

Performance Evaluation of MIMO Base Station Antenna Designs

Ramya Bhagavatula[†], Robert W. Heath Jr.[†], and Kevin Linehan[‡]

[†]Department of Electrical and Computer Engineering
The University of Texas at Austin
1 University Station, C0803, Austin, Texas, 78712
{bhagavat, rheath}@ece.utexas.edu

[‡]Andrew Corporation
2601 Telecom Pkwy, Richardson, Texas, 75080
kevin.linehan@andrew.com

Abstract

Cellular standards like the third generation partnership program (3GPP) long term evolution (LTE), ultra-mobile broadband (UMB), high speed downlink packet access (HSDPA) and IEEE 802.16e (WiMAX) support multiple-input multiple-output (MIMO) wireless communication technology. MIMO uses multiple antennas at the transmitter and receiver along with advanced digital signal processing to improve link quality and capacity. Existing base station use antenna arrays to provide transmit and receive diversity; it is not clear if shifting to MIMO will require a change in the base station antenna designs. In this article, we describe some features of an effective MIMO base station antenna. We evaluate the performance of two popular existing base station antenna designs - a vertically polarized planar array and a pair of two dual polarized base station antennas to determine if they will work well as MIMO base station antennas. We show that the dual pol array is more effective as a MIMO base station antenna. We optimize the array with two dual pols for space, cross-pol pattern isolation and port-to-port isolation to obtain the best tradeoff of data rate versus design specifications.

I. INTRODUCTION

The number of cellular service users in the world has increased by over 500% in the past decade [1]. Consumers are now demanding higher data rates to support applications like Internet access, video,

and gaming. Current cellular technologies like the global system for mobile communications (GSM) based general packet radio service (GPRS), enhanced data GSM environment (EDGE) and code division multiple access (CDMA) based CDMA2000 1x and CDMA2000 1xEV (evolution), which consists of CDMA2000 1xEV-DO (data only) and 1xEV-DV (data voice) can only partially meet the high data rate demand. Data rates of up to 100Mbps are possible using multiple-input multiple-output (MIMO) wireless communication technology, now a part of cellular standards like the IEEE 802.16 (WiMAX) [2], high speed packet access (HSPA) release 7 [3], and the third generation partnership project (3GPP) long term evolution (LTE) [4]. Cellular service providers need to make the shift to MIMO to be compliant with the latest standards and to cater to the growing demands for high data rates.

Current cellular standards like use multiple antennas at the base station to provide diversity gain. In contrast, MIMO wireless technology makes use of multiple antennas at both the transmitter (base station) and receiver (mobile terminals) in combination with specially designed algorithms to provide both capacity¹ and diversity gains *using the same bandwidth and power* as single antenna systems [5]. While it is evident that shifting to MIMO will require two or more antennas at the receiver side, it is not clear if this transition will require a change in the existing antenna designs at the base station. In this article, we evaluate the performance of two popular base station antenna designs - a vertically polarized planar array used for adaptive beamforming, and a pair of two dual polarized base station antennas² to determine the effectiveness of these designs for MIMO base stations.

First, we provide a brief background on MIMO communication technology and MIMO antenna design. We list characteristics of ‘good’ MIMO antenna designs, and then compare the performance of the two base station antenna designs mentioned, using a dual-pol array at the receiver side. At the base station, the dual pol array is found to perform better for MIMO transmission strategies than the planar array of vertically polarized elements. We also describe an optimization procedure to determine the values

¹The capacity of a communication system is the maximum data rate that can be achieved with an arbitrarily small error.

²The two ‘dual-pols’ utilize a pair of orthogonal, slant 45° linearly polarized dipole elements in each array.

of antenna parameters like inter-element spacing, cross-pol isolation³ and port-to-port isolation⁴ beyond which the performance of the antenna design for MIMO transmission strategies will not be significantly improved. As antenna designer's time and effort is spent trying to meet design specifications for antenna parameters like cross-pol and port-to-port isolation, it is important to know the optimum values of these parameters that might be far lower than the design specifications.

II. BACKGROUND

In this section, we provide a brief description of MIMO communication technology.

A. MIMO Wireless Technology

In a MIMO system, the use of multiple antennas at the transmitter and receiver introduces spatial degrees of freedom that can increase the capacity and lower bit error rates. It has been shown that the capacity of a MIMO system increases linearly with the minimum number of antennas at the transmit and receive sides, in a scattering-rich environment⁵, as shown in Fig. 1 for a single-user scenario (point to point communication link). Most practical environments, however, always display some degree of spatial correlation that degrades the capacity gains obtained using MIMO [6].

MIMO transmission strategies can be broadly classified into diversity and spatial multiplexing. While diversity aims to lower the probability of error and thereby improve the reliability of the communication link, spatial multiplexing is used to increase the achievable data rates.

- 1) Diversity: Error probability is reduced by sending multiple copies of the signal over each of the transmit antennas. These signals are coherently combined at the receiver to obtain a stronger signal.

³Cross Polarization Isolation (or cross-pol isolation) is defined as the worst case ratio between the peak co-polarized and nominal cross-polarized response, measured over the beamwidth of interest.

⁴Port-to-port isolation is defined as the transmission of power between two of the input ports of the multiport antenna under test.

⁵In scattering-rich environments, the transmitted signal reaches the receiver through several multipath components that have (on an average) low spatial correlation among each other.

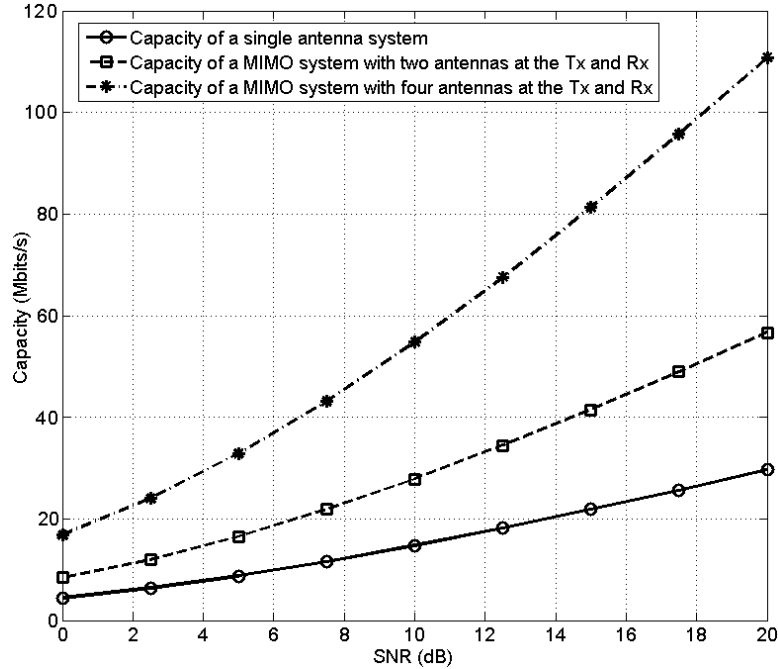


Fig. 1. Increase in the capacity of a MIMO system with the number of antennas at the transmit and receive sides, for a scattering-rich environment (for 5MHz bandwidth). It is seen that the increase is almost linear with the number of antennas.

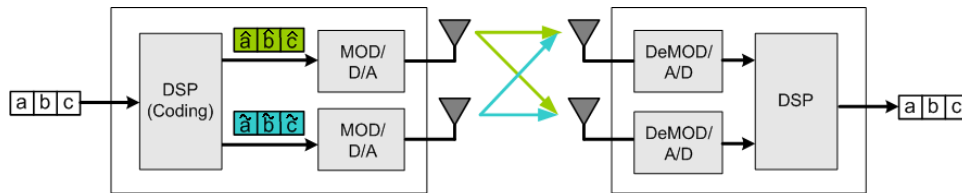


Fig. 2. Illustration of diversity-based transmission for a 2×2 MIMO system.

This is illustrated in Fig. 2, where two separately coded versions of the same signal are transmitted over each of the two transmit antennas.

- 2) Spatial multiplexing: Independent data streams are sent over each of the transmit antennas to increase the data rate of the system. Multiple antennas are used to receive these signals that are then decoded using digital signal processing techniques. This is illustrated in Fig. 3.

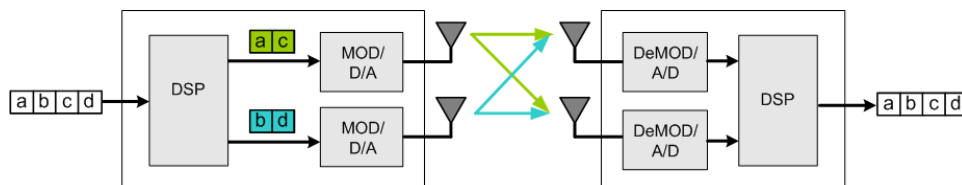


Fig. 3. Illustration of spatial multiplexing for a 2×2 MIMO system.

MIMO transmission strategies can also be classified as open-loop and closed-loop. In open-loop strategies, the transmitter does not have any knowledge of the channel and transmission follows a deterministic pattern that is independent of the channel. Open-loop transmission strategies include spatial multiplexing and diversity schemes like space time block codes, cyclic delay diversity etc. Closed-loop schemes require knowledge of the channel at the transmitter to adapt the transmitted signal to the channel. Precoding is a popular closed-loop MIMO transmission strategy. In this paper, we analyze the performance of the MIMO base station antenna designs using a closed-loop technique known as Grassmannian precoding that is adopted in the IEEE 802.16e standard [7]. More details about this method of precoding can be found in [8].

B. Impact of Antenna Design on MIMO System Performance

Currently, base stations use multiple antennas for reasons of diversity. The diversity gain obtained increases as the spatial correlation between signals reduces. In MIMO, the relationship between spatial correlation and performance is more complex [9]. For example, at the edge of the cell where signal strength is low, it is preferable to use diversity-based single stream transmission strategies that require one of the spatial channels to be significantly stronger than the others. This is possible when the spatial correlation between signals received at the antenna elements is high. In contrast, when the signal strength is high (near the base station), it is beneficial to use spatial multiplexing strategies to increase the capacity. In this situation, spatial correlation among received signals lowers the capacity gains obtained. Thus, spatial correlation has different implications in diversity-based and MIMO systems. This is the primary reason for the difference in the design principles for diversity-based and MIMO antenna arrays.

Spatial correlation might arise due to the antenna arrays employed at the transmitter and receiver (small inter-element spacing, mutual coupling etc.) or due to the channel characteristics [10]. If the wireless propagation environment has sufficient multipath, the channel spatial correlation is generally low. In contrast, when the channel does not have rich multipath or when a strong line of sight exists between the transmitter and receiver, the channel spatial correlation is considerably higher. The impact

of high channel spatial correlation can be lowered using effective MIMO antenna design techniques. For example, by using antenna arrays where the elements have orthogonal polarizations or patterns, the spatial correlation of the signals received at the antenna array can be significantly reduced, even when the channel spatial correlation is high. By spacing antenna elements far apart, or by using elements that have orthogonal radiation patterns or polarizations, it can be ensured that signals received at these antenna elements have undergone independent scattering in the propagation environment and hence, have low correlation. Effective antenna designs can be used to improve MIMO performance by utilizing the following three antenna diversity effects:

- 1) spatial diversity - spacing antenna elements far apart,
- 2) pattern diversity - using antenna elements with orthogonal radiation patterns, and
- 3) polarization diversity - using antenna elements with different (orthogonal) polarizations, example, the HV polarized array, dual pol array etc.

Research has shown that antenna array configurations at the transmitter and receiver significantly affect the performance of a MIMO system [11]. This is illustrated in Fig. 4, where we compare the capacities obtained using four different antenna array configurations consisting of four antenna elements each, with omnidirectional radiation patterns. We consider two uniform linear arrays (ULA) with inter-element spacings of half-wavelength and two wavelengths and two uniform circular arrays (UCA) with radii of half-wavelength and two wavelengths, as shown in Fig. 4(a). We assume that the same antenna array configuration is used at both the transmitter and receiver. For simulation purposes, we assume that the received arrays are centered about the endfire direction with a standard deviation of 20° . The difference in performance due to antenna design is clearly visible from Fig. 4(b). Note that the performance of the antenna arrays used in a MIMO system varies as a function of the propagation environment.

C. MIMO Base Station Antenna Design

Scattering effects might cause a transmitted signal to suffer a (small) change in its polarization. As MIMO takes advantage of multipath, the antenna design at the MIMO front end must be capable of

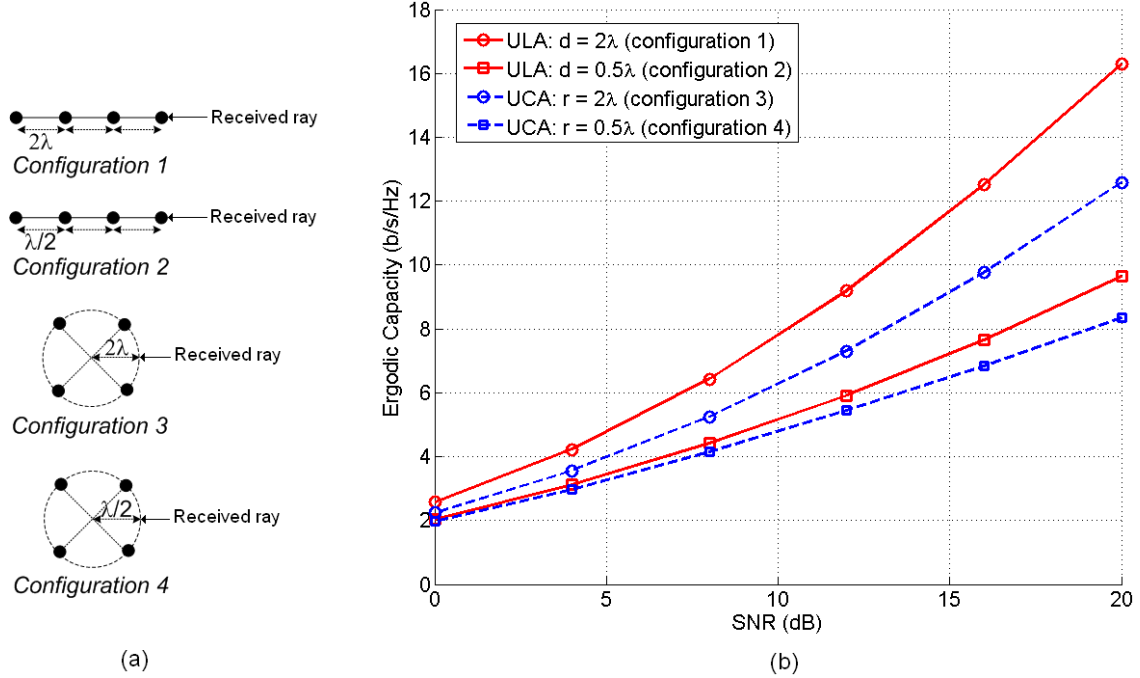


Fig. 4. Variation in the capacities of a MIMO system with varying antenna array configurations shown in the (a).

handling these changes in polarization. Further, mobile terminals might be held or placed at different orientations. MIMO antenna designs at the base station must be able to effectively tolerate random orientation effects and still provide good data rates at the receiver. The prohibitive costs of leasing tower space require that base station antennas do not occupy too much space. Further, knowledge of the optimum values of parameters like cross-pol and port-to-port isolation will enable antenna designers to reduce the time and effort needed to meet (possibly) unnecessarily high specifications of these parameters. To summarize, the requirements of an *effective* MIMO base station antenna design are that it should

- exploit the additional spatial dimension by incorporating combinations of the three antenna diversity effects in the design,
- have a structure such that it can cope with random orientation effects at the receive side,
- be able to cope with slight changes in the polarizations of the received signals (in the uplink case),
- offer a fair balance between tower space occupied and performance obtained (due to the high costs associated with leasing tower space), and,
- present a tradeoff between design specifications and performance obtained (especially for parameters

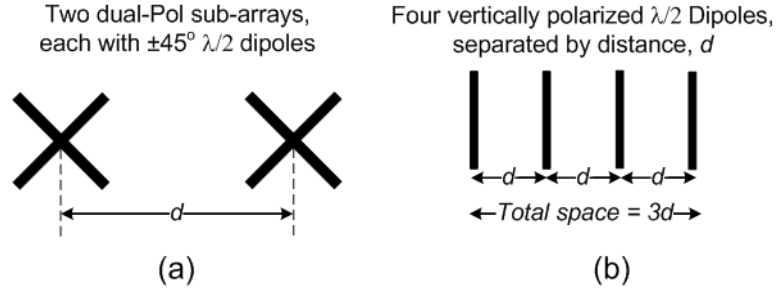


Fig. 5. The horizontal component of antenna arrays analyzed - (a) array with two dual pol sub-arrays, and (b) array with four vertically polarized half-wavelength dipoles. Note that each array has four independent ports.

like cross-pol isolation and port-to-port isolation).

III. ANALYSIS OF BASE STATION ANTENNA DESIGNS FOR MIMO AND SIMULATION SET-UP

In this section, we compare the performance of the following two popular base station antenna designs:

- 1) an array of two dual pols (shown in Fig. 5(a)), and
- 2) an array of four vertically polarized elements (shown in Fig. 5(b)), used commonly for adaptive beamforming at the base station.

Note that the array in Fig. 5(a) is based on polarization and spatial diversities, whereas the one in Fig. 5(b) is based on spatial diversity alone. In this article, we show that the two dual pol array is more *effective* as a MIMO base station antenna design.

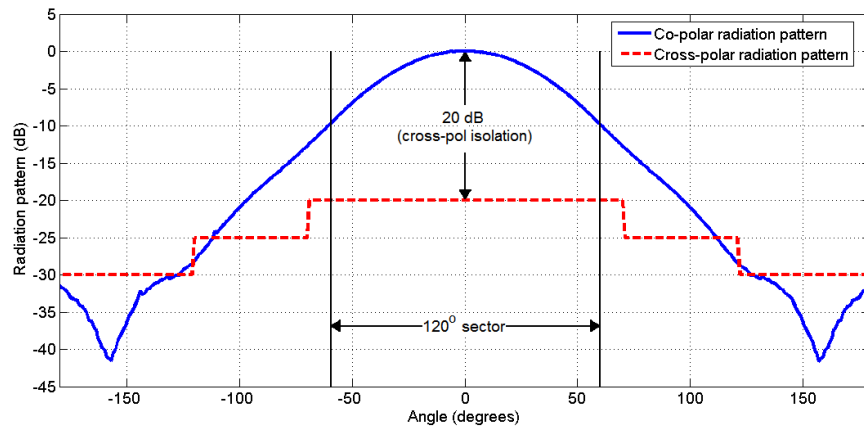


Fig. 6. The radiation gain patterns of 65° half-beamwidth antenna elements used in the antenna arrays in Fig. 5, for a 120° wide cell sector.

For simulation purposes, we assume that the base station is used in a three-sector urban micro-cell defined by the 3GPP spatial channel model (SCM), valid for bandwidths up to $5MHz$ [4]. The signal power at the base station is fixed at $45dBm$. The co-pol and cross-pol patterns for each of the antenna elements considered are illustrated in Fig. 6, for a cross-pol isolation of $20dB$. The heights of the base station (mounted on roof tops) and mobile station are assumed to be $12.5m$ and $1.5m$, respectively. It is assumed that the mobile terminals are equipped with a single dual pol antenna, i.e. we use a 2×4 MIMO system. We assume that the communication links simulated within the single sector are free of inter-user interference. Users are assumed to be located randomly throughout the sector. The data rate of each of the users is evaluated using the 3GPP SCM for the closed-loop MIMO transmission strategy described in this section. The average data rate throughout the sector is then evaluated as the mean of individual user data rates. Note that the 3GPP SCM takes into account random orientations of the mobile terminal.

We use a closed-loop MIMO transmission strategy known as Grassmannian precoding [8] that is a part of the WiMAX standard [7]⁶. In this technique, the receiver feeds back information about a precoding matrix to the transmitter. The precoding matrix is determined using the estimated channel at the receiver, based on a given criterion like minimum mean squared error, maximum capacity etc. The set of all possible precoding matrices is known to both the transmitter and receiver. The transmitter then transmits a ‘precoded’ signal formed by multiplying the original signal with the precoding matrix. In our simulations, we consider a Grassmannian precoding with four bit feedback, where the criteria is to maximize the data rate. Since, the number of receive antennas is fixed at two, we consider fixed two-stream transmission, i.e. the precoding matrix is of size $N_t \times N_s$, where $N_s = N_r = 2$.

The simulation methodology is summarized as follows.

- 1) Generate random locations in the cell for K users where $K \geq 1000$.
- 2) Use the 3GPP SCM to generate R channel realizations, $\mathbf{H}_{(d)}^{(k,r)}$, where $r = 1, \dots, R$, $k = 1, \dots, K$

⁶Note that the methodology described can be extended to any closed-loop MIMO transmission strategy.

and (d) refers to the specific antenna design in question. Include cross-pol patterns in the generation of the realizations, $\mathbf{H}_{(d)}^{(k,r)}$. Port-to-port isolation effects can be included in the scattering matrices on the transmit and receive sides. Generate the effective channel realization including scattering matrices by [12]

$$\mathbf{H}_{(d),\text{eff}}^{(k,r)} = (\mathbf{I}_{N_r} - \mathbf{S}_R)\mathbf{H}_{(d)}^{(k,r)}(\mathbf{I}_{N_t} - \mathbf{S}_T),$$

where \mathbf{I}_{N_r} denotes an identity matrix of size N_r , \mathbf{S}_R and \mathbf{S}_T represent the scattering matrices on the receive and transmit sides, respectively.

- 3) Determine the precoding matrix, $\mathbf{F}_{(d)}^{(k,r)}$ for the R realizations of each of the K users, according to the Grassmannian precoding strategy to maximize capacity [8].
- 4) Evaluate the data rate of each of the K users, $R_{(d)}^{(k)}$, $k = 1, \dots, K$ using

$$R_{(d)}^{(k)} = \mathbb{E} \left\{ \log_2 \left| \mathbf{I}_{N_s} + \frac{\rho}{N_s} \frac{(\mathbf{F}_{(d)}^{(k,r)})^* (\mathbf{H}_{(d),\text{eff}}^{(k,r)})^* \mathbf{H}_{(d),\text{eff}}^{(k,r)} \mathbf{F}_{(d)}^{(k,r)}}{\alpha_{(d)}^{(k)}} \right| \right\}, \quad \text{for } N_s = 2$$

where \mathbb{E} stands for the ergodic mean taken over R channel realizations for user k , ρ is the transmit signal to noise ratio, $|\cdot|$ denotes the determinant, and $(\cdot)^*$ refers to the Hermitian transpose. The normalization factor, $\alpha_{(d)}^{(k)} = \frac{1}{R} \sum_{r=1}^R \|\mathbf{H}_{(d)}^{(k,r)}\|_F^2 \times N_t N_r$ where $\|(\cdot)\|_F$ refers to the Frobenius norm, is used to enforce the unity average power constraint on the channel coefficients, so that the data rate obtained is only a function of the channel quality. Note that we use assumptions like zero inter-user interference for the estimation of data rates. This causes the simulated data rates to be different from the actual data rates that can be obtained in the system. Hence, these data rates are to be used for comparison purposes only.

- 5) For each antenna design, average the data rates across all the K users within the sector to obtain an estimate of the average data rate per user within the micro-cell for an antenna design d . This is given as

$$R_{(d)}^{\text{avg}} = \frac{1}{K} R_{(d)}^{(k)}.$$

Note that the average data rate is in terms of the spectral efficiency, defined as the amount of information (in bits per second or bps) that can be transmitted over a unit bandwidth in a specific communication system. For example, if a system uses $100kHz$ of bandwidth to transmit $150kbps$ of information, the spectral efficiency of the system is $1.5bps/Hz$. The spectral efficiency of a system is used to measure the efficiency of spectrum utilization. A similar simulation methodology is used in [13] to evaluate the capacity (in terms of spectral efficiency) of a single-user for the 3GPP SCM including mutual coupling effects.

IV. RESULTS

The methodology described in Section III is first used to compare the performance of the two base station antenna designs in Fig. 5 for the Grassmannian precoding strategy. We explain the reason why the array design in Fig. 5(a) outperforms the one in Fig. 5(b) both, in terms of the data rate obtained and space requirements. We also optimize the two dual pol array for cross-pol isolation and port-to-port isolation. Note that existing base station antenna designs employing diversity-based array configurations typically have an inter-element spacing $d = 10\lambda$, cross-pol isolation of $20dB$ and port-to-port isolation of $30dB$. For the planar array configuration in Fig. 5(b), this translates to a total space of $3 \times 10\lambda = 30\lambda$.

For $d = 10\lambda$, using the methodology described in Section III, we obtain the average spectral efficiency in the micro-cell for the array with two dual pols to be $6.32bps/Hz$, as compared to $6.14bps/Hz$ obtained using the planar array with four vertically polarized elements. It is evident from these data rates that both the antenna array configurations in Figs. 5(a) and (b) can be used for MIMO, but the dual pol array yields better performance. Note that the data rates are for a unit bandwidth (Hz). For a bandwidth of say, $1MHz$, the difference in the performance of the two antenna designs is about $180kbps$.

A. Optimizing the Two Dual Pol Configuration for Inter-Element Spacing, d

Inter-element spacing in an array configuration can be optimized using the methodology given in the previous section. The results are presented in Fig. 7 for the two configurations in Figs. 5(a) and (b).

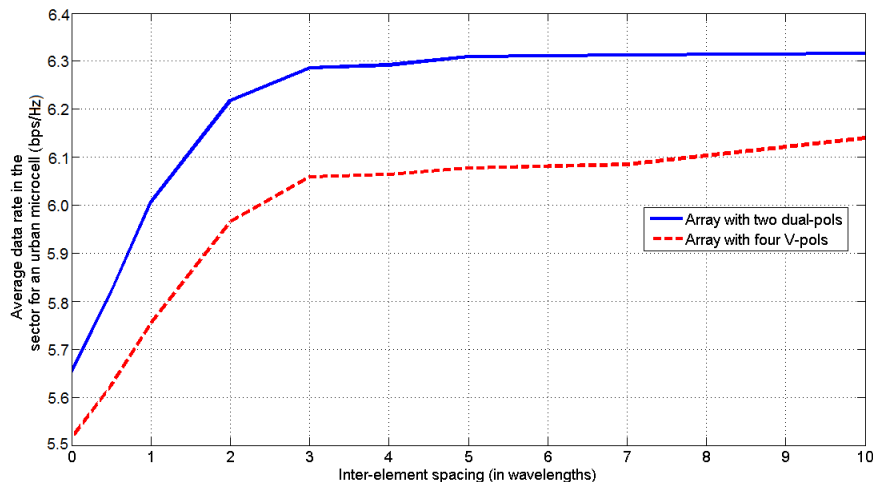


Fig. 7. Average spectral efficiency per user in an urban micro-cell versus inter-element distance d shown in Figs. 5(a) and (b), for bandwidth = $5MHz$.

From Fig. 7, it is seen that the two dual pol array configuration not only has better performance for any inter-element distance, but also occupies less space than the planar array. The two dual pol array reaches within 1% of its final performance at a distance of $d \approx 2\lambda$. The currently available standard quad ports that comprise of two dual pol arrays enclosed in a single radome and separated by an inter-element distance of approximately 1λ will yield a spectral efficiency of $6bps/Hz$ that is within 5% of the value at $d = 10\lambda$. Hence, it will offer a good compromise between minimum tower space occupied and potential MIMO performance benefits.

The planar array configuration requires a distance of $d \approx 3\lambda$ to reach within 1% of its final performance at $d = 10\lambda$. Note that while the total space required in the two dual pol array is only 2λ , the requirement in case of the ULA is $3 \times 3\lambda = 9\lambda$. Further, for the standard inter-element spacing of $\lambda/2$ in the planar array configuration used for beamforming applications, there is a performance loss of about 11% compared to the final saturation value obtained for the dual pol case.

These results are not surprising as the two dual pol array incorporates two of the three antenna diversity effects mentioned in Section II-B (space and polarization diversity) whereas the ULA implements only spatial diversity. The two dual pol array, due to the $\pm 45^\circ$ polarization is more flexible to adapt to random mobile terminal orientations, as compared to the vertically polarized antenna elements. These factors,

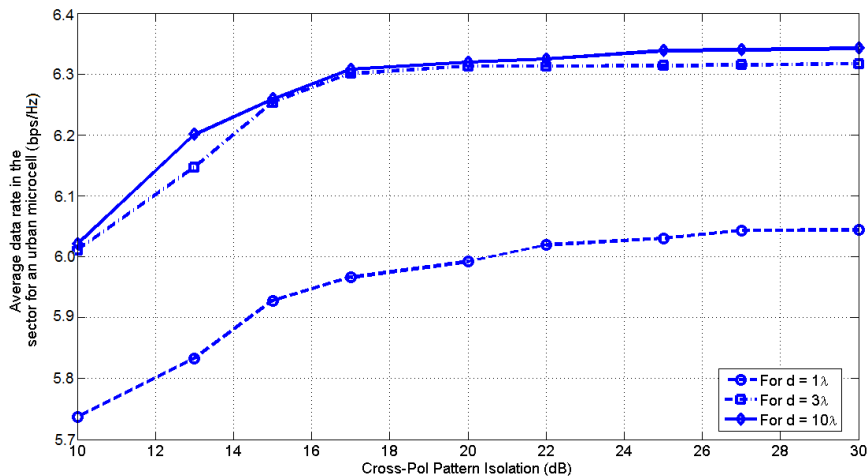


Fig. 8. Average spectral efficiency per user in an urban micro-cell (based on the 3GPP-LTE standard) versus cross-pol isolation (in dB) for the configuration shown in Figs. 5(a), for bandwidth = $5MHz$.

along with the fact that the configuration in Fig. 5(a) occupies lower space, are used to show that the two dual pol array is a better solution for a MIMO base station antenna. We now optimize the port-to-port isolation and cross-pol requirements.

B. Optimizing the Two Dual Pol Configuration for Cross Pol and Port-to-Port Isolation

It takes a considerable amount of effort on the part of the antenna designer to meet design specifications for these parameters. This effort and time can be lowered if the optimum values of these parameters are known beyond which there will be no significant improvement in data rate. In this article, we optimize the cross-pol and port-to-port isolation with respect to the data rate, using the methodology in Section III. We consider the range of cross-pol pattern isolation to be $10 - 30dB$, in accordance with common industry specifications.

The results for optimizing the cross-pol isolation are presented in Fig. 8 for three values of inter-element spacing, $d = 1\lambda$, $d = 3\lambda$ and $d = 10\lambda$, for a fixed port-to-port isolation of $30dB$. It is seen that to reach within 1% of the final data rate obtained at $30dB$ isolation, a cross-pol pattern isolation of $17dB$ is sufficient. The results for optimizing the port-to-port isolation are presented in Fig. 9 for $d = 1\lambda$, $d = 3\lambda$ and $d = 10\lambda$, fixing the cross-pol isolation at $20dB$. From the figure, it is clear that increasing the port-to-port isolation beyond $22dB$ does not change the performance significantly. Hence, it can be

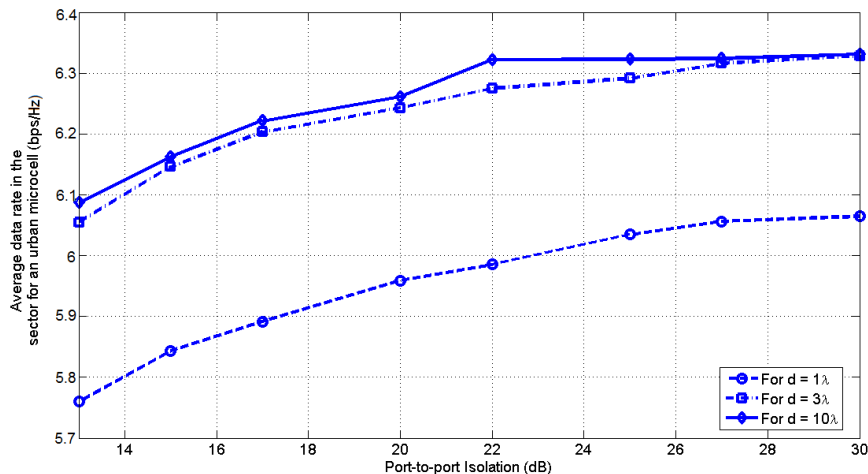


Fig. 9. Average spectral efficiency per user in an urban micro-cell (based on the 3GPP-LTE standard) versus port-to-port isolation (in dB) for the configuration shown in Figs. 5(a), for bandwidth = $5MHz$.

concluded that the optimum port-to-port isolation is about $22dB$ for good MIMO performance. Standard dual pol arrays are typically specified with a port-to-port isolation of $30dB$ due to other considerations like transmitter-receiver separation.

V. CONCLUSION

Cellular service providers need to make the shift to MIMO to cater to growing demands for high data rates. In this article, we described what makes a good MIMO base station antenna. We evaluated the performance of two popular antenna designs using the Grassmannian precoding, a closed-loop MIMO transmission strategy. We concluded that the two dual pol array configuration yields good MIMO performance and that an inter-element spacing of $d = 2\lambda$, cross-pol isolation of $17dB$ and port-to-port isolation of $22dB$ are sufficient to obtain the gains promised by MIMO. The small optimum inter-element spacing implies that the quad port configuration makes a good MIMO base station antenna design. Future work will analyze the performance of these antenna designs for other MIMO transmission strategies and multi-user MIMO systems.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of the Aileen S. Andrew Foundation for sponsoring this research through its fellowship program.

REFERENCES

- [1] P. Leo, "Cell Phone Statistics That May Surprise You," Pittsburgh Post-Gazette, Mar. 28, 2006.
<http://www.post-gazette.com>
- [2] V. Erceg et.al., "IEEE 802.16 Broadband Wireless Access Working Group," *IEEE 802.16.3c-01/29r4*, <http://ieee802.org/16>, Jul. 2001.
- [3] 3G Americas, "UMTS Evolution from 3GPP Release 7 to Release 8," http://3gamericas.com/PDFs/WP_3GA_UMTSRel-8_July07.pdf, July 2007.
- [4] 3GPP Technical Specification Group, "Spatial channel model, SCM-134 text V6.0," *Spatial Channel Model AHG (Combined as-hoc from 3GPP and 3GPP2)*, Apr. 2003.
- [5] D. Gesbert, M. Shafi, D. Shiu, P. J. Smith and A. Naguib, "From Theory to Practice: An Overview of MIMO Space-Time Coded Wireless Systems," *IEEE Jnl. on Select. Areas Comm.*, vol. 21, no. 3, pp. 281 - 302, Apr. 2003.
- [6] D. S. Shiu, G. J. Foschini, M. J. Gans and J. M. Kahn, "Fading Correlation and its Effects on the Capacity of Multielement Antenna Systems," *IEEE Trans. on Comm.*, vol. 48, no. 3, pp. 502 - 512, Mar. 2000.
- [7] J. Zhang, H. Zhang, N. V. Wales, A. Reid and V. Stolzman, "Closed-Loop MIMO Precoding with Limited Feedback," *IEEE 802.16 Broadband Wireless Access Working Group*, <http://ieee802.org/16>, Aug. 2004.
- [8] D. J. Love, R. W. Heath, Jr. and T. Strohmer, "Grassmannian Beamforming for Multiple-Input Multiple-Output Wireless Systems," *IEEE Trans. on Info. Theory*, vol. 49, pp. 2735-2747, Oct. 2003.
- [9] R. Bhagavatula, A. Forenza, and R. W. Heath, Jr., "Impact of Antenna Array Configurations on Adaptive Switching in MIMO Channels," *Proc. of Int. Symp. on Wireless Pers. Mult. Comm.*, Sept. 2006.
- [10] A. Forenza and R. W. Heath, Jr., "Benefit of Pattern Diversity Via 2-element Array of Circular Patch Antennas in Indoor Clustered MIMO Channels," *IEEE Trans. on Comm.*, vol. 54, no. 5, pp. 943 - 954, May 2006.
- [11] A. Forenza and R. W. Heath, Jr., "Impact of Antenna Geometry on MIMO Communication in Indoor Clustered Channels," *Proc. of AP-S Int. Symp.*, vol. 2, pp. 1700 - 1703, Jun. 2004.
- [12] M. L. Morris and M. A. Jensen, "Network model for MIMO systems with coupled antennas and noisy amplifiers," *IEEE Trans. on Ant. and Prop.*, vol. 53, no. 1, pp. 545-552, 2005.
- [13] S. Pan, S. Durrani and M. E. Bialkowski, "MIMO Capacity for Spatial Channel Model Scenarios," *Proc. of Aust. Comm. Thr. Wkshp.*, pp. 25 - 29, Feb. 2007.