Experimental Analysis of the Time-Varying MIMO Channel

Jon W. Wallace and Michael A. Jensen*
Department of Electrical and Computer Engineering, 459 CB, Brigham Young University, Provo, UT 84602, wall@ieee.org, jensen@ee.byu.edu

Introduction

Previous studies have demonstrated the potential for significant performance gains when using multiple-input multiple-output (MIMO) transmission in multipath wireless channels. However, realization of these benefits depends critically on the availability of channel state information (CSI) [1]. In rapidly varying channels, the required frequency of training diminishes the capacity improvement enabled by MIMO technology. Previous measurement campaigns have demonstrated some general characteristics of temporal channel fluctuations [2, 3, 4]. However, to date there does not appear to be a comprehensive analysis providing metrics for MIMO channel variation combined with real-world channel measurements. In this paper, we characterize the extent of channel time variation in an outdoor campus environment by taking narrowband measurements at 2.45 GHz in a number of representative locations and present MIMO metrics that quantify the rate of channel time variation, thus allowing channels to be classified based on their time variability.

Channel Metrics

We assume that the MIMO channel at discrete-time index n is characterized by a matrix $\mathbf{H}^{(n)}$ with $H_{ij}^{(n)}$ representing the transfer function between the jth transmit and ith receive antenna. Let the singular value decomposition (SVD) of this matrix be given as $\mathbf{H}^{(n)} = \mathbf{U}^{(n)}\mathbf{S}^{(n)}\mathbf{V}^{(n)H}$, where $\{\cdot\}^H$ is the Hermitian operator. In the following, we will refer to the ith columns of $\mathbf{U}^{(n)}$ and $\mathbf{V}^{(n)}$, symbolized by $\mathbf{u}_i^{(n)}$ and $\mathbf{v}_i^{(n)}$, as the ith receive and transmit eigenvectors, respectively, and $\gamma_i^{(n)} = S_{ii}^{(n)2}$ as the ith channel eigenvalue. Furthermore, we will denote the water-filling capacity and the uninformed transmitter capacity as C_{WF} and C_{UT}, respectively.

Eigenvalue level crossing rate ELCR_i is quantified as the number of times $\gamma_i^{(n)}$ drops below a specified threshold (which is 2 dB below the mean for this work) divided by the total distance traveled. ELCR indicates how quickly the MIMO physical layer (PHY) and medium access layer (MAC) must adapt transmission rate and modulation to the time-dependent channel quality. The eigenvalue spread (ES) indicates the amount of multipath in the channel, ranging from large values for nearly line-of-sight (LOS) channels to lower values for channels with richer multipath. Eigenvalue spread in this campaign is defined as $ES = \mathrm{dB}(\overline{\gamma}_1) - \mathrm{dB}(\overline{\gamma}_3)$, where $\mathrm{dB}(x) = 10\log_{10} x$ and $\overline{\gamma}_i$ represents the eigenvalue mean.

We can define a capacity for the case where the receiver has perfect CSI but the transmitter only has the delayed channel estimate $\widehat{\mathbf{H}}$ as

$$C_T^{(n)} = \log_2 \left| \frac{\mathbf{H}^{(n)}\mathbf{Q}(\widehat{\mathbf{H}})\mathbf{H}^{(n)H}}{\sigma^2} + \mathbf{I} \right|, \qquad (1)$$

where $\mathbf{H}$ is the true channel, σ^2 is the receiver noise variance, $\mathbf{Q}(\widehat{\mathbf{H}})$ is the optimal

1-4244-0123-2/06/$20.00 ©2006 IEEE

transmit covariance given by the water-filling solution, and $\mathrm{Tr}\{\mathbf{Q}\} \leq P_T$. When $C_T^{(n)}$ falls below the uninformed transmit capacity ($C_T^{(n)}$ with $\mathbf{Q} = \mathbf{I}$), which occurs at the motion distance d_T, the transmit CSI is no longer useful.

When both transmitter and receiver have outdated CSI, we can use $\widehat{\mathbf{H}} = \widehat{\mathbf{U}}\widehat{\mathbf{S}}\widehat{\mathbf{V}}^H$ and write the received signal as

$$\hat{\mathbf{y}}_0^{(n)} = \widehat{\mathbf{U}}^H \mathbf{y}^{(n)} = \widehat{\mathbf{S}}\mathbf{x}_0^{(n)} + \mathbf{M}^{(n)}\mathbf{x}_0^{(n)} + \widehat{\mathbf{U}}^H \boldsymbol{\eta}^{(n)}, \tag{2}$$

where $\mathbf{M}^{(n)} = \widehat{\mathbf{U}}^H \left[\mathbf{H}^{(n)} - \widehat{\mathbf{H}}\right] \widehat{\mathbf{V}}$. This procedure constructs parallel channels with gains $\hat{S}_{ii}$ but with interference controlled by the matrix $\mathbf{M}^{(n)}$. We make no assumptions about the distribution of the channel which in turn leads to unknown statistics for $\mathbf{M}^{(n)}$. We assume that the interference vector $\mathbf{M}^{(n)}\mathbf{x}_0^{(n)}$ consists of independent zero-mean Gaussian elements with variance (at time sample n) of $\{\mathbf{R}_z^{(n)}\}_{ii} = \{\mathbf{M}^{(n)}\mathbf{P}^{(n)}\mathbf{M}^{(n)H}\}_{ii}$ to preserve the self-interference power on each antenna, where $\mathbf{P}^{(n)} = \mathrm{diag}(\mathbf{p}^{(n)})$. The mutual information of this system becomes

$$C_R^{(n)} = \sum_i \log_2(1 + p_i^{(n)}\gamma_i^{(n)}/q_i^{(n)}), \tag{3}$$

where

$$q_i^{(n)} = \left\{\mathbf{M}^{(n)}\mathbf{P}^{(n)}\mathbf{M}^{(n)H}\right\}_{ii} + \sigma^2 \qquad\qquad \mathbf{M}^{(n)} = \widehat{\mathbf{U}}^H\mathbf{H}^{(n)}\widehat{\mathbf{V}} - \widehat{\mathbf{S}}. \tag{4}$$

We refer to the distance where $C_R^{(n)}$ drops to 50% of its maximum value as d_R.

Measurements

Measurements were performed with a previously reported narrowband MIMO channel sounder operating at 2.4 GHz [5]. The two basic array types used in this study are (a) a uniform linear array (ULA) of vertically polarized quarter-wavelength monopole antennas and (b) a ULA of dual-polarized patch antennas with half-wavelength spacing. Table 1 lists the name, array type, number of data sets measured, and specific notes for each of the measurement environments considered. In all cases, the transmitter remained stationary during the measurement time. For array types, 8P refers to the 8-port (4-element) dual-polarized patch antennas, and nM(x) refers to an n-element monopole ULA with an interelement spacing of $x\lambda$.

Because environment 1 (DT Field) is a large open field (surrounded by a 1.5 m-high fence composed of vertical metal rods and bricks) with a single large building nearby, fairly slow channel temporal variation is expected. Figure 1 plots a sample time evolution of the first four eigenvalues for Set 1 (patches) and Set 6 (monopoles). Monopole antennas produce rapid variations, likely due to the wide angular spread of arrivals collected by omni-directional elements. The dual-polarized patches, however, have much slower variations, not only due to directive elements that collect power over a narrower angular range, but also because of the partitioning of multipath into vertical and horizontal components. Figure 2 plots the eigenvalue probability density functions (pdfs) for four vertical patch elements with 0.5λ spacing from Set 1 versus pdfs for four monopoles with 0.4λ spacing from Set 6. These results show that the eigenvalues (and therefore capacities) are nearly identical for the

Table 1: Measurement Environments

	Name	Arrays	Sets	Notes
1	DT Field	8P 7M(0.40)	8	Open field, baseline case
2	CB Trees	8P 8M(0.44)	8	Sparse trees around building
3	Coal Yard	8P 8M(0.44)	8	Approximates suburban industrial area
4	CB Corridor	8P 8M(0.44)	6	Corridor between buildings, closed to open area transitions

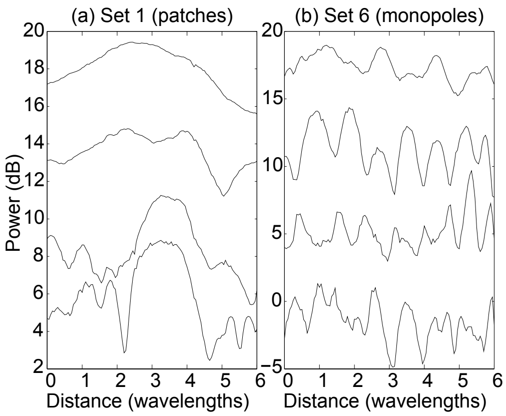

Figure 1: Sample temporal evolution of eigenvalues from Environment 1 for (a) Set 1 with patches and (b) Set 6 with monopoles.

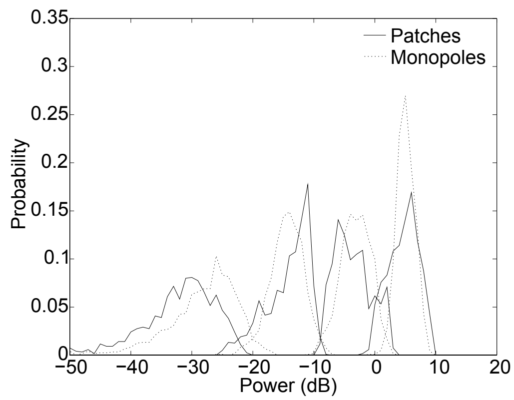

Figure 2: Eigenvalue pdfs of four patches (Set 1) compared with four monopole elements (Set 6)

two antennas. This observation suggests that antennas with more spatial selectivity may be advantageous for MIMO systems in environments with high mobility since they offer high capacity while exhibiting lower temporal variability.

Table 2 summarizes average values of the metrics for monopole and patch arrays across all of the environments in this study. These results indicate that the physical scattering environment has much less of an effect on the time variability of channels than the array configurations and orientations of the MIMO system. Dual-polarized directional patch antennas produced channels with considerably lower temporal variation than omnidirectional monopoles, indicating that spatially selective elements may be advantageous for highly mobile systems.

The measurements also indicate the level of adaptation required of advanced mobile MIMO architectures. Table 2 gives average eigenvalue crossing rates on the order of $0.4/\lambda$ and $0.2/\lambda$ for monopoles and patches, respectively, indicating that an advanced adaptive MIMO MAC/PHY would need to update its modulation and rate a few times per wavelength. On the other hand, values for d_R are about 0.2λ and 0.5λ for monopoles and patches, respectively, suggesting that training must be performed rapidly at the receive PHY to achieve high capacity. Although C_T can be quite large, indicating that transmit CSI is useful for long distances, the

Table 2: Average Metrics vs. Environment

Environment	Monopoles 1	2	3	4	Patches 1	2	3	4
ELCR_1	0.35	0.39	0.49	0.10	0.19	0.05	0.20	0.09
ELCR_2	0.53	0.31	0.38	0.15	0.24	0.08	0.33	0.21
ELCR_3	0.56	0.36	0.66	0.21	0.41	0.29	0.32	0.36
ES	10.0	7.5	8.4	6.5	8.4	8.7	7.6	10.8
C_{WF}	16.9	19.0	18.6	16.3	18.2	18.2	19.3	14.8
C_{UT}	14.6	17.0	16.4	14.1	15.8	16.2	17.2	12.5
d_T	>10	5.42	9.12	8.05	7.27	7.29	6.28	7.48
d_R	0.18	0.23	0.15	0.27	0.25	0.99	0.28	0.33

increase in capacity when the transmitter knows the channel was fairly modest for our measured channels.

Conclusion

This paper presents MIMO channel measurements conducted in an outdoor campus environment at 2.45 GHz, and analyzes the data behavior in terms of channel temporal variation. A number of useful metrics are developed to quantify MIMO time variation and its effect on system performance. The results indicate that rates of system adaptation are on the order of $\lambda/4$ for the physical layer, and 1λ for higher level adaptation of the transmission rate and modulation.

Acknowledgement: This work was supported by the National Science Foundation under Information Technology Research Grant CCR-0313056 and by the U. S. Army Research Office under the Multi-University Research Initiative (MURI) Grant # W911NF-04-1-0224.

References

[1] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanath, "Capacity limits of MIMO channels," *IEEE Trans. Inf. Theory*, vol. 21, pp. 684–702, Jun. 2003.

[2] D. P. McNamara, M. A. Beach, and P. N. Fletcher, "Experimental investigation of the temporal variation of MIMO channels," in *Proc. 2001 IEEE 54th Veh. Technol. Conf.*, Atlantic City, NJ, Oct. 7-11 2001, pp. 1063–1067.

[3] H. Xu, M. Gans, D. Chizhik, J. Ling, P. Wolniansky, and R. Valenzuela, "Spatial and temporal variations of MIMO channels and impacts on capacity," in *Proc. 2002 IEEE Intl. Conf. Commun.*, vol. 1, New York, NY, Apr. 28-May 2 2002, pp. 262–266.

[4] V. Pohl, P. H. Nguyen, V. Jungnickel, and C. von Helmolt, "How often channel estimation is needed in MIMO systems," in *Proc. 2003 IEEE Global Telecomm. Conf.*, vol. 2, San Francisco, CA, Dec. 1-5 2003, pp. 814–818.

[5] J. W. Wallace, M. A. Jensen, A. L. Swindlehurst, and B. D. Jeffs, "Experimental characterization of the MIMO wireless channel: Data acquisition and analysis," *IEEE Trans. Wireless Commun.*, vol. 2, pp. 335–343, Mar. 2003.