Reduction of Separation Distance in MIMO Systems Using Polarization Diversity

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Abstract

One of the promising techniques in communication systems is the Multiple Input – Multiple Output (MIMO) systems. The aim of these systems is increasing channel capacity, and the main problem in these systems is the required separation distance between antennas which must be greater than or equal to half wavelength. Satisfying this separation distance is difficult especially at low frequencies. In this paper we study the ability to reduce the total separation distance by using polarization diversity. Each two adjacent antenna are replaced by one dual polarized antenna. The obtained results show that the use of polarization diversity will reduce the required separation distance and the performance of the system will be better than that of classical system (without polarization diversity). This improvement is more useful at the system with greater number of antennas. Increasing the correlation between antennas due to the separation angle will reduce the channel capacity. The results also show that increasing the cross polarization discrimination XPD will increase channel capacity at low level of signal to noise ratio (SNR) and decrease it at high level of it if the attenuation for horizontally polarized signal is the same as that for vertically polarized signal (CPF=0), but if (CPF$\neq$0) then low values of XPD will improve channel capacity especially at high level of SNR. The results also prove that channel capacity inversely proportional with CPF at rural area (XPD$\neq$0), and when XPD=0 (urban area) the channel capacity linearly proportion with CPF at high level of SNR, and inversely proportional with CPF at low level of it.

Keywords: MIMO, Multiple antenna systems, Polarization diversity, Channel capacity.

تقليل المسافة الفاصلة في النظم متعددة الهوائيات باستخدام تنوع الاستقطاب

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المستخلص

تعتبر النظم متعددة الادخل- متعددة الاخراج واحدة من النظم او التقنيات الواعده في مجال الاتصالات وهدفها الاساسي هو زيادة سعة قناة الاتصال وبالتالي جودته. لكن المشكلة الاساسية في هذه النظم هي مسألة المسافات الفاصلة بين الهوائيات

والتي يجب ان تكون اكبر او مساوية لنصف طول الموجة. ان تحقيق مسافات فاصلة بهذا المقدار امر صعب وخاصة عند الترددات الواطئة، لذلك درسنا في هذا البحث امكانية استبدال كل هوائيين متجاورين بهوائي واحد ثنائي الاستقطاب وفي هذه الحالة تقل المسافة الفاصلة المطلوبة لمصفوفة الهوائيات كاملة. وقد اظهرت النتائج ان استخدام تنوع الاستقطاب امر مفيد في تحسين الاداء ومقدار هذا التحسين يكون اكبر في النظم ذات عدد الهوائيات الاكبر. تعمل الزيادة في مقدار الترابط بين الهوائيات نتيجة لزوايا الاستقطاب على تقليل سعةالقناة. كما ان زيادة نسبة تغير الاستقطاب تؤدي الى تحسين سعة القناة عند المستويات القليلة من نسبة الاشارة الى الضوضاء وتسئ السعة عند المستويات العالية منها اذا كان التوهين الذي تعانيه الموجة المستقطبة أفقيا مشابه لما تعانيه الموجة المستقطبة عموديا ,أما إذا كان التوهين الذي تعانيه الموجة المستقطبة أفقيا اكبر من التوهين الذي تعانيه الموجة المستقطبة عموديا فان تقليل نسبة تغير الاستقطاب يؤدي إلى تحسين سعة القناة وخاصة عند المستويات العالية من نسبة الإشارة إلى الضوضاء. وبينت النتائج أن العلاقة بين سعة القناة ونسبة التوهين الأفقي إلى العمودي هي علاقة عكسية في المناطق الريفية ,أما في المناطق المزدحمة فان العلاقة بين سعة القناة ونسبة التوهين الأفقي إلى العمودي هي علاقة طردية عند المستويات العالية من نسبة الإشارة إلى الضوضاء وعكسية عند المستويات القليلة منها.

1. Introduction

The use of antenna array at both ends of a wireless link(MIMO technology) has recently been shown to have the potential to drastically increase spectral efficiency through a technique known as spatial multiplexing [1-5].This leverage often referred to as multiplexing gain permits the opening of multiple spatial pipes between transmitter and receiver within the frequency band of operation for no additional power expenditure leading to a linear(in the number of antennas) increase in capacity [6-9].But these antennas are required a separation distance greater than half wavelength. The cost of increasing spatial dimensions at the base station and the mobile terminal especially at low frequencies has been an impediment to the deployment of spatial diversity in practical systems [9].

Polarization diversity provides an alternative means of increasing the diversity order with little increase in spatial dimensions [10, 11].Recent researchs in multiple antennas systems aims to reduce the spatial dimensions without degrade system performance. One of these solutions is the use of multiple polarized antennas, so this paper aimed to study the effect of many polarization factors on systems performance. These factors include: cross-polarization discrimination (XPD), co-polarized factor (CPF), and polarization separation angles at transmitter and receiver side. The rest of this paper organized as follows: section 2 introduces the channel model and states our assumptions, section 3 provides the simulation results at different conditions, section 4 states the discussion and conclusion, and finally section 5 list the references.

2. Channel model

In linear antenna system shown in Figure(1a), the relation between transmitter and receiver is govern by the following equation[12]:

$$Y = HX + n \tag{1}$$

Where Y is $N_R \times 1$ received vector, X is $N_T \times 1$ transmitted vector, H is $N_R \times N_T$ channel matrix, n is $N_R \times 1$ vector of additive white Gaussian noise, N_T is the number of antennas at transmitter side, and N_R is the number of antennas at receiver side.

The channel capacity in multiple antennas system is given by the following equation [13]:

$$C = Log_2 \left| I_{N_R} + \frac{SNR}{N_T} \times HH^* \right| \quad \text{b/s/Hz} \quad \text{(bit/second/hertz)} \tag{2}$$

Where I_{N_R} is $N_R \times N_R$ identity matrix, SNR is the signal to noise ratio at the receiver side, and H^* is the complex conjugate transpose of the channel matrix H. As we see from the above equation the channel capacity depend on many factors, the most important factor is the channel matrix. The channel matrix also depends on many factors. The most important one is the separation distance, if we refer to the separation distance at the transmitter side by d_t, and refer to the separation distance at the receiver side by d_r, then we need $(N_T - 1)d_t$ separation distance at the transmitter side, and $(N_R - 1)d_r$ separation distance at the receiver side. If we assume that $d_t = d_r = d_{sep}$ and $N_T = N_R = N$, then the separation distance will be $(N - 1)d_{sep}$ at both side (without polarization diversity). We study two cases: 2×2 case and 4×4 case in the present and absent of polarization diversity.

2.1 Case 2×2 :consider the system shown in Figure(1). In the presence of polarization diversity the channel matrix can be separated into three components:

$$H = H_T H_{CH} H_R \tag{3}$$

Where H_T is the transmitter component for the channel matrix, H_R is the receiver component for the channel matrix, and H_{CH} is the channel component for the channel matrix,

$$H_T = \begin{bmatrix} 1-\alpha_T & \alpha_T \\ \alpha_T & 1-\alpha_T \end{bmatrix} \tag{4}$$

Where α_T is the cosine of the minimum angle between the vertically polarized and the horizontally polarized antenna at the transmitter side.

$$H_R = \begin{bmatrix} 1-\alpha_R & \alpha_R \\ \alpha_R & 1-\alpha_R \end{bmatrix} \tag{5}$$

where α_R is the cosine of the minimum angle between the vertically polarized and the horizontally polarized antenna at the receiver side.

$$H_{CH} = \begin{bmatrix} h_{vv} & h_{vh} \\ h_{hv} & h_{hh} \end{bmatrix} \tag{6}$$

where h_{vv} is the relation between the vertically polarized receiver antenna with the vertically polarized transmitter antenna, h_{hh} is the relation between the horizontally polarized receiver antenna with the horizontally polarized transmitter antenna, h_{vh} is the relation between the vertically polarized receiver antenna with the horizontally polarized transmitter antenna, and h_{hv} is the relation between the horizontally polarized receiver antenna with the vertically polarized transmitter antenna.

The polarization of the transmitted signal will change due to the scattering, diffraction, and reflection .The cross polarization discrimination (XPD) is define as the average cross-coupled (vh,hv) power relative to the co-polarized(vv,hh)power[14]. XPD is produced due to the depolarization of the transmitted signal by scattering , diffraction , and reflection in the channel [11].The horizontally polarized signal will attenuated more than the vertically polarized signal and the ratio between these attenuation is co-power factor (CPF),the value of CPF between 0-15dB[15]. For these assumption the H_{CH} matrix will be as follow

$$H_{CH} = \begin{bmatrix} h_{vv} & h_{vh} \\ h_{hv} & h_{hh} \end{bmatrix} = h_{vv} \begin{bmatrix} 1 & xpd \\ xpd & cpf \end{bmatrix} \tag{7}$$

where $xpd = Log^{-1} \frac{-XPD}{10}$

and

$$cpf = Log^{-1} \frac{-CPF}{10}$$

hence

$$H = \begin{bmatrix} 1-\alpha_T & \alpha_T \\ \alpha_T & 1-\alpha_T \end{bmatrix} * h_{vv} \begin{bmatrix} 1 & xpd \\ xpd & cpf \end{bmatrix} * \begin{bmatrix} 1-\alpha_R & \alpha_R \\ \alpha_R & 1-\alpha_R \end{bmatrix} \tag{8}$$

if we assume $\alpha_T = \alpha_R = \alpha$,then

$$H = \begin{bmatrix} 1-\alpha & \alpha \\ \alpha & 1-\alpha \end{bmatrix} * h_{vv} \begin{bmatrix} 1 & xpd \\ xpd & cpf \end{bmatrix} * \begin{bmatrix} 1-\alpha & \alpha \\ \alpha & 1-\alpha \end{bmatrix} \tag{9}$$

This equation represents the channel matrix for **2**$\times$**2** antenna system in the present of polarization. There isn't any need to the separation distance for **2**$\times$**2** system in the present of polarization [d_{sep}=0]. While the separation distance for **2**$\times$**2** system in the absent of polarization is d_{sep} which must be greater than or equal to half wavelength. The channel matrix for **2**$\times$**2** system in the absent of polarization is:

$$H = H_{CH} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \tag{10}$$

where h_{ij} represent the relation between the ith receiver antenna and jth transmitter antenna.

2.2 Case 4$\times$**4:** In the same way that illustrated in section 2.1, we get:

$$H_T = \begin{bmatrix} 1-\alpha_T & \alpha_T & 0 & 0 \\ \alpha_T & 1-\alpha_T & 0 & 0 \\ 0 & 0 & 1-\alpha_T & \alpha_T \\ 0 & 0 & \alpha_T & 1-\alpha_T \end{bmatrix} \tag{11}$$

$$H_R = \begin{bmatrix} 1-\alpha_R & \alpha_R & 0 & 0 \\ \alpha_R & 1-\alpha_R & 0 & 0 \\ 0 & 0 & 1-\alpha_R & \alpha_R \\ 0 & 0 & \alpha_R & 1-\alpha_R \end{bmatrix} \tag{12}$$

$$H_{CH} = \begin{bmatrix} h_{11} & h_{11}*xpd & h_{12} & h_{12}*xpd \\ h_{11}*xpd & h_{11}*cpf & h_{12}*xpd & h_{12} \\ h_{21} & h_{21}*xpd & h_{22} & h_{22}*xpd \\ h_{21}*xpd & h_{21} & h_{22}*xpd & h_{22}*cpf \end{bmatrix} \tag{13}$$

Substitute Eqs.(11-13) in (3)to get:

$$H = \begin{bmatrix} 1-\alpha_T & \alpha_T & 0 & 0 \\ \alpha_T & 1-\alpha_T & 0 & 0 \\ 0 & 0 & 1-\alpha_T & \alpha_T \\ 0 & 0 & \alpha_T & 1-\alpha_T \end{bmatrix} * \begin{bmatrix} h_{11} & h_{11}*xpd & h_{12} & h_{12}*xpd \\ h_{11}*xpd & h_{11}*cpf & h_{12}*xpd & h_{12} \\ h_{21} & h_{21}*xpd & h_{22} & h_{22}*xpd \\ h_{21}*xpd & h_{21} & h_{22}*xpd & h_{22}*cpf \end{bmatrix} * \begin{bmatrix} 1-\alpha_R & \alpha_R & 0 & 0 \\ \alpha_R & 1-\alpha_R & 0 & 0 \\ 0 & 0 & 1-\alpha_R & \alpha_R \\ 0 & 0 & \alpha_R & 1-\alpha_R \end{bmatrix} \tag{14}$$

If $\alpha_T = \alpha_R = \alpha$ then

$$H = \begin{bmatrix} 1-\alpha & \alpha & 0 & 0 \\ \alpha & 1-\alpha & 0 & 0 \\ 0 & 0 & 1-\alpha & \alpha \\ 0 & 0 & \alpha & 1-\alpha \end{bmatrix} * \begin{bmatrix} h_{11} & h_{11}*xpd & h_{12} & h_{12}*xpd \\ h_{11}*xpd & h_{11}*cpf & h_{12}*xpd & h_{12} \\ h_{21} & h_{21}*xpd & h_{22} & h_{22}*xpd \\ h_{21}*xpd & h_{21} & h_{22}*xpd & h_{22}*cpf \end{bmatrix} * \begin{bmatrix} 1-\alpha & \alpha & 0 & 0 \\ \alpha & 1-\alpha & 0 & 0 \\ 0 & 0 & 1-\alpha & \alpha \\ 0 & 0 & \alpha & 1-\alpha \end{bmatrix} \tag{15}$$

This matrix represent the channel matrix for 4$\times$4 MIMO system where each two adjacent antenna are replaced by one dual polarized antenna and the total separation distance will be

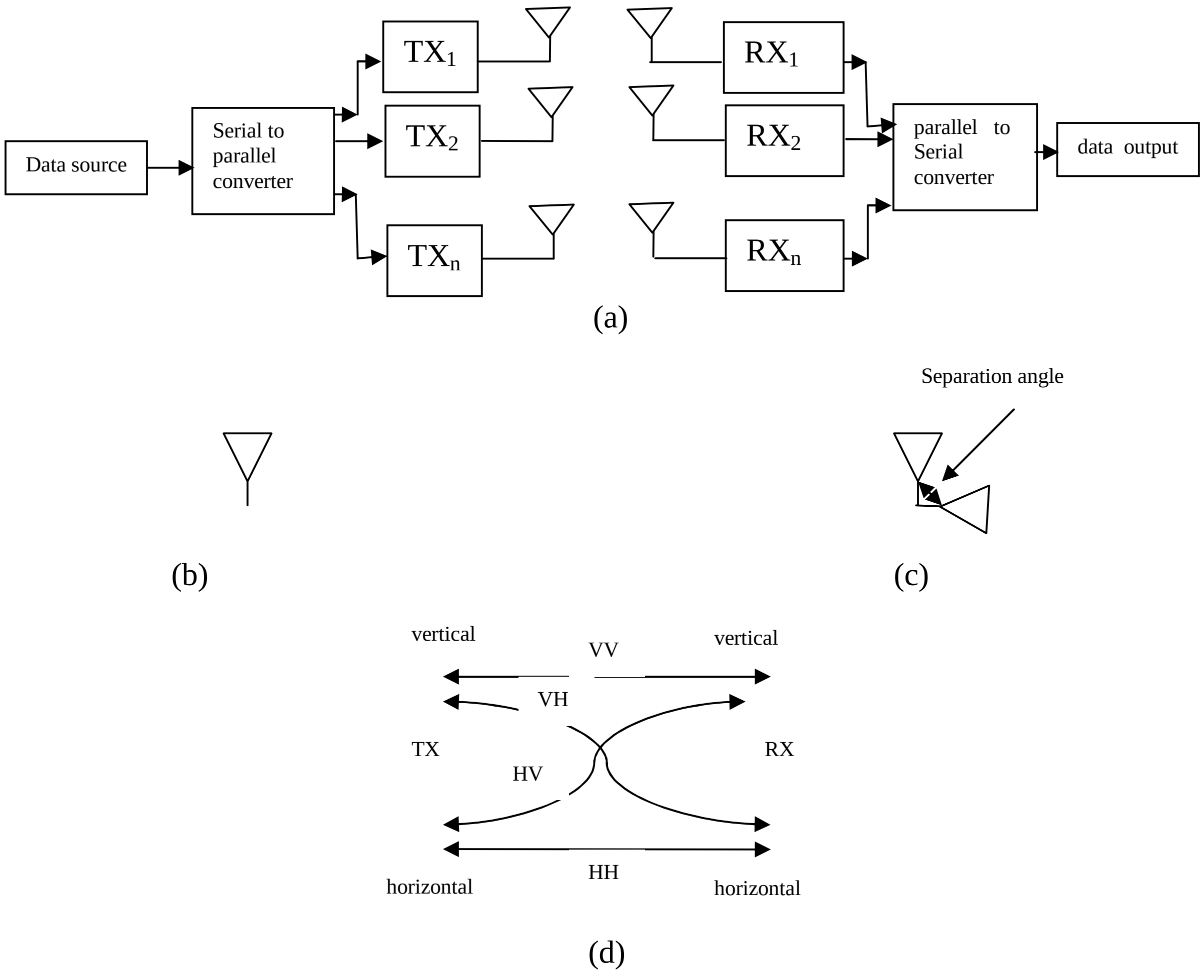
$(\frac{N}{2}-1)d_{sep} = d_{sep}$ instead of $3d_{sep}$ (without polarization diversity). The channel matrix for $\mathbf{4}\times\mathbf{4}$ system in the absent of polarization is:

$$H = H_{CH} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \quad (16)$$

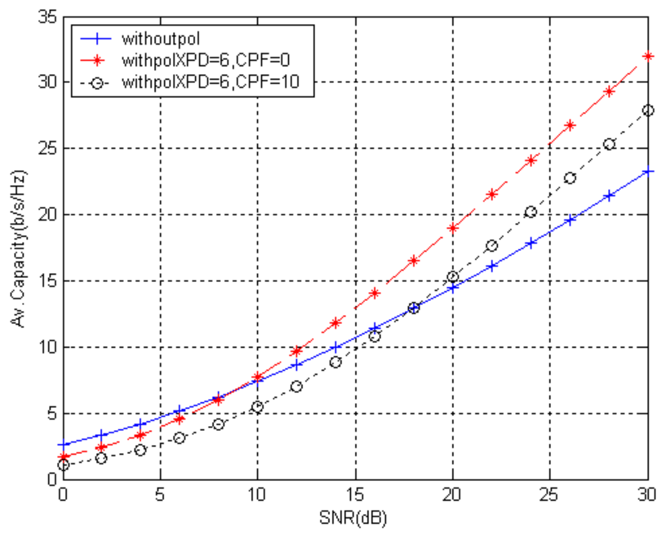
where h_{ij} represent the relation between the i^{th} receiver antenna and j^{th} transmitter antenna.

3. Simulation and results

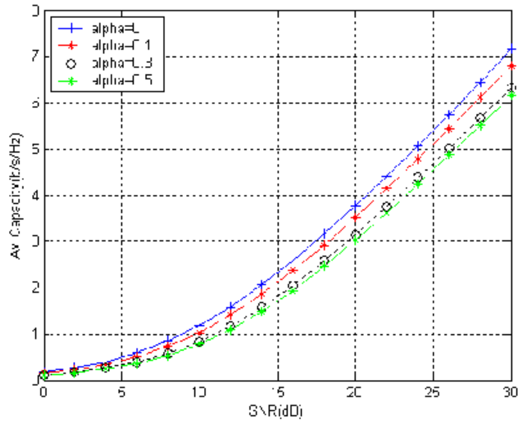
After we derive a useful expressions for the channel matrix for 2×2 and 4×4 cases as a function of polarization factors (XPD,CPF,α).We substitute these expressions in the channel capacity equation (eq.2) for the two cases .We use IEEE802.11F program to generate Rayleigh fading channel matrix coefficients h_{vv}, h_{11}, h_{12}, h_{21}, h_{22} and substitute these coefficients in channel capacity equation. After that we draw the channel capacity at different conditions. The obtained results show that the use of polarization diversity will reduce the separation distance between antennas, and at the same conditions the performance of the systems with polarization better than the systems without polarization as shown in Figure(2)for 4×4 case. If the separation angle θ between antennas become less than 90^{o} (not right angle)the separation correlation coefficient α (α=cosɵ)will increase and the channel capacity decrease as α increase in transmitter and /or receiver side as shown in Figures(3-4).If we increase the cross polarization discrimination (XPD) ,the channel capacity will improve at low level of signal to noise ratio (SNR)and disprove at high level of SNR if the attenuation for horizontally polarized signal is the same as for vertically polarized signal(CPF=0).But if the ($CPF \neq 0$) then reduce the value of XPD will improve the channel capacity for all values of SNR specially at high level of it as shown in Figures(5-10).To study the effect of co-polarization factor (CPF) we make correlation angle θ constant at right angle so that α=0,XPD constant, and vary the CPF. The obtained results show that the channel capacity inversely proportional with CPF at rural area ($XPD \neq 0$) for all values of SNR. While in urban areas (XPD=0)the channel capacity increase as CPF increase at high level of SNR and decrease as CPF increase at low level of SNR for all systems as shown in Figures(11-14).



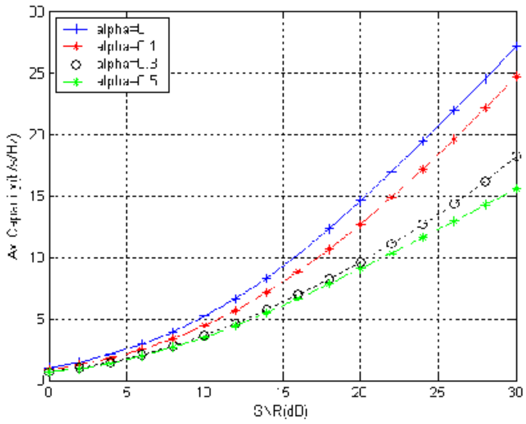
Figure(1).(a) spatial multiplexing system,(b) vertically polarized antenna,(c) dual polarized antenna , (d)schematic plot of the transmission link between transmitter and receiver indicate the components of the polarization matrix .



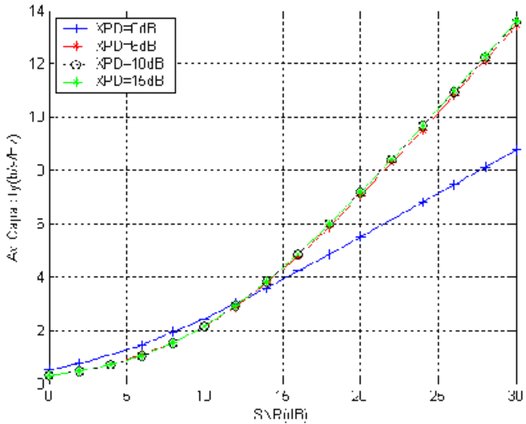
Figure(2).Channel capacity vs SNR for 4×4 system in the present and absent of polarization.



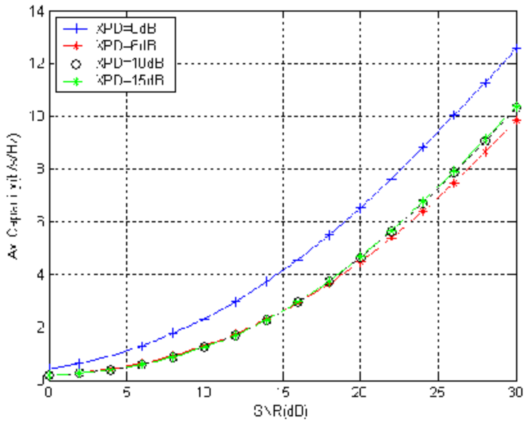
Figure(3).Channel capacity vs SNR for 2×2 system when XPD=6dB,CPF=10dB.



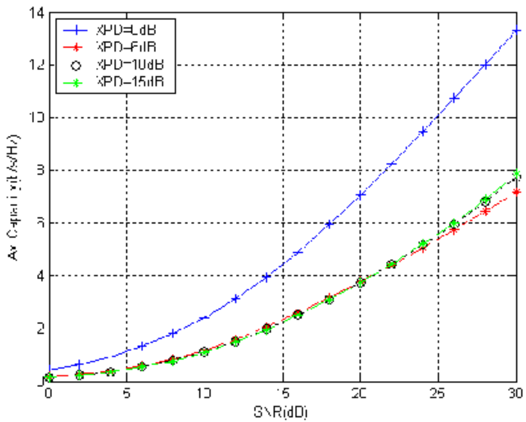
Figure(4).Channel capacity vs SNR for 4×4 system when XPD=6dB,CPF=10dB.



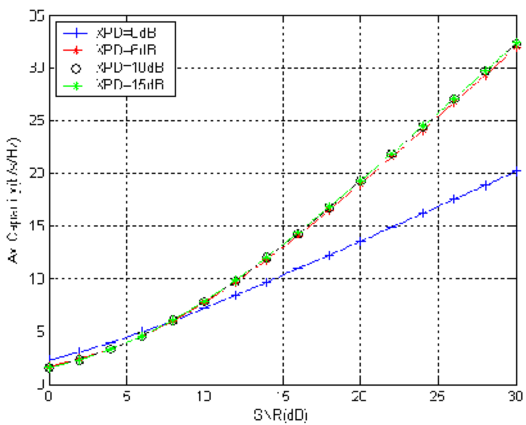
Figure(5).Channel capacity vs SNR for 2×2 system when CPF=0dB,α=0.



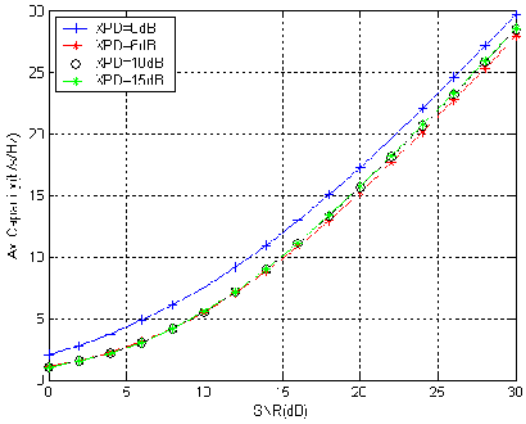
Figure(6).Channel capacity vs SNR for 2×2 system when CPF=5dB,α=0.



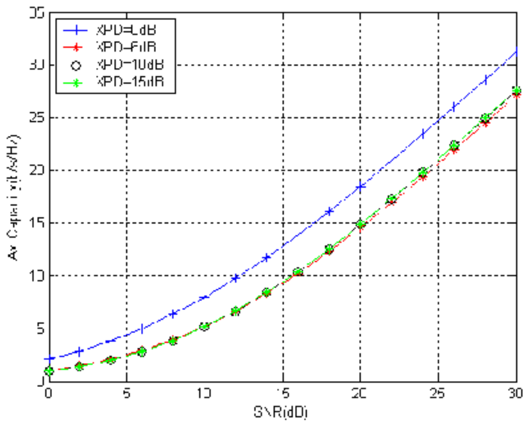
Figure(7).Channel capacity vs SNR for 2×2 system when CPF=10dB,α=0.



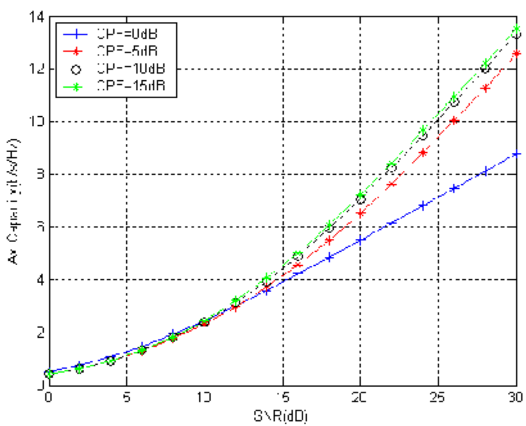
Figure(8).Channel capacity vs SNR for 4×4 system when CPF=0dB,α=0.



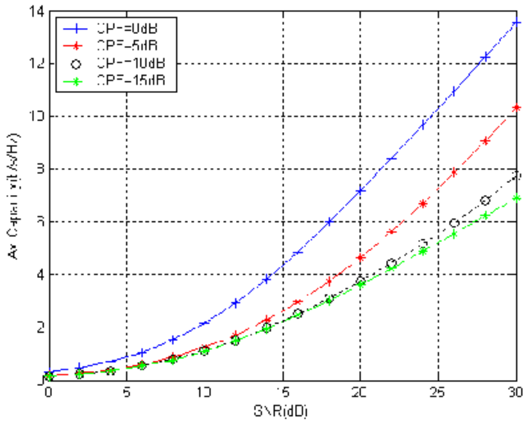
Figure(9).Channel capacity vs SNR for 4×4 system when CPF=5dB,α=0.



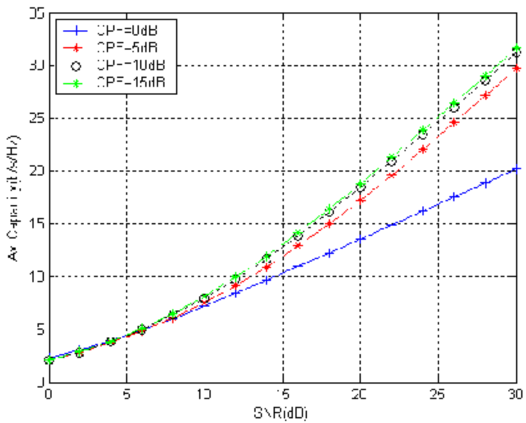
Figure(10).Channel capacity vs SNR for 4×4 system when CPF=10dB,α=0.



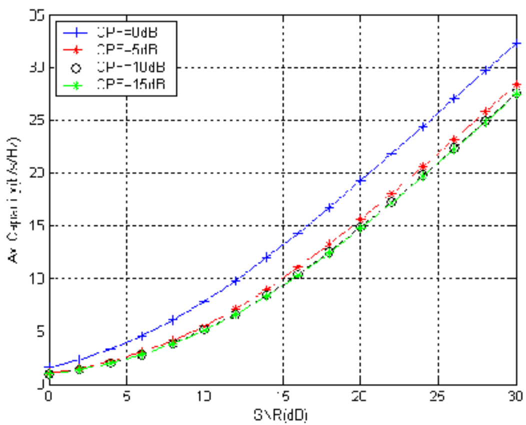
Figure(11).Channel capacity vs SNR for 2×2 system when XPD=0dB,α=0.



Figure(12).Channel capacity vs SNR for 2×2 system when XPD=10dB,α=0.



Figure(13).Channel capacity vs SNR for 4×4 system when XPD=0dB,α=0.



Figure(14).Channel capacity vs SNR for 4×4 system when XPD=10dB,α=0.

4. Discussion and conclusion

One of the main problems in multiple antenna system is the separation distance between antennas. By using dual polarized antenna we can make the total separation distance as $(\frac{N}{2} - 1) d_{sep}$ instead of $(N - 1) d_{sep}$ in non polarized state(without using polarization diversity). Without using dual polarized antenna we cannot decrease the separation distance to less than half wavelength because of the correlation between the antennas. If we can reduce the correlation between antennas, we can reduce the separation distance to small value (lower than half wavelength). We suggest that each antenna in MIMO system replaced by an endfire array of antenna i.e. the MIMO system translate from linear to planar antenna array, but each row of antenna represent one antenna with certain radiation pattern. In this case we may be able to reduce the correlation between the antennas and then reduce the separation distance.

5. References

[1] A.J. Paulraj and T.Kailath, "**Increasing Capacity in Wireless Broadcast Systems using Distributed Transmission/Directional Reception**", U.S. Patent No.5,345 599,1994.

[2] G.J. Foschini, "**Layered Space–Time Architecture for Wireless communication in a Fading Environment when using Multi-element Antennas** ", Bell Laboratories Technical Journal, pp.41-59,Autumn,1996.

[3] I.E.Teletar, "**Capacity of Multi-antenna Gaussian Channels**", European Transaction on Telecommunication, Vol.10,No.6,pp.585-595 , November /December, 1999.

[4] G.G. Raleigh and J.M. Cioffi, "**Spatio-Temporal Coding for Wireless Communications**", IEEE Transaction on Communications,Vol.46,pp.357-366, March, 1998

[5] H. Bolcskei, D. Gesbert , and A.J. Paulraj "**On the Capacity of OFDM-based Spatial Multiplexing Systems**", IEEE Transaction on Communications ,Vol.50 , pp.225-234,February, 2002.

[6] N.Seshadri and J.Winters ,"**Two Signaling Scheme for Improving the Error Performance of Frequency-Division-Duplex (FDD) Transmission Systems using Transmitter Antenna Diversity**", International Journal on Wireless Information Networks,Vol.1, No.1, pp.49-60, January,1994.

[7] J.Guey, M. Fitz, M. Bell, and W. Kuo ,"**Signal Design for Transmitter Diversity Wireless Communication Systems Over Rayleigh Fading Channels** ", IEEE Transaction on Vehicular Technology and Conference,Vol.1, pp.136-140, April/ May,1996.

[8] V.Tarokh , N.Seshadri ,and A.R. Calderbank ,"**Space-Time Code for High Data Rates Wireless Communication:Performance Criterion and Code Construction**", IEEE Transaction on Information Theory,Vol.44,pp.744-765,March,1998.

[9] V.Tarokh, H. Jafarkhani, and A.R. Calderbank, "**Space-Time Code for Orthogonal Design**", IEEE Transaction on Information Theory,Vol.45, pp.1456-1467, July,1999.

[10] R.Visoz and E.Bejjani, "**Matched Filter Bound for Multichannel Diversity over Frequency-Selective Rayleigh-Fading Mobile Channels** ", IEEE Transaction on Vehicular Technology ,Vol.49, No.5, pp.1832-1845, September, 2000.

[11] R.G.Vaughan, "**Polarization Diversity in Mobile Communications**" IEEE Transaction on Vehicular Technology ,Vol.39, No.3, pp.177-186, August,1990.

[12] R.U.Nabar, H. Bolcskei, V.Erceg, D. Gesbert, and A.J. Paulraj ,"**Performance of Multiantenna Signaling Techniques in the Presence of Polarization Diversity**", IEEE Transaction on Signal Processing ,Vol.50, No.10,pp.2553-2562, October, 2002.

[13] L.Dong, H.Choo, R.W.Heath, and H.Ling, "**Simulation of MIMO Channel Capacity with Antenna Polarization Diversity**", IEEE Transaction on Wireless Communications,Vol.4, No.4, pp.1869-1873, July,2005.

[14] T.Neubar and P.C.F.Eggers ,"**Simultaneous Characterization of Polarization Diversity Matrix Components in Pico Cells**", IEEE Transaction on Vehicular Technology and Conference,Vol.3 , pp.1361-1365, Autumn ,1999.

[15] J.V.M.Halim ,H.El-badawy, and H.M.El-Hennawy ,"**Design and Performance of Adaptive Polarized MIMO–MC-SS-CDMA System for Downlink Mobile Communication** ", Proceedings of World Academy of Science, Engineering and Technology,Vol.31, pp.50-557, July, 2008