PERFORMANCE EVALUATION OF MIMO CHANNEL WITH DUAL-POLARIZATION ANTENNAS

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Abstract

Currently, there is considerable interest in the use of multi-antenna systems with MIMO in telecommunications, in particular - dual-polarization antennas. The use of such antennas can generally improve the quality of the channel. Polarization orthogonal antennas on both the transmitter and receiver can improve communication performance. The main disadvantage of such systems with MIMO technology is the polarization loss. The article proposes to consider the possibility of orthogonalization the components of the received signals at the receiving position. It is interesting to increase the data rate (BR) and reduce data errors (BER) in wireless communication with antennas due to the adaptive polarization of the channel.

Introduction

Further development of communication systems requires the search for effective methods to ensure the quality of communication channels and electromagnetic compatibility. Using different polarizations can provide additional benefits in terms of electromagnetic compatibility [1]. The focus is on cross-polarization isolation between channels and the effect on channel quality parameters [2-5]. It is proposed to choose antennas with the minimum required values of the cross-polarization coefficient, which limit the given channel bandwidth. In wireless communications, multiple-input and multiple-output (MIMO), is a method for improving the quality, capacity, and reliability of a radio link using multiple transmission and receiving antennas to exploit multipath propagation [6-7]. The main disadvantage of systems with MIMO technology is the loss of energy due to polarization effects, and then the parameter of the receiver antenna is not equal to the signal parameter [8].

Shannon-Hartley's channel capacity theorem is applied to provide the upper bound of the data rate given a certain bandwidth and signal to noise ratio (SNR). However, the cross-polarization discrimination (XPD) of the radio wave is not considered to resolve the capacity problem in the previous investigations. For a radio wave transmitted with a given polarization, the ratio of the power received with the expected polarization to the power received with the orthogonal polarization is called cross-polarization discrimination.

1 MIMO technology

Polarization is described by time variations of the electric field vector, it is one of key characteristics of electromagnetic and optic waves. In this thesis, we investigate the applications of the polarization technology in wireless communication systems. When the cross-polarization discrimination (XPD) of the polarization antenna is considered, at the receiver, the signal to noise ratio (SNR) should be replaced by the signal to noise and interference ratio (SNIR) to indicate the receiving performance. The results show that, MIMO technology with polarization-orthogonal channels can be used to effectively improve the bandwidth of a communication channel when XPD less than the expected SNR. Therefore, designing of communication channels with MIMO dual-polarization antennas need pay some attention to the features of the antennas with minimum XPD.

In wireless communications, multiple-input and multiple-output (MIMO), is a method for improving the quality, capacity, and reliability of a radio link using multiple transmission and receiving antennas to exploit multipath propagation, as shown in Fig. 3.1. MIMO technology has become an essential element of wireless communication standards including IEEE 802.11n (Wi-Fi), IEEE 802.11ac (Wi-Fi), HSPA+ (3G), WiMAX (4G), and Long Term Evolution (4G LTE).

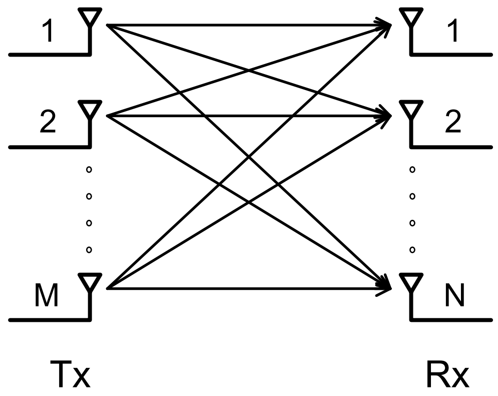

Fig. 1. Schematic diagram of MIMO technology

Two popular approaches for communicating in the MIMO channel are diversity and multiplexing **Ошибка! Источник ссылки не найден.**. Spatial multiplexing, is an approach where the incoming data is divided into multiple substreams and each substream is transmitted on a different transmit antenna, as shown in Fig. 3.2. This is motivated by the capacity improvement of the communication channels. Spatial multiplexing was first proposed by Paulraj and Kailath in 1994. Initial spatial multiplexing systems were narrowband with small delay spread, then, spatial multiplexing is being considered for wideband channels in conjunction with OFDM modulation.

MIMO diversity, on the other hand, is an approach where information is spread across multiple transmit antennas to maximize the diversity advantage in fading channels. This is motivated by the desire to reduce the probability that a fade on any one of the transmit-receive antenna links will cause a codeword error. In diversity, each pair of transmit-receive antennas provides a signal path from transmitter to receiver, as shown in Fig. 3.3. By sending the same information through different paths, multiple independently-faded replicas of the data symbol can be obtained at the receiver end. Hence, more reliable reception is achieved.

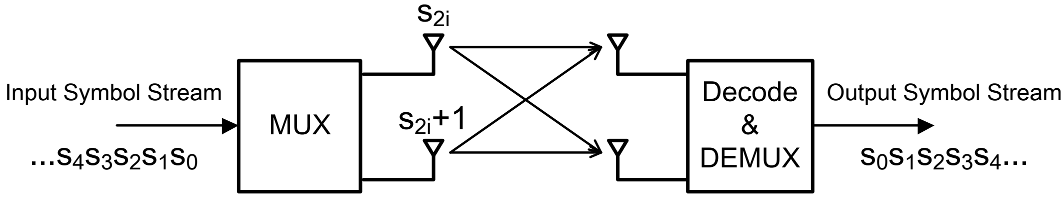

Fig. 3.2. Schematic of a spatial multiplexing system

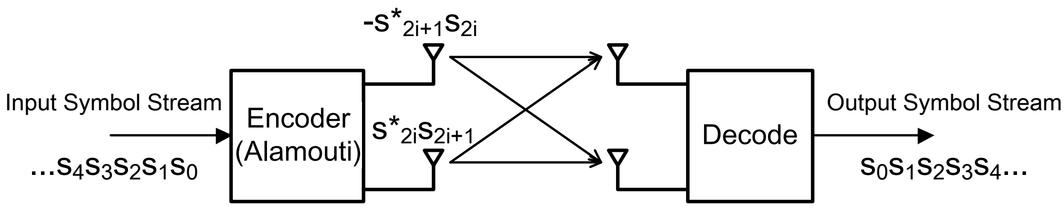

Fig. 2. Schematic of a diversity system (Alamouti scheme)

2 MIMO Signal Processing

MIMO Signal Processing is a mathematical model where vectors and matrices represent different components of different dimensions involved in a communication system. Particularly, MIMO Signal Processing takes an important relevance when multiple inputs and/or outputs are modeled in a single system. For instance, MIMO Signal Processing is widely used to model spatial systems, here each input corresponds to a radiating antenna and each output to a receiving antenna. However, the spatial dimension is not the only one that can be modeled by MIMO. Time-delayed systems that convolve channel impulse responses, Fast Fourier Transforms, frequency-time or space-time can also be modeled with MIMO Signal Processing. Therefore, polarization can be modeled using MIMO Signal Processing, where each component corresponds to each polarization. Generally, the system model with *m* inputs and *n* outputs can be described as

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{w}, \tag{1}$$

where $\boldsymbol{y} \in \boldsymbol{C}^{n}$ is the received vector and contains the output components, $\boldsymbol{H} \in \boldsymbol{C}^{n\times m}$ is the transition matrix, $\boldsymbol{x} \in \boldsymbol{C}^{m}$ is the transmitted vector and contains the input components, $\boldsymbol{w} \in \boldsymbol{C}^{n}$ is the noise vector. In this model, $\boldsymbol{H}$ is the transition matrix from inputs to outputs and is often referred to as channel matrix. Each entry of this matrix describes the statistics of the environment that affect the transmitted signal. The channel matrix characterizes the scenario and the physical dimension used in the communication system, and these dimensions including:

- Spatial Dimension: each input corresponds to the voltage of each transmitting antenna using the baseband model. Each output is the voltage measured by each receiving antenna. Hence, inputs are not orthogonal and have a physical measurement in a precise spatial position.
- Polarization Dimension: each input and output corresponds to each component of the voltage in the polarization ellipse at transmission and reception, respectively. Hence, the components are orthogonal by definition, since they correspond to the orthogonal basis chosen by convenience and the number of inputs and outputs is equal to 2, i.e., $m=n=2$.

3 Channel capacity

Shannon-Hartley's channel capacity theorem is applied to provide the upper bound of the data rate given a certain bandwidth and signal to noise ratio (SNR). It demonstrates that the effect of a transmitter power constraint, a bandwidth constraint, and additive noise can be associated with the channel and incorporated into a single parameter, called the channel capacity. For a single-input and single-output (SISO) channel, in the case of an additive white (spectrally flat) Gaussian noise interference, an ideal band limited channel of bandwidth *B* has a capacity *C* given by

$$C_s = B\log_2\left(1+\frac{P}{n_0 B}\right)=B\log_2\left(1+r_{sn}\right) \quad \text{bps}, \tag{2}$$

where *P* is the average transmitted power and N_0 is the power-spectral density of the additive noise, and r_{sn} is the receive SNR. The significance of the channel capacity is as follows: If the information rate *R* from the source is less than *C*, then it is theoretically possible to achieve reliable transmission through the channel by appropriate coding. On the other hand if $R>C$, reliable transmission is not possible.

When the channel has *m* transmitting antennas and 1 receiving antenna (MISO), when the users transmitting at equal power over the channel, the channel capacity is given by

$$C_{m1} = B\log_2\left(1+\frac{r_{sn}}{m}\sum_{i=1}^{m}\left|h_i\right|^2\right) \quad \text{bps}, \tag{3}$$

where h_i is the channel complex gain of the *i*-th transmitting antenna to receiving antenna. While the channel has 1 transmitting antennas and *n* receiving antennas (SIMO), the channel capacity is given by

$$C_{1n} = B\log_2\left(1+r_{sn}\sum_{i=1}^{n}\left|h_i\right|^2\right) \quad \text{bps}, \tag{4}$$

where h_i is the channel complex gain of transmitting antenna to the *i*-th receiving antenna. For a MIMO channel with *m* transmitting antennas and *n* receiving antennas, when the users transmitting at equal power over the channel and the users are uncorrelated. Then, the channel capacity is given by

$$C_{mn} = B\log_2\left[\det\left(\boldsymbol{I}_n + \frac{r_{sn}}{m}\boldsymbol{HH}^H\right)\right] \quad \text{bps}, \tag{5}$$

where $\boldsymbol{I}$ is an $n\times n$ identity matrix, $\boldsymbol{H}$ is the $n\times m$ channel matrix, $\boldsymbol{H}^H$ is transpose conjugate. When m>>1 and n>>1, and the bandwidth is normalized, then, the channel capacity can be simplified as

$$C_{mn} \approx \min(m,n)\log_2(1+r_{sn}) \quad \frac{\text{bps}}{\text{Hz}}. \tag{6}$$

As a result, when the SNR of the receiving antenna is certain, compared to the capacity of a SISO channel, the capacity of a MISO channel is slightly improved when the channel has a gain of $h_i\approx1$, the channel capacity of a SIMO system will be improved logarithmically as the number of receiving antennas increases, while for the MIMO channel, its capacity can be linearly improved as the minimum number of receiving and transmitting antennas increases, as shown in Fig. 4. In the simulation, the receiving SNR is set as 20 dB, and the channel gain is set as h_i=1.

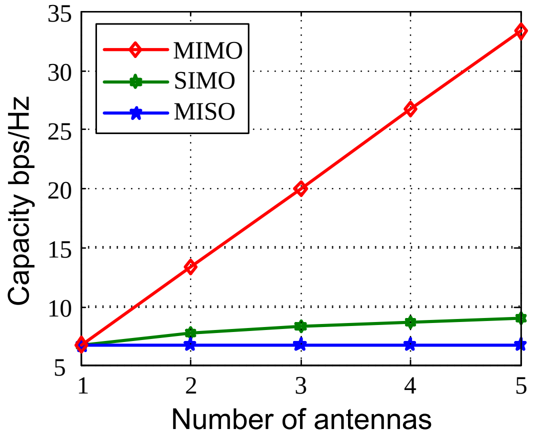

Fig. 4. Channel capacity of SISO, SIMO and MIMO systems

Fig. 5 shows the simulation results of the channel capacity with different configurations when the receiving SNR changes. As can be seen, the capacity will be improved when the SNR increases. For the SIMO systems, the capacity will be increased by 1 bps/Hz when the number of the receiving antennas increases twice, as the results of 1×2 and 1×4 channels shown in the figure. While for the MIMO system, when the minimum number of receiving and transmitting antennas increases twice, the channel capacity will be also increased two times, as the results of 2×2 and 4×4 channels shown in the figure.

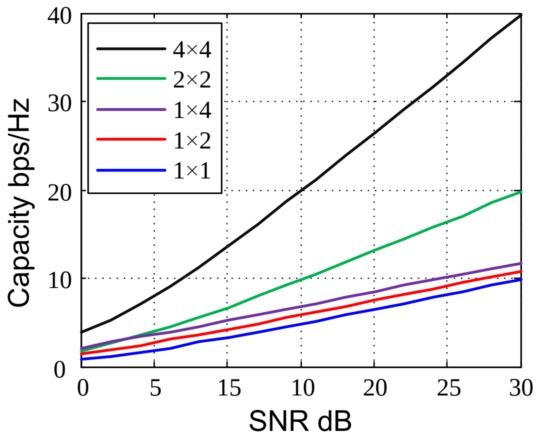

Fig. 5. Channel capacity with different configurations when the receiving SNR changes

Therefore, MIMO technology can be used to efficiently improve the channel capacity of the communication system. Note that, this improvement of capacity is achieved by increasing the complexity of signal processing.

4 Symbol error probability

In digital communication, probability that an error occurs in transmission of a symbol is called symbol error probability, and it denoted by P_e. Another type of error probability is the bit error probability. This error probability is denoted by P_b and is the error probability in transmission of a single bit. For high order digital modulation (M>2), we can bound the bit error probability by noting that a symbol error occurs when at least one bit is in error, and the event of a symbol error is the union of the events of the errors in the $k=\log_2 M$ bits representing that symbol, the relationship between the two probabilities can be written as

$$P_b \le P_e \le kP_b \quad \text{or} \quad \frac{P_e}{\log_2 M} \le P_b \le P_e . \tag{7}$$

The error probability is determined by the SNR of the received signal, the digital modulation format and the detection method. For traditional binary amplitude shift keying (2ASK) signal with non-coherent detection, binary frequency shift keying (2FSK) signal with non-coherent detection, binary phase shift keying (2PSK) with coherent detection systems, when the channel is AWGN channel, the symbol error probability equals bit error probability, and it can be expressed as

$$P_{eASK-nonc} = \frac{1}{2}\mathrm{e}^{-\frac{r_{sn}}{4}} + \frac{1}{4}\mathrm{erfc}\sqrt{\frac{r_{sn}}{4}} , \tag{8}$$

$$P_{eFSK-nonc} = \frac{1}{2}\mathrm{e}^{-\frac{r_{sn}}{2}} , \tag{9}$$

$$P_{ePSK-coh} = \frac{1}{2}\mathrm{erfc}\sqrt{r_{sn}} . \tag{10}$$

For modern advanced digital modulation techniques, multi-level symbol will be directly modulated to the RF carrier. For the multiple-FSK (MFSK) signal and coherent detection, multiple-PSK (MPSK) signal and coherent detection, and arbitrary M-ary square quadrature amplitude modulation (MQAM) signal with coherent detection, the symbol error probability can be respectively expressed as **Ошибка! Источник ссылки не найден.**

$$P_{eMFSK} = \left(\frac{M-1}{2}\right)\mathrm{erfc}\left(\sqrt{\frac{r_{sn}}{2}}\right), \tag{11}$$

$$P_{eMPSK} = \mathrm{erfc}\left(\sqrt{r_{sn}} \cdot \sin\frac{\pi}{M}\right), \tag{12}$$

$$P_{eMQAM} = \frac{N}{2}\mathrm{erfc}\left(\sqrt{\frac{3r_{sn}}{2(M-1)}}\right). \tag{13}$$

Where N means that, in the constellation of a square MQAM signal, each point has N nearest neighbors, therefore, when M=4, N=2, when M=8, N=3 and when M≥16, N=4, as shown in Fig. 3.6.

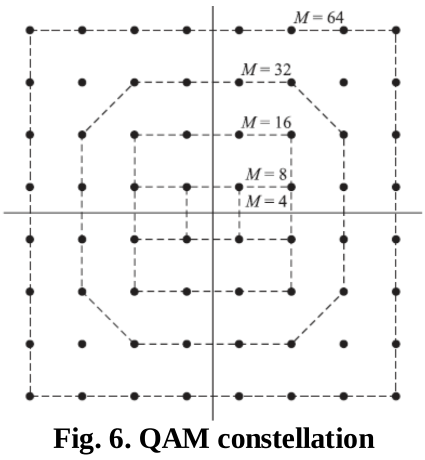

Fig. 6. QAM constellation

Note that here in high order digital modulation, r_{sn} means the SNR per symbol, while in binary modulation, r_{sn} means the SNR per bit, the relationship between them can be written as

$$r_{sn} \text{ per symbol} = \log_2 M \cdot r_{sn} \text{ per bit} . \tag{14}$$

Fig. 7(a) shows the simulated error probability for a 2×2 MIMO communication system, when the SNR changes from 0 to 30 dB. As can be seen, the ERROR PROBABILITY performance will be improved when the receiving SNR is increased. Furthermore, the 2PSK with coherent detection method has a better error probability compared with the other modulation and detection methods. For example, to obtain a P_e less than 10^{-6}, the receiving SNR of 2ASK and non-coherent detection system should be larger than 17 dB, the receiving SNR of 2FSK and non-coherent detection system should be larger than 14 dB, while the receiving SNR of 2PSK and coherent detection system should be larger than 11 dB. Therefore, the SNR requirement can be relaxed when the 2PSK and coherent detection system is utilized. Fig. 3.7(b) shows the experimental and analytic results of the P_e performance when the SNR changes from 0 to 100 (0 to 20 dB). In the simulation, the 2PSK signal is detected using non-coherent method. The analytic results agree well with the experimental results. When the receiving SNR increases, the P_e performance will be improved, and the 2PSK signal has a better error probability compared with the 2ASK and 2FSK signals.

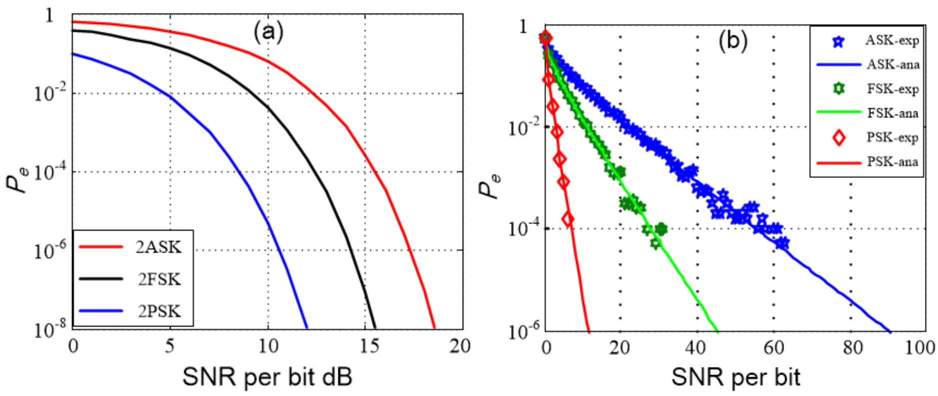

Fig. 7. (a) Error probability for different modulation and detection methods when SNR changes, (b) experimental and analytic results of the P_e when SNR changes

Figure 8 shows the simulated symbol error probability of the advanced digital modulation methods. As can be seen, to increase the channel capacity (i.e. the modulation order M increases), the receiving SNR should be improved to guarantee the P_e performance. For high order modulation (e.g. M=16), MFSK signal has a better P_e compared with the MPSK and MQAM signals, and the P_e of MPSK signal is mostly sensitive and it seriously decreased when the modulation order increased.

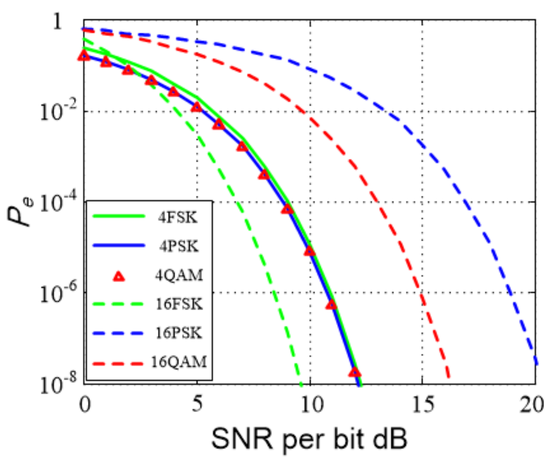

Fig. 8. Error probability of high order modulations 5 MIMO performance under polarization interference

In recent years, the use of MIMO technology with polarization-orthogonal channels has been intensively investigated **Ошибка! Источник ссылки не найден.-Ошибка! Источник ссылки не найден.**. However, the resulting bandwidth limitations due to the final isolation by polarization have not been sufficiently studied. In works **Ошибка! Источник ссылки не найден.-Ошибка! Источник ссылки не найден.** attention is paid to the polarization decoupling, however, only if there is a 2x2 configuration using the MIMO. Studies of the possibility of using an increase in the number of antennas of MIMO systems with polarization-orthogonal antennas have not been sufficiently conducted.

5.1 Signal to noise and interference ratio

An important characteristic of the radio wave is its purity of polarization. For a radio wave transmitted with a given polarization, the ratio of the power received with the expected polarization to the power received with the orthogonal polarization is called cross-polarization discrimination (XPD), which is given by

$$XPD=10\left(d_{xp}\right)=10\log\frac{P}{P_{+}}, \tag{15}$$

where P_+ is the power of the orthogonal interference component caused by the XPD. When the XPD of the receiving antenna is considered, the receiving SNR of the signal should be replaced by the signal to noise and interference ratio (SNIR). The SNIR can be expressed as

$$r_{sni}=\frac{P}{n_0 B+P_{+}}=\frac{1}{\frac{1}{r_{sn}}+\frac{1}{d_{xp}}}=\frac{r_{sn}d_{xp}}{r_{sn}+d_{xp}}. \tag{16}$$

Fig.9 shows the relationship between the SNIR and the XPD when the SNR is constant (10, 20 and 30 dB). As can be seen, due to the existing of the XPD, the performance of the system will be deteriorated, and the SNIR will be less than the receiving SNR. When the XPD increases, the SNIR will be firstly increased and then keeps unchanged after approaching the SNR value. Fig. also shows that, if the antenna has a large SNR, then a high XPD should be provided to guarantee the receiving SNR. For example, when the SNR is 10 dB, the performance can be preserved when the XPD is 20 dB, however, when the SNR is larger than 20 dB, to guarantee the performance, the XPD need to be larger than 30 dB.

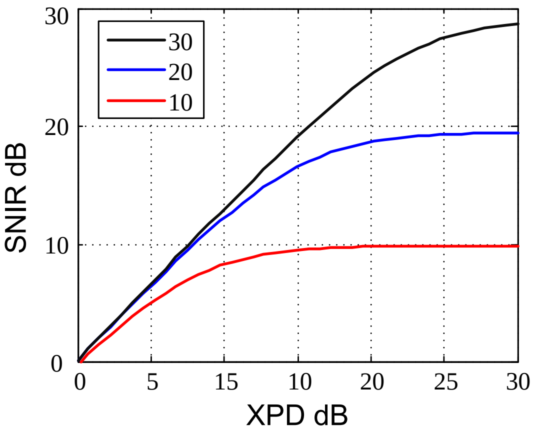

Fig. 9. Relationship between XPD and SNIR

5.2 Channel capacity

When the finite XPD is considered, the capacities for SISO, MISO, SIMO and MIMO systems can respectively expressed as

$$C_s=\log_2\left(1+r_{sni}\right)\ \frac{\text{bps}}{\text{Hz}}, \tag{17}$$

$$C_{m1}=\log_2\left(1+\frac{r_{sni}}{m}\sum_{i=1}^{m}\left|h_i\right|^2\right)\ \frac{\text{bps}}{\text{Hz}}, \tag{18}$$

$$C_{1n} = \log_2\left(1 + r_{sni}\sum_{i=1}^{n}|h_i|^2\right) \quad \frac{\text{bps}}{\text{Hz}}, \tag{19}$$

$$C_{mn} \approx \min(m,n)\log_2(1 + r_{sni}) \quad \frac{\text{bps}}{\text{Hz}}. \tag{20}$$

When the SNIR of the receiving antenna is certain, compared to the capacity of a SISO channel, the capacity of a MISO channel is slightly improved when the channel has a gain of $h_i \approx 1$, the channel capacity of a SIMO system will be improved logarithmically as the number of receiving antennas increases, while for the MIMO channel, its capacity can be linearly improved as the minimum number of receiving and transmitting antennas increases, as shown in Fig. 3.10. In the simulation, the receiving SNIR is set as 20 dB, and the channel gain is set as h_i=1. As the SNIR is comprehensively determined by the SNR and the XPD of the antenna, we also compared the two situations where the SNR equals 20 dB while the XPD equals 20 and 30 dB, respectively. As can be seen, when the XPD decreases, the SNIR will be deteriorated, as consequence, the capacity will be decreased.

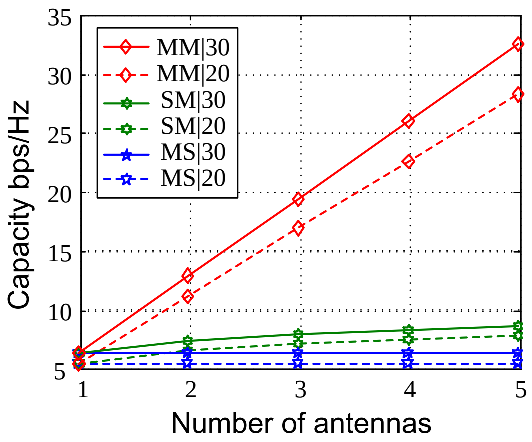

Fig. 10. Channel capacity of SISO, SIMO and MIMO systems

Fig. 11 shows the simulation results of the channel capacity with different configurations when the receiving SNIR changes. As can be seen, the capacity will be improved when the SNIR increases. For the SIMO systems, the capacity will be increased by 1 bps/Hz when the number of the receiving antennas increases twice, as the results of 1×2 and 1×4 channels shown in the figure. While for the MIMO system, when the minimum number of receiving and transmitting antennas increases twice, the channel capacity will be also increased two times, as the results of 2×2 and 4×4 channels shown in the figure.

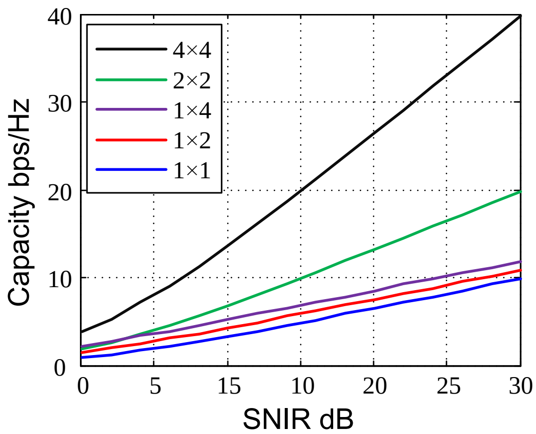

Fig. 11. Channel capacity with different configurations when SNIR changes

Fig. 12 shows the capacity of 1×2 and 2×2 channels when the XPD changes while the SNR keeps constant (20 and 30 dB). As can be seen, when the XPD increases, the capacity is firstly increased and then keeps constant. This is caused by the relationship between the XPD and the SNIR, as shown in Fig. 3.9. Furthermore, we compare the two results of the 2×2 or 1×2 channels, it can be seen that, when the SNR is larger, to obtain maximum capacity, a larger XPD should be provided, which is consistent with the analysis results in Fig 3.9.

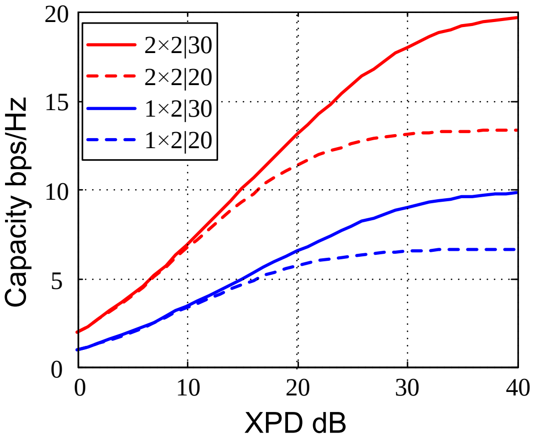

Fig. 12. Channel capacity with different configurations when the XPD changes

5.3 Symbol error probability

When the finite XPD is considered, the symbol error probability is determined by the SNIR of the received signal, the digital modulation format and the detection method. For binary amplitude shift keying (2ASK) signal with non-coherent detection, binary frequency shift keying (2FSK) signal with non-coherent detection, binary phase shift keying (2PSK) with coherent detection, and 4-QAM signal with coherent detection systems, when the channel is AWGN channel, the error probability of the recovered digital signal can be expressed as

$$P_{eASK-nonc} = \frac{1}{2} e^{-\frac{r_{sni}}{4}} + \frac{1}{4} \operatorname{erfc} \sqrt{\frac{r_{sni}}{4}}, \tag{21}$$

$$P_{eFSK-nonc} = \frac{1}{2} e^{-\frac{r_{sni}}{2}}, \tag{22}$$

$$P_{ePSK-coh} = \frac{1}{2} \operatorname{erfc} \sqrt{r_{sni}}. \tag{23}$$

For modern advanced digital modulation techniques, i.e. MFSK, MPSK, and MQAM signals combined with coherent detections, the error probability can be respectively expressed a

$$P_{eMFSK} = \left(\frac{M-1}{2} \right) \operatorname{erfc} \left(\sqrt{\frac{r_{sni}}{2}} \right), \tag{24}$$

$$P_{eMPSK} = \operatorname{erfc} \left(\sqrt{r_{sni}} \cdot \sin \frac{\pi}{M} \right), \tag{25}$$

$$P_{eMQAM} = \frac{N}{2} \operatorname{erfc} \left(\sqrt{\frac{3 r_{sni}}{2(M-1)}} \right), \quad N = \begin{cases} 2, M = 4 \\ 3, M = 8 \\ 4, M \geq 16 \end{cases}. \tag{26}$$

Fig. 13(a) shows the error probability of a 2×2 MIMO channel with different modulation and detection methods when the XPD changes and the SNR keeps constant as 10 dB. While Fig. 13(b) shows the error probability changes along with the XPD when the SNR equals 15 dB. As can be seen, compared to the results shown in Fig. 6, the error probability is deteriorated when the finite XPD is considered. Furthermore, the 2PSK modulation combined with coherent detection has a better P_e performance compared with the other methods. To guarantee a given P_e level, when the receiving SNR improved, the requirement of the XPD for the antenna can be relaxed. For example, in the MIMO system with 2PSK modulation and coherent detection, to keep the P_e less than 10^{-5}, the XPD should be larger than 20 dB when the SNR equals 10 dB, as shown in Fig.13(a), however, when the SNR improved to 15 dB, the same P_e performance can be obtained when the XPD larger than 12 dB, as shown in Fig.13(b).

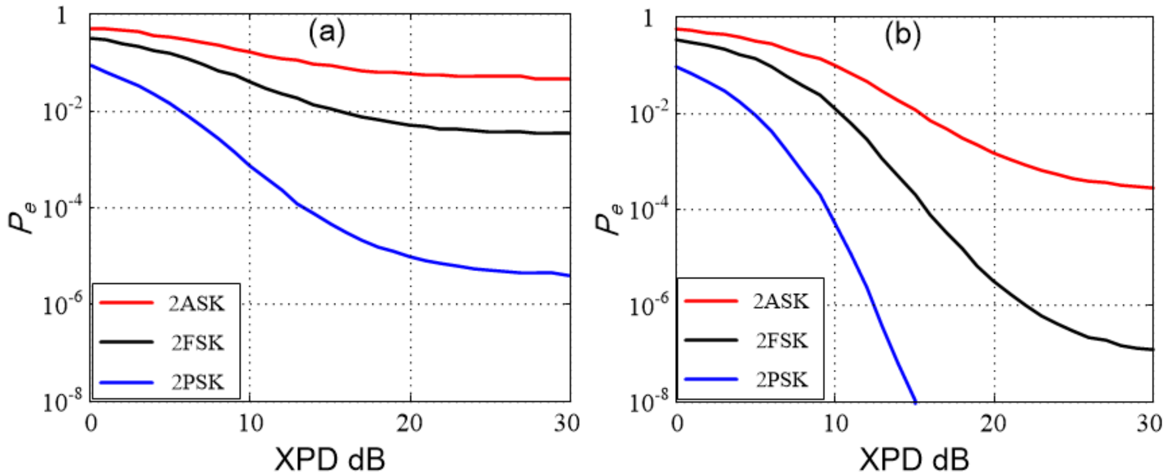

Fig. 13. Error probability for different modulation and detection methods when the XPD changes and the SNR keeps constant (a) SNR=10 dB, (b) SNR=15 dB

Fig.14 shows the error probability of the advanced digital modulations when the SNR per bit equals 20 dB. Symbol error probability of the MPSK signal is mostly sensitive to the modulation order. When the modulation order increases, the requirement of the XPD for the receiving antenna will be enhanced. For example, to keep P_e=10^{-5}, when the modulation order improved from 4 to 16, the XPD of MFSK should be enhanced from 13 to 14 dB, the XPD of MQAM should be enhanced from 13 to 21 dB, while the XPD of MPSK should be increased from 13 to 28 dB.

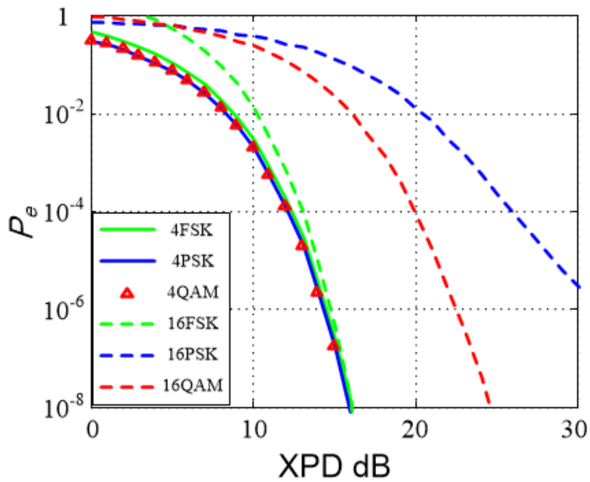

Fig. 14. Error probability of high order modulations when SNR per bit equals 20 dB

Conclusion

Thus, the results of the study of the possibility of adapting the parameters of polarization-orthogonal signals indicate the possibility of improving the quality of communication channels. We investigated applications of polarization technology in MIMO communication systems. MIMO technology with polarization-orthogonal channels can be used to effectively improve the bandwidth of a communication channel when XPD less than the expected SNR. Therefore, designing of communication channels with MIMO dual-polarization antennas need pay some attention to the features of the antennas with minimum XPD.

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