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Impact of Depolarization Phenomena on Polarized MIMO Channel Performances

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Abstract—The performance and capacity of multiple-input multiple-output (MIMO) wireless channels are limited by the spatial fading correlation between antenna elements while at transmitting or receiving side uses only single polarization. In this paper, in order to reduce the antenna correlation, the polarization diversity technique is employed. Although the spatial antenna correlation is degraded for multi-polarization configurations, the cross-polar transmissions appear. This paper highlights the impact of depolarization effect on the MIMO channel capacity for a 4×4 uniform linear antenna array. We assume that the channel is unknown at the transmitter and perfectly known at the receiver so that equal power is distributed to each of the transmit antennas. The numerical results illustrate that for low depolarization and spatial correlation effects, the capacity of single-polarization configuration behaves better than that of multi-polarization configuration.

Index Terms— Multiple-input multiple-output (MIMO) systems, channel capacity, spatial fading correlation, multi-polarized antenna arrays, depolarization effects

I. INTRODUCTION

For next-generation wireless communication systems, multiple antennas at both transmitter and receiver could be engaged to achieve higher capacity and reliability of wireless communication channels, under rich scattering environments, in comparisons with traditional single antennas. Due to the potential of MIMO systems on a limited bandwidth and transmission power, the initial researches demonstrate that the uncorrelated channel capacity can be proportionally increased according to the number of antennas [4],[5].

Unfortunately, in practice, the performances of MIMO communication channel are affected by spatial correlation and channel environments [6]. The spatial correlation depends on the array configuration such as radiation pattern, antenna spacing and array geometry. The channel environments are dependent on the environment characteristics such as number of channel paths, distribution and properties of scatterers, angle spread and cross-polarization discrimination [8]-[11]. Thus, the antenna

arrays at transmitter and receiver should be properly designed to reduce the spatial correlation effects and to improve the communication performances [11].

However, it is possible to reduce this effect traditionally by increasing antenna array spacing [11] but it is not often suitable to apply in some wireless applications which limit the array size. Therefore, for eliminating the spatial correlation effects and remaining high transmission performances, there are essentially two diversity techniques such as pattern or angular and polarization diversity techniques [12], [16]. For pattern diversity technique, the radiation of antennas should be generated in a manner to isolate the radiation pattern. For polarization diversity technique [8]-[10], [12], [13], the antennas are designed to radiate with orthogonal radiation polarizations to create uncorrelated channels for different array elements. In general, there are three diversity techniques employed in MIMO wireless systems. However, there are also other techniques such as multi-mode diversity that exploits the difference of high order modes to obtain low correlated channel [14]. Polarization diversity technique can be used with pattern diversity technique as well in order to benefit the advantages of orthogonal radiation patterns and polarizations [13].

Numerous MIMO channel models have already been proposed in literature. We focus on geometry-based stochastic channel models (GSCM) [15], [16] which calculates the channel response by taking into account the characteristic of wave propagation, both site-specific Tx-Rx environments, and the scattering mechanisms. All parameters are statistically set to closely match the measured channel observation.

In this paper, we define a geometric scattering model based on a three-dimensional double bouncing model that takes into account the antenna configuration [17]-[19]. All antennas are provided as a uniform linear array with isotropic or dipole antennas at transmitter and receiver sides. However, all scatterers are uniformly distributed on scattering areas and take into account the cross-polar discrimination (XPD). This parameter indicates the ratio of the co-polarized average power to the cross-polarized average power. Therefore scattering matrix is used to describe the depolarization of incident wave for each scatterer. Afterward, to simplify the simulated environment configuration, we assume that the angle of arrival and that of departure are uniformly distributed.

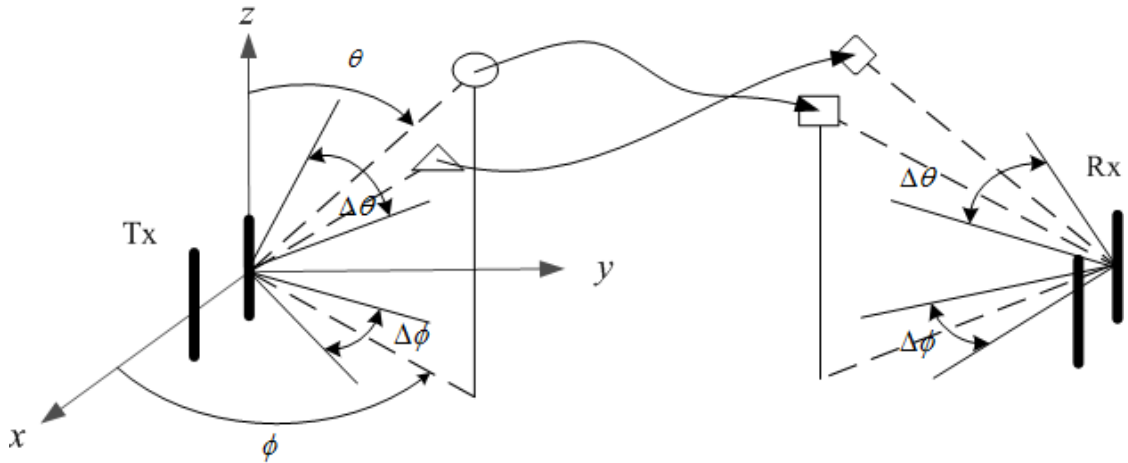


Fig. 1: Geometries of MIMO channel

We present a simulation study of the spatial correlation and moreover the channel capacity of single- and dual-polarized antenna arrays applied to 4x4 MIMO system. All antenna elements are separated by a half wavelength even in the case of the dual polarization configuration. In addition, we examine the cross-polar discrimination effects on MIMO polarized channel capacity for different antenna configurations.

In Section II, we carry out a brief of electromagnetic results regarding different electric dipoles. These results are then used in Section III to create a channel model combining the effect of space separation, polarization antenna gains and depolarization mechanisms. In Section IV, we apply the information theory in order to examine the MIMO channel capacity. Finally, in Section V, we analyze the numerical results of single- and dual-polarization configurations.

II. ANTENNAS

In practice, not only the propagation environment has an important role but the proper implementation of the antennas plays also another dominant role for determining the multiple antenna transmission performances. The receiving signals on one element antenna can correlate to that on another element antenna. Therefore, the systems, which can release the best performances, should properly reconfigure the transmitting or/and receiving antenna element arrays with the channel state information extracting from the propagation channels.

	G_x	G_y	G_z
$G_\theta(\theta, \phi)$	$-\cos \theta \cos \phi$	$-\cos \theta \sin \phi$	$\sin \theta$
$G_\phi(\theta, \phi)$	$\sin \phi$	$-\cos \phi$	0

Table 1: Patterns for different electric dipoles

One array configuration is here interested. Orthogonally oriented antennas can offer orthogonal polarization. That corresponds to a complete separation between individual channels, although the antennas are co-located, and also avoids the transmitting and receiving correlations. Thus, using multiple polarization technique is able to guarantee an effective space and cost. However, the receiving energy can be reduced due to the imbalance of depolarization mechanisms.

Three dipole antennas are concerned in this paper such as x -, y - and z -oriented dipole antennas. Their patterns of electromagnetic radiations can be simplified by neglecting path loss and distance phase because the electromagnetic radiations are homogeneously and identically diffused in the far field case. Their simple expressions of radiation patterns are given by [1]

$$G = G_\theta(\theta, \phi)\vec{\theta} + G_\phi(\theta, \phi)\vec{\phi} \quad (1)$$

where $G_\theta(\theta, \phi)$ and $G_\phi(\theta, \phi)$ are the antenna gains at elevation and azimuth directions. These gains also depends on the propagation direction. Consequently, the radiation patterns of differently oriented dipoles are shown in Table 1.

In this paper, the propagation patterns of their antennas are normalized with the isotropic antenna which is specified as the reference antenna.

III. GEOMETRIC SCATTERING MODELLING

We focus on a useful model, geometric scattering modelling which is based on an assumption that scatterers around the transmitter and receiver organize the AOD and AOA respectively within transmit and receive scattering areas [15],[16]. The scatterers are randomly located with according to a certain probability distribution. In particular, the scatterers are additionally used to represent the depolarization and attenuation mechanism of incident wave. To reduce the computational time, one

propagation path channel occurs when one of transmit and one of receive scatterers are randomly linked. Then the actual channel impulse response is then established by a simplified ray-tracing route.

By using our simulated double bounce geometric scattering model as seen in Fig.1, we employ a uniform linear array at both transmitter and receiver. The height of transmitter and receiver has the same level. Moreover, transmit and receive scatterers are uniformly distributed within an angular region characterized by $|\phi + \pi/2| \leq \Delta\phi/2$ in elevation area and $|\theta + \pi/2| \leq \Delta\theta/2$ in azimuth area at transmitter and $|\phi - \pi/2| \leq \Delta\phi/2$ in elevation area and $|\theta - \pi/2| \leq \Delta\theta/2$ in azimuth area at receiver.

Subsequently transmit and receive scatterers are randomly paired as previously mentioned. From one transmit scatterer to one receive scatterer for determining one propagation path, there is a double depolarization mechanism which is replaced by one scattering matrix. We also assume that the channel coherence bandwidth is larger than the transmitted bandwidth of the signal. This channel is usually called frequency non-selective or flat fading channel.

In case of far field transmission without the line-of-sight channel, the narrowband (flat fading) transmission channel between the antenna p at the transmitter and the antenna m at the receiver can be expressed as [18]

$$h_{mp}(t, f) = \frac{1}{\sqrt{N_S}} \sum_{i=1}^{N_S} a_m^{(i)} a_p^{(i)} \exp\{-j\vec{k}^{(i)} \cdot \vec{v}_{Rx}t - j\vec{k}'^{(i)} \cdot \vec{v}_{Tx}t + \varphi_{mp}\} \begin{bmatrix} G_\theta^m(\theta_i, \phi_i) & G_\phi^m(\theta_i, \phi_i) \end{bmatrix} \mathbf{S}_{mp}^{(i)} \begin{bmatrix} G_\theta^p(\theta_i, \phi_i) \\ G_\phi^p(\theta_i, \phi_i) \end{bmatrix} \quad (2)$$

where N_S is the number of scatterers at the receiver and the transmitter; \vec{v}_{Tx} and \vec{v}_{Rx} are the velocity vector of the transmitter and the receiver; $\vec{k}^{(i)}$ and $\vec{k}'^{(i)}$ are the vectors of wave number in the direction of the i th transmit scatterer and the i th receive scatterer where $|\vec{k}^{(i)}| = |\vec{k}'^{(i)}| = 2\pi/\lambda$; $G_\theta^p(\theta_i, \phi_i)$ and $G_\phi^p(\theta_i, \phi_i)$ are the gain in the direction of $\vec{\theta}$ and $\vec{\phi}$ of the p th transmit antenna in the direction of the i th transmit scatterer. $G_\theta^m(\theta_i, \phi_i)$ and $G_\phi^m(\theta_i, \phi_i)$ are the gain in the direction $\vec{\theta}$ and $\vec{\phi}$ of the m th receive antenna in the direction of the i th receive scatterer; t is time; $a_m^{(i)}$ is the m th element of the local vector of the receive antenna, so that the local receive vector can be expressed as $\mathbf{a}_{Rx}^{(i)} = [1 \ e^{-j\vec{k}^{(i)} \cdot \vec{r}_1} \ \dots \ e^{-j\vec{k}^{(i)} \cdot \vec{r}_{M-1}}]$, $a_p^{(i)}$ is the p th element of the local vector of the transmit antenna, where a local transmit vector is expressed as $\mathbf{a}_{Tx}^{(i)} = [1 \ e^{-j\vec{k}'^{(i)} \cdot \vec{r}_1'} \ \dots \ e^{-j\vec{k}'^{(i)} \cdot \vec{r}_{N-1}'}]$; $\mathbf{S}_{mp}^{(i)}$ are the scatter-

ing matrix for the p th transmit scatterer and the m th receive scatterer and is also defined as

$$\mathbf{S}_{mp}^{(i)} = \begin{bmatrix} S_{\theta\theta}^{(i)} & S_{\phi\theta}^{(i)} \\ S_{\theta\phi}^{(i)} & S_{\phi\phi}^{(i)} \end{bmatrix} \quad (3)$$

The cross polarization discrimination (XPD) is defined as the average power ratio of the co-polarization and the cross-polarization.

$$XPD_\theta = E\left\{|S_{\theta\theta}|^2\right\} / E\left\{|S_{\theta\phi}|^2\right\} \quad (4)$$

$$XPD_\phi = E\left\{|S_{\phi\phi}|^2\right\} / E\left\{|S_{\phi\theta}|^2\right\}$$

In some conditions such as the imbalance of depolarization and the use of different antenna patterns, $XPD_\theta \neq XPD_\phi$. We assume that the sum of the co-polarized power and the cross-polarized power keeps constant. Therefore the scattering matrix can be explained as

$$\mathbf{S}_{mp}^{(i)} = \begin{bmatrix} \sqrt{\frac{XPD_\theta}{1+XPD_\theta}} e^{j\varphi_{\theta\theta}^{(i)}} & \sqrt{\frac{1}{1+XPD_\phi}} e^{j\varphi_{\phi\theta}^{(i)}} \\ \sqrt{\frac{1}{1+XPD_\theta}} e^{j\varphi_{\theta\phi}^{(i)}} & \sqrt{\frac{XPD_\phi}{1+XPD_\phi}} e^{j\varphi_{\phi\phi}^{(i)}} \end{bmatrix} \quad (5)$$

where $\varphi_{\theta\phi}^{(i)}$ denotes phase offset of i th incident wave which changes from $\vec{\theta}$ direction to $\vec{\phi}$ direction superposing on mp channel.

IV. MIMO CAPACITY

In this section, we assume that the noise has a Gaussian distribution. Therefore, the optimal distribution of input signal is Gaussian for maximizing the mutual information (MI). The mutual information is given by [4],[5]

$$\mathcal{I} = \log_2 \det(\mathbf{I}_{N_R} + \mathbf{H}\Phi\mathbf{H}^\dagger(\mathbf{K}_n)^{-1}) \quad (6)$$

where $\Phi = E(\mathbf{x}\mathbf{x}^\dagger)$ is the spatial covariance matrix of the input vector \mathbf{x} under the total transmitting power constraint $tr(\Phi) = P_t$ and \mathbf{K}_n is the covariance matrix of the noise vector \mathbf{n} . $(\cdot)^\dagger$ denotes the conjugate transpose operator, $E(\cdot)$ is the expected value and $tr(\cdot)$ is the trace operator.

When the MIMO channel state information (CSI) is known at the receiver but unknown to the transmitter and \mathbf{n} is complex additive white Gaussian noise (AWGN) vector with zero mean, the covariance is equal to $\mathbf{K}_n = \sigma_n^2 \mathbf{I}_{N_R}$. When CSI is not available at the transmitter, the transmitter splits equally the total power to each transmitting antenna. Then the input covariance matrix is a diagonal matrix $\Phi = P_t/N_T \cdot \mathbf{I}_{N_T}$.

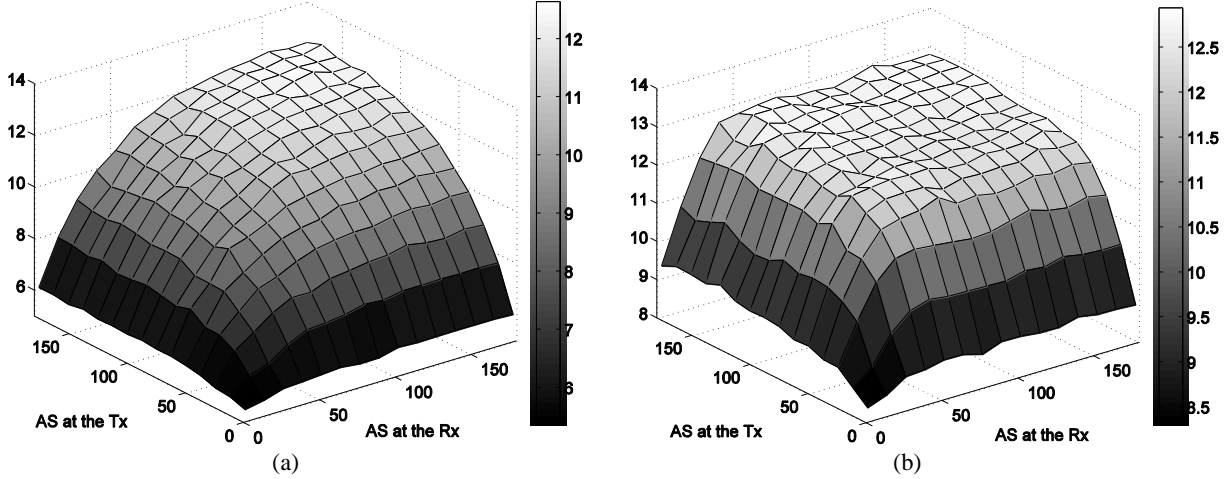


Fig. 2: 4×4 MIMO channel capacity of isotropic antennas: (a) single-polarization system and (b) dual-polarization system

Therefore, the average $MI, E(\mathcal{I})$, called the ergodic channel capacity, with equal-power allocation at transmitter can be written as

$$C_{noCSI} = E(\mathcal{I}) = E_{\mathbf{H}} \left[\log_2 \det \left(\mathbf{I}_{N_R} + \frac{P_t}{N_T \sigma_n^2} \mathbf{H} \mathbf{H}^H \right) \right] \quad (7)$$

By doing an eigenvalue decomposition, (7) can be rewritten as

$$C_{noCSI} = E_{\mathbf{H}} \left[\sum_{i=1}^M \log_2 \left(1 + \frac{P_t}{N_T \sigma_n^2} \lambda_{\mathbf{H},i}^2 \right) \right] \quad (8)$$

where $M = \min(N_T, N_R)$ that corresponds to the rank of channel matrix and $\lambda_{\mathbf{H},i}^2$ is the i th eigenvalue of \mathbf{H} .

V. SIMULATION RESULTS BASED ON GEOMETRIC SCATTERING MODELLING

A. Capacity Versus Angle Spread

The antenna correlation effect is actually one important indicator of transmission performances since lower correlation will tend to produce higher mean channel capacity for single polarization system as seen in Fig.2. Thus employing the polarization and angular diversity techniques are attractive way to improve MIMO systems. The 4×4 MIMO systems employ isotropic antennas for $\lambda/2$ antenna spacing as shown in Fig.1. In order to estimate the channel capacity of different antenna configuration, the simulated environments must be identical. Then the channel capacities are studied in terms of different antenna configurations. The radiation patterns of each antenna are normalized by the radiation pattern of an isotropic antenna.

As mentioned in previous section, the distribution of angles of departure is assumed to have a uniform elevation distribution $|\phi + \pi/2| \leq \Delta\phi/2$ and a uniform arrival azimuth distribution $|\theta + \pi/2| \leq \Delta\theta/2$ and the

distribution of angles of arrival is assumed to have a uniform elevation distribution $|\phi - \pi/2| \leq \Delta\phi/2$ and a uniform arrival azimuth distribution $|\theta - \pi/2| \leq \Delta\theta/2$ where $\Delta\phi = \Delta\theta = AS$ and $XPD_\theta = XPD_\phi = XPD = 0$ dB with 20 scatterers at both transmitter and receiver and 15 dB SNR. The aim of this section is to study the effects of angle spreads and antenna radiation patterns in terms of ergodic capacity.

Fig.2 demonstrates a 4×4 MIMO channel capacity of single- and dual- polarization schemes. For single-polarization case, only azimuth isotropic antennas are employed and for dual-polarization case, we put successively azimuth and elevation isotropic antennas in order with $\lambda/2$ antenna spacing. From Fig.2a, the MIMO channel capacity increases as the angle spread increases at transmitter and receiver for the same polarization antennas. In contrast, the dual polarization achieves better channel capacity due to the lower antenna correlation. It finds that the MIMO channel capacity is significantly dependent on the antenna correlation. The polarization diversity technique can diminish the spatial correlation effect and improve the system performances as shown in Fig.2b.

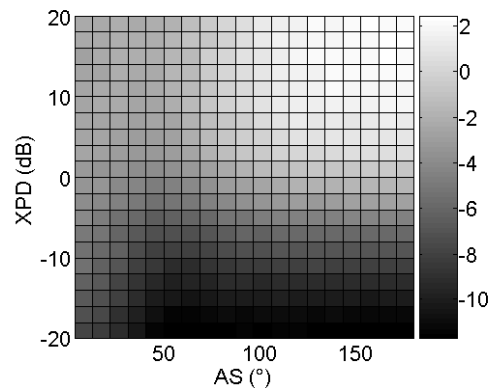


Fig. 3: Difference between the dual-polarized and the single-polarized channel capacity of 4×4 MIMO systems in the functions of XPD and AS

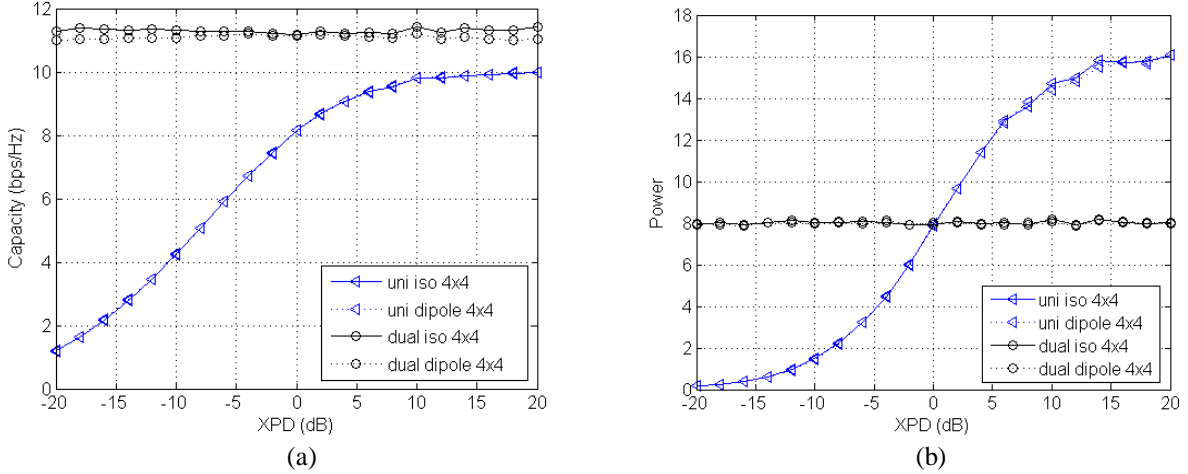


Fig. 4: A 4x4 MIMO configuration of 20° transmit and 180° receive angle spreading: (a) Channel capacity and (b) Subchannel power

B. Capacity Versus Depolarization Effects

If multi-polarized antenna array is employed, the spatial correlation effect can be reduced or eliminated due to low radiation pattern interference. Nevertheless, the cross-polarization discrimination (XPD) becomes the most important parameter because XPD represents the ratio of the co-polarized average received power to the cross-polarized average received power. Then, with high XPD value, the less energy is coupled between the cross-polarized channels. Even if the capacity of multi-polarized antenna arrays can remain high particularly at lower XPD and the higher K-factor values [17], single-polarized antenna array performance can effectively provide better than that of multi-polarized antenna array at higher XPD and lower spatial correlation value.

Fig. 3 explains the difference between dual-polarized and the single-polarized channel capacity of 4x4 MIMO systems ($\Delta C = C_{\text{single-polar}} - C_{\text{dual-polar}}$) in the functions of XPD and AS. We also consider that they have the same angle spreads (AS) at transmitter and receiver. For a high XPD and a sufficiently large angle spread, we note that the MIMO channel capacity of the single-polarized antenna is superior to that of the dual-polarized antenna because a product of the subchannel power is higher.

Fig.4 demonstrates the capacity variation in the functions of the polarization decoupling and also the subchannel power of channel matrix for the isotropic and dipole antennas. We setup a 4x4 MIMO system with 20° transmit and 180° receive angle spreading for having high transmit and low receive spatial correlation.

The channel capacity of the isotropic and dipole antenna configurations in Fig. 4a is slightly different because of the transmission power normalized in respect to the transmission power used for the isotropic antennas. That is a reason why we have the same subchannel

power for the isotropic and dipole antennas in Fig. 4b. Although MIMO subchannel power of single polarization system is superior to that of dual polarization at high XPD, the single-polarized MIMO configuration cannot benefit this high channel power due to the significant transmit correlation as shown in Fig.4a.

The subchannel power of channel matrix can be calculated by employing the Frobenius norm. The numerical results confirm that in the high XPD case, the co-polarized channels do not lose the transmission power to the cross-polarized channels. The average transmission power of single-polarized isotropic antenna arrays is $\|\mathbf{H}\|_F = N_R^x N_T^x = 4 \times 4 = 16$ due to the lack of channel power decoupling where $(\cdot)^x$ represents the dipole orientation, referred to Table 1. In contrast of low XPD, the average transmission power of single-polarized antenna arrays tends to zero, $\|\mathbf{H}\|_F \Rightarrow 0$, because of the loss of co-polarized channel power as shown in Fig.4b. The channel power is directly proportional to the channel capacity as shown in fig.4a and fig4.b. In contrast, the average transmission power of dual-polarized antenna arrays approaches to $\|\mathbf{H}\|_F \approx N_R^x N_T^x + N_R^z N_T^z = 2 \times 2 + 2 \times 2 = 8$ for high XPD, and $\|\mathbf{H}\|_F \approx N_R^x N_T^z + N_R^z N_T^x = 2 \times 2 + 2 \times 2 = 8$ for low XPD as illustrated in Fig.4b where $(\cdot)^x$ and $(\cdot)^z$ denote the dipole type shown in Table 1.

IV. CONCLUSION

The performance of MIMO communication systems is essentially affected by the spatial correlation and channel environments. The spatial correlation depends on the array configurations and the channel characteristics. Therefore to achieve the optimum performances on MIMO systems, the proper selection of array configura-

tion is required. In this paper, we studied the MIMO wireless channel capacity of single- and multi-polarized antenna arrays applied to a uniform linear array with two isotropic antenna configurations.

The simulation results demonstrate that for the non-line-of-sight (NLOS) case, the use of multi-polarization antennas can provide capacity improvement over conventional single-polarization antennas for narrow angle spread. However, when the cross-polarization discrimination is superior than 0dB corresponding to high co-polarized channel power and low cross-polarized channel power, the subchannel power of single-polarization system can be higher by employing the same polarization as that of the co-polarized channel. Thus, with high XPD and low spatial correlation values, single-polarized antenna array performance can effectively provide better capacity than that of multi-polarized antenna array. Finally, the cross-polarization discrimination should be also investigated before employing the polarization diversity technique.

REFERENCES

- [1] Constantine A. Balanis, "Antenna Theory," second Edition, *John Wiley & Sons*, New York, 1997.
- [2] L.M. Correia, Ed., *Wireless Flexible Personalised Communication (COST 259 Final Report)*, Wiley, 2001
- [3] —, *Mobile Broadband Multimedia Networks (COST 273 Final Report)*. Elsevier, 2006.
- [4] E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Trans. Telecommun.*, vol. 10, no. 6, pp. 585–595, Nov.–Dec. 1999.
- [5] G.J. Foschini and M.J. Gans, "On the limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal communication.*, vol. 6, pp. 311-335, Mar. 1998.
- [6] D.-S. Shiu, G. J. Foschini and M.J. Gans, "Fading Correlation and Its Effect on the Capacity of Multielement Antenna Systems," *IEEE Trans. Comm.*, vol. 48, no. 3, pp. 502-513, Mar. 2000.
- [7] M. Ali Khalighi, K. Raoof and G. Jourdain, "Capacity of Wireless Communication Systems Employing Antenna Arrays, a Tutorial Study," *Kluwer Academic Publishers*, vol. 23, no. 23, pp. 321-352, 2002.
- [8] P. Kyritsi et al., "Effect of antenna polarization on the capacity of a multiple element system in an indoor environment," *IEEE J. Sel. Areas Commun.*, vol. 20, pp. 1227–1239, Aug. 2002.
- [9] —, "Correlation analysis based on MIMO channel measurements in an indoor environment," *IEEE J. Sel. Areas Commun.*, vol. 21, pp. 713- 720, June 2003.
- [10] J. Lempinen, J. K. Laiho-Steffens, and A. F. Wacker, "Experimental results of cross polarization discrimination and signal correlation values for a polarization diversity scheme," in *Proc VTC*, pp. 1498 – 1502, May 1997.
- [11] M.A. Jensen and J.W. Wallace, "A Review of Antennas and Propagation for MIMO Wireless Communication," *IEEE Trans. Antennas Propagat.*, vol. 52 No. 11, Nov. 2004.
- [12] M.R. Andrews, P.P. Mitra, and R. deCarvalho, "Tripling the capacity of wireless communication using electromagnetic polarization," *Nature*, vol. 409, pp. 316-318, Jan. 2001.
- [13] T. Svantesson, M.A. Jensen, J.W. Wallace, "Analysis of electromagnetic field polarizations in multi antenna systems," *IEEE on Wireless Commun.*, vol. 3, no.2, pp. 641- 646, Mar. 2004.
- [14] T. Svantesson., "On the potential of multimode antenna diversity," in *Proc. VTC*, Sep. 2000.
- [15] 3GPP - 3GPP2 Spatial Channel Model Ad-hoc Group 3GPP TR 25.996, "Spatial Channel Model for Multiple Input Multiple Output (MIMO) Simulations," v6.1.0 (2003-09).
- [16] C. Oestges, V. Erceg and A.J. Paulraj, "Propagation Modeling of MIMO Multipolarized Fixed Wireless Channels," *IEEE Trans. Veh. Technol.*, vol. 53, no. 3, May 2004.
- [17] N. Prayongpun and K. Raoof, "MIMO Channel Capacities in Presence of Polarization Diversity with and without Line-of-Sight Path," *Journal WSEAS Trans. on Commun.*, vol. 5, no. 9, pp. 1744-1750, Sep. 2006.
- [18] K. Raoof and N. Prayongpun, "Channel Capacity Performance for MIMO polarized diversity systems," *IEEE/WCNM2005*, pp. 1-4, Sep. 23-26, 2005.
- [19] N. Prayongpun and K. Raoof, "Impact of Depolarization Phenomena on Polarized MIMO Channel Performances", *IEEE/WiCOM2007*, Sep. 21-23, 2007.