# ON POLARIZATION CHANNEL MODELING

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## ABSTRACT

The use of MIMO technology has yielded high capacity in commercial wireless systems. However, a major issue of MIMO systems is that the channel capacity is highly dependent on the correlation between antenna elements. Therefore, multi-polarized antennas have been implemented in MIMO systems to reduce the antenna correlation and realize compact devices. To better understand the performance of multi-polarized antennas as compared to their uni-polarized counterparts in MIMO transmission, polarized channel modeling is necessary. This article presents an overview of polarized channel modeling. We compare different multi-polarized MIMO models and give some tips for choosing proper MIMO systems. In addition, some open problems are discussed.


## INTRODUCTION

Compared to traditional single-input single-output (SISO) transmission in wireless systems, the use of multiple-input multiple-output (MIMO) technology offers spatial multiplexing and spatial diversity without increasing the total system power and bandwidth, thus offering the potential for substantial improvements in channel capacity and spectral efficiency. However, one major issue of MIMO systems is that the channel capacity is highly dependent on the correlation between antenna elements, and a higher correlation between antenna elements generally results in lower channel capacity, and vice versa. An antenna spacing of at least half a wavelength at the customer premises equipment and 10 wavelengths at the base station are typically required for achieving significant MIMO gain [1]. The restrictions of equipment size, power, and cost can make it difficult if not impossible to physically space the antennas far enough apart to achieve low correlation between antenna elements. Moreover, as MIMO antennas increase in number, the physical size of the MIMO antenna array becomes larger, which causes other difficulties in engineering that can restrict MIMO technology in many scenarios. In this case, the polarization of electromagnetic waves is an important resource of the wireless channel, and it can be exploited in MIMO systems to reduce correlation between antenna elements.

Measurements have shown that vertically and horizontally polarized electromagnetic waves in many non-line-of-sight (NLoS) scenarios fade almost independently, and in line-of-sight (LoS) scenarios two transmitted orthogonal polarizations will remain orthogonal through the channel [2], which means the orthogonal polarized antennas have very low correlation even when they are co-located. Hence, polarized antennas structures are a very good solution for realizing compact and robust devices [3]. In fact, multi-polarized antennas, especially orthogonal dual-polarized antennas, are strong candidates to be used in high-rate wireless communication systems, such as Long Term Evolution (LTE) systems [2]. To better understand the performance of multi-polarized antennas as compared to their uni-polarized counterparts in MIMO transmission, we should model the polarized MIMO channel.

Modeling the polarized channel is difficult because of the complexity of the polarization characteristics. Reflections, diffractions, and scattering of signal in the channel may result in channel depolarization, that is, the polarized orientation may rotate after passing through the channel from transmitter to receiver, and it is a very complicated process. A commonly used method for describing channel depolarization is to define the cross-polarization discrimination (XPD), which is a measure of depolarization in the propagation environment, and is defined as the ratio of the average received power in the co-polarized channel to the average received power in the cross-polarized channel [4]. Kwon and Stüber provided a geometric theory for channel depolarization and provided a mechanism for computing XPD based on the locations of the scatterers [5]. In addition to XPD, the correlation and gain imbalance between co-polarization and cross-polarization components need to be considered. The gain imbalance can be understood as follows: the cross-polarization component (i.e. from a vertically polarized transmitting antenna to a horizontally polarized receiving antenna) should be equal to zero so that if an antenna transmits on the vertical polarization, although the channel has a depolarization effect, most of its power will still remain in the vertical polarization, and the horizontally polarized receiver antenna may receive little power resulting in a loss of signal-to-noise ratio (SNR). Thus, polarized MIMO channel modeling is very different from traditional MIMO channel modeling. Many researchers have considered polarized channel modeling [2–4, 6–10], and most of them focus on dual-polarized systems.

Coldrey [2] modeled the polarized channel as a Ricean fading channel and decomposed the channel matrix into a fixed (LoS) part and a random or scattering (NLoS) part with polarization factor. This was a common method, which was also applied by Habib *et al*. [3] for optimizing the anten-

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na selection in multi-polarized MIMO transmission. Oestges *et al.* [1] decomposed the dual-polarized Rayleigh channel matrix into a uni-polarized correlated Rayleigh channel matrix and a polarization matrix, and described the mechanisms of the channel matrix, which we discuss later. Compared to the cylinder model in [5], Dao *et al.* [4] proposed a 3D sphere model, and discussed the correlation and capacity of the polarized MIMO channel. Also, Oestges *et al.* [8] addressed the extension of a stochastic geometry-based scattering model to multi-polarized transmissions. This model accounts for the effects of many parameters including the Rician *K*-factor, delay spread, Doppler spectrum, channel correlations, and so on.

Lei Jiang *et al.* [11] discussed the correlation coefficient between antennas, and Qin *et al*. [9] gave a simple way to calculate the correlation coefficient between antennas. Oestges [10] took several factors such as antenna cross-polar isolation (XPI), array tilting, and channel depolarization into account to obtain a complete channel model.

The aim of this article is to present an overview of polarized channel modeling. The remainder of this article is organized as follows. The following section discusses the factors that can influence the capacity of polarized systems. In the third section, the multi-polarized channel model is formulated, and different multi-polarized models are compared. In the fourth section, we give some tips for choosing proper systems. Some open problems are then discussed. Finally, we wrap up the article with some concluding remarks.

## Multi-Polarized Channel Parameters

### Antenna Array

Figure 1a shows the configuration of traditional MIMO systems, where all the antennas are half-wavelength dipole antennas. Tx denotes the transmit antenna and Rx denotes the receive antenna, and dt is the transmit antenna spacing, while dr is the receive antenna spacing. Cross-polarized antennas are shown in Fig. 1b, which consists of a vertically polarized antenna and a horizontally polarized antenna at both sides. Usually, we regard the ground as a reference, which means the antennas perpendicular to the ground are vertically polarized antennas, and the antennas parallel to the ground are horizontally polarized antennas. Thus, in Fig. 1b, Tx1 and Rx1 are vertically polarized antennas, and Tx2 and Rx2 are horizontally polarized antennas. Figure 1c shows compact cross-polarized antennas and co-located antennas. Because of the decorrelation of the cross-polarized antennas, the correlation between antennas is very low even when they are co-located, which makes them space-efficient and cost-efficient.

Another commonly used cross-polarized arrangement is shown in Fig. 1d, which uses 45° slant polarized antennas. Figure 1e shows a 4 × 4 multi-polarized antenna configuration, where each end of the link has two vertically polarized antennas and two horizontally polarized antennas. The antenna array size in Fig. 1e is half of the array size for traditional 4 × 4 MIMO systems. A triple-polarized antennas array is shown in Fig. 1f, where the three antennas polarizations are mutually orthogonal.

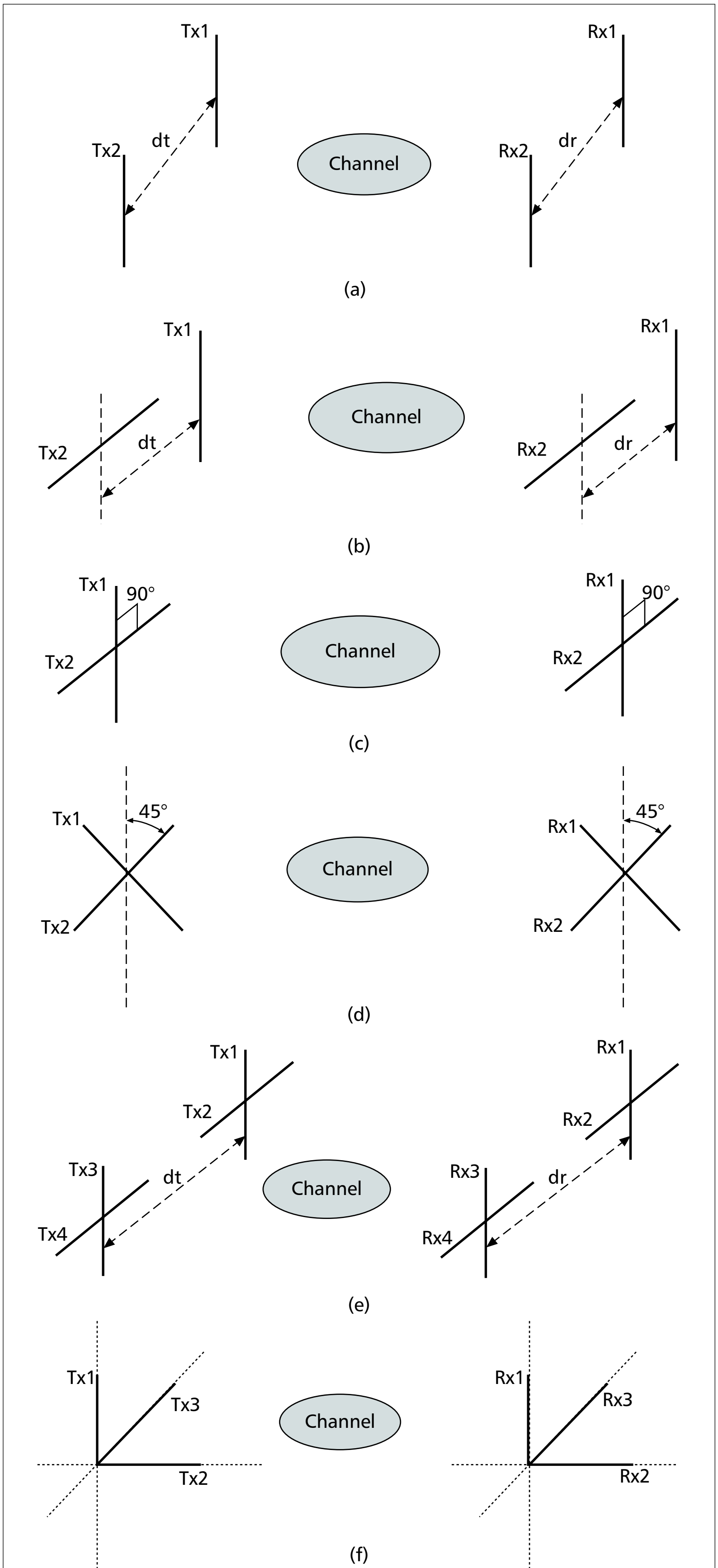


Figure 1. a) Uni-polarized MIMO; b) multi-polarized MIMO (vertical, horizontal, and separated); c) multi-polarized MIMO (vertical, horizontal, and co-located); d) multi-polarized MIMO (45° slanted and co-located); e) 4 × 4 multi-polarized MIMO array; f) triple-polarized MIMO array.

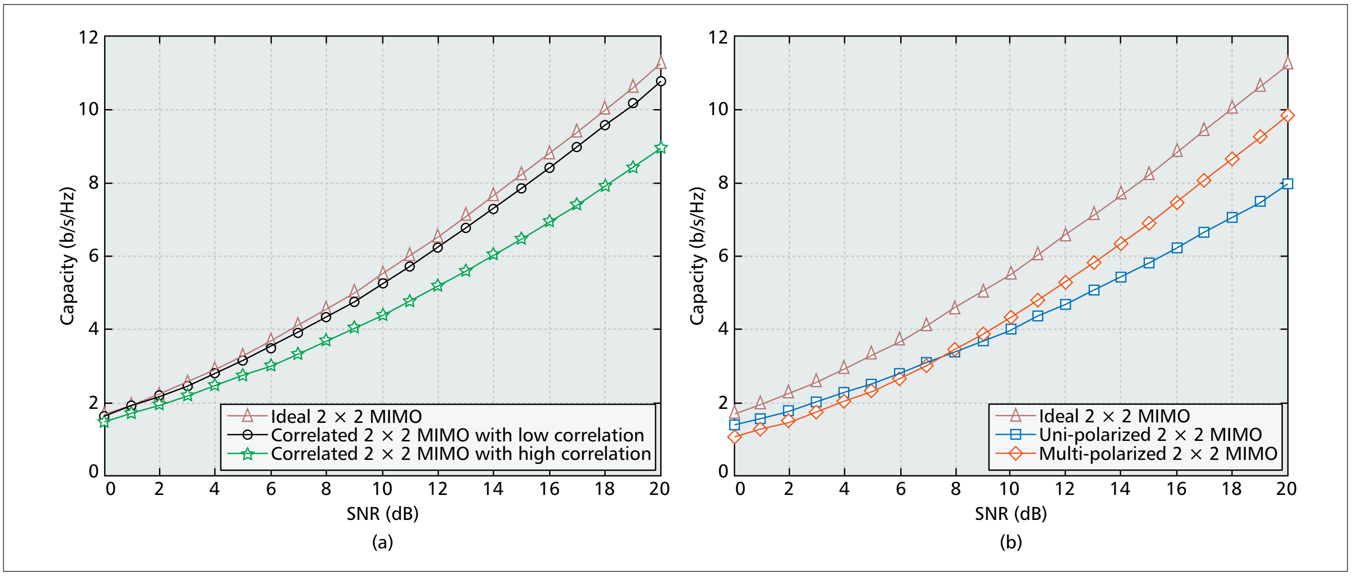


Figure 2. a) Traditional MIMO systems capacity vs. SNR at different correlations, high correlation ($\gamma(Tx) = \gamma(Rx) = 0.8$) and low correlation ($\gamma(Tx) = \gamma(Rx) = 0.4$); b) uni-polarized and multi-polarized MIMO systems capacity vs. SNR, $\gamma(Tx) = \gamma(Rx) = 0.85$.

## Correlation

The MIMO channel capacity is highly dependent on the correlation between antennas (both the Tx correlation and Rx correlation). According to the generalized MIMO capacity formula: $\mathbf{C} = \log_2[\det(\mathbf{I} + \rho/(N_t)\mathbf{H}\mathbf{H}^\mathbf{T})]$b/s/Hz[1, 3, 4, 12], where $\mathbf{I}$ is the identity matrix, $\mathbf{H}$ denotes the channel matrix, and $\mathbf{H}^\mathbf{T}$ is its conjugate transpose (for both uni-polarized and multi-polarized channel matrices). If the total transmit power is $P$, $N$ is the additive white Gaussian noise (AWGN) at each of the receiver branches, the average SNR $\rho$ at each receiver branch can be defined as $\rho = P/N$, and $N_t$ is the number of transmit antennas. Then we can obtain the MIMO capacity under different channel correlation conditions, which is shown in Fig. 2a, by using the Monte Carlo simulation method, where we generate 1000 samples of the channel and compute the average MIMO capacity. Parameter $\gamma(Tx)$ denotes the correlation between the Tx antennas, while $\gamma(Rx)$ denotes the correlation between the Rx antennas.

Ideally, the correlation between antennas is zero such that each antenna is uncorrelated with others, which is impractical in reality. We can see that higher correlation results in lower capacity, so it is important to reduce the correlation to enhance the system capacity. The MIMO antenna correlation vs. antenna spacing for the classical case of isotropic scattering is shown in Fig. 3a. Although the correlation is related to the angle spread (AS), at least a half-wavelength is required. If we use MIMO at 2.5 GHz (the corresponding wavelength is 12 cm), we need an antenna spacing of at least 6 cm at the terminals, which makes their miniaturization difficult.

As mentioned before, multi-polarized antennas can reduce the correlation, which is shown clearly in Fig. 3b, and we use the definitions and conclusions in [9]. The two antennas are co-located while both of them can rotate, and then there is an angle between them. When the angle is 0° or 180°, the correlation is equal to unity because of the same polarization and co-location. The correlation decreases as the angle increases from 0° to 90°, and the correlation is equal to zero when the angle is 90°, which becomes the orthogonal polarization. Hence, we can use the multi-polarized antennas to reduce the correlation while using less physical space than their uni-polarized counterparts.

## XPD

Theoretically, an antenna is designed to receive a signal having a certain polarization, and it is completely isolated from the cross-polarization component (i.e., the antenna has zero gain to the cross-polarization direction signal). But such is not the case in practice due to three main mechanisms [10]. The first is that the antenna has finite XPI, which means the antenna can more or less receive the cross-polarization component as well. The second is the tilt of antennas, which can take place at both ends of the link. Finally, the most important mechanism is the channel depolarization, and it can be described by the channel XPD.

As mentioned above, the XPD is defined as the ratio of the average power received in the co-polarized channel to the average power received in the cross-polarized channel,

$$XPD = \frac{E\left\{\left|h_{VV}\right|^2\right\}}{E\left\{\left|h_{HV}\right|^2\right\}} = \frac{E\left\{\left|h_{HH}\right|^2\right\}}{E\left\{\left|h_{VH}\right|^2\right\}}$$

[2, 13, 14], where $h_{XY}$ is the component in the $XY$ channel, and $E\{\cdot\}$ represents the expectation operator. Also, a variable $\alpha$, $0 < \alpha \le 1$, is defined in [2, 3, 14] for the convenience of modeling and computing, which is directly related to the XPD for the channel and corresponds to the part of the radiated power that is coupled from $V$ to $H$ and vice versa. When the discrimination between the $V$ and $H$ polarized components is perfect, $\alpha = 0$; otherwise, there is leakage between the polarizations when $0 < \alpha \le 1$. The relation between

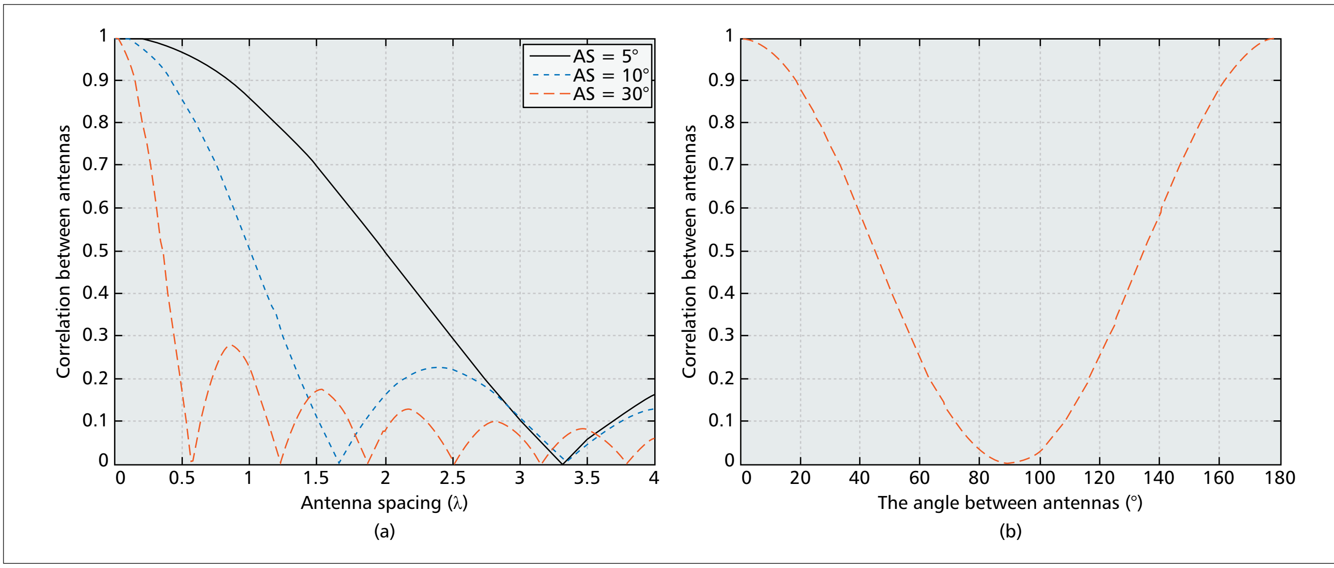


**Figure 3.** a) Uni-polarized MIMO antennas correlation vs. antenna spacing; b) multi-polarized MIMO antennas correlation vs. antenna angle.

the XPD and α is given by XPD = 1/α, which means that E{$|h_{VV}|^2$} = E{$|h_{HH}|^2$} = 1 in [14]. Meanwhile, [2, 3] relate α and the XPD as *XPD* = (1 – α)/α, which means that E{$|h_{VV}|^2$} = E{$|h_{HH}|^2$} = 1 – α. The latter model is more realistic because it assumes a conservation of power or energy, where the channel cannot output more power than is put into it.

## Multi-Polarized Channel Modeling

### Theory and Formulation

Coldrey and Habib *et al*. [2, 3] modeled the multi-polarized MIMO channel as a Ricean fading channel, such that the channel matrix is composed of a fixed (LoS) part and a random or scattering (NLoS) part according to

$$\mathbf{H} = \sqrt{\frac{k}{K+1}}\bar{\mathbf{H}} + \sqrt{\frac{1}{K+1}}\tilde{\mathbf{H}}$$

[6, 11, 14], where $K$ is the Ricean $K$-factor, which is defined as the power ratio of the LoS component to the scattering component. $\bar{\mathbf{H}}$ is a deterministic matrix representing the LoS part, while $\tilde{\mathbf{H}}$ is a random matrix representing the NLoS part. The random matrix $\tilde{\mathbf{H}}$ consists of complex Gaussian entries, which are independent from one channel realization to the next [2, 3]. As $K \to \infty$, only the LoS component is considered, and the channel matrix is determined by the LoS component. As $K \to 0$, there is only a scattering component, and the channel becomes a Rayleigh fading channel. Otherwise, the Ricean fading channel has both LoS and NLOS scattering components, which can well describe the channel transmission in reality.

Jiang *et al.* [11] found that the channel matrix for cross-polarized MIMO systems can be written as the element wise multiplication of the channel matrix for co-polarized MIMO systems with a matrix modeling the polarization relationship between the transmit and receive antennas. In particular, the cross-polarized MIMO channel matrix can be expressed as [1–3, 13, 14],

$$\tilde{\mathbf{H}}_{\mathbf{p}} = \tilde{\mathbf{H}}_{\times} \odot \left(\mathbf{R}_{\mathbf{r}}^{1/2}\mathbf{H}_{\mathbf{i.i.d.}}\mathbf{R}_{\mathbf{t}}^{1/2}\right),$$

$$\text{where } \tilde{\mathbf{H}}_{\times} = \begin{bmatrix} \sqrt{1-\alpha} & \sqrt{\alpha} \\ \sqrt{\alpha} & \sqrt{1-\alpha} \end{bmatrix}$$

is the polarization matrix, $\mathbf{R}_{\mathbf{r}}^{1/2}$ and $\mathbf{R}_{\mathbf{t}}^{1/2}$ are receive and transmit correlation matrices, respectively, and $\mathbf{H}_{\mathbf{i.i.d.}}$ is a matrix of independent and identically distributed (i.i.d.) zero mean complex-valued Gaussian random variables. Then we can obtain the capacity of multi-polarized MIMO systems as compared to the uni-polarized MIMO systems according to the MIMO capacity formula mentioned before.

### Models and Comparison

Ispas *et al.* [7] characterized the required SNR for a multi-polarized MIMO system to outperform a uni-polarized MIMO system in terms of the mutual information (MI). From Fig. 2b we can see that the multi-polarized MIMO systems do not always outperform uni-polarized MIMO systems. In the high SNR region, the multi-polarized configurations are more effective because of the reduction in the antenna correlation. However, in the low SNR region, the reduction in the correlation of the multi-polarized configurations is not enough to compensate for the power loss in the co-polarized component caused by depolarization [1, 4]. Therefore, when the SNR is low, we prefer uni-polarized MIMO. Erceg et al. [6] used the Ricean channel to model a 2 × 3 polarized channel, where the polarization configurations at the Tx and Rx may be different, that is, the configuration at the Tx may use vertical and/or horizontal antennas, while the Rx uses three 45° slant polarized antennas. They also reached the conclusion that at close distances the dual-polarized antennas offer higher capacity, while at some particular distance, the capacity of a dual-polarized antenna system can be lower than the uni-polarized counterpart caused by the loss of coupling power.

Ispas *et al.* [7] focused more on the SNR effect on the capacity, while other authors [2, 3]

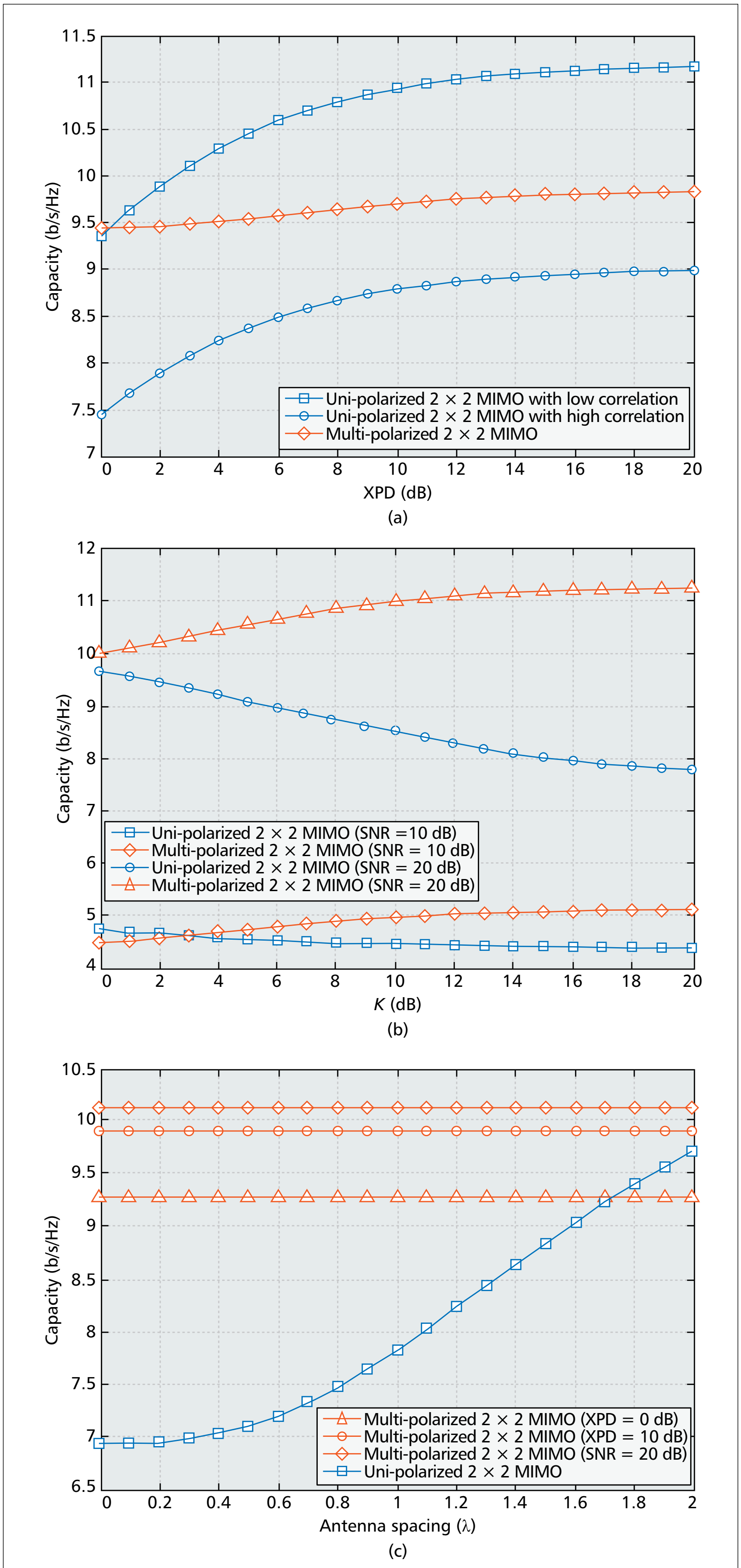


**Figure 4.** a) Uni-polarized and multi-polarized MIMO systems capacity vs. XPD, high correlation ($\gamma(Tx) = \gamma(Rx) = 0.8$) and low correlation ($\gamma(Tx) = \gamma(Rx) = 0.2$), SNR = 20 dB, and $K = 0$; b) uni-polarized and multi-polarized MIMO systems capacity vs. $K$-factor, $\gamma(Tx) = \gamma(Rx) = 0.5$, and XPD = 20 dB; c) uni-polarized and multi-polarized MIMO systems capacity vs. antenna spacing, SNR = 20 dB, and $K = 1$.

discussed how other multi-polarized parameters affect the capacity according to the channel matrix and MIMO capacity formula mentioned before. Figure 4a [2, 3] shows how the capacity is influenced by the XPD in both multi-polarized and uni-polarized MIMO systems. The capacity of both the multi-polarized and uni-polarized MIMO systems increases as the XPD increases. The XPD has a slight effect on the multi-polarized MIMO systems while having a significant effect on uni-polarized MIMO systems, and the capacity of uni-polarized MIMO systems decreases drastically as the XPD decreases. This is because a low XPD implies significant leakage between the polarizations, and uni-polarized MIMO systems will lose most of the energy due to polarization mismatch. Multi-polarized MIMO systems achieve better performance in such situations.

In Fig. 4b [2], we can see how the capacity changes as the $K$-factor varies. While the multi-polarized MIMO capacity increases as the $K$ value increases, and the uni-polarized MIMO capacity decreases as the $K$ value increases. This is because as the $K$ value increases, the LoS component becomes more dominant, so the scattering component is weakened, which results in increased correlation between antennas. Thus, uni-polarized MIMO capacity decreases while multi-polarized MIMO capacity increases due to its low correlation.

In addition to the XPD and $K$-factor, Tsen and Li [12] considered system capacity vs. antenna spacing. From Fig. 4c [12], we can see that the uni-polarized MIMO system capacity increases as the antenna spacing increases, because the correlation decreases as the antenna spacing increases. In comparison, the multi-polarized MIMO capacity has a slight change, because the multi-polarized antennas already have very low correlation, so the antenna spacing has only a slight effect on the correlation between multi-polarized antennas.

All the models discussed above are statistical models, and many other references preferred to use geometrical models to describe the multi-polarized channel. Oestges *et al.* [8] addressed the extension of a stochastic geometry-based scattering model to multi-polarized transmissions, and their proposed model allows us to simulate the effects of a wide range of parameters. Moreover, their simulation results were compared to measurements and experimental data, which made the model more convincing. Kwon and Stüber [5] used a geometrical conservation of polarization plane methodology to generate polarized complex channel impulse responses. They revealed that the XPD is dominated by the particularly strong depolarization of waves that are scattering off of objects located at particular locations as defined by their azimuth angles of arrival (AAoAs) and elevation angles of arrival (EAoAs) with respect to the receiver antenna.

Compared to [5], Dao *et al.* [4] established a two-sphere 3D geometrical model that did not focus on the XPD. They noted that the propagation characteristics of vertically polarized waves are different from those of horizontally polarized waves. The received power in the vertical-to-vertical channel is normally higher than that in the horizontal-to-horizontal channel, which means $E\{|h_{VV}|^2\} > E\{|h_{HH}|^2\}$. Jiang *et al.* [11] also considered this point as well and concluded that polarization selectivity favors vertical polarization, so the vertical-to-vertical transmission loss should be less than the horizontal-to-horizontal transmission loss during propagation. Another parameter is defined as the co-polar ratio (CPR),

$$\mathrm{CPR} = \frac{\mathrm{E}\left\{\left|h_{VV}\right|^2\right\}}{\mathrm{E}\left\{\left|h_{HH}\right|^2\right\}}$$

[4], to describe the imbalance between the vertical-to-vertical channel and the horizontal-to-horizontal channel.

From Fig. 5, we can see the CPR has a significant effect on the channel capacity, which cannot be ignored. CPR = 0 dB means $\mathrm{E}\{|h_{VV}|^2\} = \mathrm{E}\{|h_{HH}|^2\}$, which is the situation discussed above. A higher CPR results in lower channel capacity and vice versa. This is because a higher CPR means greater transmission loss in the horizontal-to-horizontal channel, which results in a greater SNR loss in the whole system.

Different models focus on the different factors, while Oestges [10] decomposed the whole channel model into several matrices and took many factors into account, such as the antenna XPI, array tilting, and channel depolarization to obtain a full channel model. Given this flexible channel model, finding the best polarization angles for the transmitter or the receiver or both may be an interesting topic. Finally, Table 1 compares the different polarized channel models.

## When Should We Choose Multi-Polarized Antennas?

Although many papers compare multi-polarized MIMO with uni-polarized MIMO, and conclude that multi-polarized MIMO systems do not always outperform uni-polarized systems, no one has summarized when we should choose multi-polarized antennas. In this section, we give some tips for choosing multi-polarized antennas.

The SNR is a dominant factor for improving the channel capacity for both multi-polarized MIMO and uni-polarized MIMO. When the SNR is high, multi-polarized MIMO is preferred because of the reduction in correlation. At low SNR, uni-polarized MIMO may still outperform multi-polarized MIMO because the power loss in multi-polarized antennas has a significant effect on capacity. If the correlation between uni-polarized antennas is low, they may have more advantages than multi-polarized MIMO because they do not have power loss. Also, if the XPD is low, multi-polarized MIMO performs more stably, because the uni-polarized MIMO has severe power loss due to the polarization mismatch. Moreover, if the LoS component is dominant in the system environment (e.g., the suburban environment), multi-polarized antennas may be more suitable due to the high $K$ value. Finally, if the scattering part is dominant in the system environment (e.g., the urban environment), uni-polarized antennas may be more suitable because of the low correlation due to richer scattering. Another advantage of multi-polarized antennas is that they can allow compact and small devices, so if the miniaturization of equipment is of primary concern, multi-polarized antennas would be the best choice.

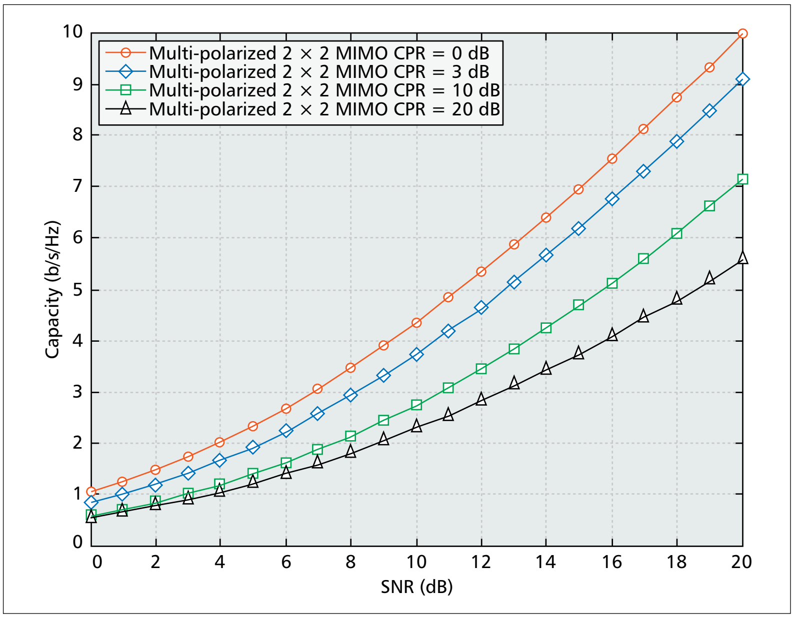


**Figure 5.** Multi-polarized MIMO systems capacity for different CPRs, Rayleigh channel.

## Future Work

Most prior literature on polarization channel modeling has focused on the dual-polarized 2 × 2 MIMO channel, which is just a special case of the multi-polarized MIMO channel. Future work may pay more attention to the general case. Recently, Kwon and Stüber [15] proposed polarization-division multiple access (PDMA) as a possible means of increasing system capacity by multiplexing distinct users in polarization NLoS wide-band wireless fading channels. Further studies of polarized channels and applications based on theoretical research and experimental measurements would be useful. Although experiments are expensive and time-consuming, they can help us to modify the theoretical models and make them more accurate.

## Concluding Remarks

This article has presented an overview of polarization channel modeling. We have compared different multi-polarized MIMO models and found that a Ricean channel model can describe the polarized MIMO channel successfully. Multi-polarized MIMO systems do not always outperform the corresponding uni-polarized MIMO systems, so the proper selection of MIMO systems needs to be carefully considered. In addition, further studies are based on theoretical research, and experimental measurements are needed to make the channel models more accurate. Methods that exploit polarization to enhance overall capacity, such as PDMA, merit further study.

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| Model | Type | Scenario | Parameters | Contribution/conclusion |
|---|---|---|---|---|
| C. Oestges *et al.* [1] | Statistical model | Rayleigh channel | SNR, XPD | Method to estimate the mutual information; uni-polarized schemes outperform multi-polarized schemes in the low SNR regime and small depolarization condition |
| Mikael Coldrey [2] | Statistical model | Ricean channel | SNR, XPD, *K*-factor | Compared the capacity of uni-polarized and multi-polarized MIMO vs. different parameters; multi-polarized MIMO does not always yield the best performance |
| Aamir Habib *et al.* [3] | Statistical model | Ricean channel | SNR, XPD,number of selected receive antennas | Investigated a model for dual and triple polarized MIMO channels; optimization algorithm to select the best antennas |
| Adrian Ispas *et al.* [7] | Statistical model | Ricean channel | SNR, XPD, *K*-factor, distance | Dual polarized MIMO outperforms uni-polarized MIMO with sufficiently high *K*-factors; *K*-factor value vs. distance |
| Manh-Tuan Dao *et al.* [4] | 3D geometrical model | Rayleigh channel | SNR, receive antenna orientation, receive antenna spacing | Proposed model can be used to evaluate the effect of arbitrary parameters and can be extended to any kind of array type |
| Kwon and Stüber [5] | 3D geometrical model | Rayleigh channel | Distance, azimuth angle of arrival, elevation angle of arrival | Geometric model to predict XPD; the XPD is sensitive to azimuth-elevation of surrounding scatterers |
| C. Oestges *et al.* [8] | Geometry-based scattering model | Ricean channel | *K*-factor, delay-spread, Doppler spectrum, channel correlations, XPD | Simulated behaviors have been compared with experimental data, and this model can be adapted to a wide range of parameters |

Table 1. Comparison of different polarized channel models.

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