-\alpha_2}{k_{21}+k_{22}+1}}\right)^2\right] P_{\text{int}} + \sigma_n^2} = \frac{\frac{k_{22}\left(1-\beta_2\left(\frac{E_b}{N_0}\right)\right)}{k_{21}+k_{22}+1}}{\frac{2E_b}{N_0}\left(\frac{k_{21}(1-\xi_2)+(1-\alpha_2)}{k_{21}+k_{22}+1}\right)+2}$$

(2.20)

Here, $\left(\sqrt{\frac{k_{22}(1-\beta_2)}{k_{21}+k_{22}+1}}\right)^2 P_{sig}$ is the signal power from LOS signal,

$\left[\left(\sqrt{\frac{k_{22}(1-\xi_2)}{k_{21}+k_{22}+1}}\right)^2 + \left(\sqrt{\frac{1-\alpha_2}{k_{21}+k_{22}+1}}\right)^2\right] P_{\text{int}}$ is the interference power combination of reflected and diffused signal and σ_n^2 is the noise power. Putting the equation of SINR we get the BER for channel component H_{22};

$$BER = \frac{1}{2} erfc \sqrt{\frac{SINR}{2}} = \frac{1}{2} erfc \sqrt{\frac{\frac{k_{22}(1-\beta_2)\frac{E_b}{N_0}}{k_{22}+k_{21}+1}}{\frac{2E_b}{N_0}\left(\frac{k_{22}(1-\varepsilon_2)+(1-\alpha_2)}{k_{22}+k_{21}+1}\right)+2}}$$

(2.21)

2.4 Conclusion

This chapter has presented a system model from satellite to ground link with a simple block diagram of 2×2 MIMO system and also block diagram of transmitter and receiver. Another main part of this chapter is theoretical analysis of 2×2 MIMO system from satellite tor ground link with the effect of cross-polarization. Where, step by step BER equation is formulated.

CHAPTER 3

PERFROMANCE ANALYSIS OF A (4×4) MIMO SYSTEM MODEL FROM SATELLITE TO GROUND LINK WITH EFFECT OF CROSS-POLARIZATION

3.1 Introduction

The multiple antenna technique, MIMO is a success story in wireless communication systems. One of the main features of MIMO is the utilization of the spatial dimension. The spatial dimension in MIMO brings significant performance improvement through array gain, spatial diversity, spatial multiplexing and interference avoidance.

When compared to older 2x2 antennas, the design complexity skyrockets. Nominal MIMO arrangements are the most frequent because most manufacturers are unable to provide four unique polarizations. Individual antenna elements are instead subjected to extensive simulation in order to establish the best location within the radome for spatial separation, ECC, and inter-port isolation. Building passive 4x4 MIMO external antennas for purposes like cell edge connectivity or fixed wireless access is likewise no longer feasible. Instead than using additional wires and connectors, active elements are incorporated within the 4x4 array.

Currently, satellite positioning reporting engineering application is using radio short message communication system [50]. Cross-polarization is an interference for satellite communication if antennas are axially placed asymmetric and signal strength can be zero when antennas are placed symmetric [51]. Above 10 GHz, cross-polarization are considered one of the causes of propagation impairments [52]. In satellite communication, BER decrease the average receives intensity for uplink and waveform distortion due to the spot dancing [53]. MIMO are widely used in ka and ku band in satellite communication. Although, it is very critical to establish MIMO channel in clear and rainy environment at ka band [54]. In short distance MIMO is studying at 60 GHz in indoor and outdoor clear environment [55].

In this paper, we analyze the BER (Bit Error Rate) with the effect of cross-polarization considering 4×4 MIMO satellite to ground link under four different areas such as open area, sub-urban area, urban area and aeronautical/marine area.

3.2 System model

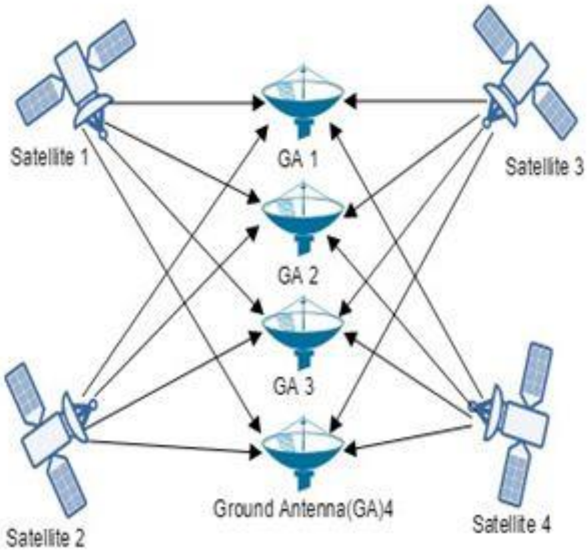

Fig. 3.1: Satellite to ground communication link

Fig. 3.1 shows the four satellites to four ground communication system. In contrast to the SISO (Single Input Single Output) communication system where it has one transmit antenna and one receive antenna, 4×4 MIMO systems has 4 transmit antennas and 4 receive antennas, as shown in Fig.3.2. This 4×4 MIMO input and output relation between transmit signal vector and receive signal is

$$y(t) = \int_{\tau}^{0} H(t,\tau)d\tau + n_i(t) \qquad (3.1)$$

Where, H(t, τ) represents time varying channel matrix, whose elements$h_{i,j}$ (t, τ)(i=1 2 3 4) and (j=1 2 3 4), denotes the time varying channel parameter form four transmitting antenna to four receiving antenna, τ denotes as delay, and n_i(t) is a noise vector, whose variance is $\sigma^2_{n_i}(t)$ and mean is zero. As the time invariant channel, so the eq^n (3.1) is simplified as eq^n (3.2) [50]

$$y(t) = Hx(t) + n(t) \qquad (3.2)$$

In eq^n (3.2), H means channel matrix and x(t) transmit signal. In receiver side, it both co-polar component and cross-polar (magnetic signal perpendicular to the electrical signal) component receives. According to the propagation signal path, territory can be divided as four like, open area, sub-urban area, urban area and marine area. In this system, we experiment with different values of polarization components in each area.

After that, compare the receiver sensitivity and power penalty for four by four MIMO satellite to ground link communication system.

3.3 Theoretical Analysis of a (4×4) MIMO System Model from Satellite to Ground Link with Effect of Cross-Polarization

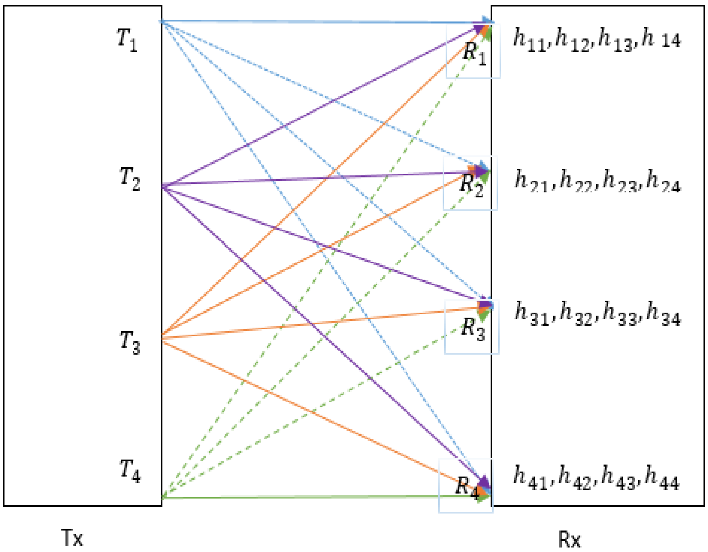

Fig. 3.2: 4×4 MIMO diversity model of satellite to ground link

The receive signal can be written as 4×4 MIMO System R=HA+V, Where R is the receive signal vector R=$[r_{11}, r_{12}, \ldots \ldots r_{44}]$, H is the channel matrix, A is the

Transmitted signal vector A= $[a_{11}, a_{12} \ldots \ldots a_{44}]$ and V is the noise vector

$$V=[v_{11}, v_{12} \ldots \ldots v_{44}]. \quad H=\begin{bmatrix} h_{11} & h_{21} & h_{31} & h_{41} \\ h_{12} & h_{22} & h_{32} & h_{42} \\ h_{13} & h_{23} & h_{33} & h_{43} \\ h_{14} & h_{24} & h_{34} & h_{44} \end{bmatrix} \tag{3.3}$$

The channel matrix H is the combine of co-polar and cross-polar components. Here, h_{11}, h_{22}, h_{33} and h_{44} are the co-polar components and remaining are the cross-polar components. In this 4× 4 MIMO system, a receive signal travel the three separate paths i.e Line-of-sight (LOS), Reflection and Diffuse path. The receiver will receive the signals including cross-polarization effect. In order to minimize the cross-polarization effect the receive signal is detected with time varying envelope k-factors can be expressed as;

$$y = \sqrt{\frac{k_1}{k_4 + k_3 + k_2 + k_1}} L(t) + \sqrt{\frac{k_2}{k_4 + k_3 + k_2 + k_1}} S(t) + \sqrt{\frac{1}{k_4 + k_3 + k_2 + k_1}} D(t) + v(t) \tag{3.4}$$

where v(t) is the Gaussian noise, L(t) is the LOS signal, S(t) is the reflection signal and D(t) is the diffuse signal. $k_1,\ k_2,\ k_3\ and\ k_4$ are the k-factors of LOS, reflected and other diffused signals respectively. We assume, the polarization scattering matrix for 4 ×4 MIMO system,

$$L = \begin{bmatrix} l_{11} & l_{21} & l_{32} & l_{41} \\ l_{12} & l_{22} & l_{32} & l_{42} \\ l_{13} & l_{23} & l_{33} & l_{43} \\ l_{14} & l_{24} & l_{34} & l_{44} \end{bmatrix}, S = \begin{bmatrix} s_{11} & s_{21} & s_{32} & s_{41} \\ s_{12} & s_{22} & s_{32} & s_{42} \\ s_{13} & s_{23} & s_{33} & s_{43} \\ s_{14} & s_{24} & s_{34} & s_{44} \end{bmatrix}, D = \begin{bmatrix} d_{11} & d_{21} & d_{32} & d_{41} \\ d_{12} & d_{22} & d_{32} & d_{42} \\ d_{13} & d_{23} & d_{33} & d_{43} \\ d_{14} & d_{24} & d_{34} & d_{44} \end{bmatrix}$$

Where L, S and D, are the LOS Reflection and Diffuse signal vector respectively. The diagonal K-factors can be written as for LOS signal

$$A_{11} = \sqrt{\frac{k_{11}}{k_{11} + k_{12} + k_{13} + k_{14} + 1}}, A_{22} = \sqrt{\frac{k_{12}}{k_{21} + k_{22} + k_{23} + k_{24} + 1}}$$

$$A_{33} = \sqrt{\frac{k_{13}}{k_{31} + k_{32} + k_{33} + k_{34} + 1}} A_{44} = \sqrt{\frac{k_{14}}{k_{41} + k_{42} + k_{43} + k_{44} + 1}}$$

And reflected signal k-factors are given below; which gives the proper channel characteristic

$$B_{11} = \sqrt{\frac{k_{11}}{k_{11} + k_{12} + k_{13} + k_{14} + 1}},\ B_{22} = \sqrt{\frac{k_{22}}{k_{21} + k_{22} + k_{23} + k_{24} + 1}},$$

$$B_{33} = \sqrt{\frac{k_{33}}{k_{31} + k_{32} + k_{33} + k_{34} + 1}},\ B_{44} = \sqrt{\frac{k_{44}}{k_{41} + k_{42} + k_{43} + k_{44} + 1}}$$

And Diffused signal k-factors are given below; this K-factor will multiply with LOS component channel that will gives the interference signal power.

$$C_{11} = \sqrt{\frac{1}{k_{11} + k_{12} + k_{13} + k_{14} + 1}},\ C_{22} = \sqrt{\frac{1}{k_{21} + k_{22} + k_{23} + k_{24} + 1}},$$

$$C_{33} = \sqrt{\frac{1}{k_{31} + k_{32} + k_{33} + k_{34} + 1}},\ C_{44} = \sqrt{\frac{1}{k_{41} + k_{42} + k_{43} + k_{44} + 1}}$$

The K-factor component of LOS channel, reflection channel and diffused channel are substitute in equation 3.5.

The desired channel matrix can be written as

$$H = L\begin{bmatrix} A_{11} & 0 & 0 & 0 \\ 0 & A_{22} & 0 & 0 \\ 0 & 0 & A_{33} & 0 \\ 0 & 0 & 0 & A_{44} \end{bmatrix} + S\begin{bmatrix} B_{11} & 0 & 0 & 0 \\ 0 & B_{22} & 0 & 0 \\ 0 & 0 & B_{33} & 0 \\ 0 & 0 & 0 & B_{44} \end{bmatrix} + D\begin{bmatrix} C_{11} & 0 & 0 & 0 \\ 0 & C_{22} & 0 & 0 \\ 0 & 0 & C_{33} & 0 \\ 0 & 0 & 0 & C_{44} \end{bmatrix} \tag{3.5}$$

Where, A, B and C indicating the Rician K-factor for different Tx and Rx combination.

We considering here line-of-sight path; which is $H_{LOS}=L\begin{bmatrix} A_{11} & 0 & 0 & 0 \\ 0 & A_{22} & 0 & 0 \\ 0 & 0 & A_{33} & 0 \\ 0 & 0 & 0 & A_{44} \end{bmatrix}$

After multiplying the L with K-factor matrix we found the SINR equation that is;

$$SINR = \frac{\left(\sqrt{\frac{k_{11}(1-\beta_1)}{k_{11}+k_{12}+k_{13}+k_{14}+1}}\right)^2 P_{sig}}{p_{\text{int}}\left\{\left(\sqrt{\frac{k_{12}(1-\xi_1)}{k_{11}+k_{12}+k_{13}+k_{14}+1}}\right)^2+\left(\sqrt{\frac{(1-\alpha_1)}{k_{11}+k_{12}+k_{13}+k_{14}+1}}\right)^2\right\}+\sigma_n^2} \tag{3.6}$$

The SINR equation is substituted in BER equation; which are evaluated in matlab simulation

$$BER = \frac{1}{2}erfc\sqrt{\frac{\frac{k_{11}(1-\beta_1)}{k_{11}+k_{12}+k_{13}+k_{14}+1}}{2E_bN_0\left(\frac{k_{11}(1-\xi_1)+(1-\alpha_1)}{k_{11}+k_{12}+k_{13}+k_{14}+1}\right)+2}} \tag{3.7}$$

This BER equation is simulated with matlab software varying the component of LOS (β) while, other components remain constant.

3.4 Conclusion

In this chapter, briefly introduce 4×4 MIMO system and a system model is showed of 4 satellite and 4 ground antennas. Therefore, theoretical analysis is done for 4×4 MIMO satellite to ground link with the effect of cross-polarizations. To generate the BER equation, first of all three diagonal matrixes is generated for three different areas like LOS, Reflection and Diffused area.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter is one of the core chapter of this thesis. After SINR and BER equation derivation of MIMO system, matlab simulation has done and the result is examined with the several environmental parameter variations. We assess the BER performance and power penalty in four different areas (open are, suburban area and urban area) with the effect of cross-polarization in MIMO antenna system.

4.2 Performance Results of (2×2) MIMO with Cross-Polarization

Following the analytical model for satellite to ground link, we evaluate the SINR and BER performance results for different satellite MIMO link parameters and four separate area i.e. open area, suburb area, urban area and aero/marine area.

4.2.1 Performance results of (2×2) MIMO with the effect of cross-polarization and variation of line-of-sight (LOS) components (β)

Table 4.1: Some Important Parameters for 2×2 MIMO for LOS components (β)

Parameters Name	**Value**
K-factors direct components (k_{11})	200,60,50,40
K-factors specular components (k_{12})	0
LOS signal components (β)	0.1-0.5
Reflected signal components (ξ)	0.3
Diffused signal component (α)	0.4
SINR (dB)	14-25

The above table shows some necessary parameters and values, which are needed to simulate. The numerical values are taken from reference paper [48]. The four different region indicate the four several values of K-factors. The table also illustrate three channel component range i.e. LOS component, reflection and diffused components.

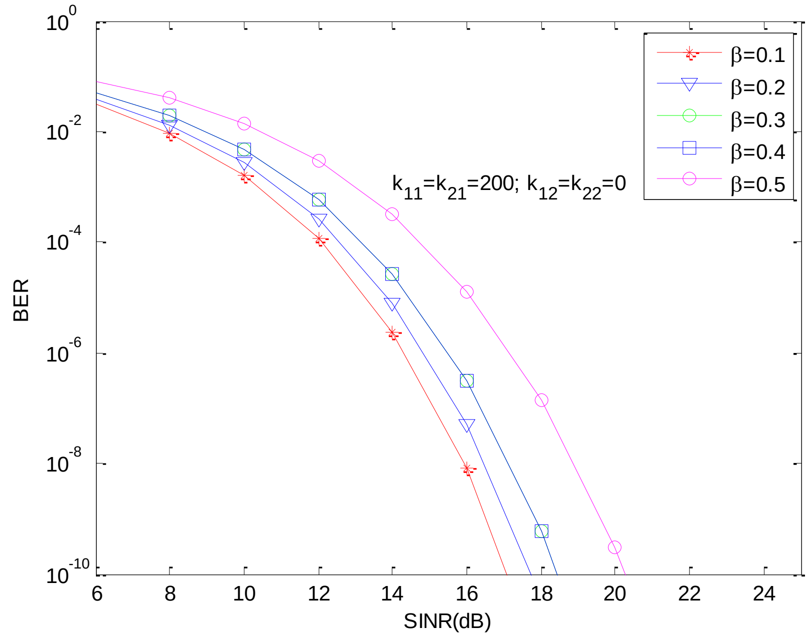

Fig. 4.1: BER VS. SINR for different value of LOS co-efficient (β) in open area for a satellite to ground link.

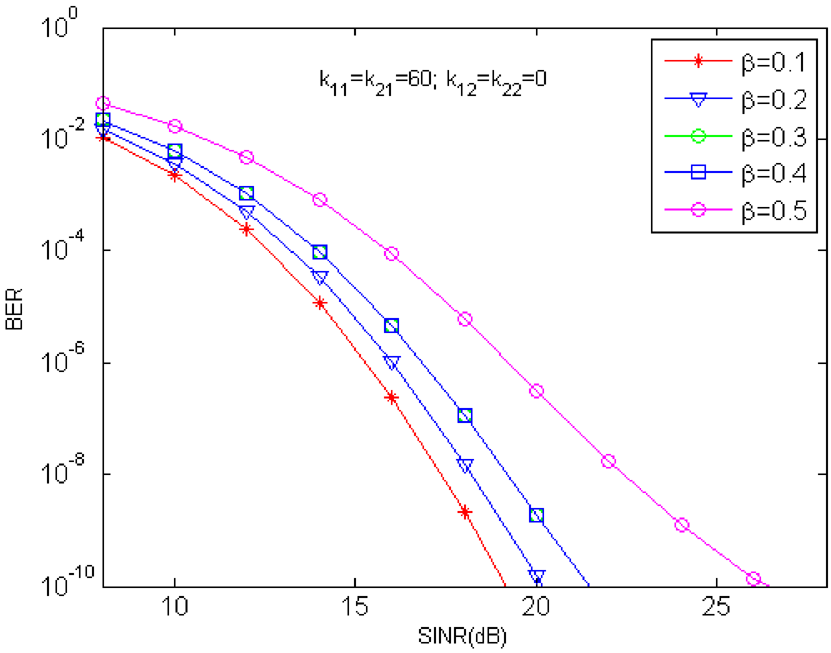

Fig. 4.2: BER vs. SINR for suburban area for a satellite to ground link.

In case of Fig.4.1, the polarization channel matrix is simulated with the following parameters: Rician K-factor $k_{11} = k_{21} = 200$ and $k_{12} = k_{22} = 0$ (neglecting specular components); XPD of the direct components, $\beta = 0.1 - 0.5$; XPD of the diffuse components, α=0.4; These values are typical for open environments. The plot of BER using SINR (dB) are shown in Fig. 4.1. for the different values of LOS component β and k_{11} direct polarized channel components and k_{12} is the specular polarized components. It is observed that BER improve with increase in SINR but degrades with increase in cross-polarization component β due to the crosstalk induced by cross-polarization are found strong form the plots and it is noticed that a higher value of β gives the higher SINR. The preceding experiment is repeated with Rician K-factor $k_{11} = k_{21} = 60$ and $k_{12} = k_{22} = 0$, which is typical for suburban areas. The XPDs are selected as following: $\beta = 0.1 - 0.5$, α=0.4, ξ=0.3. The plots (Fig. 4.2.) of BER vs. SINR for suburban area show that performance of bit error rate is about 10^{-10} when the value of polarization component declined from 0.1 to 0.5. On the other hand, if the value of LOS component (β) is increased then BER of the receive signal is decreased. It is also observed that the SINR become higher than open area.

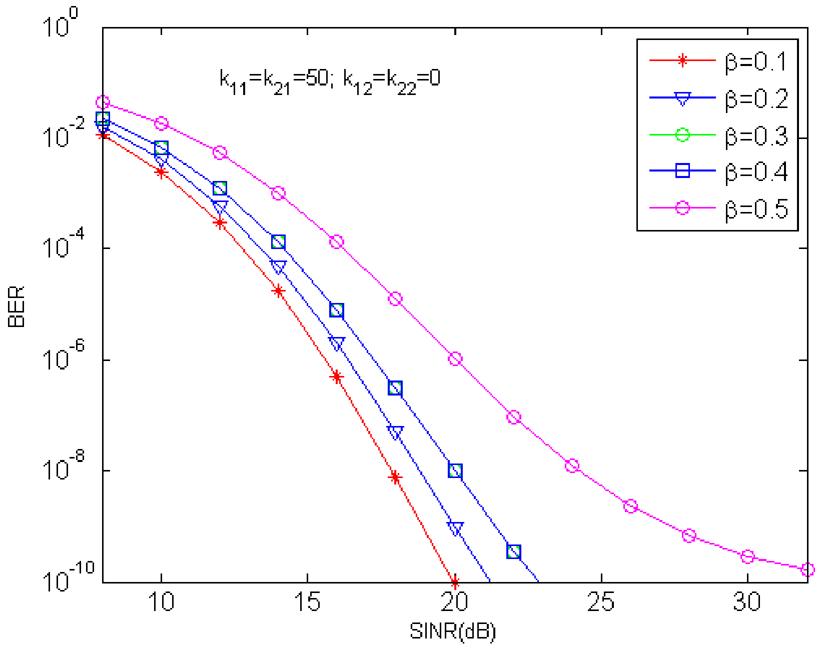

Fig. 4.3: BER vs. SINR for urban area for a satellite to ground link.

Similarly, Rician K-factor $k_{11} = k_{21} = 50$ and $k_{12} = k_{22} = 0$, which is typical for urban areas. The XPDs are selected as following: : $\beta = 0.1 - 0.5$, α=0.4, ξ=0.3. Urban area and aeronautical/marine area (Fig. 4.3-4.4) are depicted for system parameters shown in the graph. Where urban area shows the higher BER that is approximately 10^{-10}

but marine area provides 10^{-7} at polarization component 0.1. It is also noticeable that Rician K-factor has great impact in each separate area. When the value of k-factors both direct component and specular component are changed then BER of receive signal is proportionally changed. In open area, for example, specular component of k-factor is considered zero then we notice huge increase of BER which is maximum than all other experimental area.

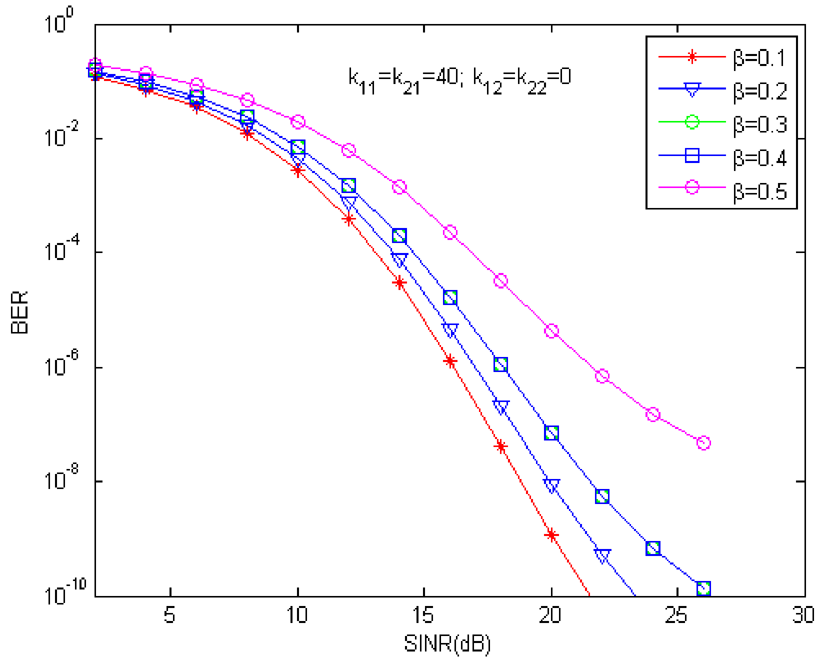

Fig. 4.4: BER vs. SINR for aero/marine area for a satellite to ground link.

It is noticed that the satellite link performance is mostly affected by cross-polarization effect in marine and least affected in open area environment. Although direct component of K-factor K_{11} =40, and specular component of k-factor K_{12} =0. As the specular component is higher that's why it also affects the BER performance to the aeronautical and marine area. The BER is become stable for β=0.5 at 10^{-7}, while BER is decreased for β=0.4, 0.3, 0.2, 0.1 and SINR also decline according to the value of LOS components β. The plots of receiver sensitivity in terms of SINR (dB) are shown in Fig. 4.5 for different environmental conditions. It is also observed that satellite link suffers significantly due to cross-polarization effect which results in power penalty.

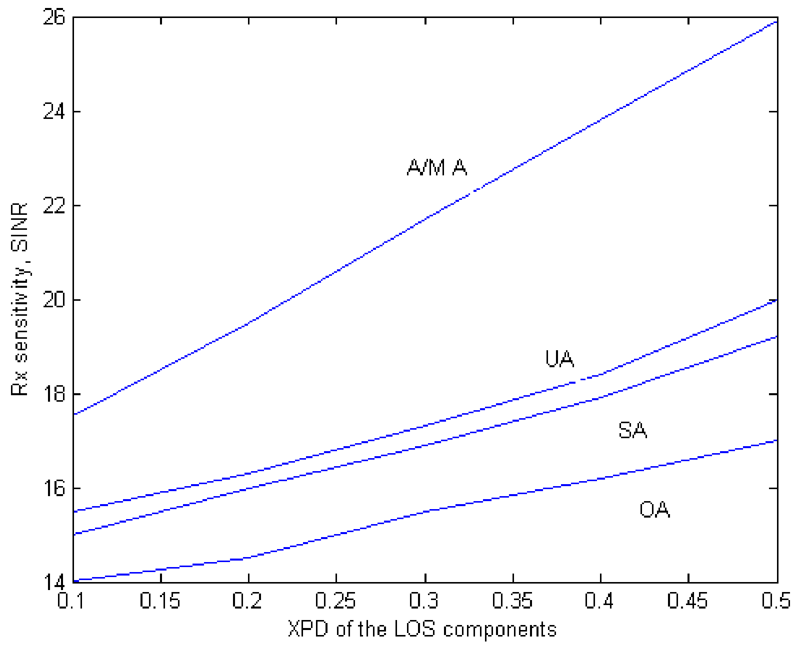

Fig. 4.5: Rx sensitivity vs. XPD of Line-of-sight (LOS) component (β) for satellite to ground link.

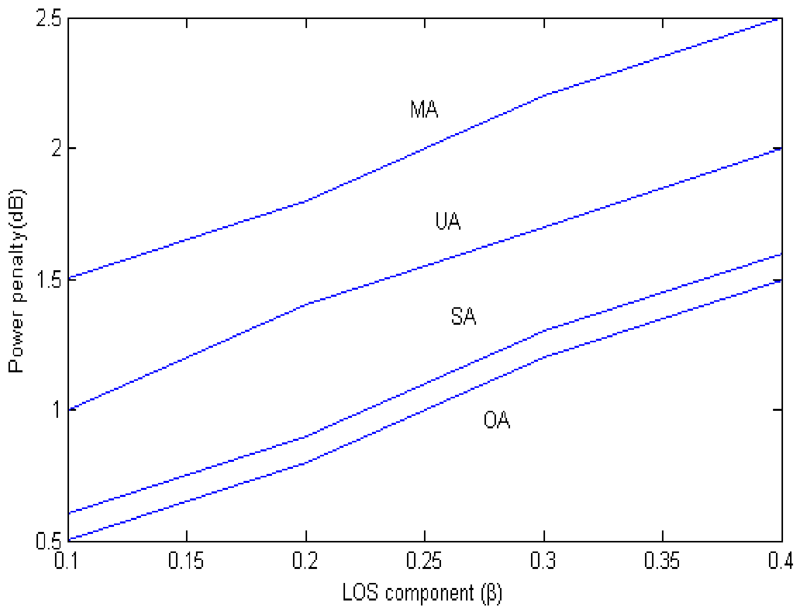

Fig. 4.6: Power penalty vs. XPD of Line-of-sight (LOS) component (β) for a satellite to ground link.

Receiver sensitivity is one of the most important specifications of any radio receiver whether it is used telecommunication broadcast or any other form of wireless communications. The ability of radio receiver to pick up the required level of radio signals will enable it to operate more effectively within its application. The selectivity and amplification of certain level are the main requirement to be a perfect receiver. Fig. 4.5 gives us information that from four different areas, such as open area, sub-urban area, urban area and aero/marine area, open area provides the sensitivity at the receiver, which is 14 dB and Other shows 15dB, 15.5dB, and 17.5 dB respectively. Whenever the ratio of bits per second per hertz is increased, there is generally a penalty to be paid in terms of power. In case of satellite communication, dc power of satellite increase same percentage. The plot 4.6 shows the power penalty is suffered by the SA, UA and marine area over the OA environment. It is formed that penalty is about 0.5 dB, 1dB, 1.5 dB and 2dB for SA, UA and A/M A respectively for $\beta = 0.3$. It is clear that power penalty is lower at open area but higher in aeronautical and marine area. The power penalty rises proportionally with the value of different area component. Comparatively, aero/marine area penalty curve is highest than others. On the other hand open area penalty curve is slightly increased.

4.2.2 Performance results of (2×2) MIMO with cross-polarization with the variation of diffuse components (α)

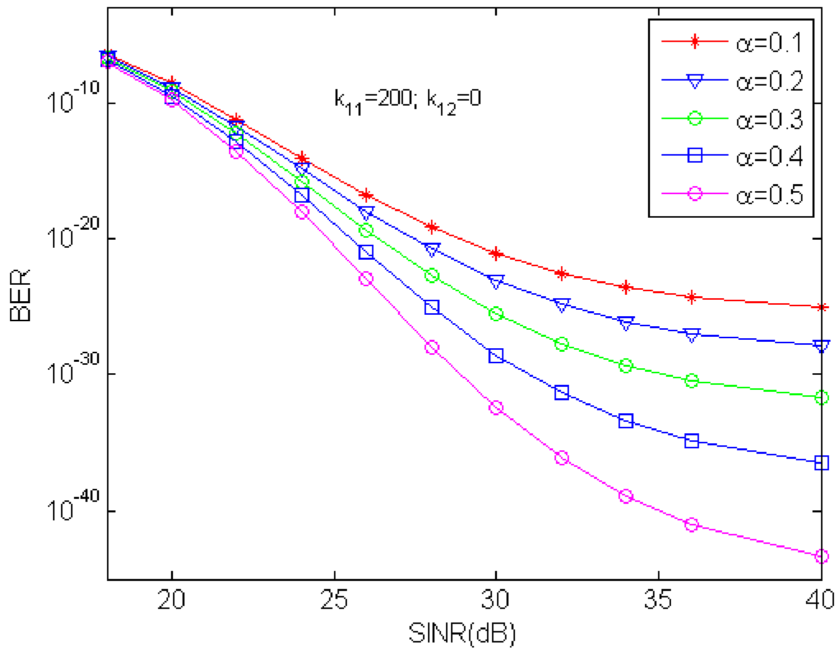

Fig. 4.7: BER vs. SINR for open area with the variation of diffused components (α) for a satellite to ground link.

In this satellite to ground system model, the receive signal has three parts line-of-sight part, reflection part and diffuse part are considered. Subsection 4.2.1 describes the line-of-sight part, where LOS component β is varied from 0.1 − 0.5 but in this subsection analysis has done by varying the diffused components α. Here diffused component values are varied from 0.1 − 0.5 and SINR is not decreased for the lower components values. The four different territories are considered Fig. 4.7 shows the results of open area. This is the BER vs SINR curve, where k_{11}=30; k_{12}=0 are the typical value for the open area. At 10^{-4}, SINR varies from 17 dB to 22 dB and for the 0.1 value of α SINR is maximum 22 dB.

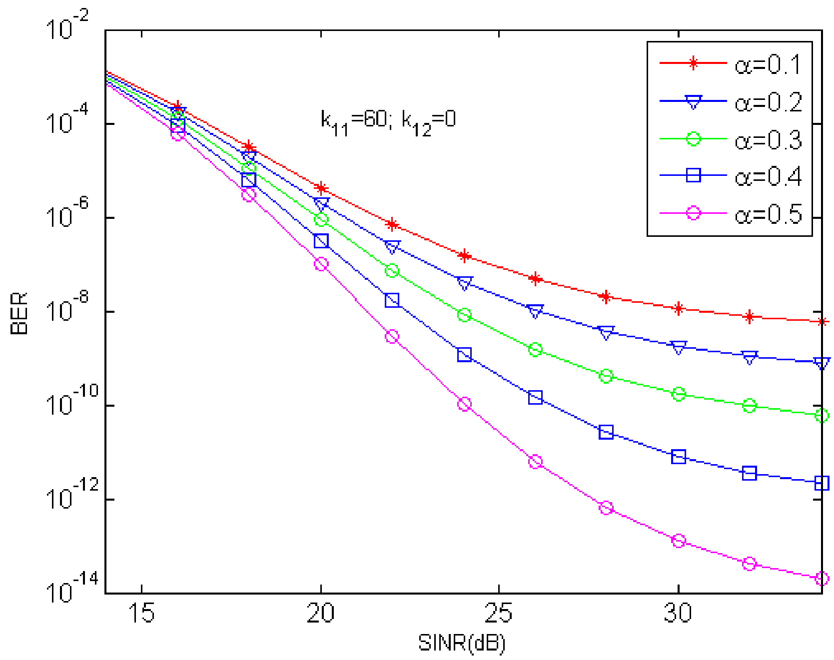

Fig. 4.8: BER vs. SINR for sub-urban area with the variation of diffused components (α) for a satellite to ground link.

The above curve indicates the BER vs. SINR for sub-urban area with the variation of diffused components (α) for a satellite to ground link for the similar variation of diffused component α from 0.1 − 0.5 but it gives the little different in SINR values than open area. In this area SINR increase 15.9 dB to 21.8 dB at 10^{-3} Bit Error Rate. The typical values for the sub-urban area is k_{11}=20 and k_{12}=0. For reflection component α=0.1 it becomes floor BER at 10^{-8}. Similarly, when reflection component is 0.4, 0.5 the BER is 10^{-10} and 10^{-12} respectively.

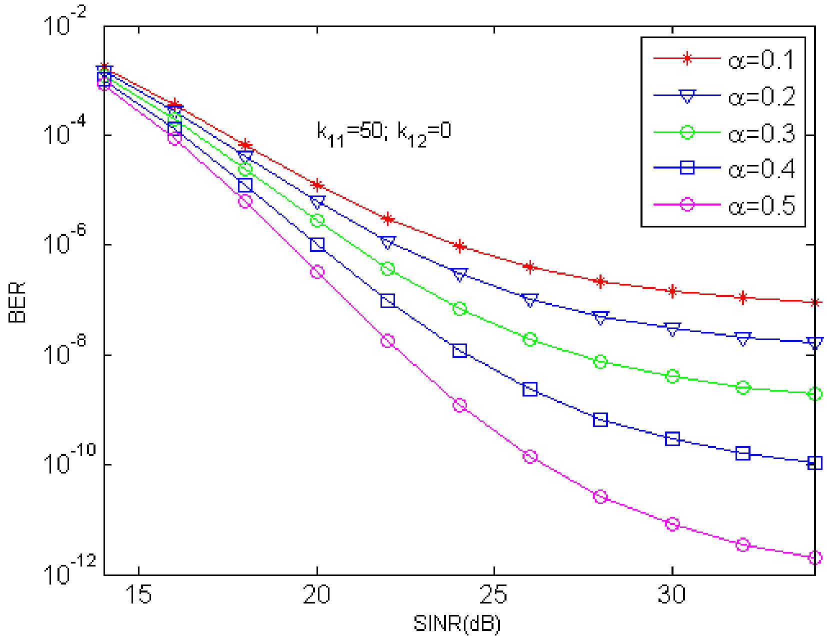

Fig. 4.9: BER vs. SINR for urban area with the variation of diffused components (α) for a satellite to ground link.

The above figure is illustrated for two components one is direct component another is specular component of rician k-factor in MIMO channel. Where direct component value is considered as k_{11}=10; and specular components is considered k_{12}=0 for urban area.

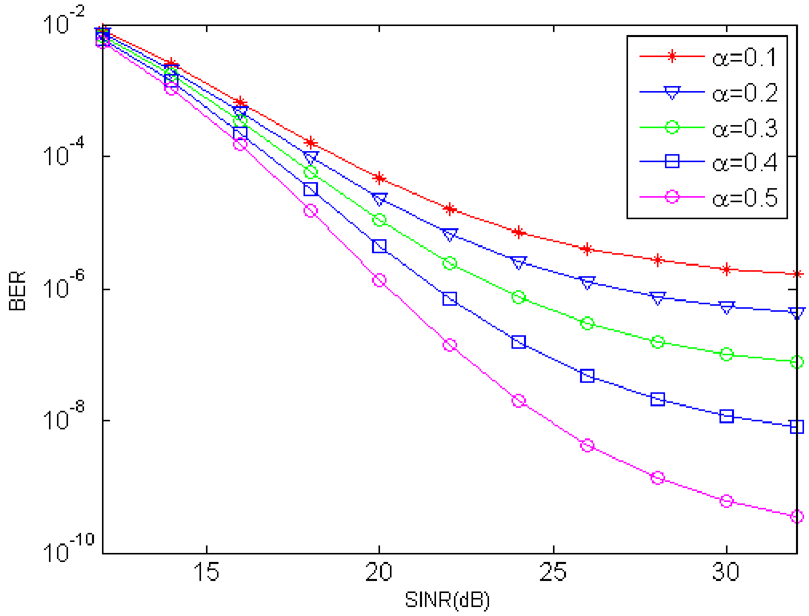

Fig. 4.10: BER VS. SINR for aeronautical/marine area with the variation of diffused components (α) for a satellite to ground link.

The above figure illustrate that BER compare to the SINR (dB) for aeronautical/ marine area for the different numerical value of diffused components for satellite to ground link. Square and circle symbol is used to clarify the BER curve for the several values. Such as square sign is used for the value of α=0.1. It is noticed that marine area shows the highest BER and lowest SINR.

4.2.3 Performance results of (2×2) MIMO with cross-polarization with the variation of reflection components (ξ)

In this thesis, Binary Phase Shift Keying (BPSK) modulation technique is used to get the performance of MIMO system. The reflection components (ξ) of the channel are considered as interference. For (2×2) MIMO system we simulate this reflection component (ξ) for different numerical values.

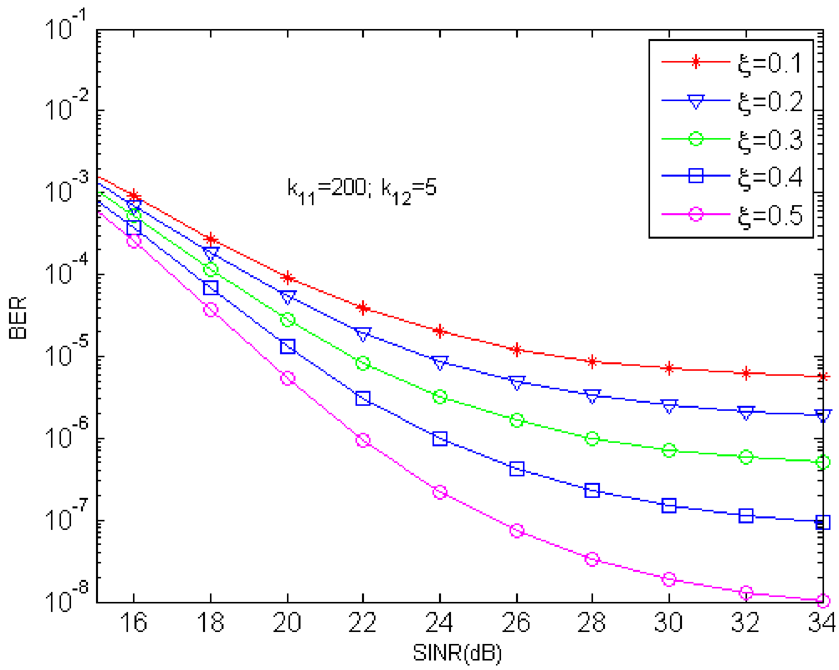

Fig. 4.11: BER vs. SINR for open area with the variation of reflection components (ξ) for a satellite to ground link.

The bit error rate performance derived as a function of SNR for (2×2) MIMO STBC multiplexing signal detector system. It is assumed the co-polar component h_{11}=200 and cross polar component h_{12}=0 which identify that this is the urban area. The figure describes that at 10^{-5} BER the curve is become floor. If I slightly increase the value of diffused component 0.1-0.5 each curve gives the higher BER rate. Fig. 4.11 shows that if decreased the reflection component's value $0.1 - 0.5$ respectively then the SINR (dB) also reduced. But BER does not change noticeably.

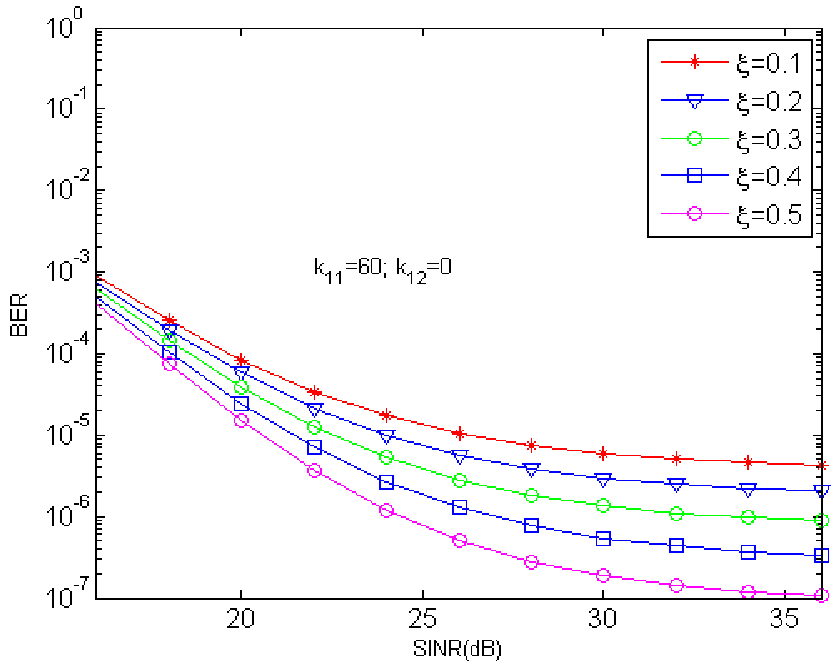

Fig. 4.12: BER vs. SINR for sub urban area with the variation of reflection components (ξ) for a satellite to ground link.

The above graph shows the Bit Error Rate vs SINR (dB) for several values of reflection components. It is assumed the co-polar component h_{11}=60 and cross polar component h_{12}=0 which identify that this is the urban area. The figure describes that at 10^{-5} BER the curve is become floor. If I slightly increase the value of diffused component 0.1-0.5 each curve gives the higher BER rate. The lowest value of reflection components shows the low SINR (dB) and highest value of reflection components shows the maximum SINR (dB). When the value of reflection components is 0.1 that gives the SINR 17 dB and 0.5 gives more than 22 dB.

The figure 4.13 shows the BER vs. SINR curve for urban area with the variation of reflection components (ξ) for a satellite to ground link. It is assumed the co-polar component h_{11}=50 and cross polar component h_{12}=0 which identify that this is the urban area. The figure describes that at 10^{-4} BER the curve is become floor.

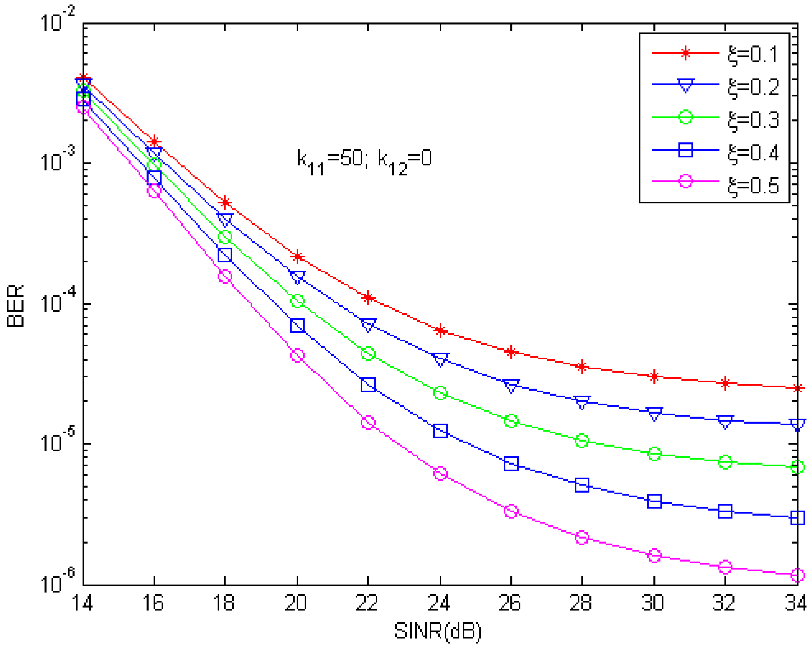

Fig. 4.13: BER vs. SINR for urban area with the variation of reflection components (ξ) for a satellite to ground link.

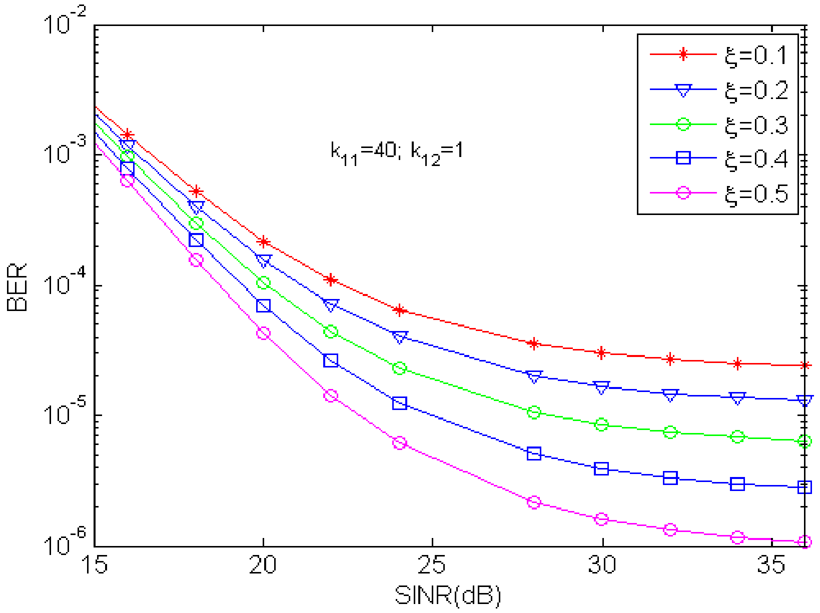

Fig. 4.14: BER vs. SINR for aeronautical/marine area with the variation of reflection components (ξ) for a satellite to ground link.

If I slightly increase the value of diffused component 0.1-0.5 each curve gives the higher BER rate for The Fig. 4.13. which describes that when the reflection component's value is 0.1. It gives the maximum SINR which approximately 24 dB. After increasing the value of reflection components that shows the lower SINR.

Fig. 4.14 describes the Bit Error Rate vs. SINR curve where vertical polarization components for example k_{11} =40 and horizontal polarization components k_{12} =1 is considered for aeronautical/marine area. But other three areas are assumed different values which is significant for each region. Both vertical and horizontal polarization make the cross polarization which seriously effect at the receive signal. BER becomes floor at range 10^{-4} to 10^{-6} with several reflection components values.

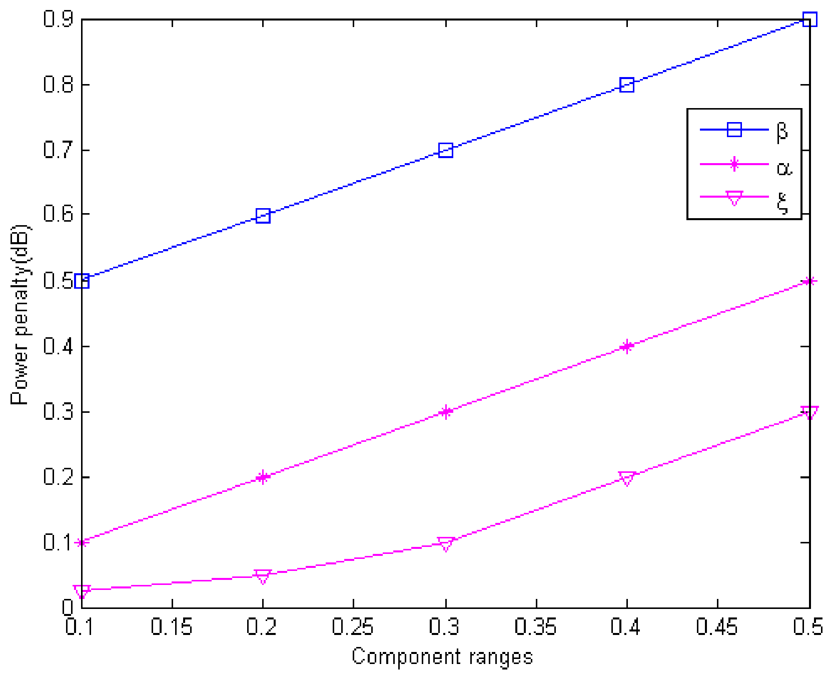

Fig. 4.15: power penalty vs the variation of LOS components (β), diffused components (α) reflection components (ξ) for a satellite to ground link.

The power penalty curve shows the power penalty comparison for three different channel components like LOS components (β), Reflection components (ξ) and Diffused components (α). The LOS component gives the higher power penalty which 0.5 dB to 0.9 dB than other diffused component is 0.1 dB to 0.5 dB and reflection component is less than 0.1dB to 0.3dB.

4.3 Performance Results of (4×4) MIMO with Cross-Polarization

Following the above theoretical analysis of 4×4 MIMO satellite to ground link, we evaluate the SINR and BER performance results for different link parameters and components in four separate areas i.e. open area, suburban area, urban area and marine area. The component factors and other relevant parameters [10] used in this paper are shown in Table 4.2.

Table 4.2: Some Important Parameters for 4×4 MIMO Satellite to Ground Link

Parameters Name	Value
K-factors direct components $(k_{11}, k_{22}k_{33}, k_{44})$	200,60,50,40
K-factors specular components (k_{12}, k_{13}, k_{14})	0
LOS signal component (β)	0.1-0.5
Reflected signal component (η)	0.3
Diffused signal component (α)	0.4
SINR (dB)	2-22

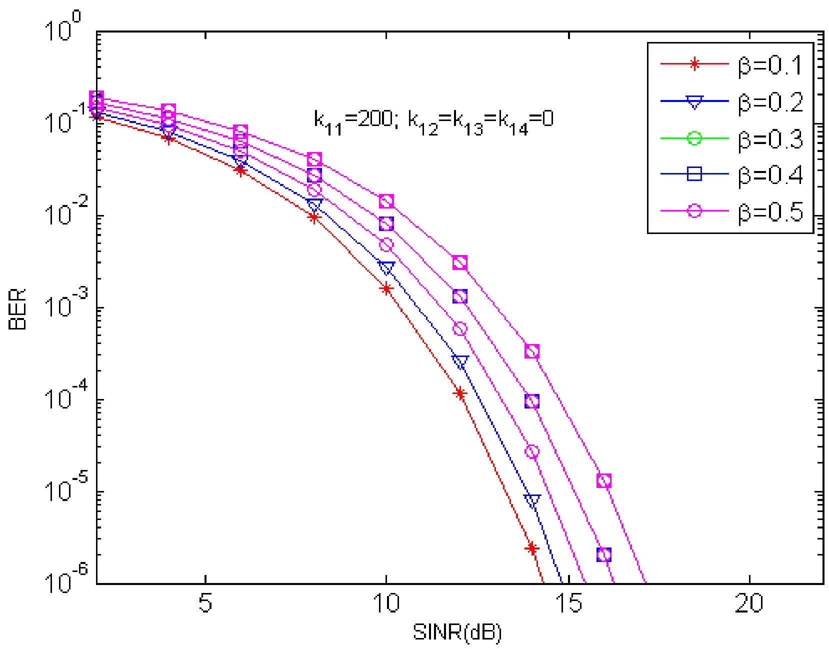

Fig. 4.16: BER vs. SINR for different value of LOS co-efficient (β) in Open area for a satellite to ground link.

The plot BER using SINR (dB) are shown in Fig. 4.16 for the different values of the XPD of the LOS components (β) and direct polarized channel components and specular channel components. It is observed that BER improve with the increase in SINR but degrades with the increment of cross-polarization component. However, Fig. 4.16 is simulated by assuming direct polarization components value of 200 and cross-polarization component 0. For the higher value of direct and cross-polarization parameters, BER curves are become floor as seen from the figure. It is also noticed that BER exhibits lower performance for the higher value of XPD components (β).

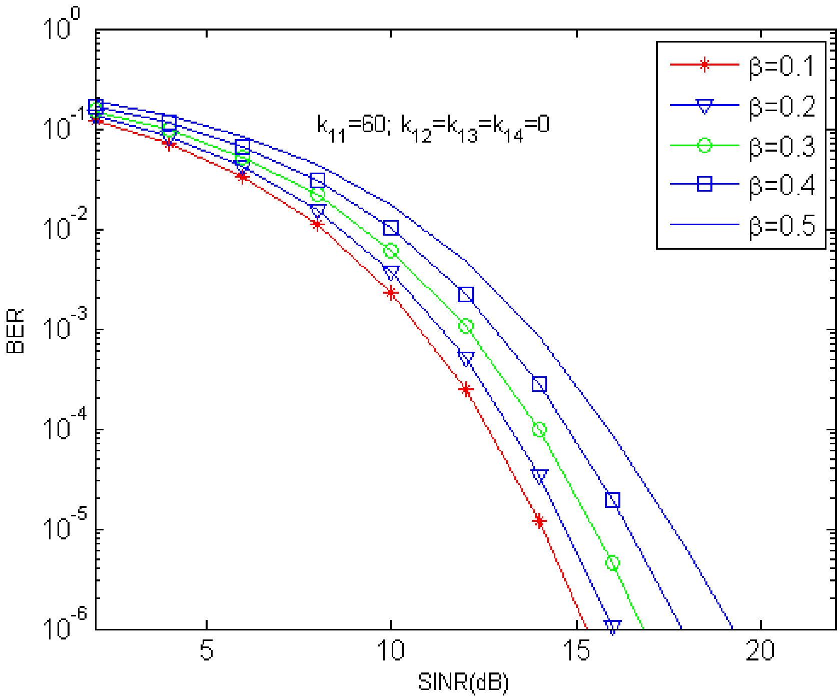

Fig. 4.17: BER vs. SINR in sub-urban area for a satellite to ground link.

Fig. 4.17 describes the BER vs. SINR curve in sub-urban area, where have some medium size buildings and tall trees and signal will scattered to reach the receiver. It is observed that the value of SINR is increasing with the value of XPD co-efficient β . In comparison with Fig. 4.17, the SINR value is found 22 dB and 19 dB for sub-urban area and open area respectively under β =0.5.

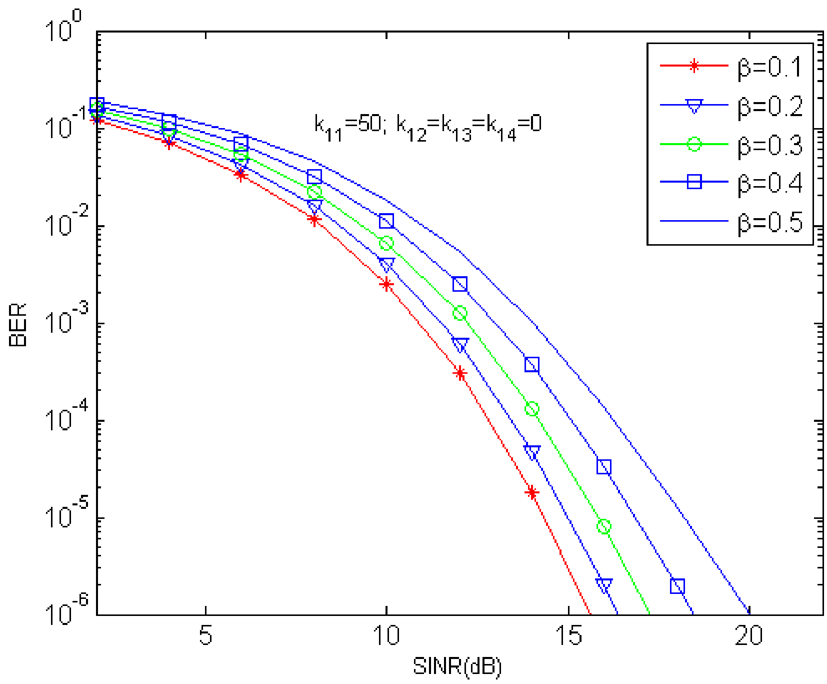

Fig. 4.18: BER vs. SINR in urban area for a satellite to ground link.

Fig. 4.18 illustrates the BER vs. SINR outcome for the urban areas varying β. he vertical component of the Rician K-factor is consider 50 and horizontal component is set zero. This figure also attained superior BER results over the other policies as evident from the figure. At 10^{-6} BER, the above diagram shows 16, 17, 18 and 19 dB approximate SINR for the fractional value of LOS component (β) which is 0.1, 0.2, 0.3 and 0.4 respectively. For β=0.5 curve gives the higher SINR value is 20 dB than others. It is noticed that better SINR as well as BER performance has been achieved for higher value of β in compared to that previous OA and SA schemes. The figure also describes that SINR is remain fixed for the value of XPD co-efficient (β) less than 0.1. Fig. 4.19 indicates the Bit Error Rate Versus SNR curve, where for the similar value of Line-of-sight components (β). The vertical component of the Rician K-factor is consider 50 and horizontal component is set zero. This figure also attained superior BER results over the other policies as evident from the figure. At 10^{-6} BER, the above diagram shows 16, 17, 18 and 19 dB SINR for the fractional value of LOS component (β) which is 0.1, 0.2, 0.3 and 0.4 respectively. For β=0.5 curve gives the higher SINR value than others.

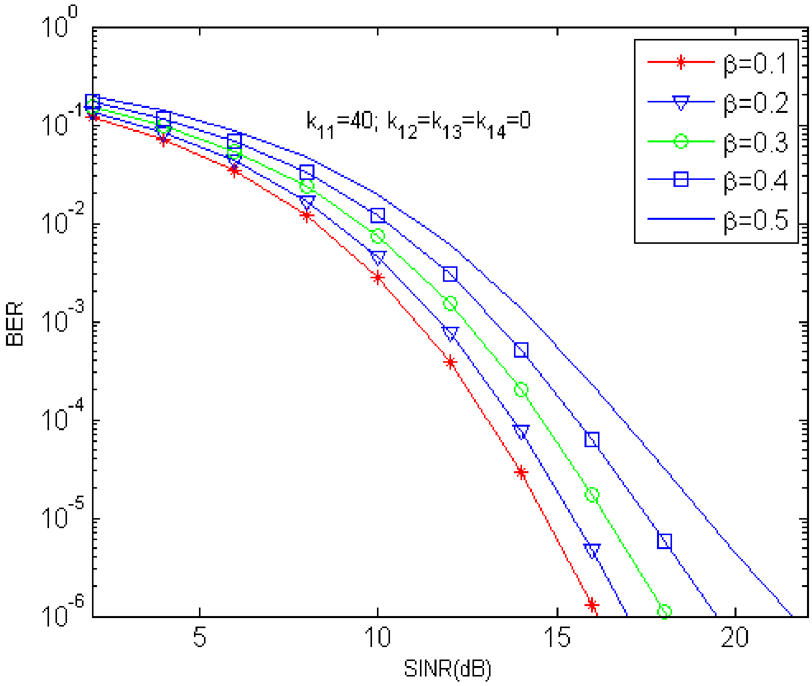

Fig. 4.19: BER vs. SINR in aeronautical/Marine area for a satellite to ground link.

Receiver sensitivity is very important metrics for wireless communication especially under noisy environment where the best accuracy is worth.

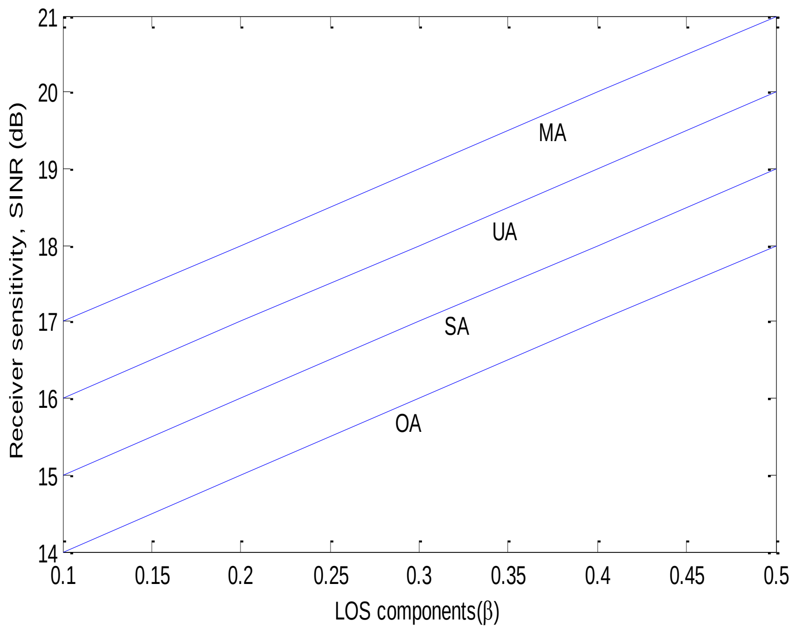

Fig. 4.20: Receiver sensitivity vs. XPD of the LOS component (β) in different area for a satellite to ground link.

Fig. 4.20 shows the Rx sensitivity in dB with XPD of the LOS components (β) for different network scenarios. As seen, RX sensitivity is more significant in open area over sub-urban area, urban area and aeronautical and marine areas. However, the SINR values at the receiver end are found 14 dB, 15 dB, 16 dB and 17 dB in four different area such as OA, SA, UA and A/MA respectively.

4.4 Power penalty comparison between 2×2 MIMO and 4×4 MIMO system

Firstly, we examined 2×2 MIMO system from satellite to ground link and power penalty is found 0.5 dB, 0.8 dB, 1 dB and 1.5 dB in OA, SA, UA and A/M area respectively in figure 4.6. According to Power penalty outcome in 2×2 MIMO settings,

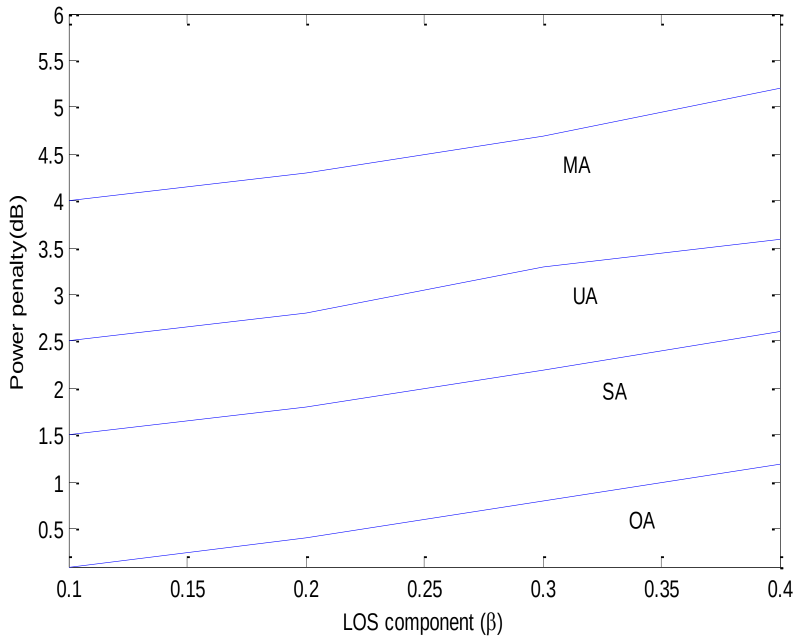

Fig. 4.21: Power penalty of (4×4) MIMO satellite to ground link.

We adopt (4×4) MIMO for attaining better power penalty performance especially under worst scenarios. Which power penalty are found 0.1 dB, 1.5 dB, 2.5 dB and 4 dB in OA, SA, UA and A/M area respectively. Moreover, a profound impact of (4×4) MIMO has been observed on receiver sensitivity analysis as evident from the Fig. 4.21

Table 4.3: Comparison of Power Penalty between (4×4) and (2×2) MIMO Configuration.

Experimental Region	**(2×2) MIMO power penalty**	**(4×4) MIMO power penalty**
Open area	0.5	0.1
Sub-urban area	0.8	1.5
Urban area	1	2.5
Aeronautical and Marian area	1.5	4.0

Table 4.3 and Fig.4.21 illustrate that power penalty is increased in each area such as suburban area, urban area, marine area for 4×4 MIMO satellite to ground link except open area. Here, open area gives the undesired value which is 0.1 dB lower than 2×2 MIMO satellite to ground link with the effect of cross polarization. The reason is reflection and diffused component both value is considered 0.3.

4.5 Conclusion

This chapter is divided into three sections: an introduction, a simulation of the 2×2 MIMO system, a simulation of the 4×4 MIMO system, and a comparison of the two MIMO systems. LOS co-efficient, diffused co-efficient, and reflection co-efficient were all altered and determined throughout the 2×2 MIMO system matlab simulation in four different territories: open area, sub-urban area, urban area, and aeronautical/marine region. It is also pointed out that which receive signal is sensible perspective to three co-efficient. Similarly, 4×4 MIMO system matlab simulation is done. After detecting and comparing the power penalty between two MIMO systems. The power penalty was also calculated, and the better system was readily defined. The conclusion and future works will be discussed in the following chapter.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The twenty-first century ushers in a new age of satellite communication. People all across the world may communicate with one another using a variety of technologies, but satellite communication is faster, more dependable, secure, and more effective. It performs well in distant areas when other communication technologies have failed. Network technology for high data rate, cross polarization effect, integrated space and terrestrial systems, heat dissipation materials, high frequency devices, and batteries are all problems that satellite communication is still confronting.

The effect of cross polarization and the power penalty caused by cross polarization in satellite communication are discussed in this thesis. An analytical model of MIMO system is developed from satellite to ground link considering the effect of polarization diversity. The system model of (2×2) MIMO and (4×4) MIMO are analyzed and compared.

At first, the analysis is carried out for SINR and BER equation in (2×2) MIMO satellite to ground link taking into account the effect of cross-polarization. For the cross polarization experiment four different area is considered such as open area, suburban area, urban area and marine area. separate typical value is set to identify the different region like open area=200, suburban area=60, urban area=50 and marine area=40. The SINR and BER results are evaluated for different channel environment using different channel fading components such as LOS component (β) and diffused component (α), reflection component (ξ).

For the channel coefficient h_{11}, LOS component (β) is varied from 0.1 to 0.5 and diffused component (α), reflection component (ξ) is 0.4 and 0.3 is fixed. SINR is detected 14dB - 24dB with BER 10^{-6}. where, cross polarization value is imposed from 40-200. It is observed that the system suffers significant amount of distortion in BER performance due to cross-polarization and suffers significant amount of power penalty at a given BER of 10^{-6}.

The amount of penalty is found to be 0.5 dB, 0.8 dB, 1 dB and 1.5 dB for open area, sub-urban area, urban area and marine area respectively and the power penalty of 2×2 MIMO satellite to ground communication system. As SINR performance not only depends on the LOS components but also reflection and diffused components. So reflection components (ξ) is changed to observed the affection of SINR and power penalty. It is found that BER curve is become flat at 10^{-6} because of higher BER due to change of reflection components (ξ).

For 4×4 MIMO satellite to ground communication system channel component increase to 16 and Rician K-factor increase from $k_1 - k_4$.

Similar steps are followed to find the power penalty of 4×4 MIMO satellite to ground communication system. 0.1dB, 1.5 dB, 2.5dB and 4.0 dB power penalty are measured for open, sub-urban, urban and aeronautical/marine area which are not higher than 2×2 MIMO system. So, 4×4 MIMO system gives better output with low power penalty.

Open area gives the undesired value which is 0.1 dB lower than 2×2 MIMO satellite to ground link with the effect of cross polarization. The reason is reflection and diffused component both value is considered 0.3.

5.2 Major Contributions

The major contribution of this thesis are pointed out briefly;

a) The effect of cross polarization from the satellite to the ground link is modeled in a MIMO system.
b) For this MIMO system, the SINR and BER equations are obtained.
c) The experiment was carried out by varying the value of their co-efficient from 0.1 to 0.5 in four different regions: open, sub-urban, urban, and aeronautical/marine.
d) For each location, the power penalty and receiver sensitivity are examined. It was discovered that the open region had the lowest power penalty of 0.5 dB for 2×2 MIMO and 0.1 dB for 4×4 MIMO.

5.3 Future Works

At this point in the proposed ponder, the power penalty of MIMO frameworks has incorporates a lot of room for improvement and expansion in numerous intriguing areas. Below is a list of some of these prospective study opportunities:

a) Work can be improved to find the effect of crosstalk due to different types of polarizations and polarization diversity transmission with MIMO satellite link.
b) Future research can be initiated for a MIMO satellite to ground link considering the effects of circular polarization in a polarization diversity scheme to block reflection fading.
c) MIMO data rate and error probability can be improved using OFDM modulation technique.
d) To resist the nonlinear distortion, APSK (Amplitude Phase Shift Keying) can be utilized in satellite communication.
e) Massive MIMO can be considered with the proposed framework show for expanding throughput and efficiency.

LIST OF PUBLICATION

The contributions of this thesis have been published international conference as listed below:

1. Sharif and S.P. Majumder, “Analytical Evaluation of BER of the Effect of Cross-polarization in a Polarization Diversity MIMO Satellite to Ground link”, *2015 IEEE International Conference on Telecommunications and Photonics (ICTP), Dec. 2015*
2. Sharif and S.P. Majumder, “Analytical SISO Bit Error Rate Evaluation of a Setellite to Ground Link Under the Interference of Log-Normal Atmospheric Turbulence”, *2016 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT), March 2016*

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ANNEXURE A

MATLAB CODES

A.1 2×2 MIMO Diversity with the Effect of Cross-polarization in Open Area

```
k11=200; k21=200; k12=0; k22=0; ita1=0.3;ita2=0.3;
bita1=0.1;bita2=0.2;bita3=0.3;bita4=0.4;bita5=0.5;alpha1=0.4; alpha2=0.4;
 [snr_dB]=[2 4 6 8 10 12 14 16 18 20 22];
for i=1:length(snr_dB)
 EbN0(i)=10^(snr_dB(i)/10);
 num1=(k11*(1-bita1)/(k11+k12+1))*EbN0(i);
dnum1=2*(k12*(1-ita1)+(1-alpha1))*EbN0(i)/(k11+k12+1)+2;
ber1(i)=0.5*erfc(sqrt(num1/dnum1)); num2=(k11*(1-bita2)/(k11+k12+1))*EbN0(i);
ber2(i)=0.5*erfc(sqrt(num2/dnum1));
num3=(k11*(1-bita3)/(k11+k12+1))*EbN0(i);
ber3(i)=0.5*erfc(sqrt(num3/dnum1)); num4=(k11*(1-bita3)/(k11+k12+1))*EbN0(i);
ber4(i)=0.5*erfc(sqrt(num4/dnum1));
num5=(k11*(1-bita5)/(k11+k12+1))*EbN0(i);
ber5(i)=0.5*erfc(sqrt(num5/dnum1)); num6=(k11*(1-bita6)/(k11+k12+1))*EbN0(i);
ber6(i)=0.5*erfc(sqrt(num6/dnum1));num7=(k11*(1-bita7)/(k11+k12+1))*EbN0(i);
ber7(i)=0.5*erfc(sqrt(num7/dnum1));num8=(k11*(1-bita8)/(k11+k12+1))*EbN0(i);
ber8(i)=0.5*erfc(sqrt(num8/dnum1));end
semilogy(snr_dB,ber1,'r-*',snr_dB,ber2,'b-v',snr_dB,ber3,'g-o',snr_dB,ber4,'b-s',snr_dB,ber5,'m-
o',snr_dB,ber6,'m-o',snr_dB,ber7,'m-o',snr_dB,ber8,'m-s')
legend('\beta=0.005','\beta=0.01','\beta=0.05','\beta=0.1','\beta=0.2','\beta=0.3','\beta=0.4','\beta=0
.5')
 axis([2 22 10^-8 10^0])
xlabel('SINR(dB)')
ylabel('BER')
txt1=texlabel('k_11=200; k_12=0');
text(8,10^-1,txt1)
```

A.2 4 ×4 MIMO Diversity with the Effect of Cross-polarization in Open Area

```
k11=200;  k12=0; k13=0;k14=0;ita1=0.3;ita2=0.3;
 bita1=0.1;bita2=0.2;bita3=0.3;bita4=0.4;bita5=0.5;
alpha1=0.4;
alpha2=0.4;
 [snr_dB]=[2 4 6 8 10 12 14 16 18 20 22];
for i=1:length(snr_dB)
 EbN0(i)=10^(snr_dB(i)/10);
 num1=(k11*(1-bita1)/(k11+k12+k13+k14+1))*EbN0(i);
dnum1=2*(k12*(1-ita1)+(1-alpha1))*EbN0(i)/(k11+k12+k13+k14+1)+2;
ber1(i)=0.5*erfc(sqrt(num1/dnum1));
 num2=(k11*(1-bita2)/(k11+k12+k13+k14+1))*EbN0(i);
ber2(i)=0.5*erfc(sqrt(num2/dnum1));
 num3=(k11*(1-bita3)/(k11+k12+k13+k14+1))*EbN0(i);
ber3(i)=0.5*erfc(sqrt(num3/dnum1));
 num4=(k11*(1-bita4)/(k11+k12+k13+k14+1))*EbN0(i);
ber4(i)=0.5*erfc(sqrt(num4/dnum1));
 num5=(k11*(1-bita5)/(k11+k12+k13+k14+1))*EbN0(i);
ber5(i)=0.5*erfc(sqrt(num5/dnum1));
 end
semilogy(snr_dB,ber1,'r-*',snr_dB,ber2,'b-v',snr_dB,ber3,'g-o',snr_dB,ber4,'b-s',snr_dB,ber5,'m-
o',snr_dB,ber6,'m-o',snr_dB,ber7,'m-o',snr_dB,ber8,'m-s')
%grid on
legend('\beta=0.1','\beta=0.2','\beta=0.3','\beta=0.4','\beta=0.5')
 axis([2 22 10^-6 10^0])
xlabel('SINR(dB)')
ylabel('BER')
txt1=texlabel('k_11=200; k_12=k_13=k_14=0');
text(8,10^-1,txt1)
```