Antenna Selection for Compact Dual-Polarized MIMO Systems with Linear Receivers

Vikram R. Anreddy and Mary Ann Ingram
School of Electrical and Computer Engineering
Georgia Institute of Technology Atlanta, Georgia 30332–0250
Email: vikram@ece.gatech.edu; mai@ece.gatech.edu

***Abstract*— Antenna selection combined with dual-polarized antennas offers an attractive alternative for realizing higher order multiple-input multiple-output (MIMO) configurations in compact, low-complexity devices. In this paper we analyze the performance of antenna selection for narrowband dual-polarized MIMO systems with linear minimum mean square error (MMSE) receivers. We theoretically analyze the impact of cross-polar discrimination on the achieved antenna selection gain for dual-polarized MIMO channels. We use channel measurement data collected at 2.4 GHz in a typical office environment to compare the performance of spatial and dual-polarized MIMO with respect to antenna selection. Our bit-error-rate (BER) results indicate that antenna selection with dual-polarized antennas can achieve significant performance gains for compact configurations with only a nominal increase in complexity.**

I. Introduction

The multiple-input multiple-output (MIMO) architecture has the potential to dramatically improve the performance of wireless systems. Much of the focus of research has been on uni-polarized spatial array configurations where antenna elements are separated in space. These systems require an inter-element spacing of the order of a wavelength to achieve significant gains in NLOS channels; even larger spacing is required for LOS channels [1]. In this regard, dual-polarized antennas have received much attention as an attractive alternative for realizing MIMO architectures in compact devices.

The main drawback of the MIMO architecture is that the gain in performance comes at a cost of increased hardware complexity in terms of multiple RF chains at the transmitter and receiver. Antenna selection is a technique which can alleviate these costs but still exploit the diversity benefits offered by the MIMO architecture. This technique has been extensively studied in the context of spatial channels (see [2] and the references therein). We emphasize that this strategy is all the more relevant for compact portable devices, which are often constrained by complexity, power and cost.

Antenna selection, when combined with dual-polarized antennas, may be a solution that could enable compact systems to exploit the benefits of the MIMO architecture with only a nominal increase in complexity. However, MIMO channels with polarization diversity cannot be modeled like pure spatial channels, because the subchannels of the MIMO channel matrix are not identically distributed [3]. They differ in terms of average received power, Ricean K-factor, cross-polar discrimination (XPD) and correlation properties [4]. As a result, the performance of antenna selection for these channels needs to be evaluated. To the best of our knowledge, this issue has not been addressed in the literature.

We consider VBLAST transmission with linear MMSE receiver signal processing [5]. The most popular antenna selection strategy has been to choose transmit or receive antennas that maximize the Shannon capacity for MIMO channels [2], [6]. However, such antenna selection solutions are unlikely to achieve optimum error performance for systems with limited complexity receivers [7]. Various approaches to minimize the BER of linear receivers have been proposed in the literature [7]–[9]. In this paper, we consider the MMSE based antenna selection approach proposed in [7], which has been shown to out-perform other techniques for spatial multiplexing systems with linear MMSE receivers.

The main objective of this paper is to analyze the performance of antenna selection for MIMO channels in the presence of polarization diversity. We provide a theoretical treatment for the 2×2 dual-polarized Rayleigh MIMO channel. We also provide empirical results for a line-of-sight (LOS) and non-LOS (NLOS) channel, measured at 2.4 GHz in a typical indoor office environment. In these measurements we have observed a coincidence of low K-factors and high XPD. In such channels, dual-polarized MIMO configurations incur an SNR and a diversity deficit when compared to spatial systems [4]. On the other hand, the correlation between the subchannels of dual-polarized MIMO channel are very low, even in the LOS environment. We use the measured channel samples to a compare the performance of antenna selection in terms of BER, between spatial and dual-polarized configurations for a range of values of the array length (L).

This paper is organized as follows: Section II discusses the dual-polarized MIMO channel and Section III presents the MMSE based antenna selection strategy. In Section IV we analytically study the effect of XPD on the performance of antenna selection in dual-polarized MIMO channels. Section V provides details about the indoor channel measurement campaign. Section V presents BER results for (2,1)/(2,1) and (4,2)/(4,2) selection for a range of values of the array length and Section VII concludes the findings of this paper.

II. Dual-polarized MIMO

Consider a system with n_t transmit and n_r receive antennas. When all the antennas are vertically polarized, the subchannels

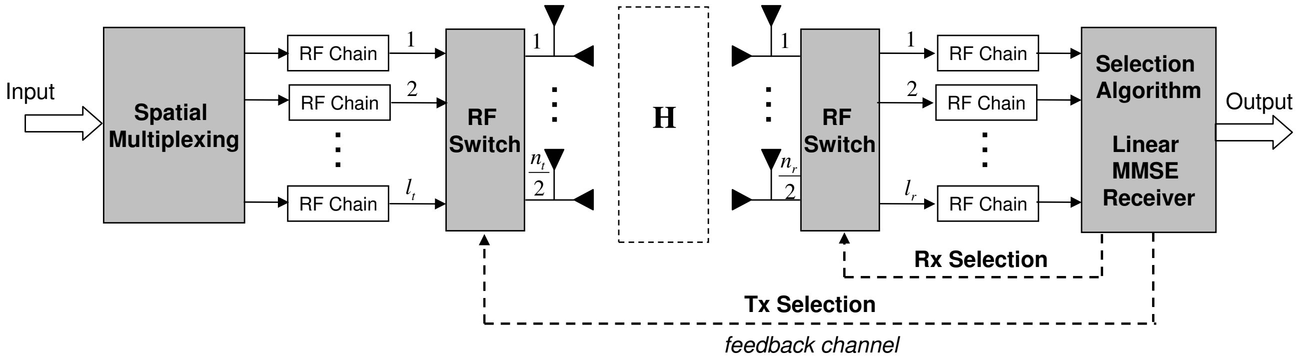

Fig. 1. Antenna Selection for Dual-polarized MIMO

of the MIMO channel matrix $\mathbf{H}$ are usually assumed to be identically distributed. However, when antennas with different polarizations are employed at either ends of the link, the properties of the co-polar subchannels differ significantly from those of the cross-polar subchannels. Hence for dual-polarized configurations, the channel matrix can be conveniently written as

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}^{VV}_{(n_r^V \times n_t^V)} & \mathbf{H}^{VH}_{(n_r^V \times n_t^H)} \\ \\ \mathbf{H}^{HV}_{(n_r^H \times n_t^V)} & \mathbf{H}^{HH}_{(n_r^H \times n_t^H)} \end{bmatrix}_{(n_r \times n_t)} \quad (1)$$

where n_t^V, n_t^H are the number of vertically and horizontally polarized elements at the transmitter, respectively. Similarly n_r^V, n_r^H are the number of vertically and horizontally polarized elements at the receiver, respectively. The elements of the submatrices $\mathbf{H}^{VV}$ and $\mathbf{H}^{HH}$ correspond to the co-polar subchannels in $\mathbf{H}$, while $\mathbf{H}^{VH}$ and $\mathbf{H}^{HV}$ correspond to the cross-polar subchannels.

The transmitted radio signal, as it traverses through the wireless channel, undergoes multiple reflections and scattering, resulting in a coupling of the orthogonal state of polarization. This phenomenon is referred to as depolarization. Cross-polar discrimination (XPD) is a measure of depolarization in a wireless channel, and is defined as

$$\begin{aligned} X_V &= E\{|h^{VV}|^2\}/E\{|h^{HV}|^2\} \\ X_H &= E\{|h^{HH}|^2\}/E\{|h^{VH}|^2\}, \end{aligned} \quad (2)$$

where $h^{IJ} : I, J \in \{V, H\}$ is an element of the sub-matrix $\mathbf{H}^{IJ}$ and $E\{Z\}$ denotes the expectation of random variable Z. Typically XPD values are high in channels with limited scattering such as LOS channels and much lower in NLOS channels. However high XPD values have been observed even in NLOS channels, in some measurement campaigns [4], [10]. Further, owing to the different propagation characteristics of horizontally polarized waves and vertically polarized waves, $\beta = E\{|h^{HH}|^2\} \leq E\{|h^{VV}|^2\} = 1$. These subchannel power losses translate into a performances loss for dual-polarized MIMO systems when compared to spatial MIMO [4].

Under LOS conditions, the co-polar subchannels are Ricean distributed whereas the cross-polar subchannels are Rayleigh distributed. This is expected due to the fact that the cross-polar subchannel gains result from depolarization of the transmitted signal. Correlation between the elements of the MIMO channel is detrimental to its performance. For spatial MIMO, a large inter-element spacing is required to lower the correlation between the subchannels in some environments [4]. However for dual-polarized MIMO, the correlation between the elements from different submatrices are very low even under LOS channel conditions [4].

Thus there are significant differences between dual-polarized and spatial MIMO channels.

III. Antenna Selection

Antenna selection refers to the process of selecting the “optimal” l_t out of the n_t available transmit antennas and/or the “optimal” l_r out of the n_r receive antennas. Symbolically we denote this process as $(n_r, l_r)/(n_t, l_t)$ selection. As shown in Figure 1, we assume the availability of a perfect low-bandwidth feedback channel for implementing selection at the transmitter.

If the receiver employs a linear MMSE (LMMSE) detector, it uses a spatial filter $\mathbf{w}$ so as to minimize the mean squared error given by: $E\{||\mathbf{w}^H\mathbf{r} - \mathbf{s}||^2\}$. For a given $l_r \times l_t$ MIMO channel matrix, $\bar{\mathbf{H}}$, the optimum weight vector is: $\mathbf{w} = \mathbf{R_r}^{-1}\bar{\mathbf{H}}$, where $\mathbf{R_r} = \bar{\mathbf{H}}\bar{\mathbf{H}}^H + N_o\mathbf{I}_{l_r}$. The residual minimum mean squared error is given by

$$\xi(\bar{\mathbf{H}}) = \text{tr}(\mathbf{I}_{l_r} - \bar{\mathbf{H}}^H\mathbf{R}_r^{-1}\bar{\mathbf{H}}). \quad (3)$$

The antenna selection strategy is devised to minimize this residual error. The selection criteria can be expressed as [7]:

$$\widetilde{\mathbf{H}} = arg \min_{S(\bar{\mathbf{H}})} \{\xi(\bar{\mathbf{H}})\}, \quad (4)$$

where $\bar{\mathbf{H}}$ is obtained by eliminating $n_r - l_r$ columns and $n_t - l_t$ rows from $\mathbf{H}$. $S(\bar{\mathbf{H}})$ denotes the set of all possible $\bar{\mathbf{H}}$, whose cardinality is $\binom{n_r}{l_r}\binom{n_t}{l_t}$. In this paper we assume optimal selection, but we note that practical suboptimal selection algorithms to implement this strategy have been proposed and they achieve near-optimal performance [7].

The input-output relation for a typical spatial multiplexing system can then be expressed as

$$\mathbf{r} = \sqrt{\frac{E_s}{l_t}}\widetilde{\mathbf{H}}\mathbf{s} + \mathbf{n}, \quad (5)$$

where $\mathbf{r}$ and $\mathbf{s}$ are the baseband complex received and transmitted vectors respectively. It is assumed that $E\{\mathbf{s}\mathbf{s}^H\} = \mathbf{I}_{l_t}$. Here, $\mathbf{I_n}$ is an identity matrix of size $n \times n$. $\mathbf{n}$ represents the complex circular Gaussian noise vector with autocorrelation $R_{nn} = N_o \mathbf{I}_{\mathbf{l_r}}$. E_s denotes the total transmit signal power. In this paper, we define SNR = E_s/N_o.

IV. Effect of XPD on Selection Gain

In this section we study the influence of XPD on gain achieved by using antenna selection. To make the analysis tractable, we consider a 2×2 dual-polarized MIMO channel. In this case the channel matrix (1) reduces to

$$\mathbf{H} = \begin{bmatrix} h^{VV} & h^{VH} \\ h^{HV} & h^{HH} \end{bmatrix}. \quad (6)$$

All the subchannels are assumed to be independent complex circularly symmetric Gaussian random variables. This is an appropriate assumption for the typical NLOS indoor channel [4]. Further, we make the simplifying assumptions that $X_V = X_H = X$, $1 \leq X < \infty$ and $\beta = 1$. We note that when $X = 1$, dual-polarized MIMO channel is equivalent to a spatial channel.

For (2,1)/(2,1) selection, the strategy outlined in (4) reduces to selecting the subchannel which has the maximum instantaneous power.

The instantaneous post processing SNR for the selected SISO channel ($\tilde{h}$) is given by YE_s/N_o where the random variable, $Y = |\tilde{h}|^2$. For a circularly symmetric complex Gaussian random variable Z with zero mean and variance σ^2, the cumulative distribution function (CDF) is given by, $F_Z(z) = (1 - e^{-z/\sigma^2})U(z)$, where $U(z)$ is the unit step function. Since all the elements of $\mathbf{H}$ are assumed to be mutually independent, the CDF of Y can be derived as follows

$$\begin{aligned} F_Y(y) &= Pr(|h^{VV}|^2 < y)^2 Pr(|h^{HV}|^2 < y)^2 \\ &= (1-e^{-y})^2(1-e^{yX})^2 U(y) \end{aligned} \quad (7)$$

The probability density function (PDF), $f_Y(y) = \frac{dF_Y(y)}{dy}$ is given by

$$\begin{aligned} f_Y(y) &= 2\big(e^{-y}(1-e^{-y})(1-e^{yX})^2 \\ &\quad + Xe^{-Xy}(1-e^{-Xy})(1-e^{y})^2\big)U(y) \\ &= 2\Big(e^{-y}(1-e^{-y}) + Xe^{-Xy}(1-e^{-Xy}) \\ &\quad + (1+2X)e^{-y(1+2X)} + (2+X)e^{-y(2+X)} \\ &\quad - (1+X)e^{-y(1+X)}(2+e^{-y(1+X)})\Big)U(y) \end{aligned} \quad (8)$$

Using the identity, $\int_0^\infty xe^{-ax}dx = 1/a^2$, $\bar{Y} = E\{Y\}$, which indicates the effective SNR gain achieved by using antenna selection, can be computed to be

$$\bar{Y} = \frac{3(1+X)}{2X} + \frac{2}{1+2X} + \frac{2}{2+X} - \frac{9}{2(1+X)} \quad (9)$$

The average SNR gain is a monotonically decreasing function of X as shown in Figure 2. The selection gain is maximum

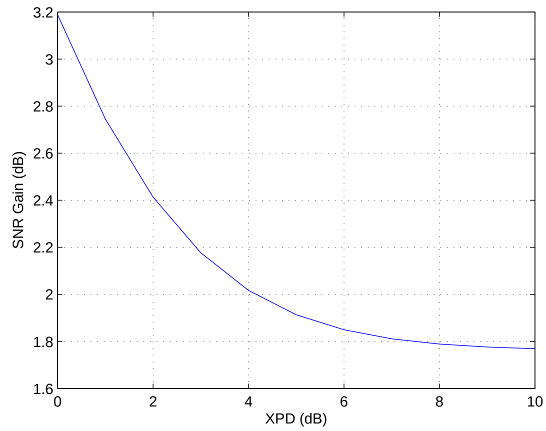

Fig. 2. Effect of XPD on (2,1)/(2,1) selection gain

at 3.2 dB when $X = 1$ and asymptotically diminishes to 1.76 dB. These values are consistent with the well known result for SNR gain of selection diversity with M independent and equal powered Rayleigh diversity branches, given by, $\bar{Y} = \sum_{i=1}^{M} \frac{1}{i}$ [5].

The probability that one of the cross-polar subchannels is selected can be computed to be

$$P(X) = Pr\{(\tilde{h} = h^{VH}) \cup (\tilde{h} = h^{HV})\} = \frac{1}{(1+X)^2} \quad (10)$$

As the XPD increases the probability of the cross-polar subchannels being selected decreases and thus the average SNR gain diminishes. Further, $\lim_{X\to\infty} P(X) = 0$, which indicates that in the limiting case, the available degrees of diversity reduce to 2 when compared to 4 for $X = 1$. Thus a high XPD results in a diversity loss for dual-polarized MIMO channels when compared to spatial channels.

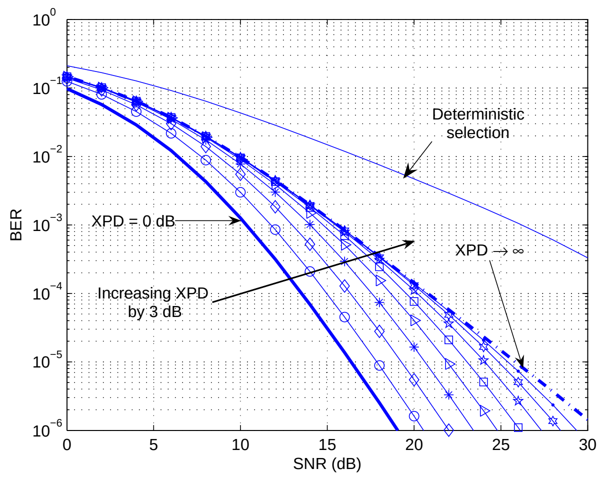

Fig. 3. Numerically evaluated BER curves for (2,1)/(2,1) selection for different XPD

For a given channel $\mathbf{H}$, the bit error rate (BER) with Gray mapped 4-QAM constellation, $Pr(\text{error}/\mathbf{H}) = Q(\sqrt{\frac{2YE_b}{N_o}})$ where $E_b/N_o = E_s/(2l_tN_o)$ is the pre-detection SNR per bit and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{x^2}{2}}dx$. The average BER can be calculated as:

$$BER = \int_{-\infty}^{\infty} Q(\sqrt{\frac{YE_s}{N_o}}) f_Y(y) dy \quad (11)$$

For a spatial MIMO channel, a closed form expression for BER can be developed and it can be shown that at high SNR, $BER \propto \frac{1}{(E_s/N_o)^d}$, where d is the diversity order [5]. As mentioned previously, the two extreme cases i.e. $X = 1$ and $X \rightarrow \infty$ result in diversity orders $d = 4$ and $d = 2$, respectively. However, for other values of X it is not easy to arrive at such insightful approximations. Hence to analyze the influence of XPD on BER, we numerically evaluate (11). As shown in Figure 3, as the XPD increases, BER performance of selection diversity deteriorates. Further, the performance degradation is more prominent at high SNR indicating a gradual decrease in diversity as the XPD increases.

The measured NLOS XPD values reported in the literature, for indoor environments vary between 0 to 9 dB [4], [10], [11]. From Figure 3, we observe that the BER curve corresponding to $X = 9$ dB, is extremely close to the worst-case ($X \rightarrow \infty$) curve for SNR < 8 dB. However as the SNR increases, $X = 9$ dB yields a BER that is significantly better than the worst-case.

Similar analysis can be done for the parameter β. As a result of these subchannel power losses, antenna selection for dual-polarized MIMO channels performs under par when compared to spatial channels. However in environments where the spatial channel is highly correlated, the performance gap diminishes as discussed in Section VI.

V. Indoor Channel Measurements

In this section, we provide a brief overview of the measurement process and describe the salient channel characteristics observed in the measured data. For a detailed discussion of the measurement process and the observations, we refer the interested reader to [4].

The virtual array MIMO measurement system [12] was used, wherein a virtual array is created by moving the antenna to arbitrary pre-programmed locations. This set-up offers great flexibility to experiment with different antenna configurations. The antennas used at both ends were dual-polarized narrowband antennas, omni-directional in the azimuth and with a frequency range of 2.400 - 2.483 GHz (model number: SPDPG-4O-H2O, Superpass Company Inc.). A virtual 50 element ($5\times5\times2$) cubicle array with a minimum inter-element spacing of $\lambda/2$ was used at both ends. The co-polar and the cross-polar subchannels were measured for each pair of transmit (Tx) and receive (Rx) locations. Previous measurements in the same environment had indicated that the coherence bandwidth of the channel is about 15 MHz. Hence corresponding to each pair of transmit and receive antenna locations, we collected six uncorrelated channel samples in the frequency range of operation. Using subarrays of the Tx and Rx cubicle arrays along with the frequency samples, we collected a number, N, of MIMO channel samples, where N depended upon the array length (L) of the configuration. $N \in \{15000, 9600, 5400, 2400\}$ for array length, $L \in \{0, \lambda/2, \lambda, 3\lambda/2\}$, respectively.

The measurement location is depicted in Figure 4. The LOS measurements were taken in the hallway, which is lined by offices on one side and laboratories. For the NLOS measurements the receiver array was moved into the adjoining laboratory and the both the door were closed.

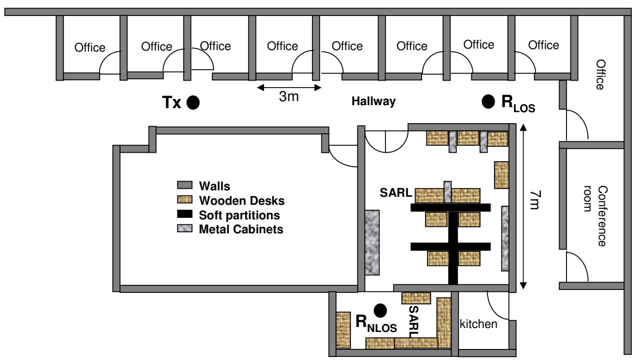

Fig. 4. Floor plan of the measurement location

The following are the key observations made based on the analysis of the measured data [4]:

1) In the hallway, the measured K-factors are 0.78 and 1.30 for VV and HH co-polar subchannels, respectively. Although counterintuitive, such low K-factors have been observed in previous measurements in the hallway environment [13]. The cross-polar subchannels followed a Rayleigh distribution. Under NLOS channel conditions, as expected all the subchannels follow a Rayleigh distribution.
2) The measured XPD values were, $X_V = 16.96$ dB and $X_H = 14.96$ in the LOS scenario, and $X_V = 8.58$ dB and $X_H = 8.29$ dB in the NLOS case. Further, $\beta = -1.6$ dB in the LOS scenario, and $\beta = -2.2$ dB under NLOS channel conditions. Thus the subchannel power losses for the dual-polarized MIMO were significant.
3) The normalized power correlation between the elements of the 2×2 dual-polarized MIMO channel matrix was upper bounded by 0.25 in the hallway and by 0.15 in the NLOS scenario. For 2×2 spatial MIMO, observed transmit (ρ^T) and receive (ρ^R) correlations values were a strong function of the inter-element spacing in the hallway as shown in Table I. Under NLOS channel conditions, the correlation values are much lower and are not dependent on spacing. We note that the magnitude of the complex correlation can be approximated from the power correlation values as $|\rho_{\text{complex}}| \approx \sqrt{\rho_{\text{power}}}$ [14].

VI. BER Results

In this section we analyze the performance of antenna selection in terms BER for dual-polarized MIMO systems,

TABLE I
MEASURED POWER CORRELATION VALUES FOR 2×2 SPATIAL MIMO

	L	$\lambda/2$	λ	$3\lambda/2$
LOS	ρ^T	0.56	0.30	0.18
	ρ^R	0.45	0.32	0.18
NLOS	ρ^T	0.19	0.05	0.02
	ρ^R	0.08	0.04	0.10

using the measured channel samples. The measured MIMO channel samples were normalized to achieve $E\{||\mathbf{H}^{VV}||_F^2\} = n_r^V n_t^V$. The other subchannels scale accordingly to reflect the power losses. This normalization facilitates a fair comparison between spatial and dual-polarized MIMO channels for a constant transmit power [4].

The input symbols s_i were drawn from a equiprobable 4-QAM constellation $\{\pm 1 \pm j\}/\sqrt{2}$. The channel was assumed to be static for a frame of 100 symbols. BER is calculated for each frame and averaged over the N channel realizations provided by the measurements. The array length is the same at the transmitter and the receiver. We consider (2,1)/(2,1) and (4,2)/(4,2) optimal antenna selection according to the criteria outlined in (4), under LOS and NLOS channel conditions for a range of values of inter-element spacing. We use exhaustive search to achieve optimal selection.

In Figures 5 and 6, we plot the BER curves for (2,1)/(2,1) selection under LOS and NLOS channel conditions, respectively. We consider a 2×2 dual-polarized (D) system with $L = 0$ and a spatial (S) system with $L = \lambda/2$. For reference we also plot the BER for a vertically polarized deterministic single input single output (SISO) link. In all the following figures, DS stands for deterministic (or "no") selection.

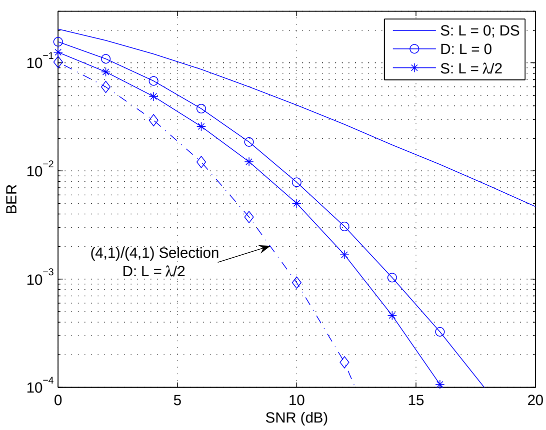

Fig. 5. (2,1)/(2,1) Antenna selection under LOS channel conditions.

In the results for the hallway, shown in Figure 5, the dual-polarized system with selection outperforms the SISO link by 8 dB at BER $= 10^{-2}$. The spatial system with selection performs better than its dual-polarized counterpart by about 1 dB, owing to the subchannel power losses in the latter configuration. This difference is not larger because the spatial MIMO with $L = \lambda/2$ suffers from high subchannel correlations (Table I).

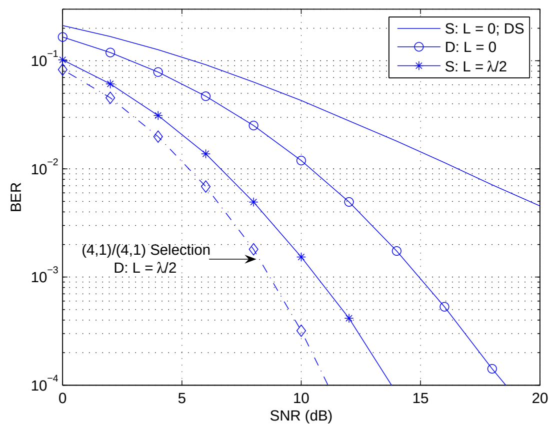

Fig. 6. (2,1)/(2,1) Antenna selection under NLOS channel conditions.

Under NLOS channel conditions, the dual-polarized system with selection outperforms the SISO link by 6 dB at BER $= 10^{-2}$. The performance gap between the spatial and dual-polarized systems in the presence of selection increases to 3.5 dB. This is because in NLOS scenarios, a spatial MIMO channel achieves significant decorrelation and hence achieves full diversity. On the other hand, dual-polarized configuration suffers from subchannel power losses. We note that despite these losses, dual-polarized antennas offer the distinct benefit of compactness over the spatial configuration.

In addition to providing compactness, dual-polarized antennas can also be used to realize higher order MIMO configurations in devices with larger form factors. To underscore this point, we also plot in Figures 5 and 6, BER results for (4,1)/(4,1) selection with dual-polarized antennas. This configuration could be realized in the same space as the spatial configuration, yet it achieves better performance under both LOS and NLOS channel conditions.

In Figures 7 and 8, we plot the BER curves for (4,2)/(4,2) selection under LOS and NLOS channel conditions respectively. A four element dual-polarized array can be realized by spatially separating two dual-polarized elements, each of which has two co-located orthogonal polarization elements. This configuration could be useful for the not-so-compact handheld devices like notebook computers. In these figures, we consider a 4×4 dual-polarized system with $L \in \{\lambda/2, \lambda, 3\lambda/2\}$ and a spatial system with $L = 3\lambda/2$. The minimum inter-element spacing between the adjacent antenna elements is maintained at $\lambda/2$. For reference we also plot the BER for deterministic selection (DS) for 2×2 spatial MIMO with $L \in \{\lambda/2, \lambda, 3\lambda/2\}$.

In the hallway, as the inter-element spacing is increased, the performance of the 2×2 spatial MIMO with deterministic selection improves owing to the decrease in the subchannel correlations and the spherical wavefront effect [1]. Further the

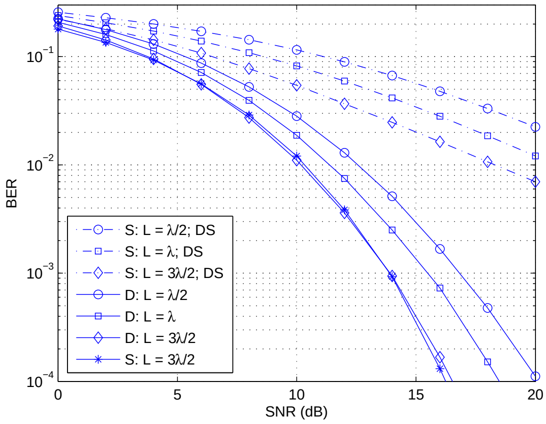

Fig. 7. (4,2)/(4,2) Antenna selection under LOS channel conditions.

performance of the 4×4 dual-polarized MIMO with selection also improves with increasing inter-element spacing because of the lower correlations between the elements of the co-polar submatrices $\mathbf{H}^{VV}$ and $\mathbf{H}^{HH}$ [4]. For an array length of $L = 3\lambda/2$, the 4×4 spatial and dual-polarized MIMO systems perform equally well. They achieve a selection gain of 8 dB at BER = 10^{-2}.

Under NLOS channel conditions, as expected, the performance is not a strong function of the inter-element spacing. For $L = \lambda/2$, the 4×4 dual-polarized system with selection outperforms the 2×2 deterministic spatial MIMO by 8.5 dB at BER = 10^{-2}. The (4,2)/(4,2) spatial MIMO with $L = 3\lambda/2$ outperforms the dual-polarized MIMO with selection by about 2.5 dB.

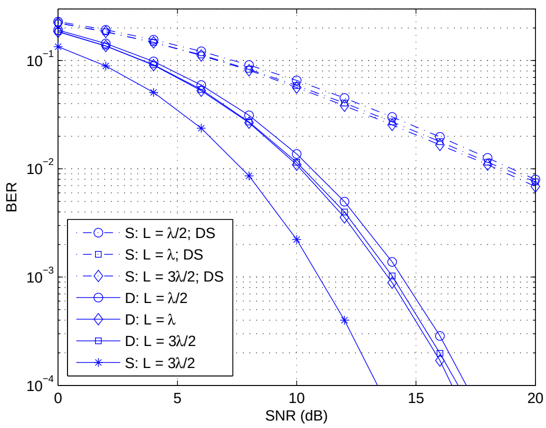

Fig. 8. (4,2)/(4,2) Antenna selection under NLOS channel conditions.

In our analysis we have assumed lossless switching. However, we note that the insertion loss of RF switches degrades the performance of any antenna selection system and should be taken into account, while designing these systems [15].

VII. Conclusion

In this paper, we have studied the performance of antenna selection for measured indoor dual-polarized MIMO channels at 2.4 GHz. We have analytically showed the selection gain diminishes as the XPD increases. Our measurement results indicate that while antenna selection with the spatial array configuration performs the best under both LOS and NLOS channel conditions, it requires a larger array length which is not always possible to realize in compact devices. On the other hand, antenna selection with dual-polarized antennas performs significantly better than deterministic selection, with only a nominal increase in complexity and with no cost in terms of space. Thus antenna selection combined with dual-polarized antennas presents an attractive solution to the problem of realizing high order MIMO architectures in compact devices.

References

[1] J.S. Jiang and M.A Ingram, "Spherical-wave model for short-range MIMO," *IEEE Transactions on Communications*, vol. 53, no. 9, pp. 1534 – 1541, Sept. 2005.
[2] A.F. Molisch and M.Z Win, "MIMO systems with antenna selection," *IEEE Microwave Magazine*, vol. 5, no. 1, pp. 46 – 56, March 2004.
[3] V. Erceg, P. Soma, D.S. Baum, and S. Catreux, "Multiple-input multiple-output fixed wireless radio channel measurements and modelling using dual-polarized antennas at 2.5 GHz," *IEEE Transactions on Wireless Communications*, vol. 3, no. 6, pp. 2288–2298, Nov. 2004.
[4] V.R. Anreddy and M.A. Ingram, "Capacity of measured Ricean and Rayleigh indoor MIMO channels at 2.4 GHz with polarization and spatial diversity," *IEEE Wireless Communications and Networking Conference*, 2006.
[5] J.R. Barry, E.A. Lee, and D.G. Messerschmitt, *Digital Communication*, Kluwer Academic Publishers, 2 edition, 2001.
[6] D. Gore, R. Nabar, and A. Paulraj, "Selecting an optimal set of transmit antennas for a low rank matrix channel," *IEEE Internation Conference on Acoustics, Speech and Signal Processing*, June 2000.
[7] S. Gaur and M. A. Ingram, "Transmit/receive antenna selection for MIMO systems to improve error performance of linear receivers," *Proceedings of International ITG/IEEE Workshop on Smart Antennas*, April 2005.
[8] D. A. Gore, R. W. Heath, and A. Paulraj, "Transmit selection in spatial multiplexing systems," *IEEE Communications Letters*, vol. 6, no. 11, pp. 491–493, Nov 2002.
[9] I. Berenguer, X. Wang, and I.J. Wassell, "Antenna selection in linear receivers: Geometrical approach," *IEE Electronic Letters*, vol. 40, no. 5, pp. 292–293, March 2004.
[10] X. Zhao, S. Geng, L. Vuokko, J. Kivinen, and P. Vainikainen, "Polarization behaviors at 2, 5 and 60 GHz for indoor mobile communications," *Wireless Personal Communications*, vol. 27, no. 2, pp. 99–115, Nov. 2003.
[11] P. Kyritsi, D.C. Cox, R.A. Valenzuela, and Wolniansky P.W, "Effect of antenna polarization on the capacity of a multiple element system in an indoor environment," *IEEE Journal on Selected areas in Communications*, vol. 20, no. 6, pp. 1227–1239, Aug. 2002.
[12] J.S Jiang, *Measurement, Modeling, and Performance of indoor MIMO channels*, Ph.D. thesis, Georgia Institute of Technology, Atlanta, GA, USA, May 2004.
[13] C.M. Tan, A.R. Nix, and M.A. Beach, "Dynamic spatial-temporal propagation measurement and super-resolution channel characterisation at 5.2 GHz in a corridor environment," in *Proc. IEEE Vehicular Technology Conference (VTC)*, Sept. 2002, vol. 2, pp. 797–801.
[14] P. Kyritsi, D.C. Cox, R.A. Valenzuela, and Wolniansky P.W, "Correlation analysis based on MIMO channel measurements in an indoor environment," *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS*, vol. 21, no. 5, pp. 713–720, June 2003.
[15] P. Sudarshan, N.B. Mehta, A.F. Molisch, and Jin Zhang;, "Antenna selection with RF pre-processing: robustness to RF and selection non-idealities," *Radio and Wireless Conference, 2004 IEEE*, pp. 391–394, Sept 2004.