POLARIZATION DIVERSITY IN CHANNEL MODELING FOR MIMO SYSTEMS

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ABSTRACT

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In a multiple-input multiple-output (MIMO) system, inter-antenna distances can be made large and uncorrelated signals can be transmitted and received when there is sufficient space at the transmitter (TX) and receiver (RX). When the antennas are closely spaced, diversity advantage is lost and communication performance degrades. In this case, polarization diversity can be used in order to decrease the correlation and improve communication performance. A detailed channel model, which includes both cross polar discrimination (XPD) and correlation coefficient, is used in this study. Transmitter is assumed to have enough space and correlation is considered for the receiver only. Received signal correlation coefficients are generated from a realistic random 3-D model including antenna polarization orientations, XPD, azimuth and elevation angles of direction-of-arrival. In this study, channels with and without correlation are considered. Polarization diversity in a 2×2 MIMO communication system is investigated for Alamouti (AL) and spatial multiplexing (SM) transmission schemes considering both BER performance and channel capacity. In addition, effects of the number of antennas on SM BER and capacity are investigated for 3×3 and 4×4 MIMO systems. BER and capacity performance of single polarization and polarization diversity are compared for constant and distance dependent random channel parameters. The relative performance of single polarization and polarization diversity system depends significantly on the channel characteristics. It is shown that polarization diversity results better BER and capacity compared to single polarization especially when there is not enough space at the receiver. Therefore, polarization diversity can be used in MIMO systems with limited antenna space, in order to improve communication performance.

Keywords: Polarization diversity, MIMO, correlation coefficient, Alamouti scheme, Spatial Multiplexing, channel capacity

ÖZ

ÇGÇÇ SİSTEMLER İÇİN KANAL MODELLEMEDE POLARİZASYON ÇEŞİTLİLİĞİ

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Bir çok-girdili çok-çıktılı (ÇGÇÇ) sistemde göndermeçte ve almaçta yeteri kadar alan varsa, anten elemanları arası mesafe yüksek yapılabilir ve ilintisiz sinyaller gönderilip alınabilir. Öteyandan, alan kısıtından dolayı antenler aynı alana yerleştirilirse, çeşitlilik avantajı kaybolur ve iletişim performansı kötüleşir. Bu durumda ilintiyi azaltmak için polarizasyon çeşitliliği kullanılabilir. Bu çalışmada çapraz polarizasyon ayrımı (ÇPA) ve ilinti katsayısı gibi polarizasyon etkilerini ele alan detaylı bir kanal modeli kullanılmaktadır. Göndermeçte yeteri kadar alan olduğu varsayılır ve ilinti sadece almaç için değerlendirilmektedir. Alınan sinyallerin ilinti katsayıları, anten polarizasyon oryantasyonları, ÇPA, yanca ve yükseliş varış açılarını içeren gerçekçi rasgele 3-boyutlu bir modelden üretilir. Polarizasyon çeşitliliği ilintili ve ilintisiz kanallar için incelenmiştir. Bu çalışmada hem ilintili hem de ilintisiz kanallar ele alınmıştır. 2×2 ÇGÇÇ iletişim sisteminde polarizasyon çeşitliliği, Alamouti (AL) ve uzaysal çoklama (UÇ) gönderme senaryolarının BER performansları ve kanal kapasitesi için değerlendirilmiştir. Ayrıca anten sayılarının UÇ BER ve kapasite üzerindeki etkileri 3×3 ve 4×4 ÇGÇÇ sistemler için araştırılmıştır. Tek polarizasyon ve polarizasyon çeşitliliğinin BER ve kapasite performansları sabit ve mesafeye bağlı rasgele kanal parametreleri için karşılaştırılmıştır. Tek polarizasyon ve polarizasyon çeşitliliğinin birbirlerine göre performansları büyük ölçüde kanal özelliklerine bağlıdır. Özellikle almaçta yeteri kadar alan olmadığı durumda, polarizasyon çeşitliliğinin tek polarizasyona göre daha iyi BER ve kapasite sonuçları verdiği gözlenmektedir. Sonuç olarak anten alanı kısıtlı ÇGÇÇ sistemlerde, iletişim performansını artırmak için polarizasyon çeşitliliği kullanılabilir.

Anahtar Kelimeler: Polarizasyon çeşitliliği, ÇGÇÇ, ilinti katsayısı, Alamouti senaryosu, Uzaysal Çoklama, kanal kapasitesi

To my family,

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CHAPTER 1

INTRODUCTION

There is a variety of MIMO diversity techniques and polarization diversity has received significant attention recently. In this thesis, effect of polarization diversity is investigated for different MIMO communication systems employing different transmission schemes under fully characterized channel model.

1.1 Motivation of Thesis

MIMO communication systems may have diversity gain and multiplexing gain so that lower BER values and higher data rates can be achieved as compared to SISO systems. As technology improves, the demand for both high speed and high performance increases drastically. Consequently the interest for MIMO system rises. Nowadays, new communication systems utilize the benefits of MIMO communication systems. For instance, some very popular systems such as LTE, WIMAX, Wi-Fi use a variety of MIMO standards with different algorithms.

Moreover, as technology improves, more than one communication system is desired in a single communication device. For example, FM receivers, GPS receivers and 3G protocols are integrated into almost every mobile phone, even into some radio transceiver. Consequently, more compact transmitter and receiver pairs are highly desired. The smaller the communication device, the more attractive it becomes. Therefore, the volume for communication hardware should become smaller. In short, improvements in technology may cause space problems.

If the antenna elements in a MIMO system can be located far enough from each other, uncorrelated transmission and reception of the signals can be realized. On the other hand, if the antenna elements can not be located far enough from each other due to lack of space, highly correlated signals are transmitted and received. Thus, the system performance may decrease.

The correlation between the transmitted or received signals depend on not only the distance between the antenna elements, but also the polarization orientations of them. When there is not enough space at the transmitter or receiver, polarization diversity can yield additional diversity and correlation can be decreased as compared to spatial diversity only case. Therefore, when there exists correlation due to insufficient inter-antenna distance and polarization diversity is employed, more uncorrelated signals can be transmitted or received which may lead to MIMO communication with higher performance and higher speed.

In this study, transmitter is assumed to be a base station and receiver is a mobile equipment. In other words, mobile equipment downlink is considered. Transmitter is assumed to have enough space so as to sufficiently decorrelate the signals to be transmitted. Thus, there is no correlation at the transmitter. Whereas, hand-held equipments are usually small and suffer from space problem. Consequently, correlation is investigated at the receiver. In this thesis, correlation is defined as the correlation between the received signals from different RX antennas. When there is not enough space and antenna elements are placed close to each other, channel coefficients of different antenna links are the same. That is the reason why correlation exists at the receiver. Since correlation is defined only for receiver, correlation coefficient refers to receiver correlation coefficient at the rest of this thesis.

When the antenna elements have different polarization orientations, the only effect is not the reduced correlation. In addition to correlation subchannel power loss is another effect of the polarization diversity on the channel. These are explained in detail in chapter 3. Polarization diversity does not always cause better performance. Due to power loss of cross polarized antennas, in some cases dual polarization has worse performance than single polarization. In this study, under different channel situations, MIMO systems with and without polarization diversity are analyzed. Therefore, this study gives significant information about both the advantages and disadvantages of the polarization diversity in a variety of cases. Thus, it can be of great importance to the MIMO system designers.

In order to investigate the performance of the MIMO systems with polarization diversity, 2×2 MIMO communication system is implemented in MATLAB environment. Fully characterized channel taking into account all the effects due to polarization differences is modelled. Using this channel and MIMO structure, Monte Carlo simulations are performed. BER performance and average capacity results of the systems with and without polarization diversity are compared for a variety of channel cases with both constant and distance dependent parameters. BPSK modulation is employed and Alamouti (AL) and Spatial Multiplexing (SM) transmission schemes are used. Maximum Likelihood (ML) algorithm is used for decoding assuming channel state information is known at the receiver. In addition to the 2×2, 3×3 and 4×4 MIMO systems are investigated for polarization diversity and correlation effects. SM BER and capacity performances of SISO and MIMO systems with different number of antennas are compared in this study.

1.2 Literature Overview

Diversity in MIMO has been a very popular and important topic for decades. Time diversity, frequency diversity, spatial diversity are the main diversity techniques. In addition to them, polarization diversity has attracted attentions of the researchers since 1970s. The first research on polarization diversity is performed by Lee and Yeh. In [1], both statistical received signal levels and average received signal levels are compared for vertical and horizontal TX-RX mobile radio antennas. The idea that polarization diversity can be used instead of spatial diversity is put forward. After that, in 1984 [2] employs two colocated and symmetrically polarized receiver antennas with 2-D received signal model including azimuth angle of arrival (AOA). Theoretical and experimental correlation, XPD and received signal levels are presented.

[3] and [4] considers receiver diversity systems. In [3] urban and suburban channel measurements are performed with colocated orthogonal RX antennas and diversity gain is investigated for Maximum Ratio Combining (MRC) algorithm. Rather than MRC algorithm in [3], [4] investigates the system gain for Selection Combining (SC) receiver diversity technique. Besides, [4] extends the received signal model in [2] from 2-D to 3-D including elevation AOA and correlation coefficients for receiver are analyzed considering polarization orientation, random azimuth and elevation AOAs. In this model antennas may not be necessarily symmetric. The receiver correlation model in [4] represents correlation

between RX antennas in more details than the previous approaches hence is more suitable for wireless channels. In this thesis study, 3-D received signal correlation model in [4] is used.

There are some studies on the colocated antennas for MIMO systems with polarization diversity. In [5] and [6], colocated electric and magnetic dipoles with identical radiation patterns but orthogonal polarizations are considered at 900MHz. Simulation results and measurements are given for these antennas. It is indicated that very low envelope correlation can be achieved with such antenna configuration.

Polarization diversity is investigated for different application fields in both outdoor and indoor environments. [7]-[9] present the MIMO channel models for different polarization diversity systems based on outdoor suburban real wireless channel measurements at 2.5 GHz, multichannel multipoint distribution service (MMDS) frequency. [7] and [8] include large scale fading parameters in addition to the small scale according to the measurements performed with (±45°) polarized antennas. Distance dependent K-factor and XPD parameters formulized in [7] are also utilized in this thesis study. Moreover, capacity results are calculated with respect to the communication distance based on the measurements and channel model [7]-[9]. Additionally, [10] gives the outdoor channel measurements and throughput simulation results based on measurements for adaptive LTE protocols. Whereas, [11] and [12] state the received signal levels and quality of the received signals based on the measurements for receiver polarization diversity at 1800 MHz GSM frequency.

In [13]-[15], capacity results are presented for polarization diversity systems based on simulations, rather than measurements. [13] considers deterministic channels for comparison of single and dual polarized systems. [14] uses tridipole antenna electromagnetic simulations for channel determination. In [15], capacity and other performance parameters like beamforming algorithm and antenna selection algorithm are evaluated for TD-HSPA+ systems employing dual polarization.

As for BER performance of polarization diversity, in [16]-[20], BER performances of different MIMO systems are investigated. In [16] analytical BER expression for SM is derived and BER performance of dual polarized systems is investigated for constant channel parameters. The research in [16] is extended to AL in [17]. In [17], BER expression for AL is included as well as for SM, yet performance is still compared for constant parameters. Analytical BER expressions for AL and SM are compared with simulation results for dual polarized systems. [18] and [19] use power control mechanisms assuming CSIT. BER performance and system gains for MRC are compared for orthogonal polarization diversity and spatial diversity systems with constant channel parameters as in [16] and [17]. In [19] Rayleigh fading environment is considered for RX diversity systems, whereas in [18] Nagakami-m fading is considered and TX diversity is employed including AL BER performance.

[20] proposes a MIMO channel model for satellite communication with polarization diversity. This channel model has three components such as a LOS signal, a reflected signal and a diffuse signal. BER performances of different systems are compared for constant channel parameters corresponding to urban, suburban and open unobstructed satellite-earth channels.

Polarization diversity can be employed in indoor applications in addition to the outdoor. There are some valuable studies in the literature considering polarization diversity in indoor environments. [21]-[25] present the measurements of the channel parameters in different indoor environments. In terms of capacity comparison, [21] state that if the space is not a limitation spatial diversity can be selected, whereas [22]-[24] indicate that polarization diversity is a good candidate for spatial diversity. In [24], it is also stated that diversity gain of polarization diversity is worse than single polarization under indoor WLAN channels. Additionally, in [26] MIMO channel model capacity simulation results for microcell based on this channel model are presented for polarization diversity systems. Single and dual polarizations have comparable capacity performance [26].

In [27]-[29] measurements are performed in reverberation chamber in which large number of MIMO antenna elements can easily be set-up. When there are more than two antenna elements rather than orthogonal polarization, different angular separations can perform better. In [27] 3x3 MIMO diversity gains of spatial and angular separations are compared. Some correlation measurements for large number of antenna elements are presented in [28] and [29]. It is shown that angular separation of the antennas can be used instead of spatial separation. Therefore, polarization diversity can yield more compact antenna arrays considering both capacity and diversity gain. Moreover, orthogonal polarization may not be the optimum polarization orientation for large number of MIMO arrays.

1.3 Contributions in the Thesis

In this thesis, both BER and capacity performances of single and dual polarized systems are compared for AL and SM transmission schemes. There are some reasons for the fact that AL and SM are chosen for transmission scenario. The first one is that AL and SM are two distinct schemes. AL algorithm is mainly based on combination of the received signals, while SM is based on multiplexing of the signals to be transmitted. Therefore, the effect of polarization difference at the TX and RX can be different on these two schemes. Another reason is that there exist some studies investigating polarization diversity for AL and SM in the literature. The previous studies are based on the constant channel parameters. However, in this thesis both constant and distance dependent channel parameters are used in order to investigate the performance. Real wireless environment can be simulated using distance dependent channel parameters. Another reason is AL and SM schemes are the main schemes which are the key points of many other techniques. Thus, analyzing these schemes may give opinion about some other schemes. Final reason is that in new communication systems like LTE, WIMAX or WLAN different types of AL and SM schemes are employed. Thus, this study can present idea on designing TX-RX antenna polarizations of these systems.

Channel models for MIMO systems employing polarization diversity at the TX and RX are widely known in the literature [7],[8],[9], [26]. In this study, a combination of the channel models present in the literature is used. Channel is modeled for both single and dual polarizations. In our study constant and distance dependent random channel parameters are used for MIMO channel modeling.

Furhtermore, transmitter is assumed to have no space constraint and receiver antenna configuration is investigated for two cases. The first case is that the receiver has no space constraint just like the transmitter, which leads to uncorrelated received signals. The other case is that the receiver antennas are colocated due to space problem at the receiver. This problem has been investigated for both outdoor and indoor environments. Yet, the investigation of polarization diversity with and without received signal correlation is of great importance. In this study, correlated and uncorrelated receiver antenna arrays can be compared for single and dual polarizations. Furthermore, in the correlated case, the receiver correlation model for the antenna elements with polarization diversity is used [4] and the 3-D correlation model includes polarization orientation angles of the antennas and random azimuth and elevation AOAs of the incoming multipath signals. Azimuth and elevation angles are generated from random distributions [30]. Therefore, receiver correlation coefficients are generated from random parameters based on real wireless measurements.

BER performance is one of the most important feature of a communication system. In this thesis, BER performance of AL and SM are compared for single and dual polarized systems which is very crucial for system designs. Especially, thanks to the results of the simulations the performance of a communication system can be predicted before implementation. Thus, possible advantages or disadvantages of polarization diversity can be foreseen and more robust and efficient system designs can be implemented according to the results in this study.

Furthermore, average capacity results for single and dual polarizations under different channel conditions are investigated in this study. Capacity of a system is a measure of data rate and speed of the communication and just like BER performance it is also one of the most important parameters of a communication system. Presenting the capacity results in addition to the BER performance, communication systems with spatial and polarization diversity can be investigated in terms of both speed and error performance criteria. Although there are some studies which can be found in the literature and includes BER performance or capacity results, this thesis study presents valuable information about comparison of single and dual polarized antenna configurations for different channel cases in a very compact and useful manner.

In addition, the effects of increasing number of antennas in a MIMO system can be found in this study. 3×3 and 4×4 MIMO systems with and without polarization difference are investigated for correlated and uncorrelated channels. SM is employed in these MIMO systems. SM BER and capacity results can be found in this thesis. BER together with capacity results are very significant in order to investigate the communication performance of a system. These results can help a MIMO system designer in selecting the number of antennas and polarization orientations.

1.4 Applications of This Study

The results of this study give very important information to the engineers designing a MIMO system. By using polarization diversity, more uncorrelated signals can be transmitted and received and a significant performance increase can be provided. New communication system designs may utilize the benefits of polarization diversity or existing MIMO systems may be optimized employing polarization diversity. The results about the polarization analysis in this study, can be a guide to most of the MIMO communication systems and polarization diversity can be applied in all space-lacking MIMO communication systems such as GSM, 3GPP, HSPA, WIMAX, LTE, WIFI, even radio systems. Yet, this study is mostly dedicated to small hand-held devices occupying multi communication features in single device since these devices should be compact and user friendly as well as having high performance.

In addition, different channel parameters corresponding to a variety of real world channels are considered in this study. For instance, higher K-factor represents a channel with higher LOS signal power. Moreover, urban communication areas have much lower K-factor and XPD due to depolarization mechanisms. Therefore, the results in this study give significant information about the performance of real world channels. Furthermore, performance of distance dependent channel parameters used in this study informs the readers about the communication in suburban channels.

BER and capacity results which are the two key parameters of a communication system are presented for different MIMO channels with single polarization and polarization diversity. BER performances for two different and very important techniques, AL and SM, are investigated in this study. AL algorithm is based on power combination of all subchannels and SM scheme utilizes channel diversity. Consequently BER performance of any transmission scheme based on power combination algorithm or channel diversity, for different MIMO polarization orientations and different number of antennas can be predicted and the results in this study can be used for applications of such coding schemes. Furthermore, capacity results of different MIMO channels with and without polarization diversity are presented. Therefore, the results in this thesis can be used for many types of communication systems and channels which have space or polarization diversity.

1.5 Outline of Thesis

In Chapter 1, past studies about polarization diversity in MIMO communications are given. Motivation of this thesis and contributions to the literature by this study are stated. Additionally, application fields of this study are presented.

In Chapter 2, large and small scale fading effects of wireless communications are considered and from deterministic multipath signals statistical Rayleigh and Ricean fading channel models are derived. Furthermore, SISO BER results are compared for no channel (AWGN only) case, Rayleigh fading and Ricean fading with different K-factor values.

In Chapter 3, a detailed MIMO channel model used in this thesis is presented. Variable and constant channel components are explained. Antenna polarization effects on the channel and correlation phenomenon for polarization diversity employed systems are stated.

Chapter 4 states the MIMO system model used in this study. AL and SM transmission schemes and ML receiver algorithms used in this thesis are defined in this chapter. Additionally, average capacity formulations and information about simulation environment are given.

Chapter 5, 6 and 7 include the results obtained in this study. In chapter 5, single and dual polarized 2×2 MIMO systems' BER performances for AL and SM schemes and capacity comparisons are performed with constant K-factor and XPD. These systems are analyzed for both correlated and uncorrelated channel cases.

In Chapter 6, rather than constant channel parameters in Chapter 5, distance dependent K-factor, XPD and correlation coefficient values are used in order to investigate the effects of polarization on the BER and capacity performance of 2×2 MIMO.

In Chapter 7, the number of antennas in a MIMO system is investigated with polarization diversity. BER for SM and capacity results of SISO, 2×2, 3×3 and 4×4 MIMO configurations are presented considering single polarization and polarization diversity cases. Distance dependent channel parameters as well as constant ones are used for performance evaluation of these systems.

Chapter 8 is the conclusion part which is the brief summary of the results obtained in this thesis.

CHAPTER 2

WIRELESS COMMUNICATION

Rather than wired communication, wireless communication has been very famous and demanding recently. Mobility is the main reason for choosing wireless communication. However, wireless communication systems incur channel effects and fading which may severely effect performance.

2.1 Large Scale Fading

Communication signals are transmitted via electromagnetic waves. Signals transmitted from the transmitter, have a certain amount of power and this power is attenuated by the effect of the propagation environment. Electromagnetic waves encounter some kind of distortions caused by absorption, reflection, scattering and diffraction during propagation. The signal power level may change within large distances which is called as large scale fading. In general, large distance refers to large with respect to the wavelength of the electromagnetic waves. There are two large scale fading types such as free space path loss and shadowing.

Even if there is not any obstacle to create distortion, the signal power is attenuated by the effect of the propagation medium and this is called as free space path loss. Path loss increases with the square of the distance between the TX and RX antenna and decreases as the wavelength of the electromagnetic wave increases. Under the effect of path loss only, the transmitted and received power can be related by the well-known formula:

$$P_r = P_t G_t G_r \frac{\lambda^2}{(4\pi d)^2}, \tag{2.1}$$

where P_r and P_t are the received and transmitted power levels respectively and G_r and G_t are the RX and TX antenna gains. d corresponds to the distance between TX and RX antennas and λ is the wavelength.

The other large scale fading is shadowing. Shadowing is the sharp changes of the received power caused by environmental conditions in a large area. Usually shadowing is observed when some obstacles suddenly block the signal with the effects of absorption, reflection, scattering and diffraction. Although some models for shadowing exist, the most popular one is the log-normal distribution [31].

On the course of this study, large scale fading phenomena are ignored. The received power can be thought as normalized by path loss and shadowing effects. This study is specifically interested in the small scale statistical fading properties of the communication channel

2.2 Small Scale Fading

In a scattering environment, propagating electromagnetic waves also experience multipath effects of the channel rather than large scale fading. Due to constructive and destructive effects of the different multipath components, the received signal power changes very rapidly in small distances on the order of the wavelength. The received signal level changes with not only the distance but also the time. The channel has a time varying characteristics since the transmitter, the receiver and the scatterers may move. This time and distance dependent, rapid effect of the communication is called small scale fading of the propagating signal.

When there are many scatterers around the receiver, multipath components of the transmitted signal can not be modelled and evaluated individually. For this reason, statistical channel models are used [31]-[33].

When the wave reflects from a surface, the original signal experiences amplitude and phase changes. Additionally there exists a time delay between incoming and reflected signal. If there are many scatterers, the propagating wave encounters many reflections and scatterings. Many multipath components occur and reach to the receiver. To model the multipath effects, channel impulse response can be written considering the sum of all multipath components of the signal.

$$h[\tau, t] = \sum_{n=0}^{N(t)} \alpha_n(t) e^{(-j\phi_n(t))} \delta(\tau - \tau_n) \tag{2.2}$$

This equation represents the channel response at time t to an impulse at time t-τ. In this equation, τ_n represents the time delay of the n^{th} multipath component. Time delays are caused by the fact that different multipath components incoming to the receiver have different reflection paths. α_n and ϕ_n are the amplitude and phase respectively.

This is the general channel impulse response equation involving multipath components of the received signal. The maximum delay difference between the LOS signal component and the multipath components with the largest delay is called delay spread. If the delay spread of the channel is smaller than the inverse of the communication bandwidth, narrowband fading is assumed. In narrowband case response delay is ignored and (2.2) reduces to:

$$h[t] = \sum_{n=0}^{N(t)} \alpha_n(t) e^{(-j\phi_n(t))} \tag{2.3}$$

The phase term $\phi_n(t)$ includes the phase effects caused by due to not only the path delays but also the Doppler frequency shift. $\phi_n(t)$ can be expressed as:

$$\phi_n(t) = 2\pi f_c \tau_n(t) - \phi_{Dn} \tag{2.4}$$

Since generally carrier frequencies are large, the delay phase term, $2\pi f_c \tau_n(t)$, in the phase equation can be assumed to be very large and Doppler phase term can be neglected. A small change in the delay of a multipath component leads to a very rapid phase changes of the multipath component. These rapid phase changes cause destructive and constructive combinations of the received multipath signals. Consequently, the combination of these signals with different phases results in the sudden changes of the received signal power.

2.2.1 Rayleigh Fading

The in-phase and quadrature components of the channel response can be written as:

$$h_I[t] = \sum_{n=0}^{N(t)} \alpha_n(t) cos(\phi_n(t)) \tag{2.5}$$

$$h_Q[t] = \sum_{n=0}^{N(t)} \alpha_n(t) sin(\phi_n(t)) \tag{2.6}$$

Since a phase change corresponding to a small delay is very rapid, it can be assumed that the phase of the channel, $\phi_n(t)$, is uniform over all angles [$-\pi, \pi$]. If Central Limit Theorem is recalled; sum of a large number of iid random variables has Gaussian distribution. In our case, the number of multipath components N(t) is large and the phase is uniformly distributed. In-phase and quadrature components of channel response can be approximated as Gaussian distributed with zero-mean. The channel coefficient consists of in-phase and quadrature components and can be written as,

$$h = h_I + jh_Q \tag{2.7}$$

$$|h| = \sqrt{h_I^2 + h_Q^2} \tag{2.8}$$

Since h_I and h_Q are Gaussian distributed random variables with zero mean and σ^2 variance, the magnitude of h is a Rayleigh distributed random variable with zero mean and $2\sigma^2$ variance and it has the pdf of:

$$p_X(x) = exp(-x^2/2\sigma^2)x/\sigma^2 \tag{2.9}$$

The average received signal power, P_r refers to the power received after path loss and shadowing effect and can be defined by mean of the channel power which is $2\sigma^2$. As stated in section 2.1, in this study, large scale effects are not included. For this purpose, the channel power in other words the channel variance is taken as unity.

2.2.2 Ricean Fading

For Rayleigh fading case, the mean of the channel amplitude is zero due to the uniform phase assumption, as stated in 2.2.1. If there is a fixed component of the received signal, then the channel has a mean rather than zero. In this case, the channel amplitude has the Ricean distribution with non-zero mean and it has the pdf of:

$$p_X(x) = exp[-(x^2 + P_c/P_v)]I_0(2z\sqrt{P_c}/P_v)2x/P_v \tag{2.10}$$

In this equation, P_c is the mean square of the channel amplitude, in other words the power of the received signal's constant component and P_v is the variance of the channel amplitude, in other words the power of the variable multipath signals. P_c is introduced as LOS component of the received signal.

Channel coefficients are generated for each symbol period. In order to generate the Ricean channel coefficients, Rayleigh channel coefficients can be combined with constant channel power with a ratio, called Ricean K-factor.

$$h = \sqrt{\frac{K}{K+1}}e^{j\phi} + \sqrt{\frac{1}{K+1}}h_{rayl}, \tag{2.11}$$

where K-factor is the ratio of the power of the constant component of the received signal to the power of the variable component of the received signal, $K = P_c/P_v$. h_{rayl} is the Rayleigh distributed random variable with zero mean and unity variance.

Considering the channel fading effect, baseband received signal can be written as,

$$y = \sqrt{E_s}hs + n, \tag{2.12}$$

where n is the Gaussian distributed receiver noise with zero mean and unity variance. Noise variance represents the noise power and for power normalization purpose it is taken as unity. In this study, the performance is evaluated for SNR value of the system and SNR is defined as the ratio of the transmitted signal power to the receiver noise power. Taking the noise power as unity, SNR can be simply adjusted by signal energy.

Figure 2.1 illustrates the BER vs SNR performance of AWGN communication link, Rayleigh and Ricean channels for BPSK modulation type. Due to fading of the signal, Rayleigh channel, corresponding to 0 K-factor, has about 17 dB performance loss compared to no fading case (AWGN only link) at BER value of 10^{-3}. Moreover, as the K-factor increases and the channel coefficient mean increases, the channel recovers from deep fade and BER performance increases. Note that, Rayleigh channel corresponds to Ricean channel with 0 K-factor and AWGN link corresponds to K-factor of infinity.

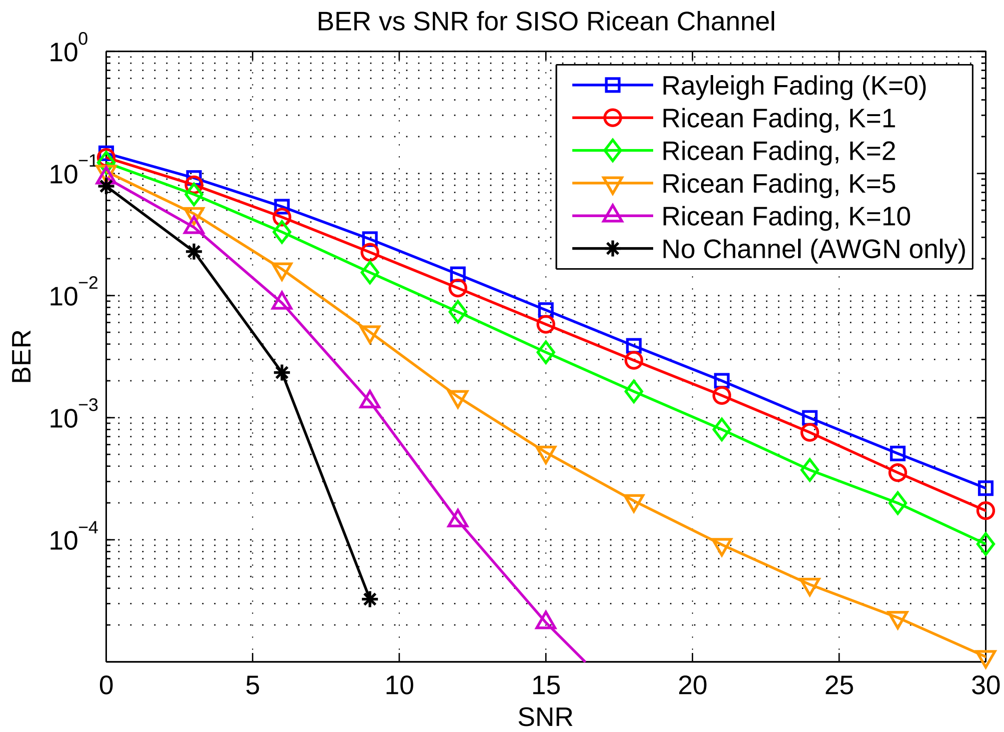


Figure 2.1: BER for Rayleigh and Ricean fading channels

CHAPTER 3

MIMO CHANNEL MODEL

MIMO communication system is based on the transmission and reception from multiple antennas rather than single antenna in SISO systems. The power attenuation for a communication link due to fading effect is explained in chapter 2. To overcome fading some diversity techniques, such as spatial diversity, time diversity and frequency diversity are commonly used. In this study, one of the diversity techniques for MIMO systems, polarization diversity is investigated.

3.1 Polarization diversity

Polarization of an electromagnetic wave defines the orientation of electric field vector. If an electromagnetic wave propagates towards a certain direction, the electric field may change sinusoidally in both axis perpendicular to the propagation direction. There are two main types of electromagnetic polarization.

The first one is linear polarization. If the electric field is in a fixed direction, it is called linear polarization. More specifically, as shown in fig. 3.1 assuming the propagation direction is z-axis, if the electric field vector is in x-direction, the electromagnetic wave is said to have horizontal polarization, whereas if the electric field is in y-direction, the electromagnetic wave is said to have vertical polarization. Moreover, if there are both horizontal and vertical electric field components with the same phase, it is also defined as linear polarization.

If there is a 90° phase difference between x and y components of the electric field with the same magnitude, it is called circular polarization. Another type of circular polarization is elliptical polarization which consists of the quadrature components of the electric field with the phase difference of 90° but not the same magnitude [34].

Polarization of the propagating wave is initially introduced by the TX antenna structure. For instance, considering a dipole antenna, the electric field vector is in the direction of the antenna orientation. The RX antenna can receive electromagnetic waves which have the same polarization as itself without power loss. If there is a polarization difference between TX and RX antennas, there exists a power loss due to polarization difference. Moreover, the communication system with TX and RX antennas having horizontal and vertical polarizations respectively or vice-versa suffers the most power loss due to orthogonally polarized antennas. This phenomenon is characterized by cross polar discrimination (XPD). XPD is the ratio of the received power of the co-polarized TX and RX antennas to the received power of the cross-polarized antennas ($XPD = P_{co-pol}/P_{cross-pol}$).

After the electromagnetic wave is transmitted from TX antenna with a certain polarization orienta-

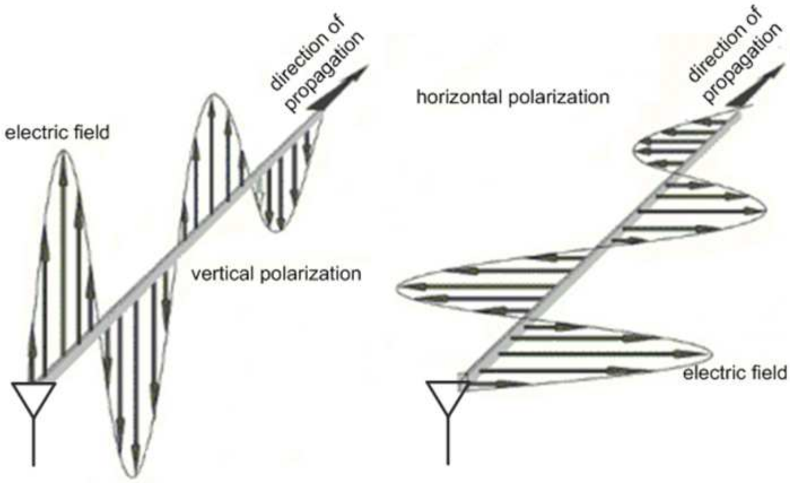


Figure 3.1: Linear Polarization

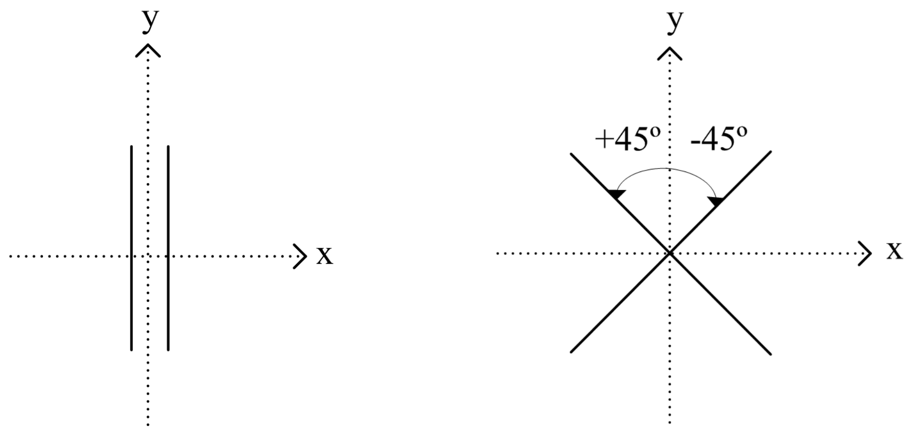
tion, due to propagation mechanisms, such as reflection, diffraction, scattering, refraction, the initial polarization is changed, which is called depolarization of electromagnetic waves. Therefore, the initial polarization effect loses its significance and consequently the subchannel power loss due to XPD decreases. As the distance between TX and RX antennas increases, the propagation mechanisms becomes more effective and the depolarization increases. XPD decreases with distance and has log-normal distribution in real wireless communication channels, as reported in [7]

The idea of the polarization diversity is based on the polarization difference of the antennas. In order for a MIMO system to utilize polarization diversity, there has to be a polarization difference. There are mainly two effects of the polarization difference in MIMO systems on the channel. The first one is subchannel power loss, as defined by XPD. This effect is explained in details in previous paragraphs.

The next effect of polarization difference is on correlation coefficient. If there is enough spatial separation of antenna elements in MIMO system, the transmitted and received signals are uncorrelated. However, if the inter-antenna spacing at the TX or RX is not large enough due to space problem, polarization diversity can be used in order to have lower correlation coefficient than the co-polarized antenna configuration. To sum up, polarization difference can decrease correlation coefficient which may cause performance improvement of MIMO systems.

Therefore, XPD and correlation coefficient should be considered in a MIMO system employing the antennas with the polarization difference. In this study, a 2×2 MIMO wireless system is considered where the TX side is assumed to be the base station (BS) and RX side is a mobile equipment. The effect of TX and RX antenna polarizations is analyzed by comparing two different polarization orientation, namely single and dual polarizations. In Fig.3.2a single polarized antenna configuration is shown. The TX and RX antennas have the same polarizations. On the other hand, as illustrated in fig.3.2(b), in dual polarized case TX and RX antennas have slant (±45°) polarization orientations (with respect to y axis).

For dual polarization instead of horizontally and vertically polarized antennas, slant polarized antennas are used. The reason underlying this selection is in a rich scattering environment like a city centre, urban or even suburban conditions there are lots of buildings, trees, etc. and the depolarization caused by the different obstacles are different for vertical and horizontal polarizations, [21]. In other words, horizontally and vertically polarized electromagnetic waves may depolarize differently. On the other hand, when slant polarization is used, the depolarization due to scattering can be assumed to be symmetric and polarization effects can be taken as the same for both polarizations. That is why slant polarized antennas are considered in this study.



(a) single polarization (b) dual polarization

Figure 3.2: Single and dual polarized antenna configurations

3.2 Channel Model

As stated in chapter 2, in this study the channel does not include large scale fading. It has Ricean distribution and is assumed to be narrowband flat fading. Rather than a single channel coefficient in SISO case, the MIMO channel is a matrix with a constant (or LOS) component and a variable (or NLOS) component. 2×2 MIMO model can be illustrated in fig. 3.3.

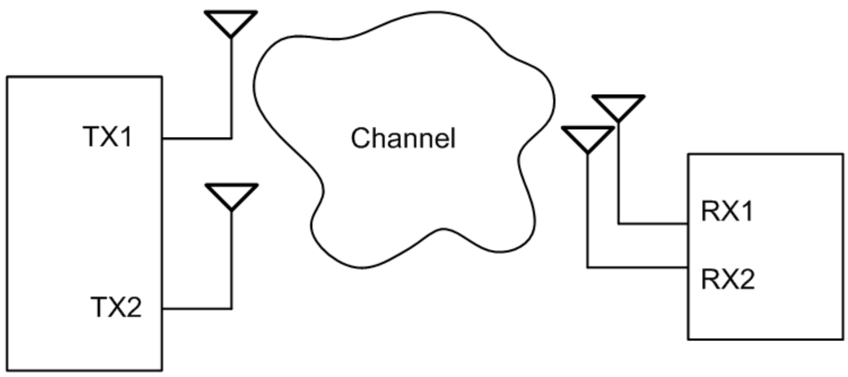


Figure 3.3: MIMO system

The channel matrix can be written as [7],

$$\mathbf{H} = \sqrt{\frac{K}{K+1}}\mathbf{H_c} + \sqrt{\frac{1}{K+1}}\mathbf{H_v} \tag{3.1}$$

In this model, **H** is $n_r \times n_t$ channel matrix whose elements are channel coefficients of corresponding communication links between TX-RX antenna element pairs. K is the Ricean K-factor as defined in chapter 2. K is highly dependent on the distance between the TX and RX antennas. As the distance increases, received power of the variable signal increases due to propagation mechanisms and consequently K-factor decreases. K-factor can be calculated from measurements, by the ratio of the gain of the constant channel component to the gain of the random channel component [36].

Furthermore, K-factor is found to be log-normally distributed in real wireless channels and modeled in [7]. K-factor is modeled as; $7.85\text{-}4.51\log_{10}(d/d_0)+7.91X$, dB ,where X is the Gaussian distributed zero mean unity variance random variable and d_0 is the normalization distance which is taken to be 1km in the simulations. This model is valid for medium range, suburban environment.

3.2.1 Constant Channel Component

Constant channel component, $\mathbf{H_c}$, represents the channel component for the fixed (or LOS) part of the received signal. It includes the effect of phase differences caused by the array orientation differences between TX and RX antennas. As stated in [9], $\mathbf{H_c}$ can be defined as,

$$\mathbf{H_c} = \mathbf{D_r}\mathbf{H_u}\mathbf{D_t}, \tag{3.2}$$

where $\mathbf{H_u}$ is all one matrix, $\mathbf{D_r}$ and $\mathbf{D_t}$ are diagonal matrices introducing the array orientations for RX and TX sides respectively. The array orientation is shown in fig. 3.4.

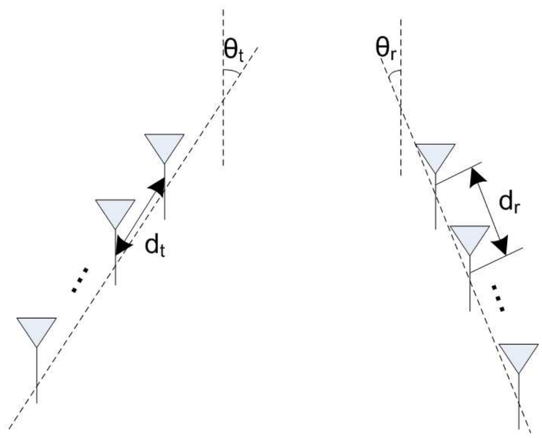


Figure 3.4: Array orientations of TX and RX antenna elements

Anti-diagonal elements of $\mathbf{D_r}$ and $\mathbf{D_t}$ are zero and diagonal elements can be expressed as,

$$D_{r_{ii}} = e^{(-j2\pi(i-1)d_r \sin\theta_r)} \tag{3.3}$$

$$D_{t_{ii}} = e^{(-j2\pi(i-1)d_t \sin\theta_t)} \tag{3.4}$$

θ_r and θ_t are the azimuthal array orientation angles and can be taken as uniformly distributed over the range [±10°] and [±30°], [9].

d_r and d_t are the wavelength normalized inter-antenna distances of RX and TX arrays respectively. In addition to the phase effect of the array orientations, these inter-antenna distances specify the spatial correlation. d_t can be large since TX side is assumed to have sufficient space. Besides, at RX side, there is usually lack of space and the RX antennas are taken to be co-located due to space problem.

When the polarization diversity is employed, H_c includes subchannel power loss in addition to the phase effect. In dual polarized antenna configuration case, the subchannel power of cross-polarized TX and RX antennas are lower than the co-polarized antennas' subchannel power. As previously explained in section 3.1, this phenomenon is called XPD. In dual polarized case, $\mathbf{H_c}$ includes not only phase effect but also XPD effect due to polarization difference:

$$\mathbf{H_c} = \begin{bmatrix} e^{j\phi_{11}} & \frac{e^{j\phi_{12}}}{\sqrt{XPD_c}} \\ \frac{e^{j\phi_{21}}}{\sqrt{XPD_c}} & e^{j\phi_{22}} \end{bmatrix}, \tag{3.5}$$

where ϕ_{ij} represents the phase effect of constant channel component and XPD_c is the XPD value of the received signal's constant component. XPD_c decreases with distance and it has log-normal distribution in real wireless communication channels as reported in [7].It is modeled as $3.86\text{-}2.97\log_{10}(d/d_0)+$ 5.69X ,dB ,where X is the Gaussian distributed zero mean unity variance random variable.

3.2.2 Variable Channel Component

In addition to the constant channel component, variable component also exists in the channel. Variable channel matrix represents the NLOS channel and is defined by $\mathbf{H_v}$, whose elements are correlated Rayleigh distributed random variables:

$$\mathbf{H_v} = \sqrt{\mathbf{R_{RX}}}\mathbf{H_{iid}}\sqrt{\mathbf{R_{TX}}}, \tag{3.6}$$

where $\mathbf{H_{iid}}$ is the matrix whose elements are iid Rayleigh random variables with zero mean and unity variance. If there exists a signal correlation between RX and/or TX antenna elements, iid Rayleigh channel matrix can be correlated by the RX and TX correlation matrices, $\mathbf{R_{RX}}$ and $\mathbf{R_{TX}}$ respectively [9], [35]. Diagonal elements of $\mathbf{R_{RX}}$ and $\mathbf{R_{TX}}$ are one. Anti-diagonal elements, ρ_{RXij}, are correlation coefficient values for different RX antennas and ρ_{TXij} are correlation coefficient values for different TX antennas. Correlation of the received signals are explained in detail in 3.2.2.1.

The correlated Rayleigh fading coefficients for the i_{th} RX and j_{th} TX antennas are represented by X_{ij}. For dual polarized antenna configuration, there exists a subchannel power loss due to cross polarization just as in constant channel component.

$$\mathbf{H_v} = \begin{bmatrix} X_{11} & \frac{X_{12}}{\sqrt{XPD_v}} \\ \frac{X_{21}}{\sqrt{XPD_v}} & X_{22} \end{bmatrix} \qquad (3.7)$$

In the equation 3.7, XPD_v is the XPD of variable component of the received signal and meaningful for the channel corresponding to only the dual polarized antenna configuration not for the single one. Just like XPD_c, XPD_v has a log-normal distribution, rationally 1.79-1.49$\log_{10}(d/d_0)$+ 2.71X ,dB ,where X is the Gaussian distributed zero mean unity variance random variable. For single polarization, XPD_v is unity.

3.2.2.1 Correlation Coefficient for Polarization Diversity

The inter-antenna distances specify the correlation coefficients. If the inter-antenna spacing is large uncorrelated signals can be transmitted and received. On the other hand, if the antenna elements are located close to each other, transmitted and received signals become correlated. In this study, TX inter-antenna spacing is assumed to be very large, and there is no correlation between TX antennas. Since the transmitted signals are assumed to be uncorrelated, in this study correlation coefficient refers to RX correlation coefficient solely.

RX correlation coefficient of a Rayleigh fading channel is very effective on the performance. In order to observe the effect of RX correlation coefficient on BER performance, BER vs. correlation coefficient plots are drawn in fig. 3.5. BER curves of 2x2 MIMO correlated Rayleigh fading channel for AL and SM schemes are indicated at constant 15dB SNR value. For both AL and SM schemes, up to correlation coefficient of 0.6, there is not a serious performance change. However, after at correlation coefficients larger than 0.6, both AL and SM BER values get higher and when there is full correlation BER values are the largest for both AL and SM. SM BER is $9\text{x}10^{-4}$ at 0 correlation and 10^{-2}at full correlation. Considering 2x2 MIMO correlated Rayleigh channel for AL, BER curve increases from 10^{-6} at 0 correlation to $2\text{x}10^{-4}$ at full correlation. Therefore, it can be seen from fig. 3.5 that small correlation coefficient values do not significantly change the BER performance of AL and SM schemes. However, for correlation coefficients larger than 0.6, performance worsens and after correlation of 0.8 BER sharply degrades both for AL and SM.

There are two RX correlation cases considered in this study. The first one is that there is no space limitation at the receiver just like transmitter and received signals are uncorrelated. In this case there is no correlation effect for the receiver. In the second case, there is not enough space at the receiver. It is assumed that there is no spatial diversity at the receiver and due to close distance between RX antenna elements received signals become correlated. Correlation is defined as the correlation between the received signals from different RX antennas. When the antenna elements are placed close to each other, channel coefficients of different TX-RX pairs are the same. That is the reason why correlation exists at the receiver.

When there is no spatial diversity, polarization diversity leads to lower correlation coefficient than single polarization. This is one of the main advantages of polarization diversity. Orthogonally polarized RX antennas receive highly uncorrelated signals as compared to single polarization case. When there is not enough space, polarization difference causes diversity. Furthermore, in this study, RX antena elements are assumed to be colocated due to space problem. In this case, single polarized antenna configuration has full correlation. Whereas for dual polarized configuration, correlation coefficient models are considered in [2],[4] and some correlation measurements are reported in [3],[28],[29],[21],[23]. In this study, RX correlation coefficient modeling for polarization diversity described in [4] is used.

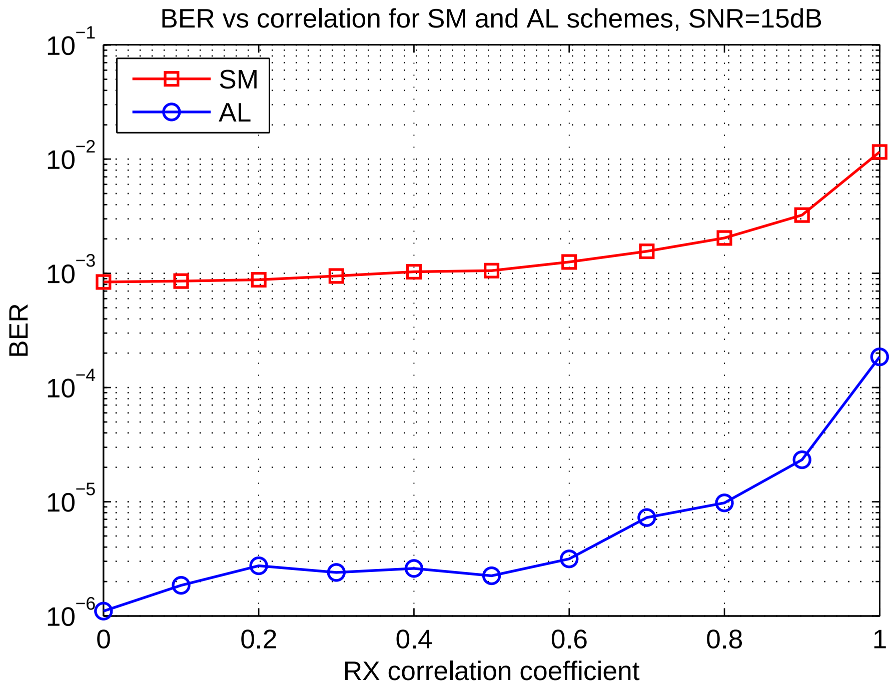


Figure 3.5: AL and SM BER vs. RX correlation for Rayleigh fading channel at 15dB SNR.

In this model received signals from two colocated RX antennas are considered in 3-D. The RX antenna polarization orientation angles and 3-D AOAs of the received signals are shown in figure 3.6. ψ_1 and ψ_2 are the polarization orientation angles of the 1st and 2nd antennas with respect to y-axis, respectively as illustrated in fig. 3.6 (a). Moreover, fig. 3.6 (b) shows the incoming signal's azimuth angle, β and fig. 3.6 (c) shows the incoming signal's elevation angle, γ. The azimuth angle, β can be assumed as uniformly distributed over all angles due to uniform scattering environment, whereas, the elevation angle γ has Gaussian distribution with mean 20° and variance 20°, in urban and suburban environments [30].

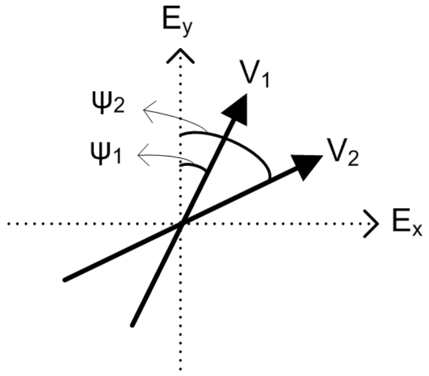
The horizontal and vertical electric fields at the receiver, E_x and E_y are defined by,

$$E_x = r_x e^{(j2\pi ft - \phi_x)} \tag{3.8}$$

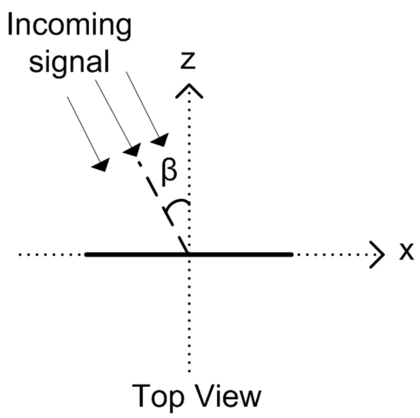
$$E_y = r_y e^{(j2\pi ft - \phi_y)} \tag{3.9}$$

The horizontal and vertical electric fields are assumed to be uncorrelated. Due to Rayleigh fading, the magnitudes of electric fields r_x and r_y are iid Rayleigh signals and the phases ϕ_x and ϕ_y are uniform.

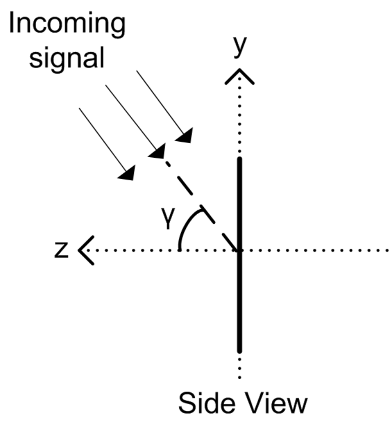
If there is not any azimuth or elevation AOAs of incoming signals, the signals come from opposite of the centres of the antennas. In this case, the received signals are just the superposition of the received signals' horizontal and vertical components. However, in the presence of azimuth and elevation, the signals received from the RX antennas, V_1 and V_2, can be written as;



(a) Polarization orientation angles



(b) Azimuth angle



(c) Elevation angle

Figure 3.6: Received signal 3-D model

$$V_1 = E_x sin\psi_1 cos\beta + E_y cos\psi_1 cos\gamma \tag{3.10}$$

$$V_2 = E_x sin\psi_2 cos\beta + E_y cos\psi_2 cos\gamma \tag{3.11}$$

The correlation coefficient ρ_{12} between the received random signals is defined as;

$$\rho_{12} = \frac{E\{V_1V_2\} - E\{V_1\}E\{V_2\}}{\sqrt{E\{(V_1 - E\{V_1\})^2\}E\{(V_2 - E\{V_2\})^2\}}} \tag{3.12}$$

where E{} is the expected value operator, in other words time-averaging operator. The time averaged power ratio of the vertically polarized electric field to the horizontally polarized electric field is called cross polar ratio (XPR). XPR is defined as, $XPR = E[r_y^2]/E[r_x^2]$. Substituting the received signals V_1 and V_2 and introducing the XPR, the equation 3.12 results in:

$$\rho_{RX12} = \frac{\tan(\psi_i)\tan(\psi_j)\cos^2\beta + XPR\cos^2\gamma}{\sqrt{(\tan^2(\psi_i)\cos^2\beta + XPR\cos^2\gamma)(\tan^2(\psi_j)\cos^2\beta + XPR\cos^2\gamma)}} \tag{3.13}$$

As it can be seen from fig. 3.6 (a), the antennas are colocated in this model, which means that spatial diversity is not employed. In this case, the only decorrelation mechanism for the received signals from two different antennas is the polarization difference. Equation 3.13 states that if there is no polarization difference, i.e. the RX antennas are in the same polarization orientation, the received signals are fully correlated. Thus, single polarized antenna configuration has full correlation. This situation is expected by intuition that colocated antennas are fully correlated and proven by the correlation analysis in 3-D model.

CHAPTER 4

MIMO SYSTEM MODEL

Multiple antennas can be used instead of SISO systems in order to increase data rate and communication reliability. There are two main advantages of MIMO systems over SISO systems; namely, diversity gain and multiplexing gain. In a wireless link, signals suffer from attenuation due to fading. However, since there is more than one subchannel in a MIMO system, when one communication link encounters a deep fade the other may not be in as much fade, which is the general situation for MIMO systems. Increase in SNR results in better performance, providing communication reliability and this is called diversity gain. Additionally since more than one communication link can be established via TX and RX antennas, data rate can be enhanced in MIMO systems, which is called multiplexing gain. In this study, to analyze the effects of the polarization diversity on MIMO system performance, Alamouti and spatial multiplexing transmission schemes are used.

4.1 Transmission Techniques

4.1.1 Alamouti Scheme

As the MIMO communication system idea improved, a variety of transmission and reception algorithms had risen. To obtain diversity gain, at first RX diversity schemes have been considered. Systems with single TX and multi RX antennas, namely SIMO systems, generate the opportunity for different combining techniques, such as selection combining, equal gain combining, maximum ratio combining. The most efficient one among them is maximum ratio combining (MRC) which is based on the idea of combining the received signals from different antennas after factorizing by the conjugates of channel coefficients corresponding to the related subchannel. MRC needs channel state information at the receiver (CSIR). Knowing the channel coefficients, the received signals from each antenna is multiplied by the conjugate of the corresponding channel coefficient and the processed signals from each antenna are summed up as in eqn. 4.2.

$$\mathbf{y} = \sqrt{E_s}\mathbf{hs} + \mathbf{n} \tag{4.1}$$

$$\mathbf{y_{mrc}} = \mathbf{h^H} * \mathbf{y} = \sum_{\mathbf{i=1}}^{\mathbf{n_r}} [\sqrt{E_s}(|\mathbf{h_i}|^2\mathbf{s}) + (\mathbf{h_i^* n_i})] \tag{4.2}$$

The received signal vector is processed and thanks to proper combining of the received signals from different RX antennas, received SNR increases with respect to single receiver branch as shown in eqn. 4.4.

$$SNR_{singlebranch} = E_s|h_i|^2/\sigma_n^2 \tag{4.3}$$

$$SNR_\Sigma = \frac{E_s\left(\sum_{i=1}^{n_r}|h_i|^2\right)^2}{\left(\sum_{i=1}^{n_r}h_i^* n_i\right)^2} = E_s\frac{\sum_{i=1}^{n_r}|h_i|^2}{\sigma_n^2} \tag{4.4}$$

Diversity gain is defined as the ratio of the averaged total received SNR to the averaged single branch SNR, without any combination. Remembering 3.2, channel is normalized by the received signal power and hence channel coefficients have unity power. Therefore SNR is maximized and the diversity gain is n_r in MRC. It is said that MRC has full diversity order when the weight factor for each branch is selected as the conjugate of the corresponding channel coefficient.

$$Diversity\ \ gain = \frac{E\{SNR_\Sigma\}}{E\{SNR_{singlebranch}\}} = n_r \tag{4.5}$$

After SIMO ideas with RX diversity techniques, TX diversity has started to attract attention and in 1998 Alamouti presented a novel TX diversity technique, known with his name, the Alamouti (AL) TX diversity technique [37]. AL scheme is one of the most widely used TX diversity schemes in wireless MIMO systems when channel state information at the transmitter (CSIT) is not present. In this study only CSIR is assumed.

AL is applicable to not only 2×1 MIMO systems but also to the MIMO systems with two TX and multi RX antennas. Using Alamouti encoding, performance of a communication system can be extended at the expense of reduced data rate.

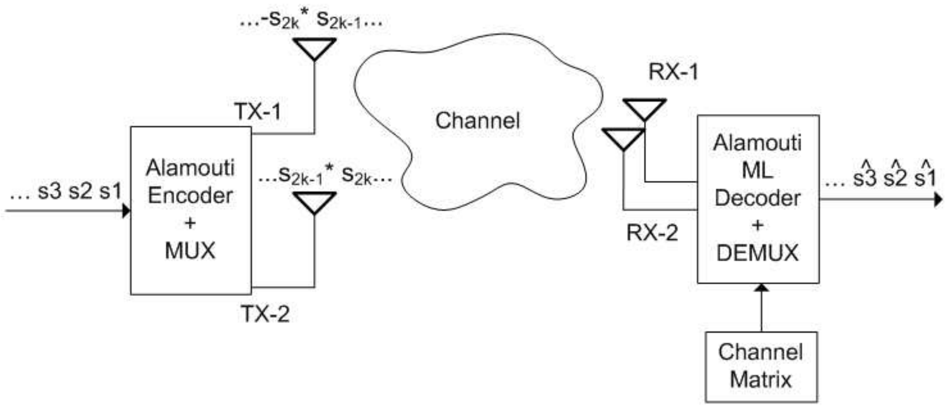


Figure 4.1: Alamouti System Block Diagram

AL system schematic can be seen in fig. 4.1. In AL, the idea is to transmit somehow correlated signals from each TX antennas without need to know the channel state information at the TX. The sequence to be transmitted from TX antennas in AL scheme is:

$$\begin{aligned} TX1 &\Rightarrow \ ...[-s_2^*\ s_1] \\ TX2 &\Rightarrow \ ...[\ s_1^*\ \ s_2] \end{aligned}$$

In two symbol period, two different symbols can be sent through the wireless channel. To use AL scheme, channel coefficients should be constant over at least two symbol period. Manipulating channel matrix properly and combining the received signal power at the receiver leads to diversity gain increasing performance.

In two symbol period, the second symbol transmitted from the first TX antenna is negative complex conjugate of the first symbol transmitted from the second antenna and the second symbol from the second TX antenna is complex conjugate of the first symbol from the first antenna.

AL is generally used with single RX antenna however, it can be extended to multi RX antennas. Since in this study 2×2 system is considered, 2×2 system is explained in details.

The channel matrix is constant over two symbol period and it can be written as:

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}, \tag{4.6}$$

where h_{ij} is the channel coefficient of the subchannel between i_{th} RX and j_{th} TX antennas.

The received signals from the 1_{st} RX antenna in two symbol period is:

$$\begin{aligned} y_{11} &= \sqrt{E_s}(h_{11}s_1 + h_{12}s_2) + n_{11} \\ y_{21} &= \sqrt{E_s}(h_{12}s_1^* + h_{11}(-s_2)^*) + n_{21} \end{aligned} \tag{4.7}$$

The received signals from the 2_{nd} RX antenna in two symbol period is:

$$\begin{aligned} y_{12} &= \sqrt{E_s}(h_{21}s_1 + h_{22}s_2) + n_{12} \\ y_{22} &= \sqrt{E_s}(h_{22}s_1^* + h_{21}(-s_2)^*) + n_{22} \end{aligned} \tag{4.8}$$

In these equations, y_{ti} represents the received signal from the i_{th} RX antenna at time t and n_{ti} is the noise at the i_{th} receiver at time t. s_1 and s_2 are the symbols transmitted from TX antennas in this sample two symbol period.

Taking the conjugate of the received signal at time t=2 and then writing the signals from 1_{st} RX antenna in two symbol period is:

$$\begin{aligned} y_{11} &= \sqrt{E_s}(h_{11}s_1 + h_{12}s_2) + n_{11} \\ y_{21}^* &= \sqrt{E_s}(h_{12}^*s_1 + (-h_{11})^*s_2) + n_{21}^* \end{aligned} \tag{4.9}$$

Taking the conjugate of the received signal at time t=2 and then writing the signals from 2_{nd} RX antenna in two symbol period is:

$$\begin{aligned} y_{12} &= \sqrt{E_s}(h_{21}s_1 + h_{22}s_2) + n_{12} \\ y_{22}^* &= \sqrt{E_s}(h_{22}^*s_1 + (-h_{21})^*s_2) + n_{22}^* \end{aligned} \tag{4.10}$$

Modifying channel matrix to use for the 1_{st} and 2_{nd} RX antenna signals:

$$\mathbf{H_{AL1}} = \begin{bmatrix} h_{11} & h_{12} \\ h_{12}^* & -h_{11}^* \end{bmatrix} \tag{4.11}$$

$$\mathbf{H_{AL2}} = \begin{bmatrix} h_{21} & h_{22} \\ h_{22}^* & -h_{21}^* \end{bmatrix} \tag{4.12}$$

Multiplying the Hermitian of the AL channel matrices with the received signals from the 1_{st} and 2_{nd} RX antennas respectively and then combining the received signals:

$$\mathbf{y_{AL}} = \mathbf{H_{AL1}^H} \begin{bmatrix} y_{11} \\ y_{21}^* \end{bmatrix} + \mathbf{H_{AL2}^H} \begin{bmatrix} y_{12} \\ y_{22}^* \end{bmatrix} \tag{4.13}$$

$$\mathbf{y_{AL}} = \begin{bmatrix} h_{11}^* & h_{12} \\ h_{12}^* & -h_{11} \end{bmatrix} \begin{bmatrix} \sqrt{E_s} h_{11} s_1 + h_{12} s_2 + n_{11} \\ \sqrt{E_s} h_{11}^* (-s_2) + h_{12}^* s_1 + n_{21}^* \end{bmatrix} + \begin{bmatrix} h_{21}^* & h_{22} \\ h_{22}^* & -h_{21} \end{bmatrix} \begin{bmatrix} \sqrt{E_s} h_{21} s_1 + h_{22} s_2 + n_{12} \\ \sqrt{E_s} h_{21}^* (-s_2) + h_{22}^* s_1 + n_{22}^* \end{bmatrix} \tag{4.14}$$

The result of the Alamouti encoding transmission and combining of the received signals from different antennas can be written as:

$$\mathbf{y_{AL}} = \begin{bmatrix} (|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2) s_1 + (h_{11}^* n_{11} + h_{12} n_{21}^* + h_{21}^* n_{12} + h_{22} n_{22}^*) \\ (|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2) s_2 + (h_{12}^* n_{11} - h_{11} n_{21}^* + h_{22}^* n_{12} - h_{21} n_{22}^*) \end{bmatrix} \tag{4.15}$$

As can be seen from eq. 4.15, the signal power is increased due to Alamouti transmission scheme and combination algorithm at the receiver. The diversity gain for Alamouti scheme is 2n$_r$ as proven in 4.18.

$$SNR_{singlebranch} = E_s |h_i|^2 / \sigma_n^2 \tag{4.16}$$

$$SNR_{\Sigma} = \frac{E_s \left(\sum_{i=1}^{n_r} |h_{i1}|^2 + |h_{i2}|^2 \right)^2}{\left(\sum_{i=1}^{n_r} h_{i1}^* n_{1i} + h_{i2}^* n_{2i} \right)^2} = E_s \frac{\sum_{i=1}^{n_r} (|h_{i1}|^2 + h_{i2}^2)}{\sigma_n^2} \tag{4.17}$$

$$Diversity\ \ gain = \frac{E[SNR_{\Sigma}]}{E[SNR_{singlebranch}]} = 2n_r \tag{4.18}$$

2×n$_r$ MIMO system with Alamouti TX diversity scheme doubles the diversity gain of 1× n$_r$ SIMO system with MRC RX diversity. Diversity gain of 2×n$_r$ Alamouti scheme is 2n$_r$ the same as 1×2n$_r$ MRC algorithm theoretically. Fig. 4.2 shows the BPSK modulation BER comparison of SISO system, 1×2 MRC and 1×4 MRC RX diversity, 2×1 AL and 2×2 AL TX diversity schemes under pure Rayleigh fading channel. AL systems have nearly 3dB worse performance than MRC counterparts at all SNR values. The reason underlying this fact is that SNR is defined as the ratio of the total transmission power to noise power. Since there are two TX antennas in AL system, symbol power transmitted from each antenna is 3 dB lower than MRC system with one TX antenna keeping the total radiated TX power the same. If performance is compared with respect to average SNR of TX antenna, 2×1 AL has the same BER performance as 1×2 MRC and 2×2 AL has the same BER as 1×4 MRC due to the same diversity gain of both systems. When compared to SISO system without any RX or TX diversity, 2×1 AL has about 12 dB better performance and 2×2 AL has about 20 dB better performance than SISO system at BER value of 2x10^{-4}.

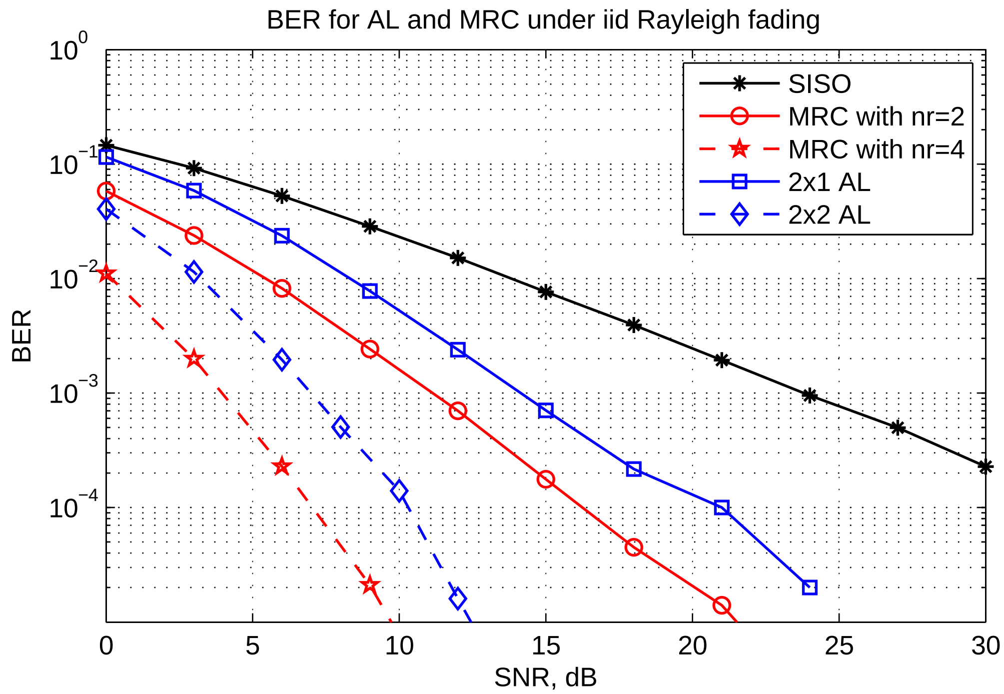


Figure 4.2: BER comparison for AL and MRC schemes under Rayleigh fading

4.1.2 Spatial Multiplexing

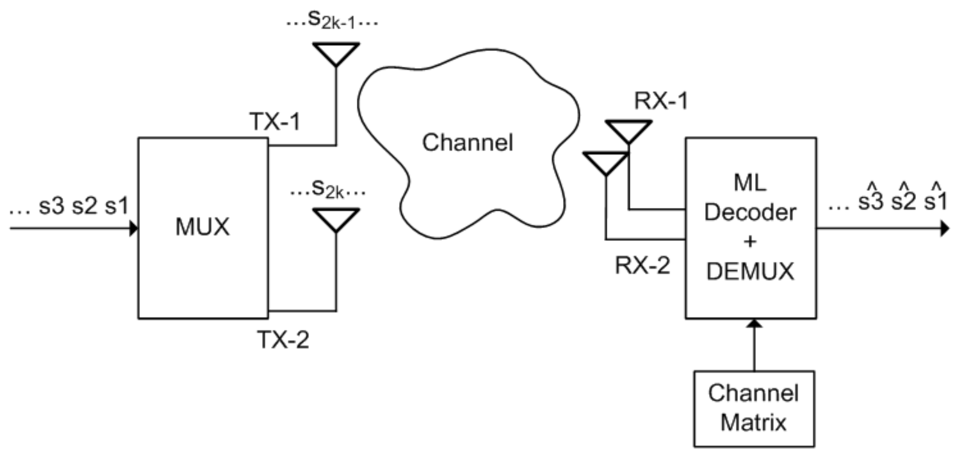


Figure 4.3: Spatial Multiplexing System Block Diagram

In spatial multiplexing, the idea is based on transmission of independent symbols from different TX antennas. By this way, the data rate is increased as compared to single TX antenna. Independent sequences are sent simultaneously from each TX antenna as shown in fig. 4.3.

Spatial multiplexing (SM) system has worse BER performance, in general, than Alamouti scheme. AL

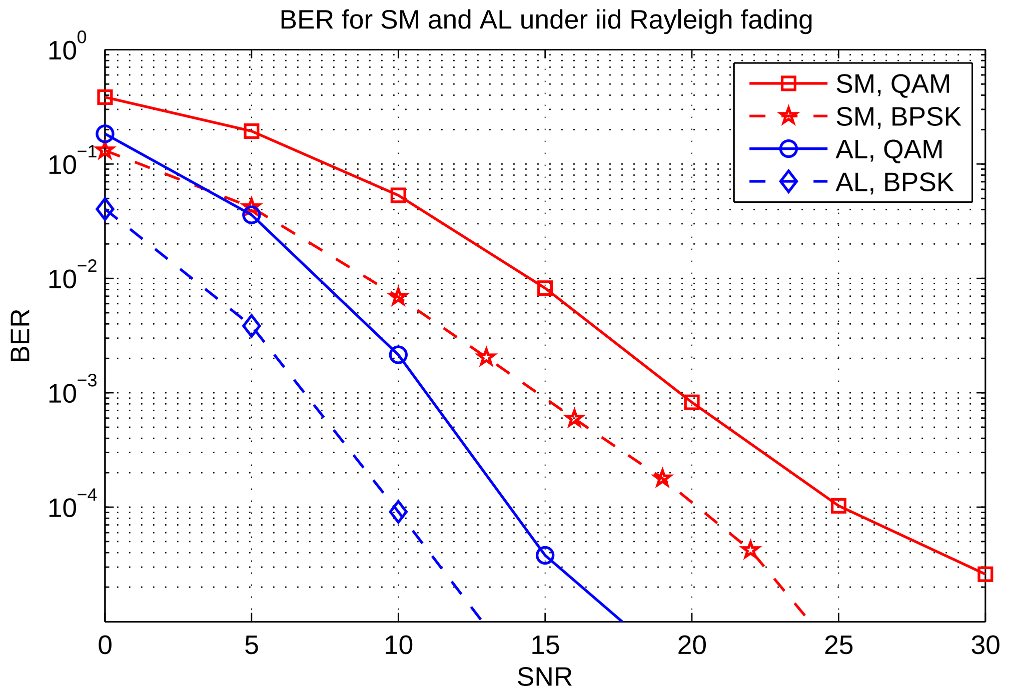


Figure 4.4: BER comparison for SM and AL schemes under Rayleigh fading

has both TX and RX diversity and the received signals from different antennas are combined efficiently. In SM there is no combining algorithm at the receiver. However, SM has increased data rate in contrast with Alamouti scheme for 2×2 MIMO system. This can be explained so that, in AL scheme up to two successful symbols can be sent whereas in SM up to four independent symbols can be sent in two symbol period.

In fig. 4.4 performance of 2×2 MIMO systems with AL and SM algorithms are illustrated for BPSK and QAM modulation types under pure Rayleigh fading channel. At BER value of 10^{-4}, AL has about 10dB better BER performance than SM for both BPSK and QAM modulation types. However, SM has twice data rate of AL. To equalize the data rates and perform fair comparison, AL scheme with QAM and SM with BPSK modulations can be compared. For low SNR values, AL with QAM and SM with BPSK performs barely the same. Yet, after SNR > 10 dB AL with QAM outperforms SM with BPSK and the difference becomes nearly 6dB at BER value of 10^{-4} under pure Rayleigh fading channel.

4.2 Receiver Decoding: Maximum Likelihood Algorithm

In the simulations and algorithms used in this study, maximum likelihood (ML) algorithm is used at the receiver in order to successfully detect the symbols. Channel coefficients are assumed to be perfectly known at the receiver. Since channel state information at the receiver (CSIR) is assumed, ML algorithm utilizes the channel coefficients and tries to find the minimum distance between the received signal and all possible modulation points.

For SISO case the baseband received signal is;

$$y = \sqrt{E_s} hs + n \tag{4.19}$$

The ML estimate of the transmitted symbol s can be written as;

$$ML \;\; estimate = argmin_{s_i} \; |y - \sqrt{E_s} hs_i|^2 \tag{4.20}$$

Knowing the channel coefficients, ML algorithm tries all the possible constellation points and compares the distance to the received signal. The symbol with the minimum Euclidean distance to the received signal is selected as the estimate of the transmitted symbol.

In RX diversity only case, i.e. SIMO, single symbol is transmitted yet more than one signal are received from different antennas. In this case one symbol is being tried to be detected by using a processed channel coefficients. In MRC RX diversity technique, Hermitian of channel matrix is multiplied by itself and this processed channel coefficient is used. This generates diversity gain and significantly increases SNR.

For SIMO case the baseband received signal is;

$$\mathbf{y} = \sqrt{E_s}\mathbf{Hs} + \mathbf{n} \tag{4.21}$$

The ML estimate of the transmitted symbol s for MRC can be written as;

$$\begin{aligned} ML \;\; estimate_{MRC} &= argmin_{s_i} \; |y - \sqrt{E_s}\mathbf{h}^H\mathbf{h}s_i|^2 \\ &= argmin_{s_i} \; |y - \sqrt{E_s}\sum_{i=1}^{n_r}|h_i|^2 s_i|^2 \end{aligned} \tag{4.22}$$

In MIMO case, since more than one symbol is transmitted, rather than a single symbol, multi symbols in a symbol vector are tried to be detected. Thus a code vector including all combinations of possible symbols is used and estimate vector is determined by choosing the symbol vector satisfying minimum distance for all symbols in the vector separately.

For MIMO case the baseband received signal is;

$$\mathbf{y} = \sqrt{E_s}\mathbf{Hs} + \mathbf{n} \tag{4.23}$$

As for AL scheme, just like MRC, SNR is increased by properly combining the received signals from different antennas in two symbol period. Frobenius norm [1] of the channel matrix is used as the channel in ML algorithm. Thus processed channel matrix becomes the summed magnitude squares of the channel coefficients.

The ML estimate of the transmitted vector **s** for 2×n$_r$ MIMO with AL scheme can be written as;

$$\begin{aligned} ML \;\; estimate_{AL} &= argmin_{\mathbf{s}} \; |\mathbf{y} - \sqrt{E_s}|\mathbf{H}|^2_{\mathbf{fro}}\mathbf{s}|^2 \\ &= argmin_{\mathbf{s}} \; |\mathbf{y} - \sqrt{E_s}\sum_{\mathbf{i=1}}^{\mathbf{n_r}}(|\mathbf{h_{i1}}|^2 + |\mathbf{h_{i2}}|^2)\mathbf{s}|^2 \end{aligned} \tag{4.25}$$

[1] Frobenius norm of an M× N matrix:

$$|\mathbf{X}|^2_{\mathbf{fro}} = \mathbf{Tr}(\mathbf{XX^H}) = \sum_{\mathbf{i=1}}^{\mathbf{N}}\sum_{\mathbf{j=1}}^{\mathbf{M}}|\mathbf{h_{ij}}|^2 \tag{4.24}$$

Finally for the SM scheme, no smart diversity algorithm is employed and the original channel matrix is used in ML decoder.

The ML estimate of the transmitted vector **s** for $n_t \times n_r$ MIMO with SM scheme can be written as;

$$ML\ \ estimate_{SM} = argmin_{\mathbf{s}}\ |\mathbf{y} - \sqrt{E_s}\mathbf{Hs}|^{\mathbf{2}} \tag{4.26}$$

4.3 Capacity

Capacity of a channel is defined as the maximum data rate which can be achieved with arbitrarily low error probability. It is a measure of communication speed of the channel. Capacity for SISO system can be written as;

$$C_{SISO} = Blog_2(1 + hh^* SNR) \tag{4.27}$$

The unit of the capacity is bits per second indicating the speed of the communication over communication bandwidth B. In this study bandwidth is omitted and capacity is investigated in bps/Hz unit. Omitting bandwidth still defines the data rate of the system. By just multiplying the bandwidth normalized capacity with the desired communication bandwidth, designers or system planners can simply calculate real capacity over a wireless channel.

Capacity is highly dependent on the channel gains and whether these coefficients are known at TX or not. Some smart power management algorithms such as water-filling can be used when channel state information is known at TX. There are some studies investigating the performance of polarization diversity assuming CSIT [18], [19]. Yet, in this study as previously stated only CSIR is assumed and total power to be radiated is uniformly distributed over TX antennas. Extending the SISO capacity equation to MIMO capacity without CSIT;

$$C_{MIMO} = Blog_2\left(det\left[I + \frac{SNR}{n_t}\mathbf{HH^H}\right]\right) \tag{4.28}$$

Without CSIT and any power management algorithm, total power is divided by number of TX antennas. Consequently, SNR is divided by n_t.

For an instant of the communication and single channel matrix, the abovementioned equations represent the capacity. However, in order to obtain the accurate results for probabilistic channels expected value of the capacity should be considered. Therefore average capacity of a MIMO channel can be written as:

$$C_{MIMO} = BE\left\{log_2\left(det\left[I + \frac{SNR}{n_t}\mathbf{HH^H}\right]\right)\right\} \tag{4.29}$$

4.4 Simulation Setup

All the simulations are performed in MATLAB environment. In the simulations, AL and SM schemes are used as transmission scheme and ML decoding algorithm is employed as decision algorithm while comparing single and dual polarized antenna configurations. Packet data transmission with packet size of 10^2 symbols is used. Channel coefficients are assumed to be constant over one packet length and they change from packet to packet. Yet, noise signal at the receiver changes for each symbol reception. BER plots are obtained via 10^5 Monte Carlo packet trials for each SNR value. SNR is defined as the ratio of the total symbol energy transmitted from all TX antennas to the noise power at the receiver. Taking the E_s as energy per symbol, total energy transmitted from TX antennas is $n_t E_s$. Noise variance is used as noise power. SNR can be written as $SNR = E_s n_t/\sigma_n^2$. As modulation type, BPSK and QAM modulations are used. Channel is assumed to be perfectly known at the receiver (CSIR) and it is not known at the transmitter (no CSIT).

In the channel model, it is indicated that, two of the main parameters K-factor and XPD are distance dependent and simulation of fully characterized wireless communication link can be performed. Yet, in order to correctly analyze the results of the simulations with distance dependent channel, the performance with constant parameters should be known priorly. For this purpose, the results are divided into two chapters as constant and distance dependent channel parameters. In the simulation plots, iid Rayleigh fading and SISO curves are added as reference for different channel cases and these reference curves are used to evaluate the single and dual polarization performance more clearly. Additionally, in order to investigate the effect of number of antennas in a MIMO system with and without polarization diversity, 3×3 and 4×4 MIMO systems performances are included in the simulation results.

CHAPTER 5

MIMO CHANNEL EVALUATION WITH CONSTANT K-FACTOR AND XPD

In this chapter, simulation results for constant channel parameters, namely K-factor and XPD are presented using the MIMO channel and system models described in chapter 3. 2×2 MIMO wireless system is simulated in order to investigate the effect of polarization diversity. Single and dual polarized antenna configurations are evaluated considering Alamouti and spatial multiplexing schemes.

In this chapter K-factor has two constant values as 0 and 10. 0 K-factor corresponds to pure Rayleigh fading and K-factor of 10 is highly Ricean fading channel with 10 times larger constant channel power than variable channel power. In addition, XPD value is selected as either 6dB or 10dB in 10 base logarithmic scale. Note that, XPD value is meaningful for only dual polarized configuration and it is not used in single polarization channel.

As specified in 3.2.2.1, TX interantenna spacing is assumed to be large such that TX correlation coefficient is not considered. Correlation coefficient refers to only RX correlation coefficient. Polarization diversity is evaluated for two cases of RX interantenna spacing. If there is enough space at the receiver such as in section 5.1, spatial diversity is present, received signals are uncorrelated and RX correlation coefficient is zero regardless of the polarization orientation. Thus, the only polarization diversity effect is XPD causing channel power loss. On the other hand, when there is not enough space at the receiver to uncorrelate the signals received from different RX antennas, there exists correlation between the received signals. In order to investigate the effect of correlation, the received antennas are assumed to be colocated and only decorrelation mechanism is polarization diversity. Channels with correlation effects are considered in 5.2.

5.1 Uncorrelated channel with constant K-factor and XPD

In this section spatial diversity is assumed such that there is no channel correlation. Both TX and RX antenna elements are sufficiently separated from each other.

5.1.1 XPD comparison

In order to observe the effect of XPD, XPD is changed from 6dB to 10dB, for two constant K-factor values, 0 and 10. XPD effect of dual polarization is analyzed for BER and capacity performance.

5.1.1.1 BER performance

AL scheme

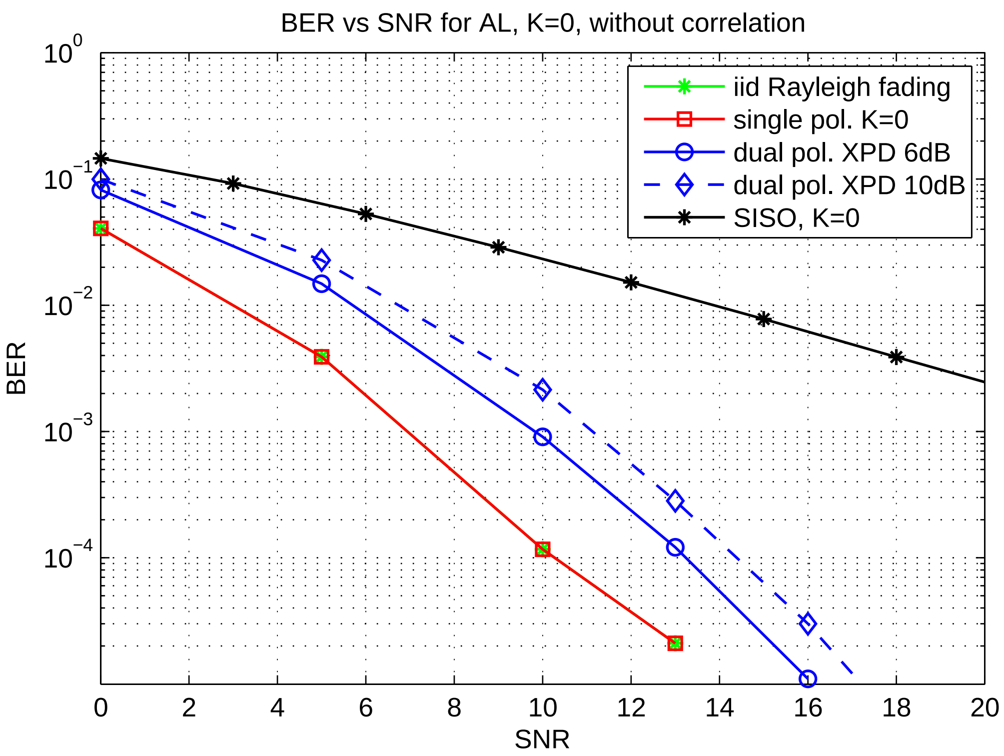


Figure 5.1: BER comparison for AL, uncorrelated channel with K=0

Fig. 5.1 illustrates BER vs SNR graph for AL with uncorrelated channel and zero K-factor. Firstly, single polarized channel matrix is the same as pure Rayleigh fading and they have the same performance. Dual polarization has nearly 3dB worse BER performance than single polarization at all SNR values. This is caused by XPD and power loss of dual polarized configuration. Since AL algorithm is based on power combination of the signals from different RX antennas by using the channel coefficients, power loss due to XPD worsens the BER performance of dual polarization. Moreover, when XPD is increased from 6dB to 10dB dual polarized configuration incurs about 1dB performance loss and the difference between single polarization increases to nearly 4dB. Yet, dual polarization with 10dB XPD still has more than 10dB better performance than SISO Rayleigh fading case at BER value of 10^{-3}.

When K-factor is increased to 10, this means that constant power of the channel is 10 times the variable power which refers to a closer communication distance. As shown in fig. 5.2, performance of both single and dual polarized configurations increase about 4dB with respect to 0 K-factor case. Single polarization has about 2.5 to 3dB better performance than dual polarization due to XPD just as in 0 K-factor case. As XPD increases from 6dB to 10dB, dual polarization performance worsens about 0.5 dB when K-factor is 10.

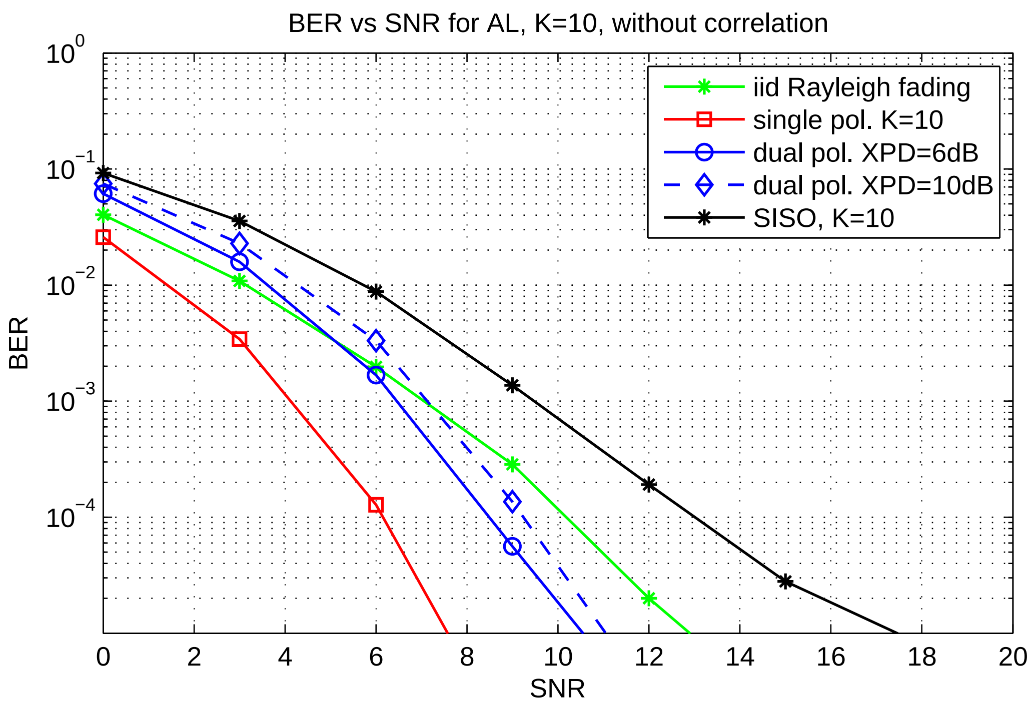


Figure 5.2: BER comparison for AL, uncorrelated channel with K=10

SM scheme

Fig. 5.3 shows the BER performance for the cases when SM is used to compare the single and dual polarizations under uncorrelated channel with constant 0 K-factor and XPD of 6dB and 10dB. Single polarization has about 2.5dB better performance than dual polarization with 6dB XPD at BER value of 10^{-4}.

Increase of XPD from 6dB to 10dB worsens the performance of dual polarization 2dB at BER value of 10^{-4}, when K=0. This is due to the fact that K=0 means pure Rayleigh fading and XPD decreases the power of the crosspolarized subchannels. This result is similar to BER of AL algorithm at K=0, fig. 5.1. In addition, SISO has worse performance than MIMO systems since 0 K-factor means strong fading for SISO channel.

Yet, when K-factor is increased to 10, constant channel component is dominant and channel matrix becomes rank deficient. At high K-factor XPD transforms the constant channel matrix to full-rank which leads to performance gain for dual polarization, as also stated in [17], [16]. Dual polarization with 6dB XPD has lower BER than single polarization, especially at high SNR regime and the difference becomes approximately 3.5dB at BER value of 10^{-5} as indicated in fig. 5.4. Although XPD leads to power loss, as XPD increases at high K-factor the performance of dual polarization improves. This is due to the fact that channel eliminates rank deficiency with XPD. Moreover, as XPD increases, dual polarization SM BER improves and dual polarized configuration with XPD=10dB is 3dB better than XPD=6dB case at BER value of 10^{-5}.

Furthermore, SISO case with K=10 outperforms single and dual polarizations since SM encounters

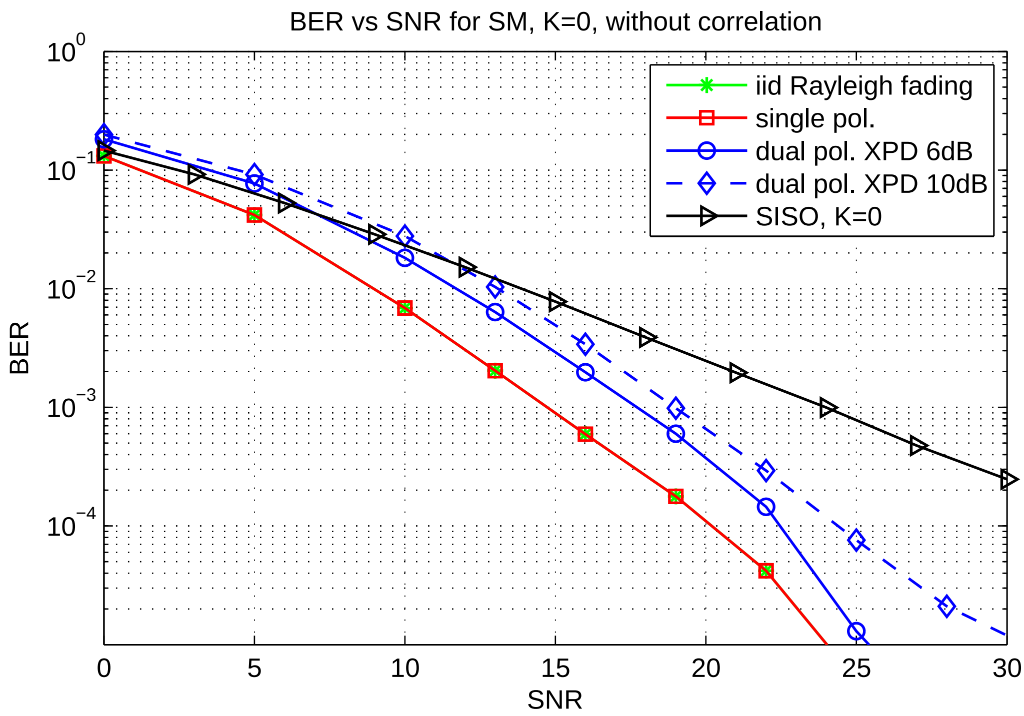


Figure 5.3: BER comparison for SM, uncorrelated channel with K=0

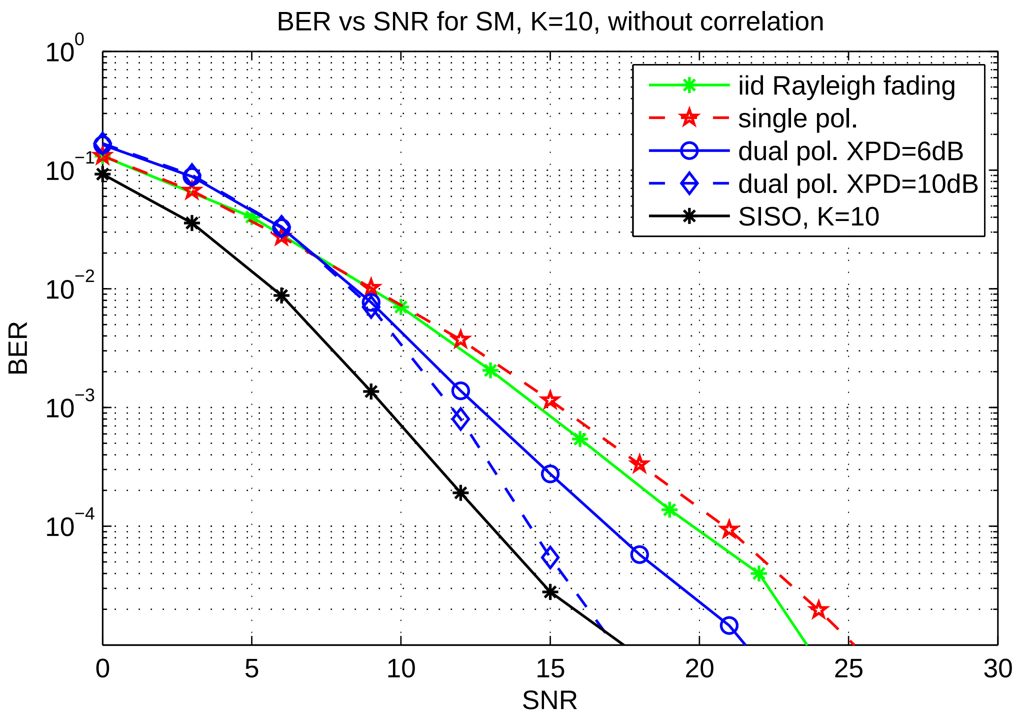


Figure 5.4: BER comparison for SM, uncorrelated channel with K=10

performance degradation due to low rank MIMO channel at high K-factor. Whereas, SISO performance increases nearly 17 dB with the increase of K-factor from 0 to 10. 2×2 SM BER performance is worse than SISO but the trade-off is data rate. MIMO systems can provide multi-user communication and increased data rate as compared to SISO.

5.1.1.2 Average Capacity

Fig.5.5 illustrates the capacity results for uncorrelated channel with 0 K-factor. When K-factor is 0 and channel is uncorrelated, single polarization channel is the same as iid Rayleigh fading and they have the same average capacity results just like BER performance. In addition, dual polarized configuration has nearly 1bps/Hz lower capacity than single polarized one due to XPD and as XPD increases from 6dB to 10dB, capacity of dual polarization decreases in a very small scale. Additionally, single polarized MIMO system has about 5 bps/Hz and dual polarized MIMO system has about 4bps/Hz higher capacity than SISO.

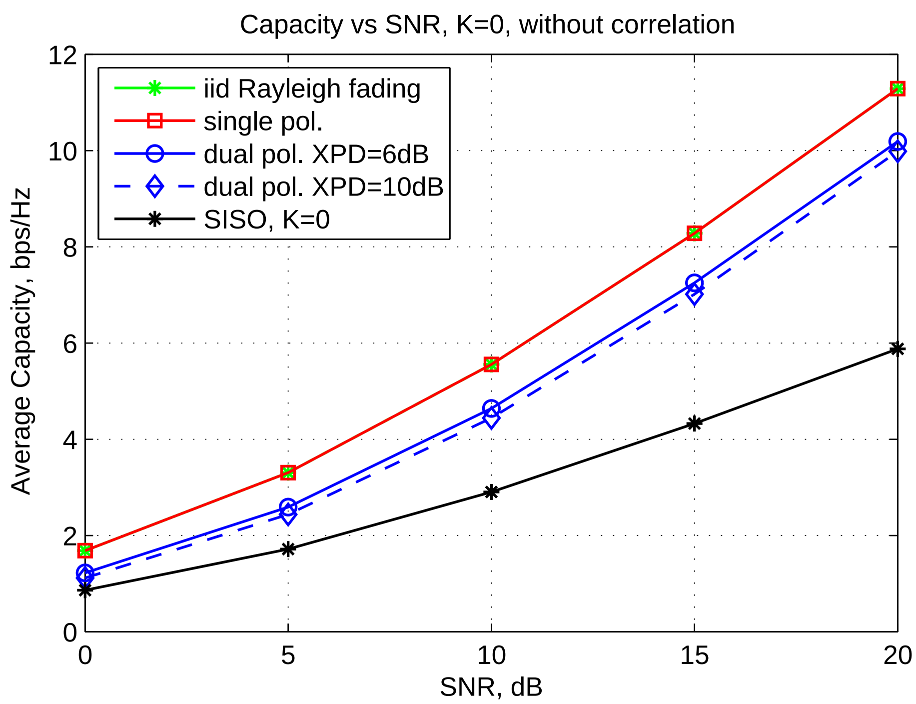


Figure 5.5: Average capacity, uncorrelated channel with K=0

Fig. 5.6 shows the capacity results for uncorrelated channel with K-factor of 10. When K-factor is 10, single polarization capacity decreases since channel is low rank and has high condition number. Just as in BER comparison for SM, XPD eliminates the effect of rank deficiency of the channel and dual polarization is not significantly effected from high K-factor. As XPD increases, capacity of dual polarization increases. At low SNR, capacity of single polarization is a little bit higher than dual polarization; however, when SNR>10dB dual polarization outperforms single polarization. The capacity difference between single and dual polarization is 0.7 bps/Hz when XPD is 6dB and 1.2bps/Hz when XPD is 10dB, at SNR value of 20dB. Moreover, although SISO capacity increases with the increase of K-factor from 0 to 10, MIMO capacity is much higher than SISO capacity.

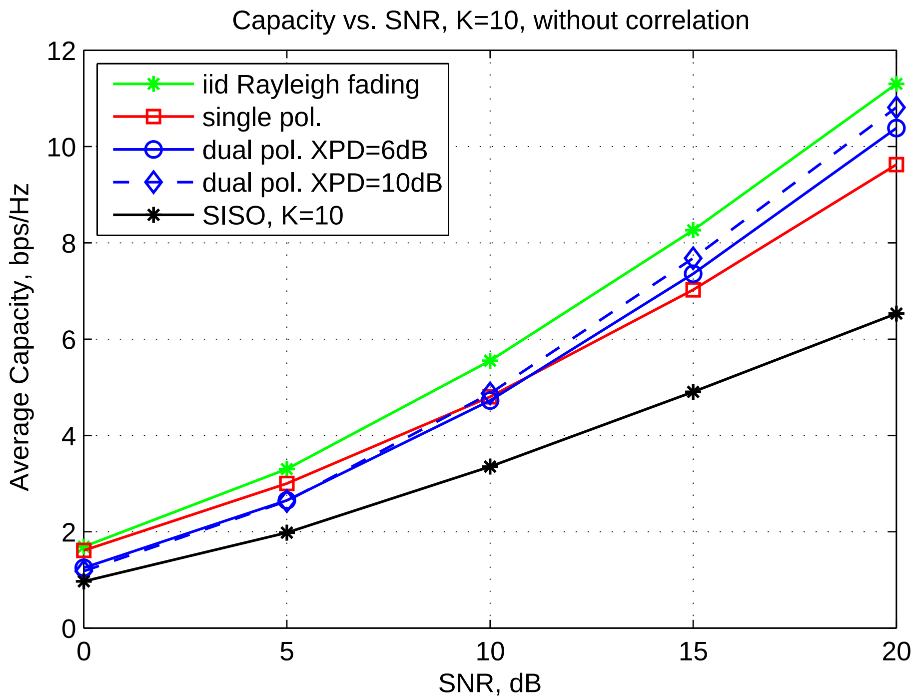


Figure 5.6: Average capacity, uncorrelated channel with K=10

5.1.2 K-factor comparison

In this section, effect of K-factor on BER and capacity performance of single and dual polarizations is investigated for constant XPD. K-factor value of 0 and 10 are compared in the same plot for 6dB XPD without correlation effect.

5.1.2.1 BER performance

AL scheme

BER curves of single and dual polarizations for AL under uncorrelated channels with K=0 and K=10 are figured in fig. 5.7. Single polarization has about 3dB better BER than dual polarization for K-factor of both 0 and 10. Since AL BER performance is based on channel power combination and XPD causes subchannel power loss for dual polarization, single polarization is better than dual polarization regardless of K-factor. K-factor can be interpreted as a measure of communication distance and single polarization is better for AL at both small and large distances. Furthermore, when K-factor is increased from 0 to 10, both single and dual polarizations has about 4dB better performance at BER value of 10^{-4}. As explained earlier for cross channel power handicap for dual polarization, since AL performance is based on power combination, high K-factor refers to less fading of the signals and leads to performance increase with respect to 0 K-factor.

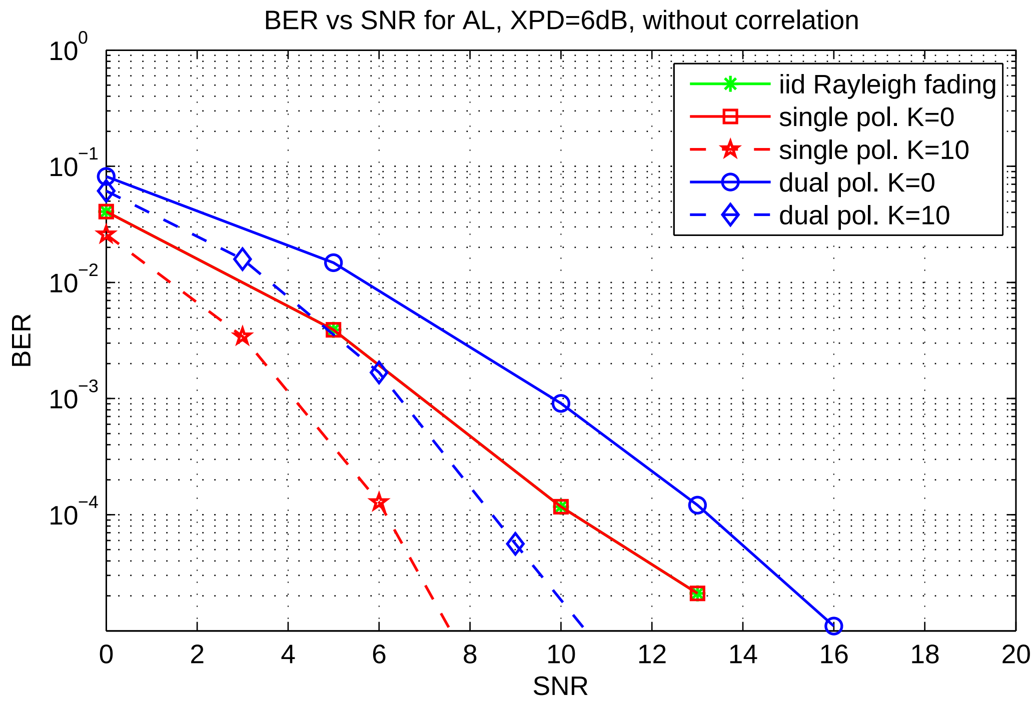


Figure 5.7: BER comparison for AL, uncorrelated channel with XPD=6dB

SM scheme

Fig. 5.8 illustrates the BER curves of single and dual polarizations for SM. Received signals are uncorrelated. K-factor is compared for constant XPD of 6dB. Single polarization has similar performance for both K-factor of 0 and 10. The reason underlying this fact is that although high K-factor refers to less fading and it is expected to cause better BER. However, for SM algorithm channel diversity is important and high K-factor leads to low rank channel. As a result, K-factor of 10 results worse performance than 0 K-factor for single polarization. However, dual polarization has about 4dB better BER performance at K-factor of 10 than at 0 K-factor. This is caused by two reasons. The first one is that the higher the K-factor is, the less fading level the channel encounters. The other one is the XPD of dual polarization, making the low-rank channel matrix high rank.

5.1.2.2 Average Capacity

Fig. 5.9 shows the average capacity results for K-factor comparison with 6dB XPD. With the increase of K-factor from 0 to 10, single polarization encounters a capacity decrease just like SM BER performance. This is caused by low rank channel due to dominance of constant channel component. The capacity decrease of single polarization is nearly 1.8bps/Hz at 20dB SNR. However, dual polarization capacity is nearly not effected by the K-factor increase since XPD eliminates the effect of rank deficiency. Capacity and SM BER performance analysis are similar since both of them are based on channel rank.

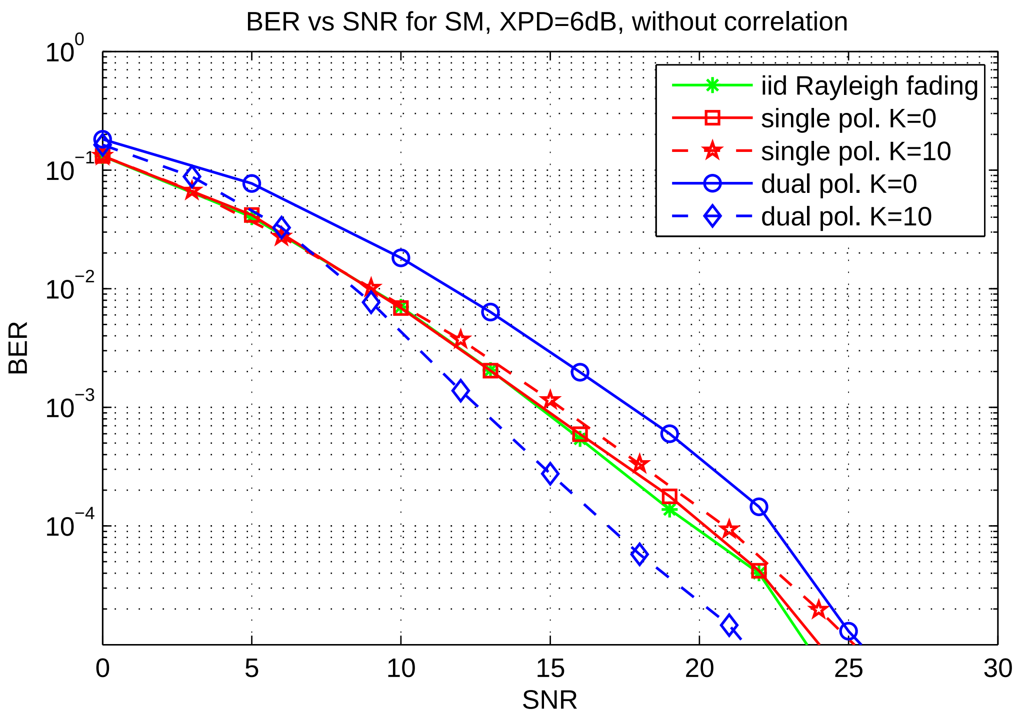


Figure 5.8: BER comparison for SM, uncorrelated channel with XPD=6dB

5.2 Correlated channel with constant K-factor and XPD

When there is not enough space at the receiver to uncorrelate the signals received from different RX antennas, there exists correlation between the received signals. In section 5.1, there is no correlation effect. Yet, at this section of the study, RX antennas are assumed to be co-located due to space problem at the receiver. In this case, single polarized antenna configuration has full correlation and the correlation coefficients for dual polarized antenna configuration are generated from equation 3.13. XPD is taken to be constant as 6dB in correlated channels and K-factor is either 0 or 10.

5.2.1 BER performance

5.2.1.1 AL scheme

Fig. 5.10 illustrates the performance of AL scheme under correlated channel with K=0. When K-factor is 0, the variable channel component and correlation effect dominate. As previously specified, for uncorrelated case single polarization has better BER performance than dual polarization. However, in correlated case, when one subchannel encounters deep fade, the other subchannel also suffers deep fade and performance decreases significantly.

Without correlation, single polarization has 3dB better performance than dual polarization. When the channel is correlated, both single and dual polarized configurations performance worsens. Due to correlation, BER of single polarization deteriorates 6dB, while dual polarization with lower correlation has about 2.5dB performance loss at BER of 10^{-4}. Since dual polarization has less correlation than

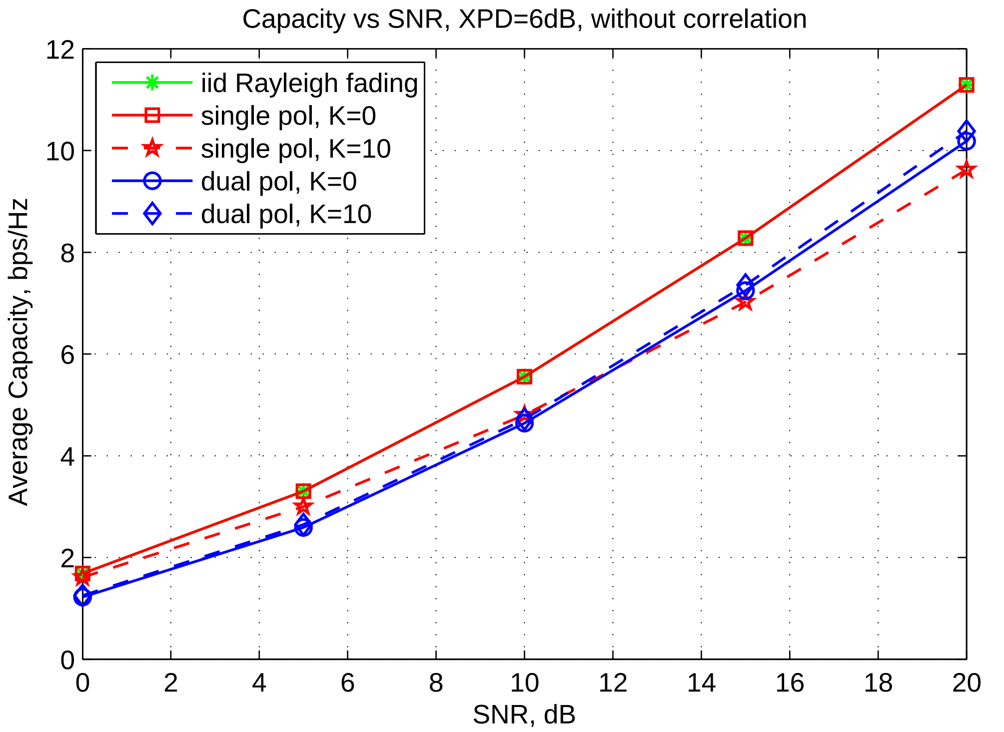


Figure 5.9: Average capacity, uncorrelated channel with XPD=6dB

single polarization, the BER difference in uncorrelated case diminishes and both systems have close performance. Even when SNR>15dB dual polarization outperforms single polarization. Moreover, although single polarization has disadvantage of high correlation, it still has more than 10dB better AL BER than SISO at BER value of $2x10^{-4}$.

When K-factor is increased to 10, the correlated variable channel component and correlation are not very significant. As shown in fig. 5.11, dual polarization is not effected by the correlation and single polarization has about 1dB worse performance as compared to without correlation case. Performance loss of single polarization due to high correlation does not compensate the performance loss of dual polarization due to XPD. Single polarization has still 1.5dB better BER performance at BER value of 10^{-4}. This result is caused by power loss of dual polarization due to XPD as in uncorrelated channel case. However, the difference in correlated channel case is not as high as in uncorrelated case due to lower correlation of dual polarization. Additionally, since AL is based on power combination algorithm, SISO BER for AL is higher than all MIMO cases considered.

5.2.1.2 SM scheme

Fig. 5.12 shows BER of SM scheme for 0 correlated channel K-factor. Dual polarization has performance loss of nearly 2.5 dB at $4x10^{-4}$ BER with respect to uncorrelated channel case with K=0 due to low correlation coefficient values. On the other hand, single polarization suffers from high correlation and performance degrades significantly nearly 14dB at $4x10^{-4}$ BER. Thus, dual polarization outperforms single polarization approximately 6dB at $4x10^{-4}$ BER in correlated channel case with K=0. In addition, SISO has about 1dB better SM BER than dual polarized MIMO channel with correlation

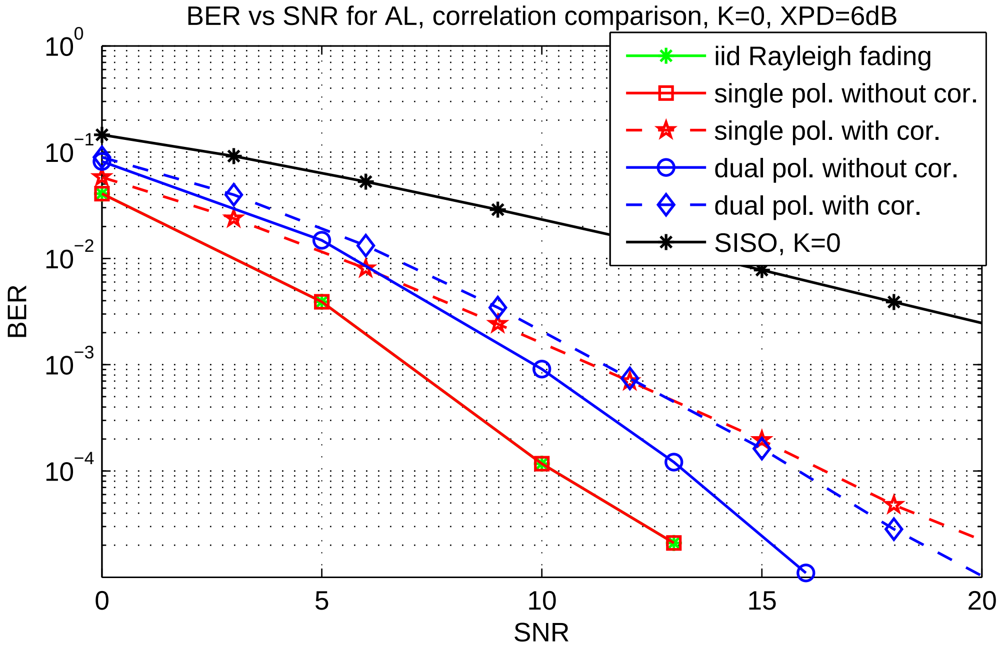


Figure 5.10: BER comparison for AL, correlated channel with K=0

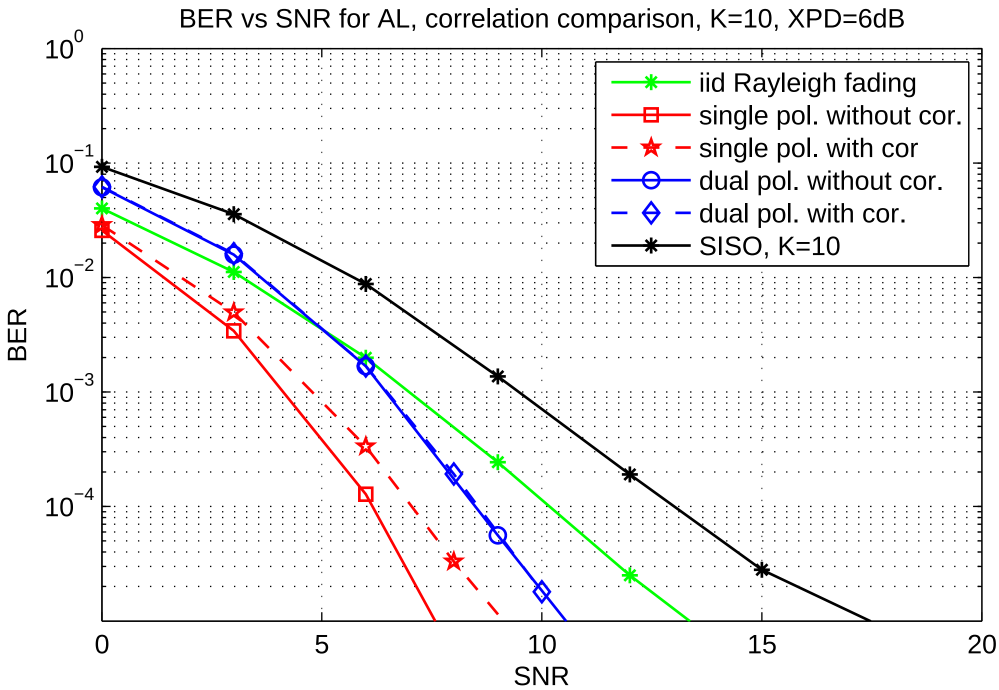


Figure 5.11: BER comparison for AL, correlated channel with K=10

which means that rather than employing 2×2 MIMO with 2 colocated RX antennas simply using one antenna may perform better in terms of SM BER. However, for accurate communication performance comparison capacity of the channels should also be taken into account.

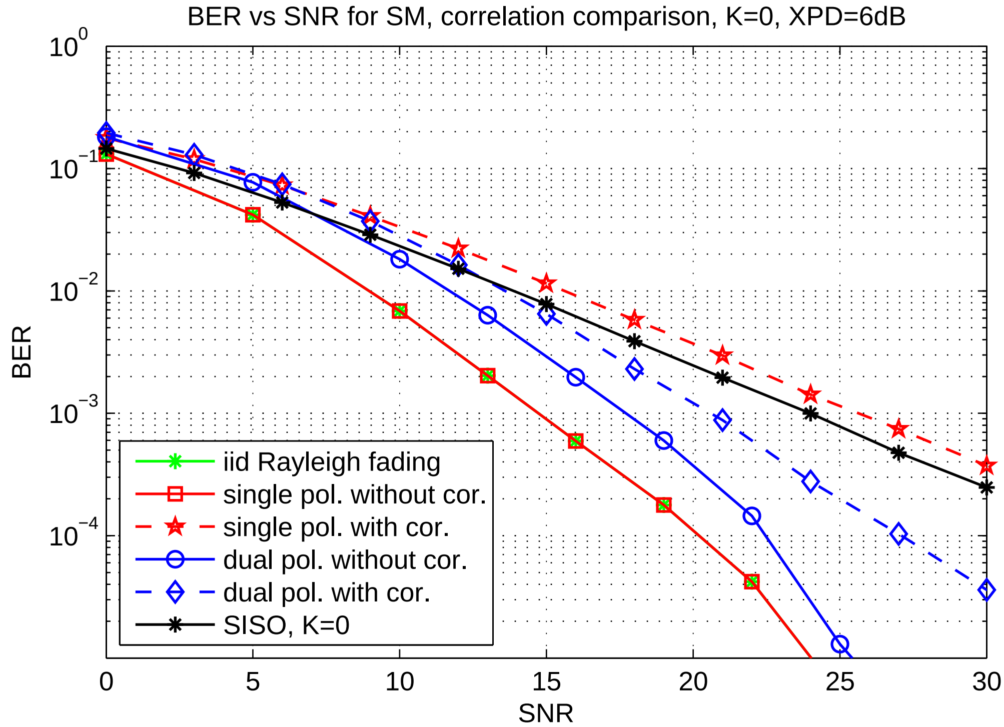


Figure 5.12: BER comparison for SM, correlated channel with K=0

At high K-factor correlation effect becomes less important and the performance difference between correlated and uncorrelated channel cases decreases. Fig. 5.13 illustrates BER performance for SM under correlated channel with K=10. Dual polarization performs nearly the same under channels with and without correlation effect due to both high K-factor and low correlation coefficient. Low correlation at high K-factor is effectless for dual polarization. Additionally, thanks to XPD dual polarization has already 5dB better performance than single polarization at BER value of 10^{-5} even in no correlation case. When correlation is included, single polarization encounters performance degradation of more than 10dB at BER of 10^{-4} with respect to uncorrelated channel. Dual polarization has already better BER performance than single polarization in uncorrelated case. Consequently, in correlated channel case, dual polarized configuration outperforms single polarized case about 13dB at 10^{-4} BER. In addition at high K-factor SISO can be used for SM BER because of the fact that SISO has better BER than MIMO systems with and without polarization diversity when correlation is considered.

5.2.2 Capacity

Fig. 5.14 illustrates the average capacity curves for correlation comparison at 0 K-factor. When there is no correlation effect, single polarization has higher capacity than dual polarization due to subchannel power loss of dual polarization. When the correlation is present, capacities of both polarizations decrease. At 20dB SNR, single polarization capacity decrease is about 4bps/Hz whereas capacity decrease of dual polarization is about just 0.5bps/Hz. Consequently, when the RX antennas are colocated and correlation is present, dual polarization has more than 2bps/Hz higher capacity than single polarization. Although the RX antennas are colocated, single polarization has about 1.2bps/Hz higher

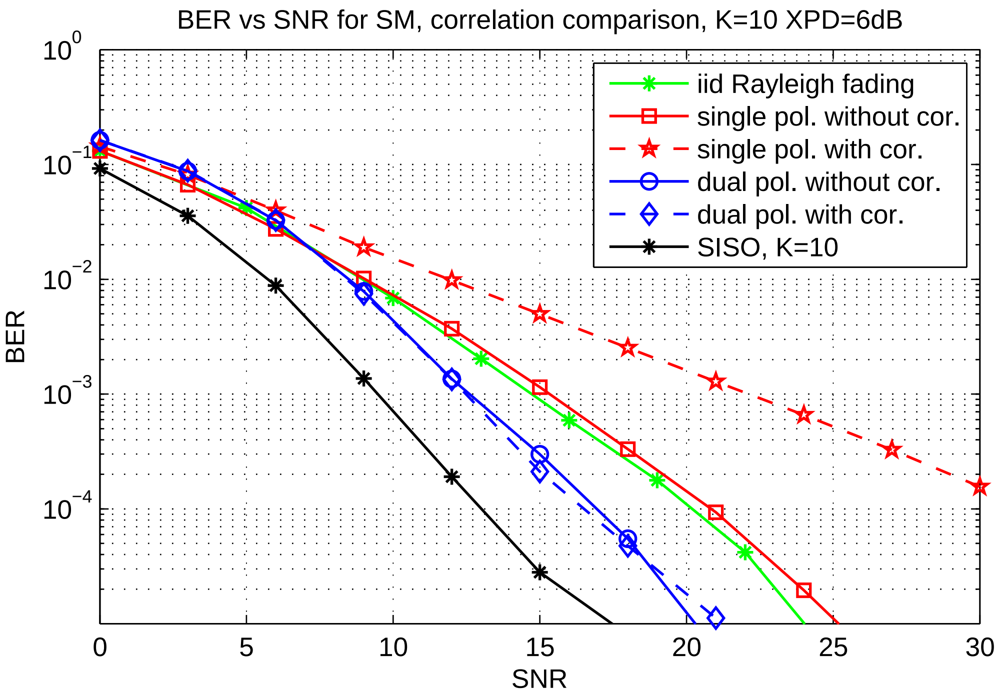


Figure 5.13: BER comparison for SM, correlated channel with K=10

capacity than SISO system at 20dB SNR. Furtermore, dual polarization has about 3.5bps/Hz higher capacity than SISO despite correlation.

Fig. 5.15 shows the capacity results for correlated channel with K-factor of 10. At K-factor of 10, both for correlated and uncorrelated channels capacity results are very similar to the BER performance analysis of SM. When there is no correlation, dual polarization capacity is higher than single polarization capacity at high SNR, since XPD increases the channel rank. Capacity of dual polarization does not change with correlation. On the other hand, single polarization encounters a sharp capacity decrease of 2bps/Hz at 20dB SNR. Therefore, in the presence of correlation, dual polarization capacity is nearly 3bps/Hz higher than single polarization capacity. Additionally, single polarization capacity is still about 1bps/Hz higher than SISO. There is a trade-off between SM BER and capacity for correlated channel. For correlated channel with high K-factor SISO has better SM BER than even dual polarized MIMO, whereas capacity of dual polarization is higher than SISO. Moreover, MIMO systems with and without polarization diversity always have better BER for AL than single polarization. Therefore, when there is correlation, dual polarization can be used for AL BER and capacity.

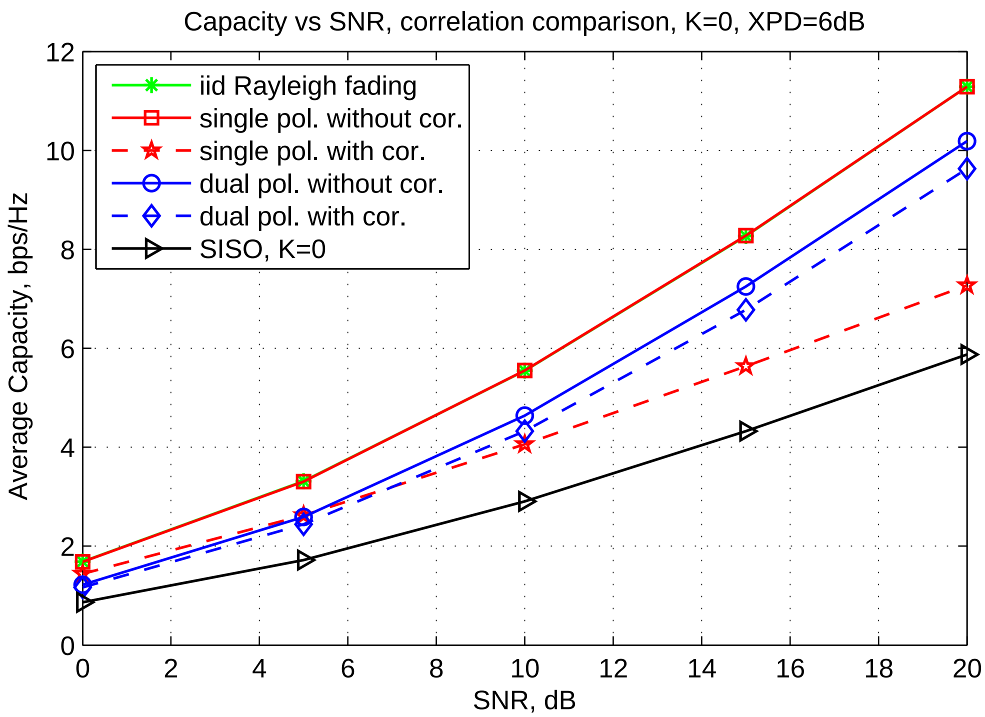


Figure 5.14: Average capacity, correlated channel with K=0

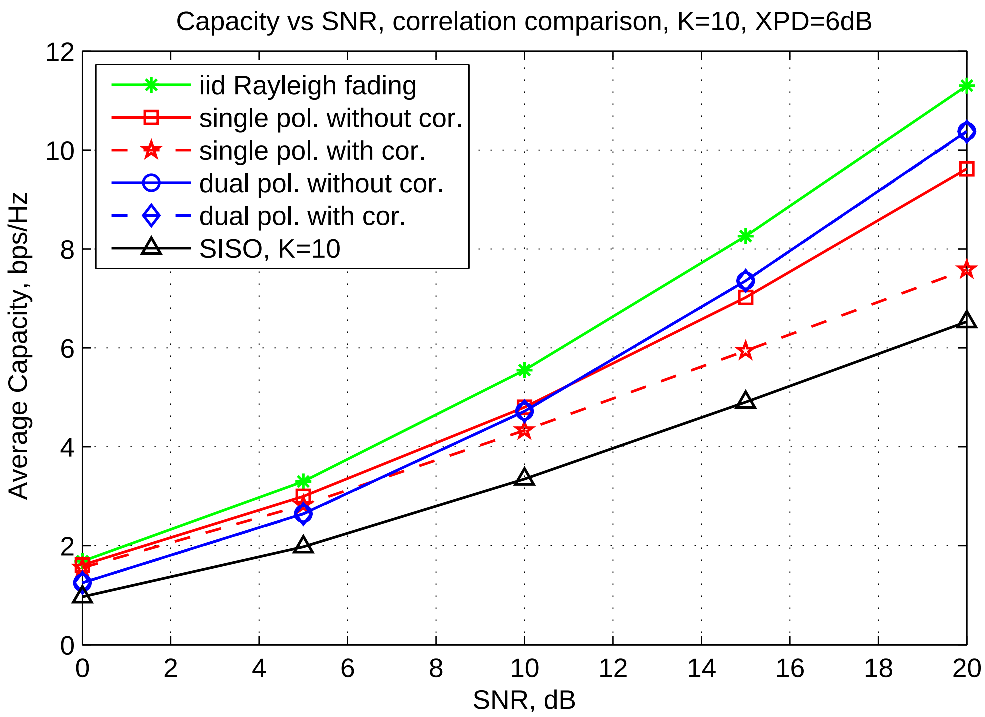


Figure 5.15: Average capacity, correlated channel with K=10

CHAPTER 6

MIMO CHANNEL EVALUATION WITH DISTANCE DEPENDENT K-FACTOR AND XPD

In this chapter, K-factor and XPD values are generated from distance dependent random variable models as explained in chapter 3. These models are based on real wireless channel measurements. Using fully characterized distance dependent channel model, performances of different communication systems can be compared according to the distance between the TX and RX antennas. BER performance and capacity results are presented using realistic channel models. Just as in chapter 5, 2×2 MIMO wireless system is simulated for polarization diversity analysis. Single and dual polarized antenna configurations are evaluated considering Alamouti and spatial multiplexing schemes. Average capacity results for different channels employing single and dual polarizations are also given in this chapter. Just as in chapter 5, results are classified in two groups according to the RX inter-antenna spacing or in other words correlation.

The distance between TX and RX antennas is taken as 1km and 6km for the comparison of close and far distances. K-factor and XPD values for each channel realization are generated from distance dependent log-normal distributions. Moreover, in the presence of correlation, random correlation coefficients are also obtained using polarization orientation angles, azimuth and elevation AOAs and distance dependent XPD values.

6.1 Distance Comparison with Uncorrelated Channel

Single and dual polarization BER and capacity results are compared for 1km and 6km distances. In this section it is assumed that there is no space constraint and correlation effect.

6.1.1 BER performance

6.1.1.1 AL scheme

Fig. 6.1 illustrates BER vs SNR graph for AL scheme. Since dual polarization suffers from subchannel power loss due to orthogonal polarizations of the antennas, XPD leads to power loss of combined received power for AL algorithm. Consequently, dual polarization has worse BER than single polarization both for 1km and 6km communication distances. The difference is approximately 2dB for 1km and 1.5dB for 6km.

Furthermore, the only channel parameter which is based on the distance change and effects the single polarization performance, is the K-factor. Yet, K-factor change from 1km to 6km does not effect performance significantly. BER of single polarization for 1km is about 0.5dB lower than BER for 6km. For dual polarization in addition to the K-factor, XPD plays an important role on the performance of dual polarization. BER for AL is expected to worsen as the distance increases since the fading becomes more dominant at larger distance. Whereas for dual polarization as the distance increases, XPD decreases as well and BER performance is positively effected with XPD decrease. Combining the K-factor and XPD effects on dual polarization, BER remains nearly unchanged for 1km and 6km. Additionally, MIMO systems have much better BER than SISO systems regardless of distance.

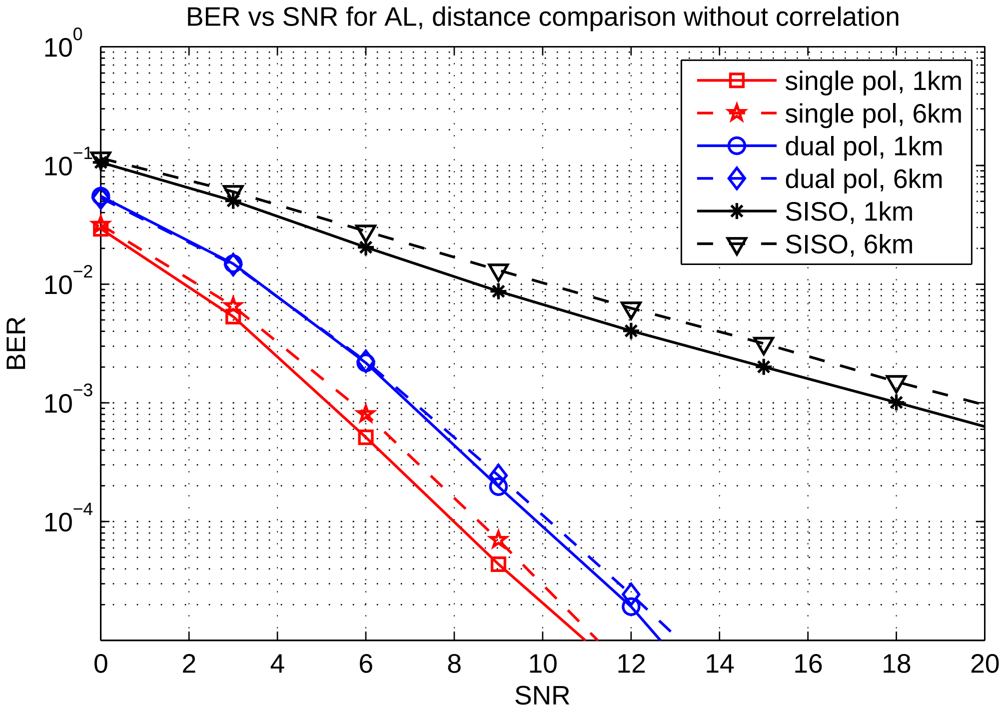


Figure 6.1: BER comparison for AL, distance comparison without correlation

6.1.1.2 SM scheme

Fig. 6.2 shows the SM BER performance for single and dual polarizations at 1km and 6km under uncorrelated channel. The distance does not effect BER of both types of polarization considerably at low SNR. After SNR>15dB the differences become clear.

At high SNR, for both distances dual polarization has better performance than single polarization. This is caused by the XPD effect at high K-factor as explained in chapter 5. Even at 6km distance, K-factor and constant channel has still effect on BER and XPD can increase the channel matrix rank causing better performance of dual polarization. At 6km, dual polarization has about 1.5dB better performance than single polarization at BER value of 10^{-4}. At 1km distance since K-factor is higher dual polarization has nearly 3dB better BER than single polarization. Additionally, as SNR increases the performance difference gets larger. Dual polarization outperforms single polarization for both distances even without correlation.

Additionally, as distance increases from 1km to 6km, K-factor decreases and variable channel component becomes more dominant. This increases the rank of the channel matrix for MIMO. However SISO channel suffers from stronger fading. On the contrary to MIMO systems, SISO BER for SM decreases with the increase of communication distance. Furthermore, for both distances MIMO systems have better BER than SISO.

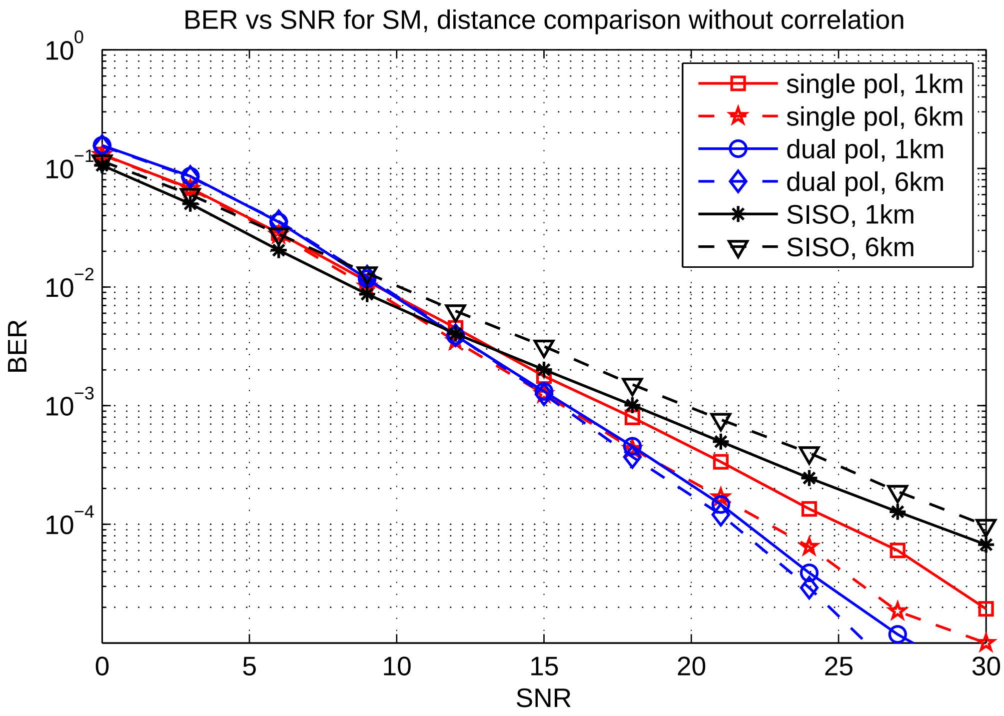


Figure 6.2: BER comparison for SM, distance comparison without correlation

6.1.2 Average Capacity

Single and dual polarization capacity curves for uncorrelated channel at 1km and 6km distances are indicated in fig. 6.3. Dual polarization capacity is nearly unchanged with respect to the communication difference. Capacity curves of dual polarization for 1km and 6km are very close to each other. Similar to dual polarization, single polarization capacities for 1km and 6km are very close at low SNR. However, as SNR increases channel term in the capacity equation becomes dominant and capacity for 6km becomes higher than capacity for 1km. As distance increases and K-factor decreases, channel has better eigenvalue distribution and lower condition number. This is the reason for higher capacity at 6km than at 1km for single polarization. Whereas SISO capacity is slightly lower at 6km than at 1km due to K-factor decrease.

At 1km distance and low SNR, single polarization has little bit higher capacity than dual polarization and when SNR>15dB dual polarization capacity becomes larger than single polarization capacity. The difference is about 0.4bps/Hz at 20dB SNR. As for 6km, at low SNR just like at 1km distance single polarization capacity is higher than dual polarization. As SNR increases, the difference disappears and single and dual polarization capacities are nearly the same at 20dB SNR for 6km.

In addition, MIMO systems have higher capacity than SISO systems for both distances. Single polarized MIMO has about 3.4bps/Hz at 1km and 4bps/Hz at 6km higher capacity than SISO at 20dB SNR. MIMO with polarization diversity has about 3.7bps/Hz at 1km and 4bps/Hz at 6km higher capacity than SISO at 20dB SNR.

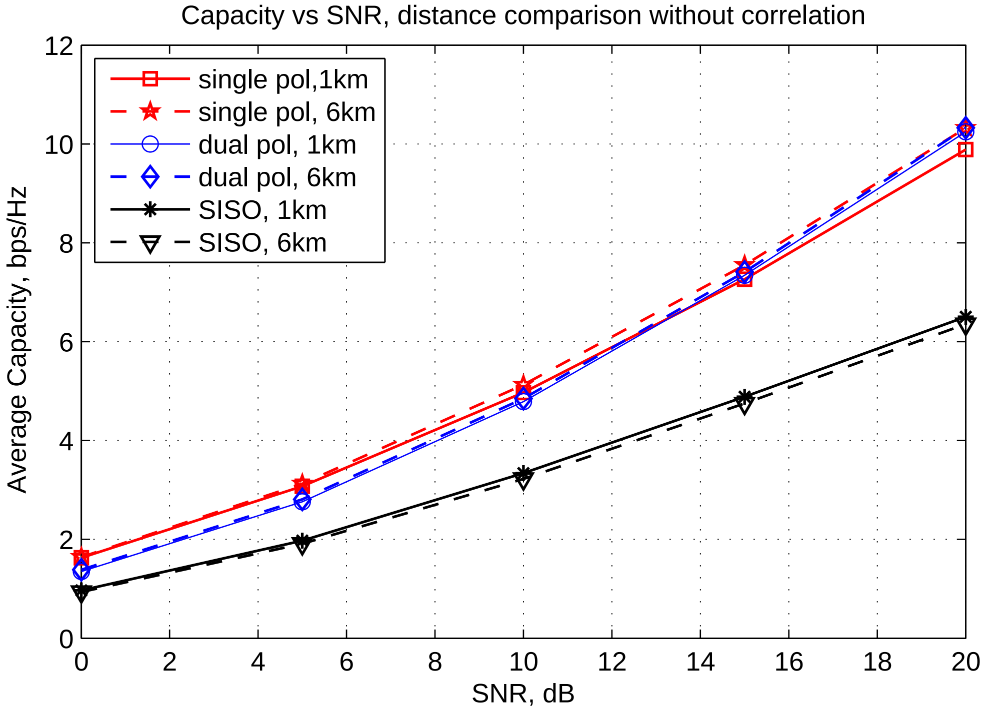


Figure 6.3: Average capacity, distance comparison without correlation

6.2 Correlated channel

In this section there is no spatial diversity for receiver and there exists correlation between the received signals. Correlation coefficients are randomly generated from eqn. 3.13.

6.2.1 BER performance

6.2.1.1 AL scheme

Fig. 6.4 illustrates the single and dual polarization BER performances for AL scheme with and without correlation effect at 1km. As previously explained, when there is no correlation, single polarization has better BER performance than dual polarization due to power loss of dual polarization. When the correlation is present due to space limitation, single polarization is exposed to severe performance degradation. At BER value of 10^{-5}, single polarization with correlation has 6dB worse performance than single polarization without correlation. However, due to polarization diversity and low correlation coefficients, dual polarization BER performance is nearly the same in cases with and without correlation. Although in uncorrelated case single polarization has about 2dB better performance than dual polarization, for correlated channel case dual polarization outperforms single polarization nearly 4dB at BER value of 10^{-5}. Moreover, single and dual polarized MIMO systems with and without correlation has much better BER than SISO when AL scheme is used.

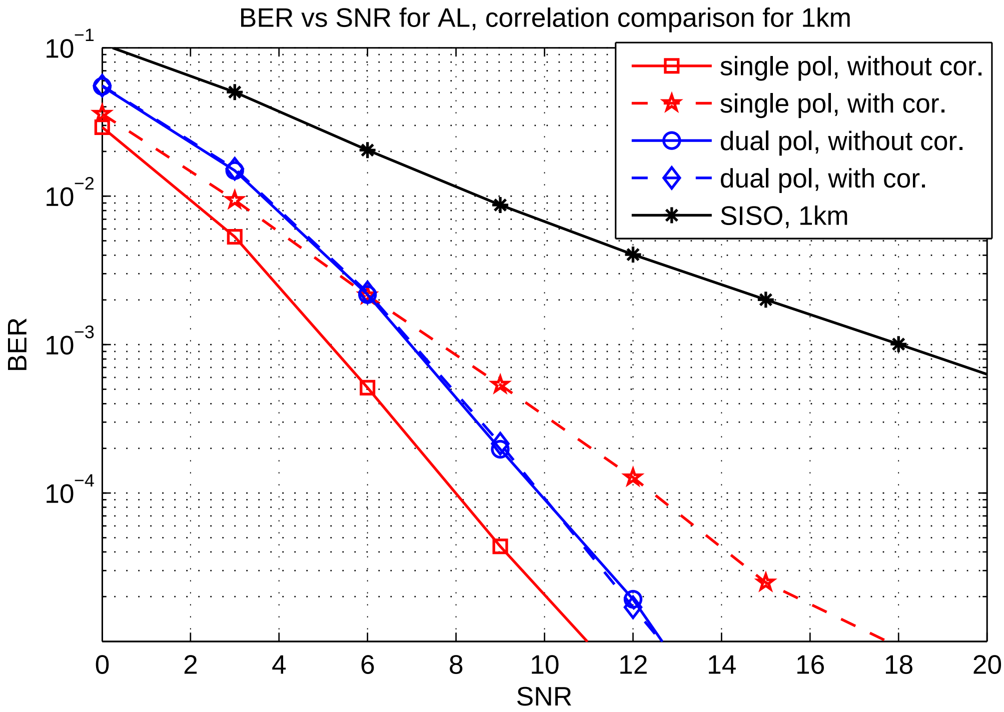


Figure 6.4: BER performance for AL, correlation comparison for 1km

Fig. 6.5 shows the correlation comparison of AL BER for 6km. When the communication distance is increased to 6km, K-factor is still non-zero and single polarization has better performance than dual polarization due to XPD in uncorrelated case. Just as in 1km case, dual polarization performance is nearly unaffected by the correlation. On the other hand, single polarization with correlation has about 7dB worse performance than uncorrelated case. Consequently, in correlated case, dual polarization performance is about 5dB better than single polarization performance at BER value of 10^{-5}. Similar to 1km, MIMO systems have much better BER for AL than SISO.

6.2.1.2 SM scheme

Fig. 6.6 indicates the BER curves of single and dual polarizations for SM at 1km. For uncorrelated case, at low SNR single and dual polarizations perform similarly whereas at high SNR dual polarization has better BER than single polarization due to XPD increasing the channel matrix rank at high K-factor. When correlation is present, dual polarization performance decreases nearly 0.5dB at BER of 10^{-5} yet, single polarization performance degrades nearly 8dB at 10^{-4} BER. Therefore, dual polarization performance is significantly better than single polarization when the RX antennas are colocated. Moreover, BER of SISO system is about 5dB better at 2x10^{-}4 BER than single polarized MIMO with correlation which means that rather than using two colocated antennas simply using one performs better for SM BER. However, dual polarization with correlation has about 5dB better SM BER than SISO due to low correlation.

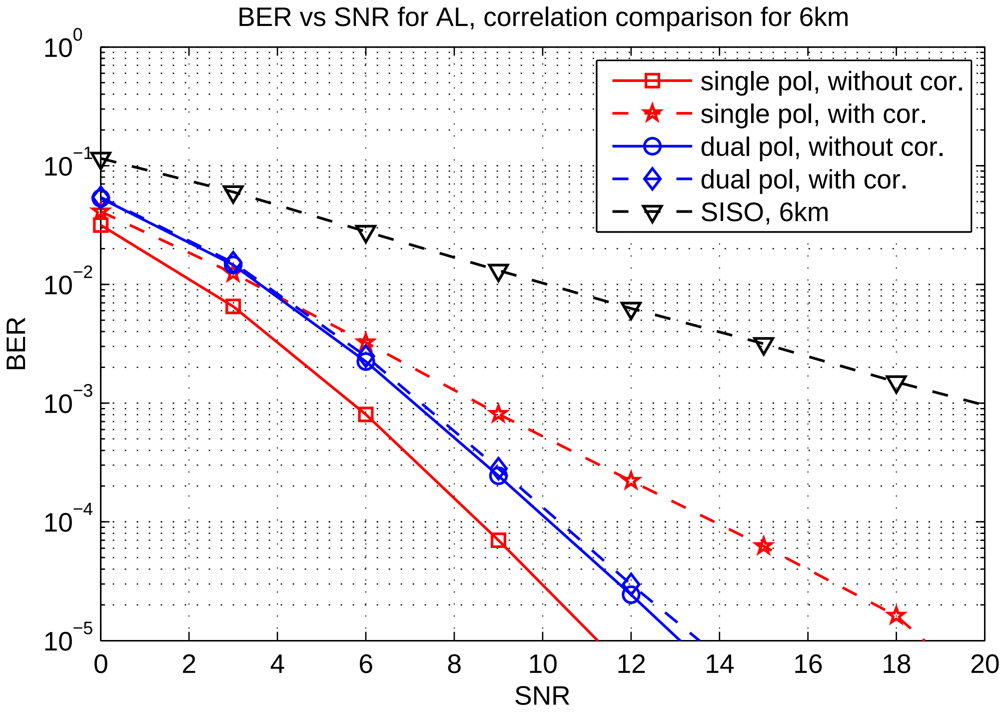


Figure 6.5: BER performance for AL, correlation comparison for 6km

When the distance is 6km K-factor decreases but still it is effective on the performance comparison. The results for 6km are similar to the results for 1km as in fig. 6.7. At high SNR and under uncorrelated channels dual polarization BER performance is better than single polarization. When there is correlation, single polarization performance degrades more than 10dB at 10^{-4} BER, while dual polarization performs nearly the same as uncorrelated case. Thus, dual polarization has much lower BER than single polarization when there is no spatial diversity. The difference is greater than 10dB at BER of 10^{-4}. Additionally, SISO has 3dB better BER than single polarization, whereas 7dB worse BER than dual polarization at 2x10−4 BER, when correlation is present at 6km.

6.2.2 Average Capacity

Average capacity results of single and dual polarizations are illustrated in fig.6.8 in order to analyze the correlation effect at 1km distance. When the RX antennas are sufficiently separated and the received signals are uncorrelated, single and dual polarization capacities are very close to each other. At 0dB SNR, single polarization is about 0.3bps/Hz higher than dual polarization capacity on the contrary at 20dB SNR, dual polarization is about 0.3bps/Hz higher than single polarization capacity. When there is correlation effect, single polarization capacity significantly decreases with respect to uncorrelated case. However, dual polarization has nearly the same capacity in uncorrelated channel due to low correlation coefficient. Dual polarization capacity is 2.6bps/Hz higher than single polarization capacity at 20dB SNR. Despite the severe capacity degradation due to full correlation, single polarization capacity is still 1bps/Hz larger than SISO capacity.

For 6km distance and when there is no correlation, at low SNR, single polarization has a little bit higher

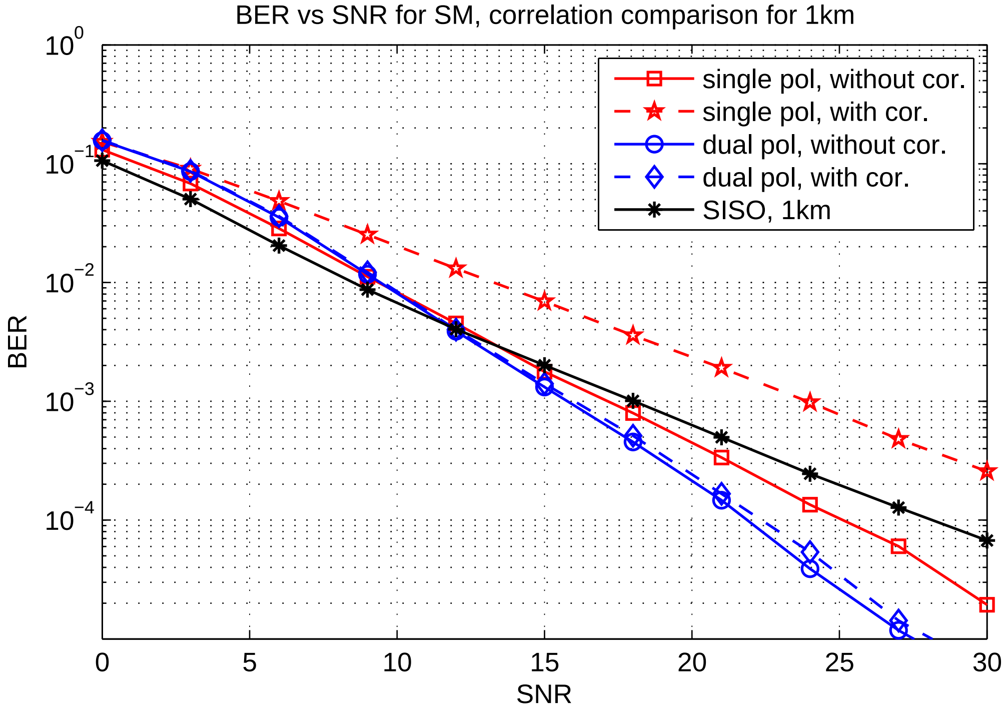


Figure 6.6: BER performance for SM, correlation comparison for 1km

capacity than dual polarization and at high SNR, this difference disappears as shown in fig. 6.9. Just as in 1km case, dual polarization is nearly unaffected by the correlation, however single polarization encounters very sharp capacity decrease. Therefore, dual polarization capacity is 2.7bps/Hz higher than single polarization capacity. Yet, single polarization with correlation still has nearly 1.1bps/Hz higher capacity than SISO case.

Capacity comparison between single and dual polarizations is very similar to SM BER performance comparison. This was also observed in chapter 5 while considering constant channel parameters. The reason for this similarity is that channel rank, eigenvalue distribution and condition number is crucial for SM BER and capacity. Higher channel rank, closer eigenvalue distribution and lower condition number results in lower BER and higher capacity. However, in AL scheme this is not the case, because AL algorithm is based on power combination of the received signals.

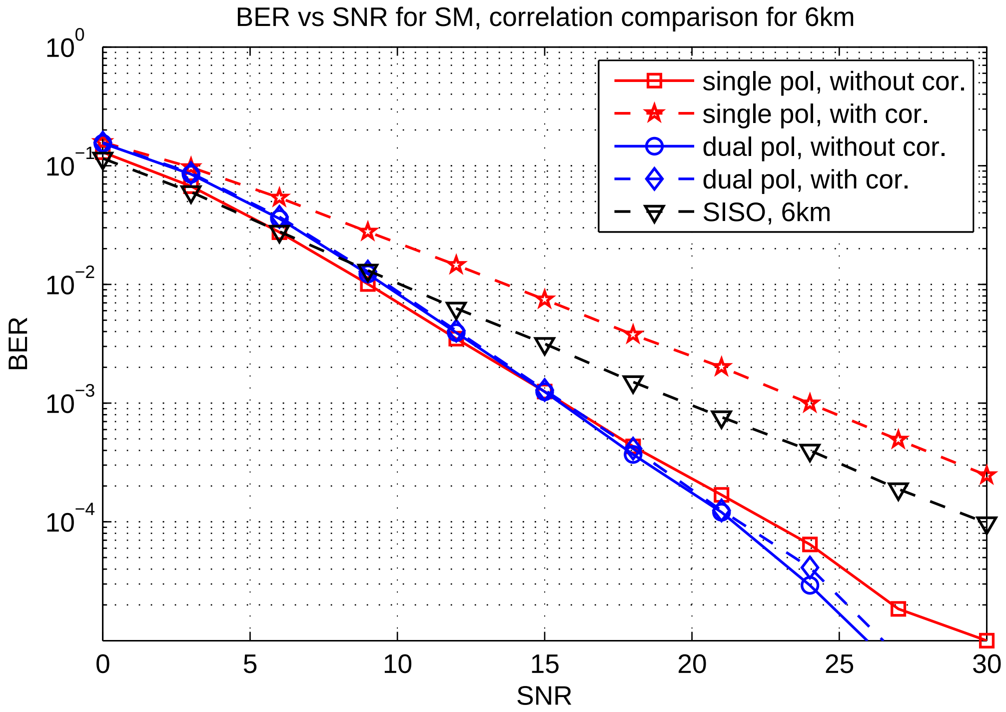


Figure 6.7: BER performance for SM, correlation comparison for 6km

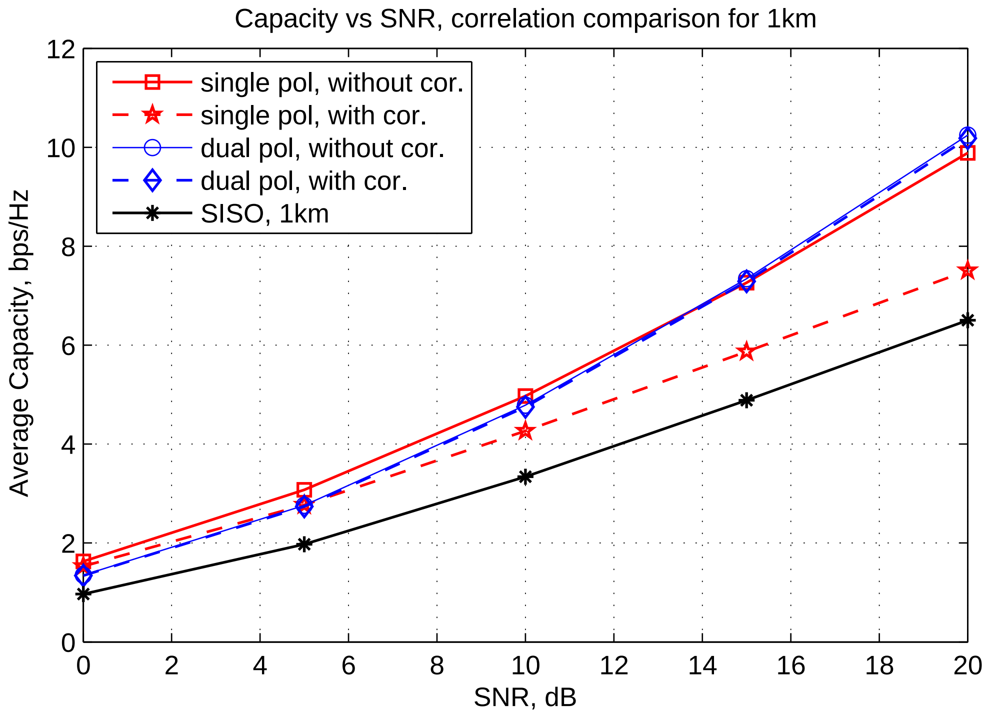


Figure 6.8: Average capacity, correlation comparison for 1km

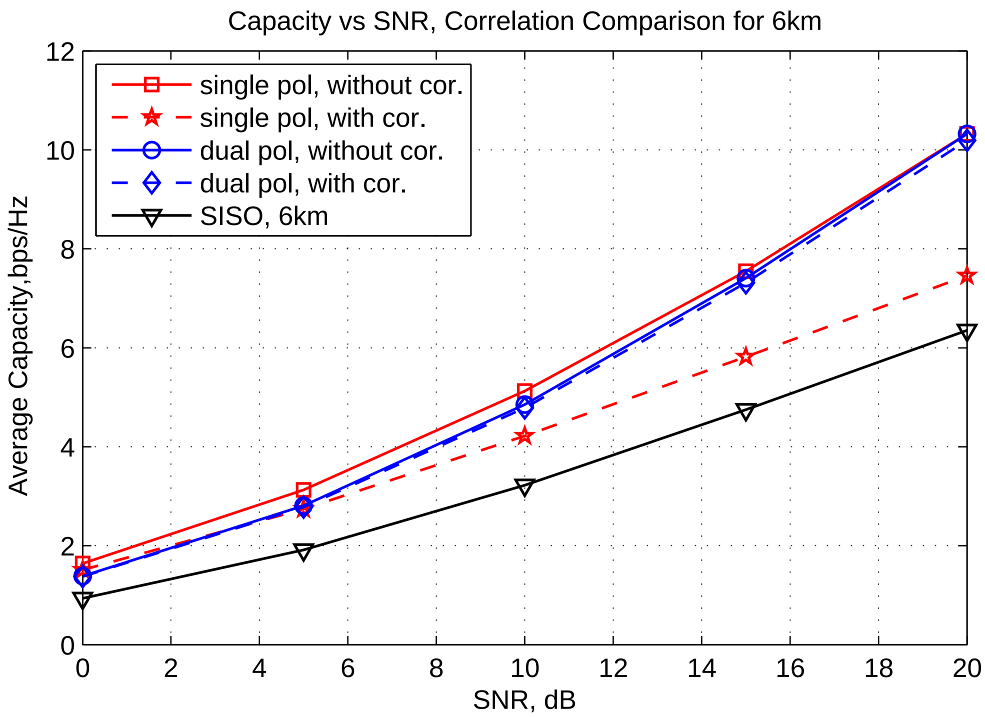


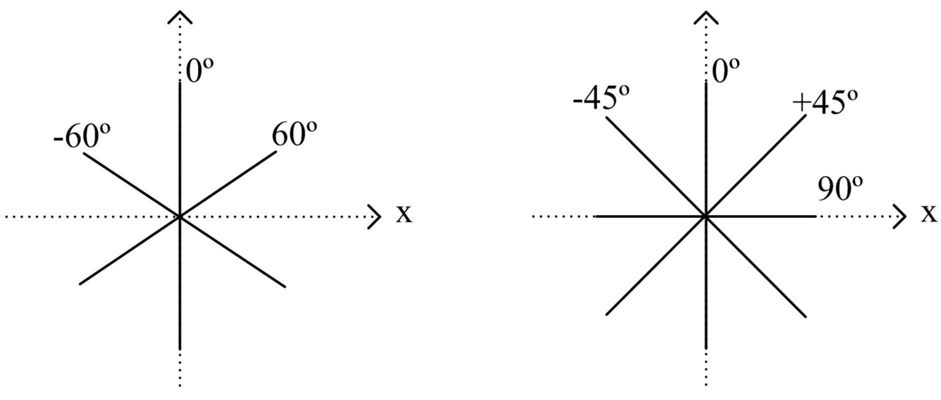
Figure 6.9: Average capacity, correlation comparison for 6km

CHAPTER 7

MIMO CHANNEL EVALUATION WITH MORE NUMBER OF ANTENNAS

In chapters 5 and 6, 2x2 MIMO system is employed and single and dual polarizations are compared in 2x2 wireless MIMO channels. In this chapter the number of antennas is increased. 3×3 and 4×4 MIMO antenna configurations with and without polarization diversity are considered for both constant and distance dependent K-factor and XPD values. In addition to 3×3 and 4×4 MIMO performance results, SISO system for the corresponding K-factor and 2x2 single and dual polarized MIMO configuration results are presented in this chapter, in order to compare the number of antennas of a MIMO system with and without polarization diversity.

In 2×2 MIMO configuration, polarization orientation is chosen as ±45° in dual polarization. When the number of antennas is increased, polarization of antenna elements are uniformly oriented in polarization diversity employed case. Fig. 7.1 shows the RX and TX antenna polarization orientations for 3×3 and 4×4 MIMO systems when polarization diversity is employed. As shown in fig. 7.1-a, 0° and ±60° orientations are used for 3×3 MIMO configuration with polarization diversity. Similarly, antenna elements of 4×4 MIMO system with polarization diversity have polarizations of 0°, ±45° and 90° as in fig. 7.1-b. Therefore, symmetric and uniform polarization orientations are used in both 3×3 and 4×4 MIMO systems.



(a) 3x3 MIMO

(b) 4x4 MIMO

Figure 7.1: Polarization orientations of 3x3 and 4x4 MIMO configurations

When the RX and TX antennas have the same polarizations, there is no power loss due to polarization difference. On the other hand if the RX and TX antennas have different polarization orientations there exists power loss due to polarization difference. When an RX antenna element is orthogonally polarized with respect to a TX antenna element, the power loss is the largest and characterized by XPD. Transmitting the signal from a certain polarization, XPD is defined as the ratio of the received signal power of the copolarized RX antenna to that of the crosspolarized RX antenna. In case of polarization difference between TX and RX antennas rather than orthogonal polarization, the power loss is defined based on XPD value. Power loss of any polarization difference is linearly generated from XPD. Therefore, when there is non-orthogonal polarization difference between an RX and a TX antenna such as in 3×3 and 4×4 cases, power loss is calculated from XPD by normalization of polarization difference angle with respect to 90°.

MIMO channels with and without polarization diversity are evaluated for BER performance using SM scheme. The performances of MIMO systems with and without polarization diversity are analyzed without coding. Additionally, the effects of polarization diversity on the communication speed of 3×3 and 4×4 MIMO cases are investigated via capacity vs SNR curves.

Just as in chapters 5 and 6 TX interantenna distance is assumed to be sufficiently large to ignore TX correlation. RX correlation is considered in two cases. In the first case, all RX antenna elements are separated and there is no RX correlation effect. In the other case, due to space limitation RX antenna elements are colocated leading to full correlation for single polarization. The RX correlation coefficient values for the systems with polarization diversity are generated from equation 3.13 considering elevation and azimuth AOAs of the incoming multipath signals and polarization orientations.

7.1 Uncorrelated Channel

In this section it is assumed that there is no space constraint and there is no correlation at the TX and RX.

7.1.1 Constant K-factor and XPD

K-factor value of 0 and 10 are used for the comparison of number of antennas. 0 K-factor refers to pure Rayleigh fading case for single polarization without polarization diversity and K-factor of 10 corresponds to a channel with strong LOS or constant component. Furthermore, XPD is taken to be 6dB in this subsection. As explained in this chapter's introduction, XPD value is the power loss of orthogonally polarized antenna configurations and when the polarization angle difference between a TX and an RX antenna element is different than 90°, power loss is linearly obtained from XPD value.

7.1.1.1 SM scheme BER performance

Fig. 7.2 illustrates SM BER vs SNR graph of SISO, 2x2, 3x3 and 4x4 MIMO systems with and without polarization diversity. K-factor is 0 and XPD is 6dB. Since K-factor is 0, only variable channel component is present. The channel has full rank since there is no correlation effect. In this case, subchannel power loss due to polarization difference leads to performance degradation for polarization diversity and single polarization has better BER performance regardless of number of antennas. Due to power loss, all 3 MIMO systems with polarization diversity has about 3dB worse performance than their single polarization counterparts, at BER value of 10^{-4}.

As the number of antennas increases, the rank of the channel increases and SM BER performance of MIMO systems both with and without polarization diversity improves. The slopes of BER curves sharpen. Single polarized 4×4 MIMO system has about 2dB better BER than 3×3 MIMO and about 7dB better than 2×2 at BER value of 10^{-4}. The situation is similar for polarization diversity employed MIMO systems. When polarization diversity is present 4×4 MIMO outperforms 3×3 MIMO as 2dB and 2×2 as nearly 6dB at BER value of 10^{-4}. Moreover, all MIMO systems have much greater performance than SISO since there is no diversity for SISO.

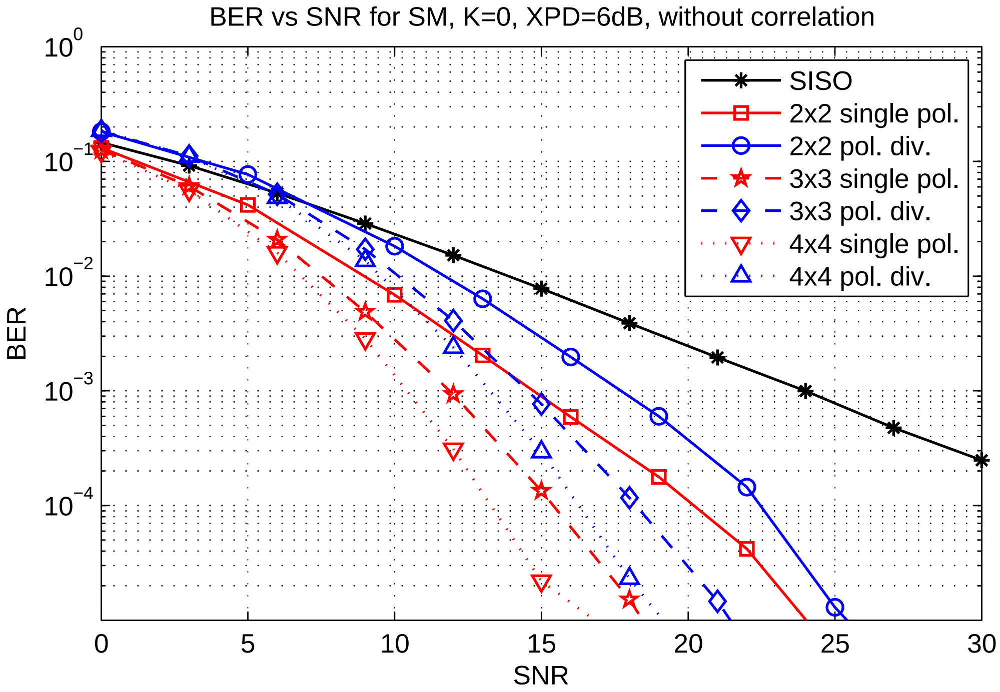


Figure 7.2: BER comparison for SM (0 K-factor, 6dB XPD, no correlation)

When K-factor is increased to 10, constant channel component becomes effective. As shown in fig. 7.3, SISO outperforms all MIMO configurations since higher K-factor makes the SISO channel gain closer to unity. SISO system gets rid of the fading effect of the channel and approaches to AWGN case which significantly increases BER performance.

As for MIMO systems and polarization comparison, systems with polarization diversity is better than single polarization in terms of BER performance since power loss caused by polarization difference improves the channel rank at high K-factor. Polarization diversity becomes effective especially at high SNR. For 2×2 MIMO after 10dB SNR, polarization diversity is better and it has up to 4dB better BER than single polarization. Similarly, for 3×3 and 4×4 cases when SNR>15dB polarization diversity is effective yet the performance difference is smaller than 1dB at 10^{-5} BER. As the number of antennas increases, polarization orientations get closer to each other and power loss causing performance improvement for polarization diversity at high K-factor decreases. That is the reason why polarization diversity has much greater BER performance than single polarization for 2×2 system but does not have such large performance difference for larger number of antennas. In addition, BER of 2×2 MIMO with polarization diversity is better than other MIMO systems with polarization diversity. However, the slope of 2×2 system is smaller than the slopes of others. As SNR increases performance of MIMO systems with polarization diversity get closer and 4×4 MIMO even outperforms 2×2 system at BER value of 10^{-5}.

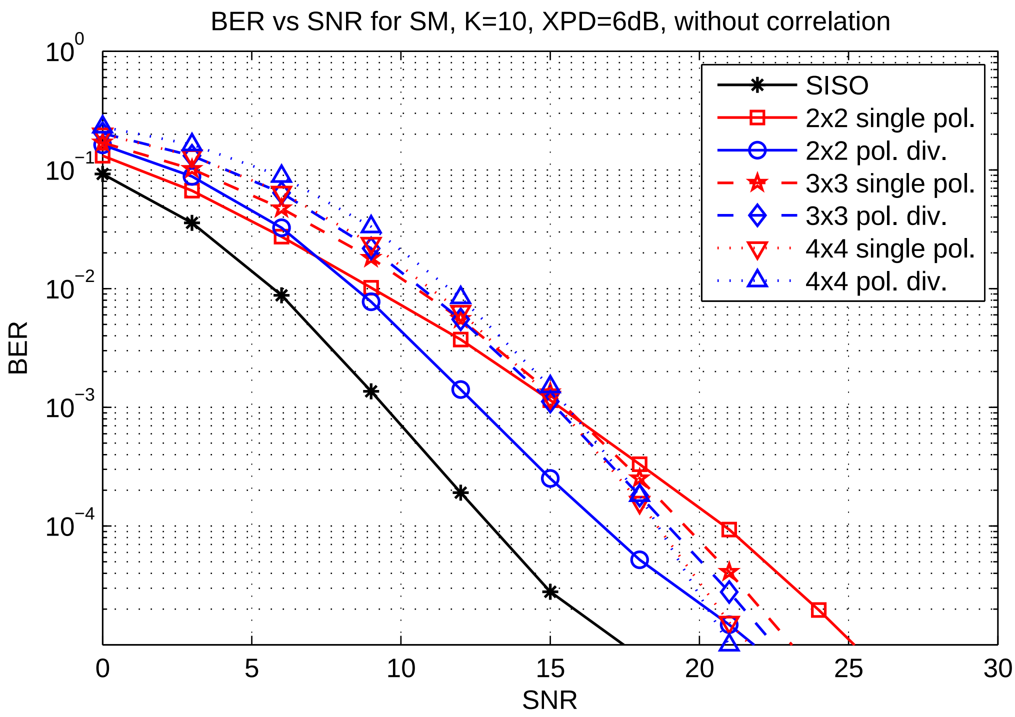


Figure 7.3: BER comparison for SM (K-factor of 10, 6dB XPD, no correlation)

7.1.1.2 Average Capacity

Capacity comparison of single polarization and polarization diversity for 0 K-factor and 6dB XPD is illustrated in fig. 7.4. SISO and MIMO systems with different number of antennas are considered. At high SNR capacity results are linearly dependent on the channel rank and since channel rank is minimum of n_r or n_t at 0 K-factor, capacity results are linearly dependent on the number of antennas. As the number of antennas increases, capacity results increase linearly. For instance at 20dB SNR, SISO capacity is 5.8bps/Hz, 2×2 MIMO capacity is 11.3bps/Hz, 3×3 MIMO capacity is 16.7bps/Hz and 4×4 MIMO capacity is 22.3bps/Hz under uncorrelated channel with 0 K-factor without polarization diversity.

MIMO systems with polarization diversity incur subchannel power loss which results in capacity decrease with respect to single polarization when there is no space constraint and correlation. At 20dB SNR, polarization diversity has about 3bps/Hz lower capacity for 4×4 MIMO, 2bps/Hz for 3×3 MIMO and 1.1bps/Hz for 2×2 MIMO configurations as compared to single polarization cases.

Fig.7.5 shows the capacity results of different polarizations and different number of antennas for K-factor of 10. When K-factor is increased from 0 to 10 SISO capacity increases from 9.1 to 9.8 bps/Hz at 30dB SNR, since as K-factor increases SISO channel fading becomes insignificant and channel coefficient approaches to unity. However, this is not the case for MIMO systems. As K-factor increases single polarization encounters severe capacity degradation since channel rank decreases. High power loss due to orthogonal polarization results in 1.2bps/Hz higher capacity for 2×2 MIMO with polar-

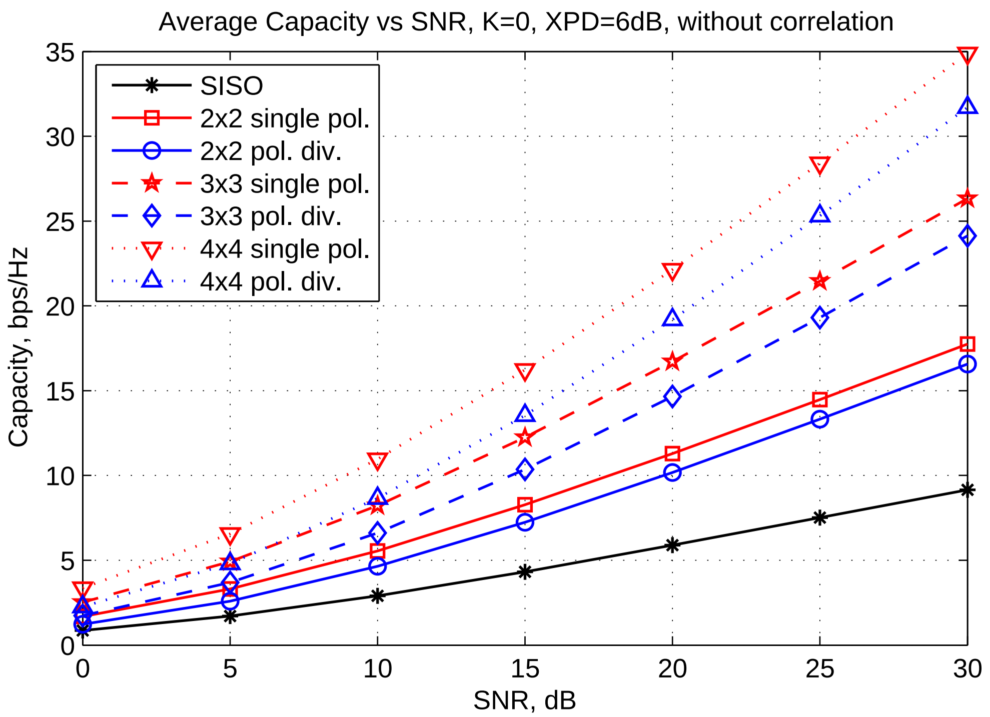


Figure 7.4: Average capacity (0 K-factor, 6dB XPD, no correlation)

ization diversity at 30dB SNR. However, as the number of antennas increases angular separation of antennas and subchannel power loss decreases. For 3×3 and 4×4 MIMO, subchannel power loss due to polarization difference is not as high as for 2×2 MIMO. Single polarized 3×3 MIMO has higher capacity at low SNR. Polarization diversity has higher slope than single polarization and as SNR increases polarization diversity outperforms single polarization. At 30dB SNR 3×3 MIMO with polarization diversity has about 0.5bps/Hz higher capacity than single polarization. Furthermore, for 4×4 MIMO case, at low SNR single polarization has higher capacity than polarization diversity. At 30dB SNR, the difference disappears and polarization diversity reaches single polarization capacity.

7.1.2 Distance dependent K-factor and XPD

BER for SM scheme and average capacity results are investigated for 3km communication distance. K-factor and XPD values are generated from log-normal distributions explained in chapter 3. Just to remember that these models are based on the measurements on suburban channel [7].

7.1.2.1 SM scheme BER performance

Fig. 7.6 illustrates SM BER curves of SISO and MIMO systems for uncorrelated channel at 3km distance. Both single polarization and polarization diversity cases are investigated in order to analyze the effects of polarization on different MIMO scenarios. At 3km distance K-factor has a mean of 5.7dB. MIMO systems have better BER performance especially at high SNR than SISO since K-factor is not very high.

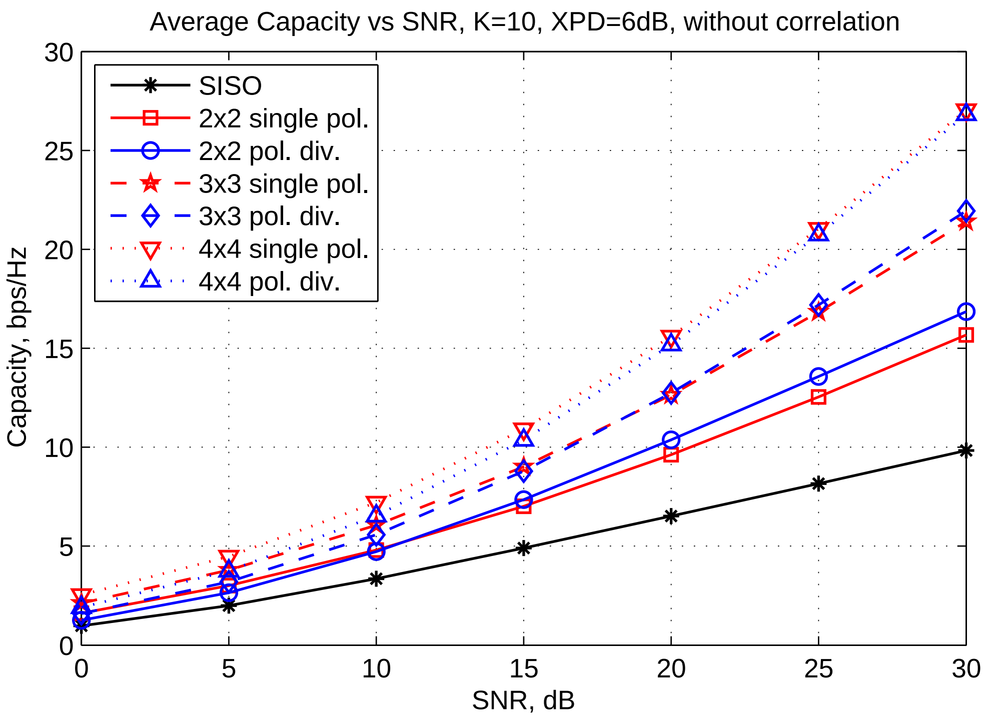


Figure 7.5: Average capacity (K-factor of 10, 6dB XPD, no correlation)

Without polarization diversity, 2×2,3×3 and 4×4 MIMO have nearly the same BER. When the polarization diversity is employed, MIMO systems with polarization diversity outperforms single polarized MIMO systems with the same number of antennas. For 2×2 and 3×3 MIMO, polarization diversity has about 2dB better performance than single polarization and when the number of antennas is 4, polarization diversity has nearly 6dB better BER performance than single polarization at 10^{-4} BER. It seems that there is not a strong relation between the number of antennas and BER performance of SM scheme when distance dependent K-factor and XPD models based on real wireless channel measurements are used. It is clear that 4×4 MIMO with polarization diversity has the best performance and 4 antenna elements are the best among the others for polarization diversity at 3km distance. The reason underlying this fact is the polarization orientation of 4×4 system.

7.1.2.2 Average Capacity

Fig. 7.7 shows the capacity curves of SISO and MIMO systems with and without polarization diversity. The channel is generated with the K-factor and XPD values for 3km distance. It is assumed that there is no space limitation and correlation. As the number of antennas increases, capacity results increase as expected since the diversity order of the channel increases. As for polarization analysis, for 3km distance there is no very distinct capacity difference between single polarization and polarization diversity. Since K-factor and XPD are moderate MIMO systems with an without polarization diversity have nearly the same capacity.

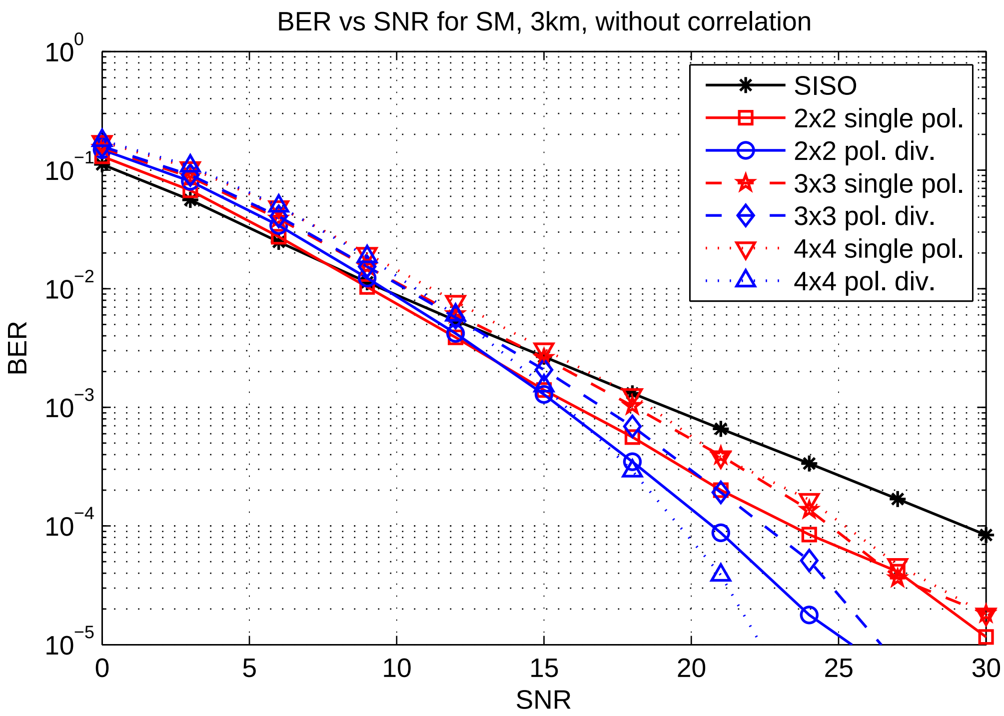


Figure 7.6: BER comparison for SM (3km distance, no correlation)

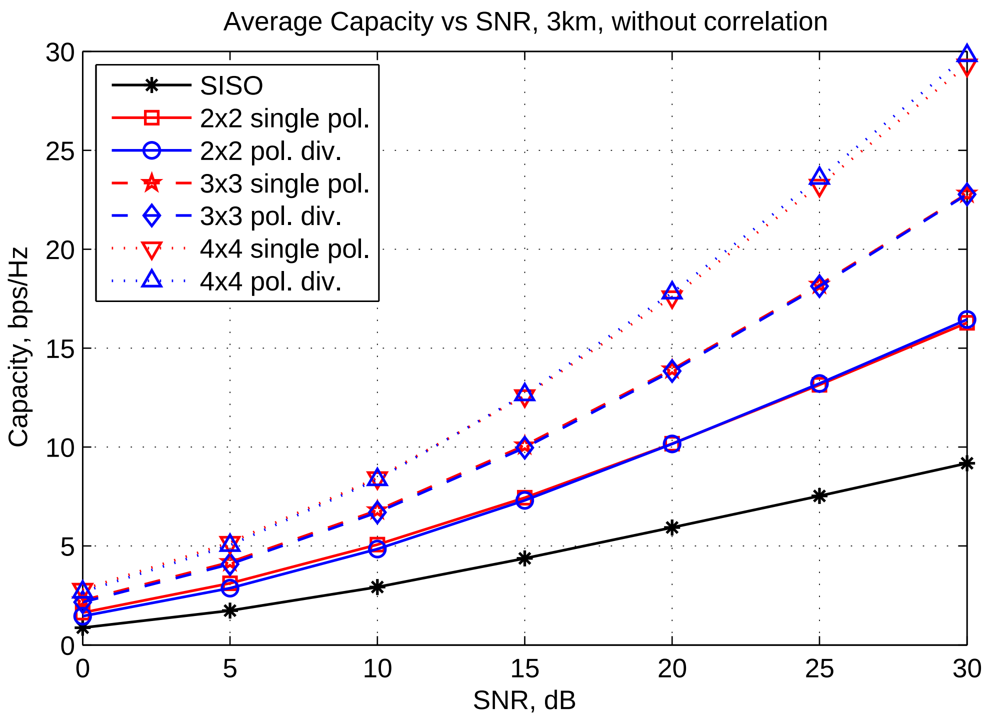


Figure 7.7: Average capacity (3km distance, no correlation)

7.2 Correlated channel

In this section there is no spatial diversity for receiver and the antennas are assumed to be colocated due to space limitation at the RX. There exists correlation between the multipath received signals. Correlation coefficients correlate variable channel component elements and they are randomly generated from eqn. 3.13. Correlation between two antenna elements are based on the angular separation between those elements. Moreover, azimuth and elevation AOAs of the incoming signals and cross polar ratio of the orthogonally polarized antenna elements are considered in correlation.

7.2.1 Constant K-factor and XPD

Just as in uncorrelated channel case, K-factor is selected as 0 and 10 and XPD is taken to be constant as 6dB.

7.2.1.1 SM scheme BER performance

Fig. 7.8 illustrates SM BER curves for SISO and MIMO cases with 2, 3 and 4 antenna elements with 0 K-factor and 6dB XPD. Since 0 K-factor means only variable channel component exists, correlation is very effective on the channel and BER performance. When there is no polarization diversity, very sharp performance decrease is observed and SISO case is better than all MIMO configurations. Therefore, if SM is used without any coding and the RX antennas are colocated due to space problem, rather than using MIMO with more than 1 TX and RX antennas, simply using SISO system results better BER. Despite higher BER, capacity results of MIMO systems without polarization diversity should be taken into account for accurate system performance analysis.

SISO and MIMO systems with single polarization have the same slope and as the number of antennas increases from 1 to 4, BER performance worsens gradually. However, for polarization diversity case, as the number of antennas increases lower BER values are achieved and 4×4 MIMO with polarization diversity has the best performance.

When the polarization diversity is employed, angular separation of antenna elements leads to lower correlation coefficients than single polarization case which causes much better BER performance. For instance 4×4 MIMO with polarization diversity has about 13dB better performance than single polarization at 10^{-3} BER and 3×3 MIMO with polarization diversity has 10dB better performance than 3×3 single polarized MIMO at 6×10^{-4} BER.

When K-factor is increased to 10, SISO has the best performance as shown in fig. 7.9 since there is no correlation effect for SISO and high K-factor eliminates the effect of fading. When there is no polarization diversity, MIMO performances are very similar to 0 K-factor case. As the number of antennas increases from 2 to 4, there is performance loss due to full correlation just as in correlated channel with 0 K-factor.

If the antennas are angularly separated and there is polarization diversity, 2×2 MIMO is the best and 3×3 and 4×4 MIMO configurations with polarization diversity have nearly the same performance. 2×2 MIMO has about 2dB better BER performance than 3×3 and 4×4 configurations at 10^{-4} BER. However, 2×2 BER curve has lower slope than the other MIMO systems and at BER of 10^{-5} they perform nearly the same.

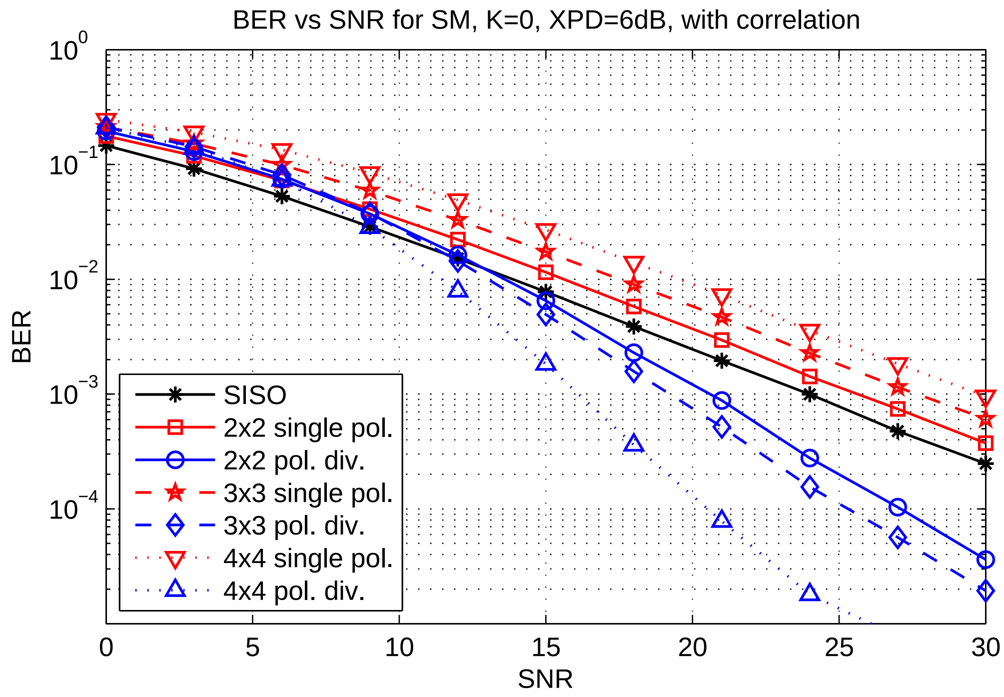


Figure 7.8: BER comparison for SM (0 K-factor, 6dB XPD, with correlation)

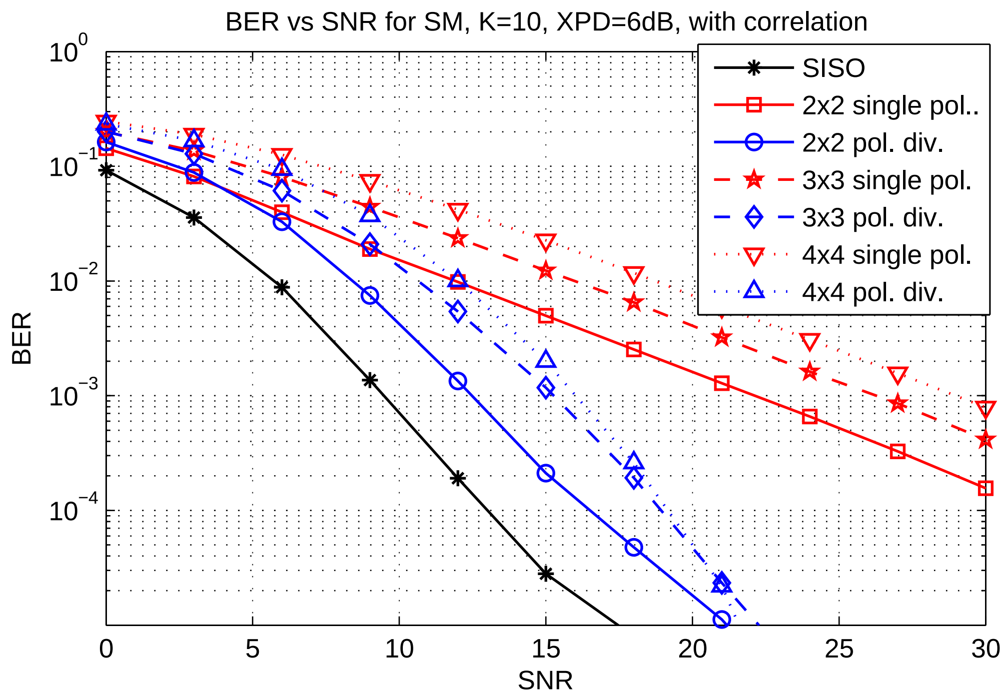


Figure 7.9: BER comparison for SM (K-factor of 10, 6dB XPD, with correlation)

7.2.1.2 Average Capacity

Capacity results for correlated channel with 0 K-factor and 6dB XPD are presented in fig. 7.10. It is clearly seen that capacity and SM BER results are very related. MIMO systems without polarization diversity have capacities much lower than polarization diversity cases for all number of antennas and the capacity difference gets larger as the number of antennas increases. 2×2 MIMO has about 2.2bps/Hz capacity difference whereas 3×3 MIMO has about 4.7bps/Hz and 4×4 MIMO has about 8bps/Hz capacity difference between single polarization and polarization diversity cases at 20dB SNR. As expected, 4×4 MIMO has the highest capacity in polarization diversity case.

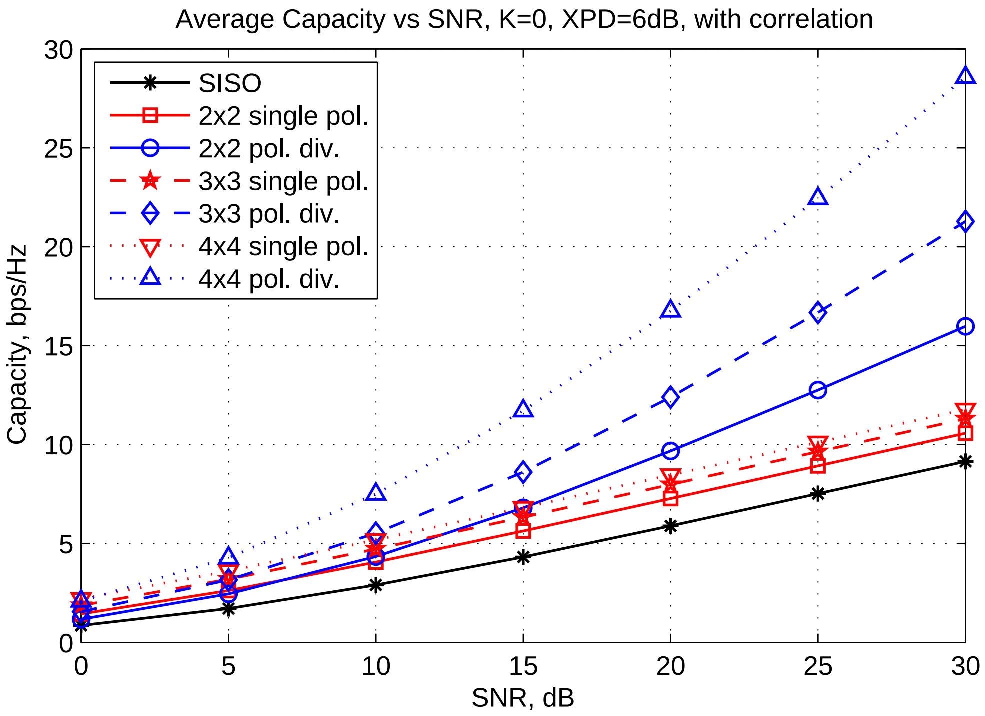


Figure 7.10: Average capacity (0 K-factor, 6dB XPD, with correlation)

When K-factor is increased to 10, as shown in fig. 7.11, capacity comparison for polarization difference and number of antennas is very similar to 0 K-factor case with correlation. Single polarizations have much lower capacities than polarization diversity systems since at high K-factor constant channel component with high condition number is dominant. Additionally variable channel component is low rank due to high correlation. On the other hand, when there is angular separation between the antenna elements, unlike single polarization, constant channel component has higher rank due to power loss. Besides, variable channel component for polarization diversity does not suffer from high correlation coefficients since polarization diversity causes lower correlation. Thus, MIMO systems with polarization diversity have much higher capacity values than single polarizations and the capacity difference gets larger as the number of antennas increases. The capacity difference between the single polarization and polarization diversity is about 6bps/Hz for 2×2, 10.3bps/Hz for 3×3 and 14bps/Hz for 4×4 MIMO configurations at 30dB SNR.

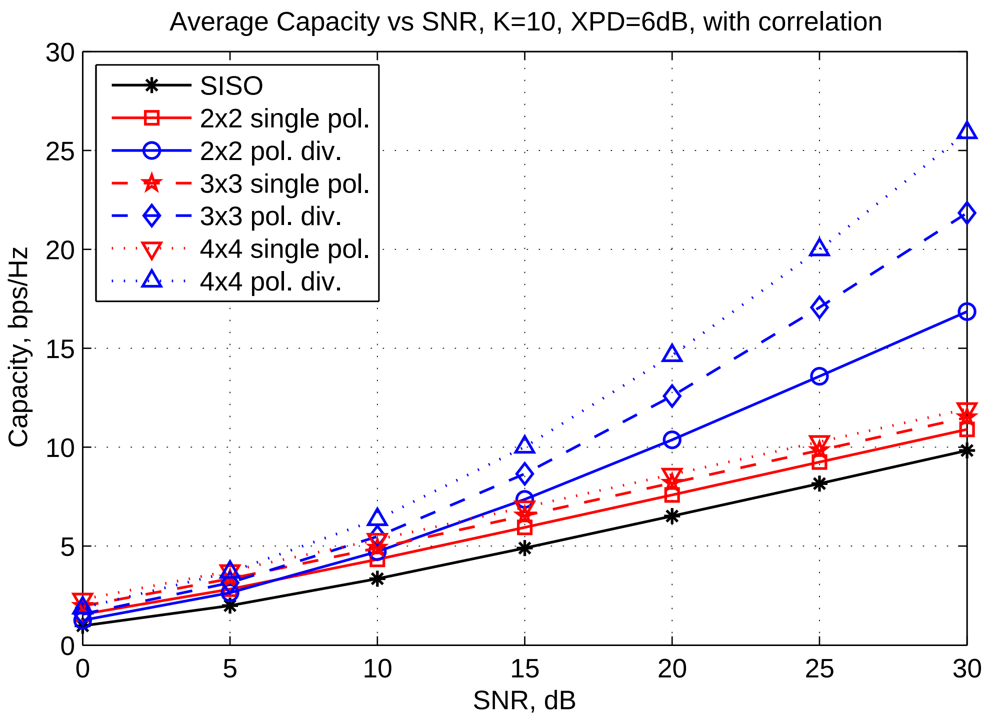


Figure 7.11: Average capacity (K-factor of 10, 6dB XPD, with correlation)

7.2.2 Distance dependent K-factor and XPD

BER for SM scheme and capacity results are obtained for K-factor and XPD generated for 3km distance. Correlation is present and correlation coefficient values are obtained using distance dependent XPD values.

7.2.2.1 SM scheme BER performance

Fig. 7.12 indicates the SM BER curves for SISO and MIMO systems with and without polarization diversity under correlated channels for 3km distance. For single polarization, as the number of antennas increases BER performance degrades due to high correlation. SISO has about 5dB better performance than 2×2, 8dB better performance than 3×3 and about 11dB better performance than 4×4 MIMO systems without polarization diversity at 10^{-3} BER when the RX antennas are colocated. However, MIMO systems with polarization diversity has better BER than SISO and single polarized MIMO systems.

At low SNR all 3 MIMO configurations have very close BER performance and after SNR>15dB BER curves differ from each other. There is not a pattern of the number of antennas and BER performance when polarization diversity is present. 3×3 MIMO with polarization diversity has about 1.5dB worse performance than 2×2 system which has about 2dB worse BER than 4×4 MIMO. Therefore, 4 antenna seems the best among the other number of MIMO antennas when polarization diversity is employed.

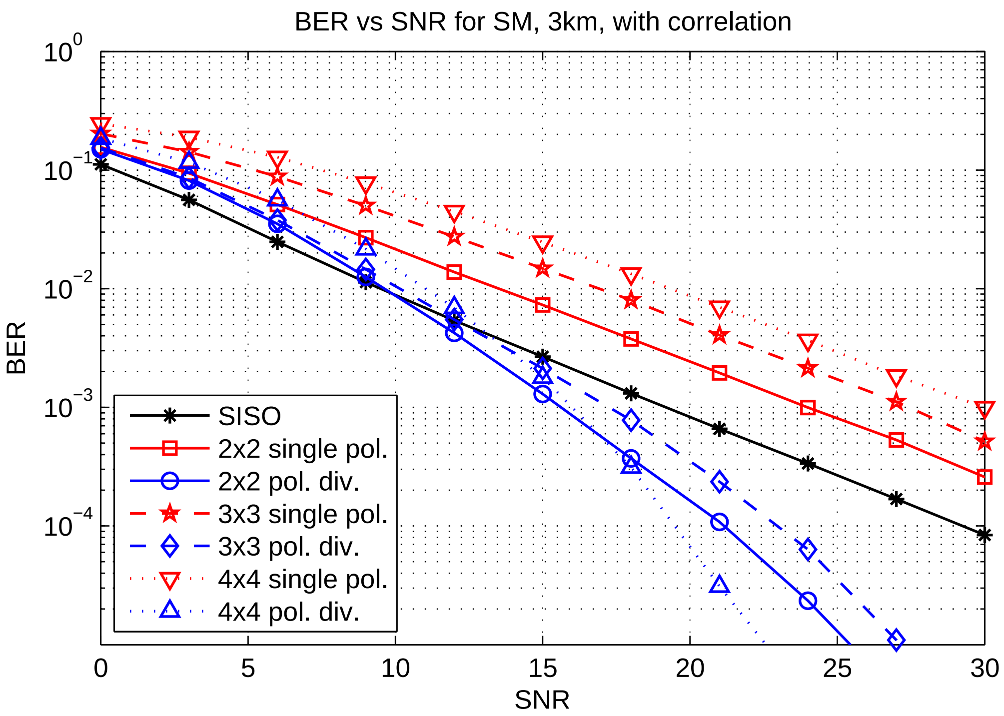


Figure 7.12: BER comparison for SM (3km distance, with correlation)

7.2.2.2 Average Capacity

Fig. 7.13 shows the capacity results of SISO and MIMO systems for correlated channel at 3km distance. Capacity results are very dependent on the correlation. When the correlation is present, the capacity comparison is very similar for K-factor of 0, 10 and distance dependent K-factor. SISO has the lowest capacity and single polarized MIMO capacities increase with the same slope as the number of antennas increases. However, MIMO systems with polarization diversity has much higher capacities than MIMO systems without polarization diversity under correlated channels. As the number of antennas increases correlation becomes more effective and the difference between single polarization and polarization diversity increases. At 30dB SNR, 2×2 MIMO with polarization diversity has about 5.5bps/Hz higher capacity than single polarized 2×2 MIMO, whereas 3×3 MIMO with polarization diversity has about 10bps/Hz higher capacity than single polarized 3×3 MIMO and 4×4 MIMO with polarization diversity has more than 16bps/Hz higher capacity than single polarized 4×4 MIMO.

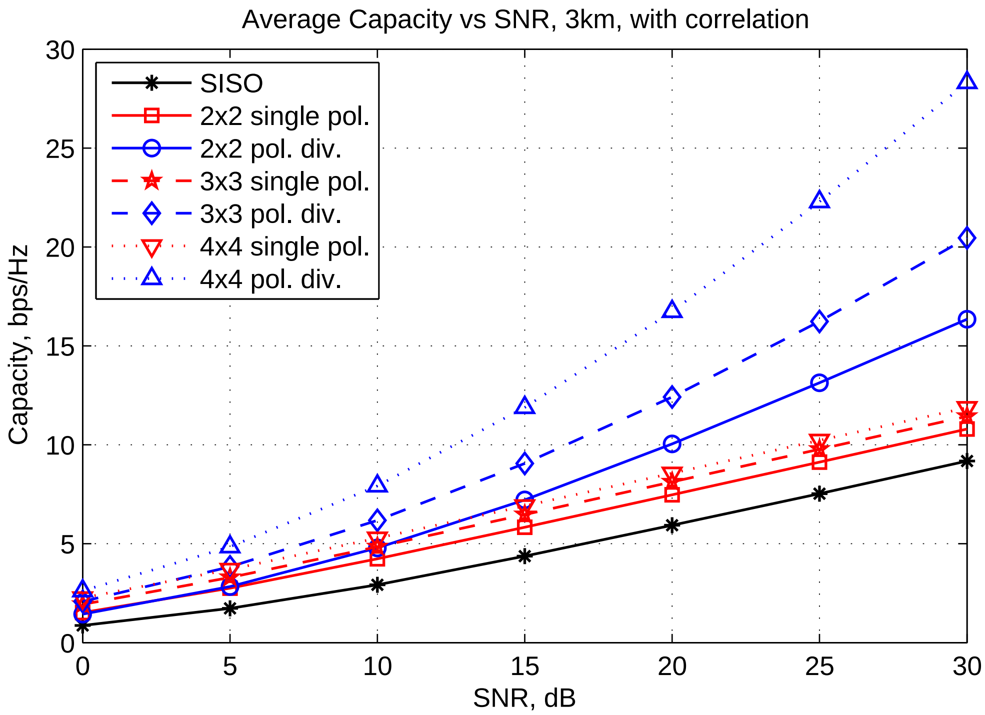


Figure 7.13: Average capacity (3km distance, with correlation)

CHAPTER 8

CONCLUSION

Diversity is the main cause of MIMO systems' advantage over SISO. There is a variety of diversity techniques such as time diversity, frequency diversity, spatial diversity. Polarization diversity is one of the MIMO diversity techniques however it is not as widely known and popular as the others. In this thesis, MIMO polarization diversity is investigated.

Statistical Ricean and Rayleigh fading models are obtained from deterministic multipath signals. MIMO channel model is presented using these fading models and the parameters based on the previous studies. Variable and constant channel components are included in this channel model. XPD is introduced into the MIMO channel model due to polarization differences between TX and RX antennas. Moreover, polarization differences cause lower correlation coefficients for MIMO systems with polarization diversity. In other words, MIMO channel model used in this study is a detailed combination of MIMO channel knowledge including polarization diversity effects.

Polarization diversity can be used in MIMO systems in order to increase the diversity order of the system in case of spatial diversity is not present. If there is enough space at TX or RX uncorrelated signals can be transmitted and received. However, if due to space constraint interantenna distances are small, correlation problem arises which causes performance degradation. If polarization diversity is employed lower correlation coefficients can be achieved. In this study, TX is assumed to have no space limitation and only RX correlation coefficient is considered since TX is assumed to be base station and RX is mobile equipment. There are two channel cases according to the receiver correlation. In the first case, receiver is assumed to have sufficiently large space so as to receive uncorrelated signals from different antennas and therefore, there is no correlation effect. In the second case, due to space problem at the receiver, antennas are colocated and correlation effect exists at the channel. Correlation coefficients are generated from a 3-D model including polarization orientations, XPD values, azimuth and elevation AOAs.

Both constant and distance dependent K-factor, XPD and correlation values are used for correlated and uncorrelated channel cases. Alamouti and spatial multiplexing are used as transmission schemes and ML detection is employed for receiver algorithm. Single polarized and dual polarized 2×2 MIMO systems' BER performance for AL and SM are compared for uncorrelated and correlated channel states at different K-factor and XPD values. In addition, capacity results are presented for these channels.

The conclusions for the results of several simulations can be summarized as follows:

- When there is not space limitation, uncorrelated signals can be received. AL BER of single polarization is lower than AL BER of dual polarization for all constant and distance dependent channel parameters since AL is based on power combination of received signals from all subchannels and dual polarization suffers from cross polar channel power loss. As XPD increases, AL BER for dual polarization degrades expectedly. For SM, dual polarization has better BER than single polarization for even uncorrelated channel cases, unless K-factor is low. The reason underlying this fact is that at high K-factor constant channel component, which has low rank, is dominant and XPD increases rank of the channel by dividing cross polar subchannel elements. As XPD increases, dual polarization SM BER decreases at high K-factor. Whereas at low K-factor, dual polarization SM BER worsens with the increase of XPD since variable channel component is dominant at low K-factor and variable channel has full rank without correlation. Just as BER for SM, capacity of dual polarization is lower at low K-factor and higher at high K-factor than that of single polarization due to XPD. The capacity comparison is very similar to SM BER comparison since both performances are based on channel diversity.

- When there is space constraint at the receiver and channel has correlation, AL and SM BER and channel capacity performances degrade. Signals can be received with lower correlation when RX antennas have different polarization orientation as compared to single polarization. When the correlation is present, dual polarization has better BER for SM scheme than single polarization, regardless of K-factor. As for AL, BER worsens with the presence of correlation although AL scheme is based on power combination from all subchannels. The reason of this fact is that when one subchannel is in deep fade, the other is also in deep fade at high correlation. Therefore, correlation eliminates the diversity advantage of MIMO systems. When AL scheme is employed, at low K-factor, dual polarization, which has worse BER performance than single polarization in uncorrelated channel case, has very close performance to single polarization. At high K-factor dual polarization performance is nearly unaffected by the correlation and single polarization performance degrades due to high correlation. Dual polarization has still worse performance than single polarization just as in uncorrelated channel case. Moreover, when correlation is present the difference between AL BER performance of single and dual polarizations decreases. Additionally, capacity of single polarization decrease much sharper than dual polarization and dual polarization has much higher capacity than single polarization regardless of K-factor.

- In addition to the constant channel parameters, distance dependent K-factor and XPD are used to investigate the performance of polarization diversity in real wireless suburban channels. For uncorrelated distance dependent channel, single polarization has better BER for AL than dual polarization regardless of distance. As for SM scheme, on the contrary to AL, dual polarization has better BER than single polarization for both close and far distances. At far distance, single and dual polarization SM BER performances improve slightly since K-factor decreases and channel elements have better distribution. Capacity of single and dual polarizations are very similar in uncorrelated case.

- When there is space limitation, for both small and large distances single polarization incurs severe performance degradation due to correlation. On the other hand dual polarization is nearly unaffected by correlation. Consequently, AL and SM BER and capacity results of dual polarization are better for correlated channel with distance dependent K-factor and XPD.

- In this study, number of antennas in a MIMO system with polarization diversity is investigated, in addition to 2×2 MIMO channel evaluations. SM BER and channel capacity of SISO, 2×2, 3×3 and 4×4 MIMO systems are compared for correlated and uncorrelated channels. When there is no correlation effect, at low K-factor as the number of antennas increases, BER and capacity results improve. Moreover, systems with polarization diversity performances are worse than single polarizations due to subchannel power loss. At high K-factor SISO has the best BER performance since high K-factor eliminates the fading effect of SISO channel. Rather than using

MIMO systems SISO can be chosen for a channel with high K-factor. But, the advantage of the MIMO is high capacity. Capacity increases with the increase of number of antennas.

- When there is correlation, MIMO systems with polarization diversity has better BER and capacity performance than single polarization for constant and distance dependent channels. SISO has better BER than single polarized MIMO systems and single polarization BER degrades with the increase of number of antennas. Capacity of polarization diversity increases sharply as the number of antennas increases. On the other hand, single polarization capacity also increases with the increase of number of antennas but this increase is very low as compared to increase of polarization diversity capacity. Use of single polarized MIMO system may not be worth such low capacity increase. Therefore, rather than using MIMO systems with colocated receiver antennas, SISO system can be used for BER as well as capacity. In addition, SISO has better BER than MIMO systems with polarization diversity for correlated channels with high K-factor. Yet, capacity of polarization diversity is much higher than SISO and as the number of antennas increases capacity increases sharply.

To sum up, when there is enough space in 2×2 MIMO, single polarization can be selected for AL and dual polarization can be selected for SM and capacity unless K-factor is very low. When there is not enough space at the receiver and antennas are colocated, polarization diversity can be used instead of single polarization for BER and capacity in all channel cases. Additionally, SISO can be used instead of MIMO systems for better BER at high K-factor. However, capacity of MIMO systems with polarization diversity are much higher than SISO. When high speed communication is desired, more number of antennas can be used. Finally, if there is space limitation and correlation is present, MIMO systems with polarization diversity should be used for BER and capacity.

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