Spatial and polarization characterization of MIMO channels in rural environment

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1 Introduction

Use of MIMO communication techniques is of particular interest for peer to peer communications, where the nodes are often placed in highly scattering environments. Past measurements have found that large MIMO capacities are supported in urban environments [2], [3]. To demonstrate a real-time, mobile, networked MIMO system in a realistic tactical environment, the Defense Advanced Research Projects Agency (DARPA) has instituted a program called Mobile Network MIMO (MNM) [1]. The first stage of this program is to demonstrate such a system in a rural wooded environment in Lakehurst, NJ using multiple MIMO equipped nodes using an ad hoc network in a bandwidth of up to 25 MHz. Each node is a vehicle with 8 transmit and 10 receive antennas.

Some of the key propagation questions addressed here are whether the channels offer enough scattering richness to benefit from MIMO systems in rural environments ranging from densely wooded to open field with large but sparse clutter within Line of Sight. The measurements were conducted at a site in Lakehurst, located in the Pinelands of southern New Jersey. The area shown in Figure 1 is approximately 3.2 km by 4.8 km. Features include several very large hangars around points H,G,V and X, open areas, runways, and mostly single story buildings. The vegetated areas consist primarily of pine trees about 10 m in height. There is some gentle terrain variation, as evident by the 10 foot contour intervals in Figure 1. Capacity enhancement due to polarization is measured. A correlation based spatial channel model is found to result in capacities within 10% of measured ones, with a median error of 3%.

2 Dually polarized MIMO characterization

Multi-antenna measurements were conducted at 2.5 GHz using a narrowband 16×16 sounder used in urban measurements in Manhattan [2]. Here two array

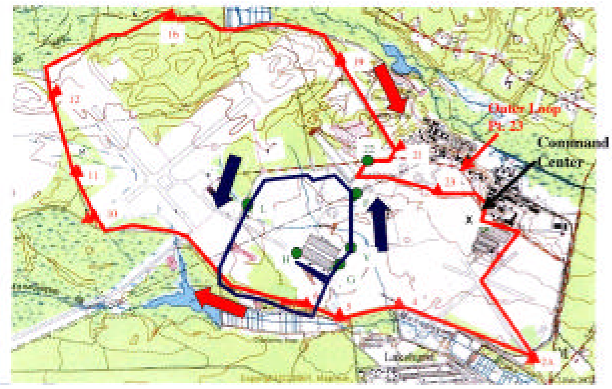

Figure 1: Map of Lakehurst, NJ site and MNM demo configuration.

arrangements were employed: a vertically polarized array, deploying 16 vertically polarized antennas on both the transmitter and receiver, and a dually polarized array, which had 8 vertically and 8 horizontally polarized antennas at both the transmitter and receiver.

The vertically polarized arrays consisted of azimuthally omnidirectional antennas with 8 dBi vertical gain. Both transmit and receive arrays were arranged in a nearly square 4×4 grids on the roofs of the vans, with about 20 inches (4 wavelengths) separation between nearest neighbors.

A dually polarized array was mounted on both of the measurement vans employing vertically polarized antennas described above and azimuthally omnidirectional horizontally polarized antennas with 9 dBi vertical gain. The sounder reported a 16×16 **H** matrix every 3 ms. The vans were driven at 10–20 mph during measurements so as to allow quasi-stationary channel snapshots while collecting statistically diverse H matrix data over longer time records

Distribution of measured capacities using only vertically polarized as well as dually polarized arrays are compared in Figure 2. Use of dual polarization is observed

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to improve median capacity by 8 bps/Hz.

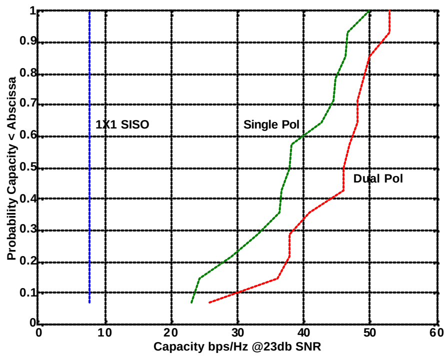

Figure 2: Distribution of observed vertical and dual-pol 8x10 capacities for long range links evaluated at 23 dB system SNR.

As a measure of relative channel richness, all channels in Figure 2 had the received SNR normalized to 23 dB for every instantiation. Such normalization results in the SISO channel, plotted for comparison, having the capacity of a non-faded channel of the same SNR. While the capacity evaluated at a fixed system SNR is a measure of scattering richness of a MIMO channel, a better metric of system performance may be a capacity evaluated at the expected operational SNR. This would account for different propagation losses suffered on different links. The expected operational SNR may be estimated using measured pathloss for each link as

$$SNR_{op} = 10\log_{10} P_T + G_T + G_R - L_{cable_T} - L_{cable_R} \\ - PL - F - 10\log_{10}\left(kTB\right) \text{ (dB)} \quad (1)$$

where k is the Boltzmann constant and T is the ambient temperature. It is assumed here that the noise figure F = 3 dB, bandwidth B=25 MHz, total transmit power P_T = 40 W, receiver and transmitter antennas gains G_T=G_R=8 dB, and receiver and transmitter cable losses are $L_{cable_T} = L_{cable_R} = 3\,dB$. The maximum effective SNR is often limited by the effects such as transmitter non-linearities, phase noise, etc. For the purposes of computing capacities here, the maximum effective SNR is taken here to be 23 dB. The distribution of measured capacities using the dually polarized 8×10 array is compared against corresponding SISO and 1×10 (SIMO) capacities in Figure 3. It may be observed that median 8x10 MIMO capacities are nearly eight times the capacities achievable by a SISO system under the same SNR. It may be concluded that a significant gain in link capacity is possible through the use of multiple antennas in such rural channels.

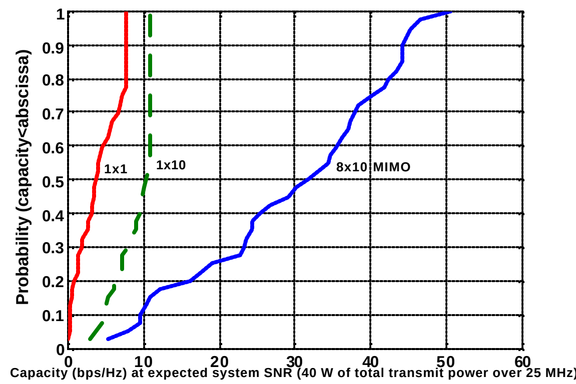

Figure 3: Measured capacities of measured channels for 1×1, 1×10, and 8×10 systems for a finite transmit power.

To account for the diversity advantages offered by multi-antenna systems, the capacities plotted in Figure 3 are 90th percentile capacities allowing for the channel to undergo small-scale fading.

Use of both vertically and horizontally polarized antennas introduces additional quantities that are needed to accurately characterize the channel. One such quantity is the difference in pathloss suffered by vertically and horizontally polarized signals $PL_{VV} - PL_{HH}$. During measurements the receive vehicle was moving along for about 4 meters. For each pair of locations the pathloss is estimated by averaging over the corresponding antennas as well as over time. The difference in spatially averaged measured pathlosses suffered by the vertically and horizontally polarized signals was found to range from +6 to –6 dB, with a median close to 0 dB, implying that the channel does not give either polarization preferential treatment.

Another quantity of importance is the cross-polarization coupling present in the channel. It is a measure of the relative power penalty due to polarization mismatch, suffered by receiving the signal emitted in one polarization by an antenna polarized in the orthogonal polarization. The cross-polarization discrimination $xpol$ is defined here as $xpol = \sqrt{\dfrac{PL_{VV}PL_{HH}}{PL_{VH}PL_{HV}}}$ .where the pathlosses for various combinations of receive and transmit antenna polarizations are expressed as linear power ratios. Cross-polarization discrimination was observed to vary from 2 to 19 dB, with a median of 8.5 dB, which may be compared to 6 dB reported in urban channels. It should be noted that large values of cross-polarization result in a reduction in total received power from what one might expect as a particular receive antenna will only see a weak signal emitted from orthogonally polarized transmit antennas. At the same time it is found that cross-polarized signals are largely uncorrelated. Use of dually polarized arrays on short range

LOS links (ranging from about 50 to 150 meters) was found to increase the median capacity from 30 to 44 bps/Hz.

Measured pathloss values for the long range links are plotted as a function of transmitter-receiver separation in Figure 4. Also plotted is the least mean square regression line. The regression line represents pathloss (dB) as a function of distance x (meters):

$$PL = -4.05 + 44\log_{10} x \qquad (2)$$

The regression line is computed for distances from 200 meters to 4,000 meters, so extensions outside this range should be treated with caution. The median pathloss at 1 km is 128 dB and the standard deviation of error of the regression fit was found to be 17.5 dB. The relatively large standard deviation of error may be attributed in part to the heterogeneity of the environment, that included large open areas, wooded areas, and areas with large obstructions, such as hangars, which become more significant with low antenna height. In a cellular environment, characterized by a tall base station, a representative pathloss for suburban, level terrain, with moderate to heavy tree density is 120 dB in the median at 1 km, and 9 dB shadow fading standard deviation [7].

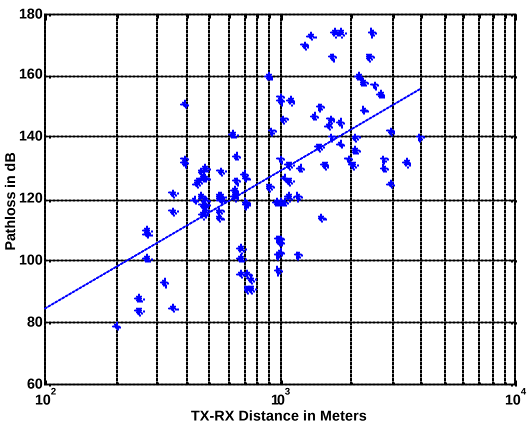

Figure 4. Measured pathloss with regression line.

3 Spatial channel model

To develop a spatial model, spatial correlations were deduced from data. For compactness the correlations were modeled as decaying exponentially with antenna separation along the vehicle *x* and perpendicular to the vehicle *y* :

$$\Phi(x,y) = e^{-\alpha_x|x|}e^{-\alpha_y|y|} \qquad (3)$$

where the decay constants α_x and α_y are determined through fitting to data. A compete correlation matrix of, say, a receiver array may be generated using representation (3) for any two antennas, separated by *x* meters along the vehicle and *y* meters across the vehicle. To test the adequacy of this representation, an ensemble of narrowband synthetic **H**-matrices was generated by imposing a spatial correlation at the receiver and the transmitter arrays on an ensemble of matrices of *iid* complex Gaussian channel coefficients H_{iid} using

$$\mathbf{H} = \Phi_R^{1/2}\mathbf{H}_{iid}\Phi_T^{1/2} \qquad (4)$$

where the receiver correlation matrix Φ_R and the transmitter correlation Φ_T may be computed for the desired antenna configuration. A median capacity of an ensemble of such synthetic **H**-matrices may be compared to the corresponding capacity computed from measured channel coefficients. Correlation coefficients between various antenna elements were computed for antennas displaced along and across the vehicle with 4λ, 8λ, and 12λ separations (λ=0.12 m at 2.5 GHz). A correlation coefficient between two transmit antennas is estimated from the data as:

$$\Phi_{1,2} = \frac{\langle h_{n,t1}h_{n,t2}^*\rangle}{\sqrt{\langle |h_{n,t1}|^2\rangle\langle |h_{n,t2}|^2\rangle}} \qquad (5)$$

where $\langle . \rangle$ denotes averaging over all receivers as well as over time as the van was driven a distance of about 4 m. Similar processing is done for receive antennas. To determine the correlation coefficients as a function of antenna spacing and disposition (i.e. along or across the array), the amplitudes of appropriate correlation coefficients are averaged. Over the entire data set, the median correlation decay constant was found to be about 0.7 m^{-1}, with 20% of links having decay constants of 0.1 m^{-1} or lower, resulting in lower capacity.

Two effects are prominent in reducing the accuracy of capacity prediction. One is the case where the model assumed in (4) is correct but the correlation parameters where estimated with error. This may occur, for example, in cases where there are not enough independent samples used to estimate channel response correlations, as is discussed below. Another source of inaccuracy is where the model itself is incorrect, e.g. the case where the channel correlations are not separable into a product of transmitter correlation and receiver correlation (non-Kronecker correlation [4]) as well as channels that are not Gaussian-distributed at all, as in the case of a keyhole [5] or pinhole channel [6]. In the case of a keyhole or pinhole channel, use of (4) results in an overprediction of channel capacity, as effective rank of the matrix is constrained not through correlations alone but through capacity pinching. It may be observed that using (5) to estimate correlation in conditions of relatively narrow angle spread over a finite aperture results in few independent samples. This leads to an overestimation of correlation and an underprediction of capacity. This was found in this work in the short range LOS measurements, where the error between measured capacity and capacity predicted based on (4) and (5) would reach up to 25%. Excluding the LOS measurements, the median error between predicted and measured capacities was about 3%. When both LOS and non-LOS channels are considered, most errors were still within 10%. Similar accuracy was reported using a separable correlation model in urban cellular environment in [2]. For reference, representing the channel coefficients as a set of *iid* complex Gaussian random variables would result in a 20% error in median computed capacity. Within the reported accuracy, the separable (Kronecker) channel model (4) is judged adequate for non-LOS channels measured in this work.

4 Conclusions

An extensive campaign to characterize the multi-antenna radio propagation channel between two ground based platforms was conducted in a rural area of Lakehurst, NJ. Dozens of links with ground level transmitter and receiver arrays were characterized in mixed wooded/open terrain over ranges of up to 4 km. MIMO capacity was computed for an 8×10 MIMO system using the measured **H**-matrices. It was found that median 8×10 MIMO capacity supported by the channel was about 8 times the corresponding 1×1 capacity, and 3.2 times the corresponding 1×10 capacity. It was found that using arrays containing antennas of both horizontal and vertical polarizations improves capacity for short range LOS channels by almost fifty percent. Some key findings for the rural peer-to-peer channel as compared to the cellular channel may be noted:

- Considerably larger spatial correlations (exponential decay of spatial correlation with a median characteristic constant on the order of 0.7 m^{-1} as compared to about 5 m^{-1} found for a mobile in Manhattan [2]).
- Shadow fading with far larger variation (standard deviation of 17.5 dB as compared to about 8 dB often reported in cellular measurements)
- Significant MIMO capacity, when antennas are spaced widely, offering about 80% of corresponding *iid* channel capacity. Similar capacities were observed in urban areas with smaller arrays.
- Lower cross polarization coupling of about –8.5 dB, yet overall benefit from use of dual polarization at modest SNRs.

5 References

[1] J. Freebersyser, "MNM project briefing", http://www.darpa.mil/ato/solicit/MNM/briefings/freebersyser.pdf

[2] D. Chizhik, J. Ling, P. Wolniansky, R. Valenzuela, N. Costa, K. Huber, "Multiple input multiple output measurements and modeling in Manhattan", *IEEE J. on Select Areas of Communications, special issue on MIMO*, April, 2003.

[3] K. Sulonen, P. Suvikunnas, L. Vuokko, J. Kivinen, P. Vainikainen, "Comparison of MIMO antenna configurations in picocell and microcell environments", *IEEE J. of Selected Areas of Communications*, June, 2003, pp. 703- 712.

[4] E. Bonek, H. Özcelik, M. Herdin, W. Weichselberger, J. Wallace, "Deficiencies of a Popular Stochastic Channel Model", *6th International Symposium on Wireless Personal Multimedia Communications (WPMC'03)*, Oct, 2003.

[5] D. Chizhik, G. Foschini, M. Gans, R. Valenzeula, "Keyholes, correlations, and capacities of multielement transmit and receive antennas", *IEEE Trans. on Wireless Communications*, April 2002.

[6] D. Gesbert, H. Bolcskei, D. Gore, A. Paulraj, "Outdoor MIMO Wireless Channels: Models and Performance Prediction", *IEEE Trans. on Communications*, Dec. 2002.

[7] V. Erceg, L.J. Greenstein, S.Y. Tjandra, S.R. Parkoff, A. Gupta, B. Kulic, A.A. Julius, R. Bianchi, "An Empirically Based Path Loss Model for Wireless Channels in Suburban Environments", *IEEE J. on Selected Areas of Communications*, July 1999.