Simulation of MIMO Channel Capacity with Antenna Polarization Diversity

Liang Dong, *Member, IEEE,* Hosung Choo, *Member, IEEE,* Robert W. Heath, Jr., *Member, IEEE,* and Hao Ling, *Fellow, IEEE*

***Abstract*— A simulation study of the channel capacity of a MIMO antenna system exploiting multiple polarizations is carried out. We focus on a simple yet realistic tri-monopole antenna structure, taking into account of all the mutual coupling and casing effects using the computational electromagnetics solver NEC. Simulation results show that, with a special transmit geometry, using the collocated tri-monopole antennas at a size-constrained receiver can offer channel capacity that approaches the capacity of an uncorrelated MIMO Rayleigh channel. In addition, it is shown that the capacity increase is mainly attributed to polarization diversity instead of pattern diversity. Furthermore, we find that the mutual coupling and casing effects in the tri-monopole system can actually provide a large capacity increase with less constraint on the antenna configurations than the idealized tri-dipole system.**

***Index Terms*— MIMO systems, fading correlation, channel capacity, multiple polarizations.**

I. Introduction

A promising way of achieving high data rate in wireless communications is to use multiple antennas at both the transmitter and the receiver, forming a multiple-input multiple-output (MIMO) system [1], [2]. Parallel subchannels can be established between the transmitter and the receiver antennas if the fading of the transmitter-receiver pairs is uncorrelated [3]. Correlated fading can pose a serious problem, typically at the mobile handset where the spacing of antenna elements is highly constrained. Polarization diversity and pattern diversity have been exploited to decrease the signal correlation of local antennas at mobile handsets [4]. The performance of a MIMO system employing dual-polarized antennas has been investigated in [5] and [6].

Recently, many researchers have examined the *multiple polarizations* for a MIMO antenna system. Andrews et. al [7] argued for a wireless MIMO link that provides six uncorrelated signals with three electric dipoles and three magnetic dipoles at the transceiver. They assumed an antenna model with ideal polarizations and a rich scattering environment, and verified their analysis experimentally using three orthogonal electric dipoles. Svantesson [8] studied the effect of multipath angular spread on the channel capacity of such a system, and showed that the capacity increase is due to a combination of polarization and pattern diversity. Stancil et. al [9] presented experimental results verifying that co-located electric and magnetic dipoles can be used to realize independent channels. Andersen and Getu [10] proposed an antenna cube with an electric dipole on each of the twelve edges. The diversity among the antennas is a combination of space and polarization diversity.

In this letter, we present a simulation study to investigate the capacity of a multi-polarized MIMO channel. The capacity increase is affected by various system parameters, such as antenna configurations, propagation environments, and system assumptions. For the mobile handset, we use a realistic antenna structure consisting of three collocated monopole antennas mounted on a small box (to simulate the handheld unit). The Numerical Electromagnetics Code (NEC) [11], a full-wave computational electromagnetic solver, is used to simulate the antenna radiation patterns and polarizations taking into account of all the mutual coupling and casing effects. The antenna pattern from the NEC model is verified by measured data from an experimental prototype. Based on the simulation results, we examine the effect of different propagation environments, pinpoint the channel capacity increase from polarization and pattern diversity, and compare the performance to idealized dipole-antenna systems.

II. MIMO Channel Capacity with Antenna Polarization Diversity

We assume a MIMO downlink with n_T transmit antennas at the base transceiver station (BTS) and n_R receive antennas at the mobile station (MS), where the channel is known to the receiver but not to the transmitter. When the transmitted signals are independent with equal power at each antenna, the ergodic channel capacity taken over the probability distribution of $\mathbf{G}$ is given by [1]

$$C = E\left\{\log_2\left[\det\left(\mathbf{I}_{n_R} + \frac{P}{n_T N}\mathbf{G}\mathbf{G}^\dagger\right)\right]\right\} \qquad (1)$$

where $\mathbf{G}$ is an $n_R \times n_T$ transfer matrix of the flat-fading channel, P is the total transmitted power, and N is the variance of the independent Gaussian noise at each receive antenna. Both the signal strength and the channel correlation can affect the capacity [5]. Focusing on the effect of channel correlation on the capacity, we normalize the channel in the sense that $E[||\mathbf{G}||_F] = \sqrt{n_T n_R}$, where $||\cdot||_F$ denotes the Frobenius norm. This normalization has been used in other work such as [12]. A deeper study of normalization issues, along the lines of [13], is a topic for future work.

This work was supported by the Texas Higher Education Coordinating Board under the Texas Advanced Technology Program.

L. Dong is with the Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556 USA (e-mail: ldong1@nd.edu).

H. Choo is with the School of Electronic and Electrical Engineering, Hongik University, Seoul, Korea (e-mail: hschoo@hongik.ac.kr).

R. W. Heath, Jr. and H. Ling are with the Department of Electrical and Computer Engineering, the University of Texas at Austin, Austin, TX 78712 USA (e-mail: rheath@ece.utexas.edu; ling@ece.utexas.edu).

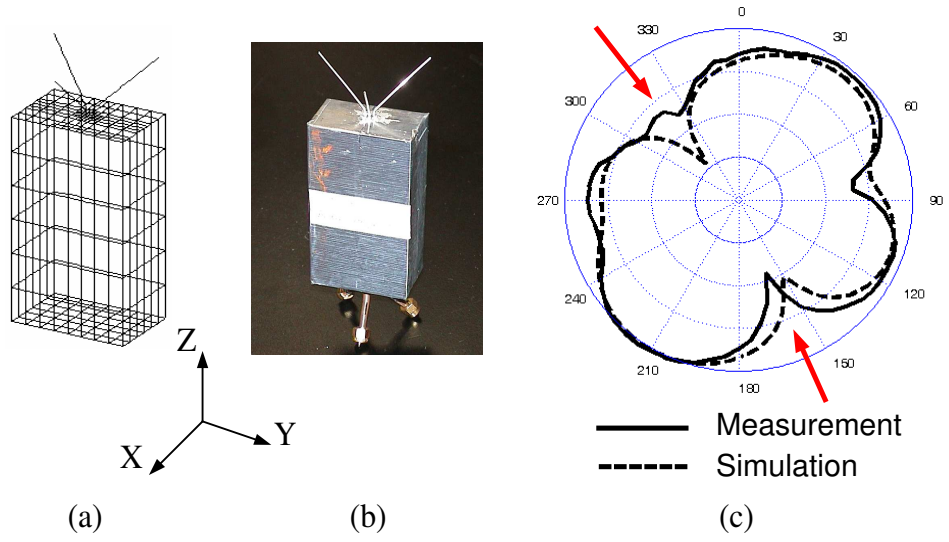


Fig. 1. MS prototype with three quarter-wavelength monopoles (polarization diverse antennas). (a) NEC model, (b) Experimental model, (c) X-Z section of antenna radiation patterns from NEC simulation and measurement.

The elements of $\mathbf{G}$ are correlated by an amount that depends on the propagation environment as well as the polarization of the antenna elements and the spacing between them. One model for $\mathbf{G}$ that takes the fading correlation into account splits the correlation into two independent components as *receive correlation* and *transmit correlation*, $\mathbf{G} = \mathbf{\Psi}_r^{1/2}\mathbf{G}_w\mathbf{\Psi}_t^{1/2}$ [14], [15]. $\mathbf{\Psi}_r$ and $\mathbf{\Psi}_t$ are respectively the covariance matrices of the receive and transmit antennas, and $\mathbf{G}_w$ has uncorrelated complex Gaussian entries. Suppose receive antennas i and j, with field patterns $\mathbf{A}_i$ and $\mathbf{A}_j$ respectively, are exposed to the incident wave represented by electric field $\mathbf{E}$. We assume that the phase angles of E_θ and E_ϕ are independent and uniformly distributed in $[0, 2\pi)$, and they are independent for waves arriving from different directions. Thus the $(i,j)^{th}$ entry of $\mathbf{\Psi}_r$ is [16]

$$\mathbf{\Psi}_r^{(i,j)} = \frac{1}{\sigma_i\sigma_i} \oint E\left\{\left(\mathbf{A}_i(\Omega)\cdot\mathbf{E}(\Omega)\right)\left(\mathbf{A}_j^*(\Omega)\cdot\mathbf{E}^*(\Omega)\right)\right\} d\Omega \tag{2}$$

where σ_i and σ_j are the variances of signals received by antennas i and j, respectively. Ω is the solid angle over (θ, ϕ). In general, $\mathbf{A}_i$ and $\mathbf{A}_j$ contain both amplitude and phase. Suppose antennas i and j are collocated with no spatial diversity, it follows that the phases of $\mathbf{A}_i$ and $\mathbf{A}_j$ are the same with respect to angle Ω. As in (2), the entries of $\mathbf{\Psi}_r$ are the weighted correlations between receive antennas, where the weights are the angular spectrum of the incident field $\mathbf{E}$. In order to achieve large channel capacity, $\mathbf{\Psi}_r$ needs to be close to an identity matrix. The correlation coefficient $\mathbf{\Psi}_r^{(i,j)}$, for $i \neq j$, can be diminished by reducing the similarity in antenna polarizations and/or patterns over the angular space.

III. System Assumptions and Handset Model

In the simulation, we consider a MIMO system that employs three transmit antennas at the BTS and three receive antennas at the MS. The antennas at the BTS can be placed sufficiently apart to provide decorrelation. Therefore, the channel matrix $\mathbf{G}$ has the same statistics as $\mathbf{\Psi}_r^{1/2}\mathbf{G}_w$ [17]. The orientations of the BTS antennas are different, e.g. 90° slanted to each other, in order to provide multi-polarized transmission. Based on the results on dual-polarized systems [5], [6], it is unlikely that the scatterers, especially in a suburban environment, would depolarize signals significantly. However, incident waves with different polarizations are important for the receiver to exploit the antenna polarization diversity. With this special transmit geometry coupled with the random orientation of the receive handset, we may assume that the incident waves arriving at the MS have equal average power in all polarizations.

The MS has a compact array structure consisting of three quarter-wavelength monopoles mounted on a conducting box of dimensions $3 \times 5 \times 10$ cm^3 (to simulate the handheld unit). With a carrier frequency of 2 GHz, the length of each monopole antenna is about 3.75 cm. The feed points of the monopoles are closely collocated. Each antenna is symmetrically slanted with an angle ω with respect to the zenith, thus creating polarization dissimilarity. The Numerical Electromagnetics Code (NEC) is used to simulate the antenna radiation patterns and polarizations. We used the standard "active element" approach to fully take into account of the electromagnetic coupling between the elements and casing effects. This approach determines the gain pattern with one element excited and all the other elements terminated in their source impedances [18]. Fig. 1(a) shows the wire mesh used in the NEC simulation. Fig. 1(b) shows an experimental MS antenna prototype. The antenna radiation patterns from simulation and measurement are compared in Fig. 1(c). It shows the patterns in the xz-plane at $\omega = 45^\circ$, with the excitation at one antenna port and 50-ohm terminations at the other two ports. The antenna pattern from the NEC model agrees well with that from the measurement. The NEC results are used throughout our simulations.

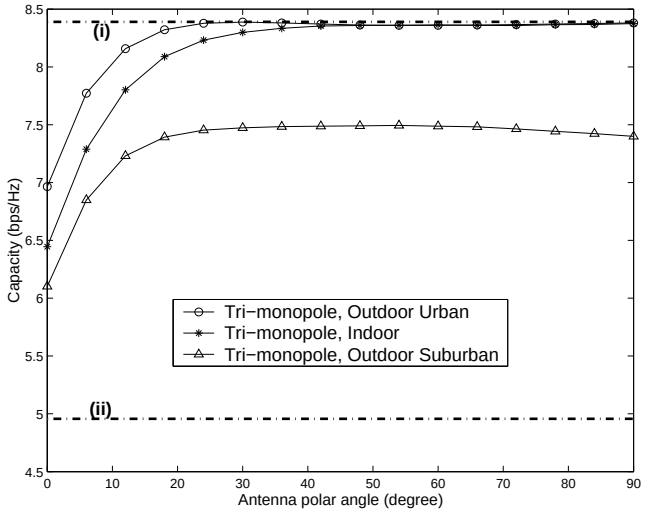


Fig. 2. Channel capacity of a 3×3 MIMO system with antenna polarization diversity in various environments. Average receiver SNR 10 dB. (i) Capacity of 3×3 Rayleigh channel, (ii) Capacity of 3×1 Rayleigh channel.

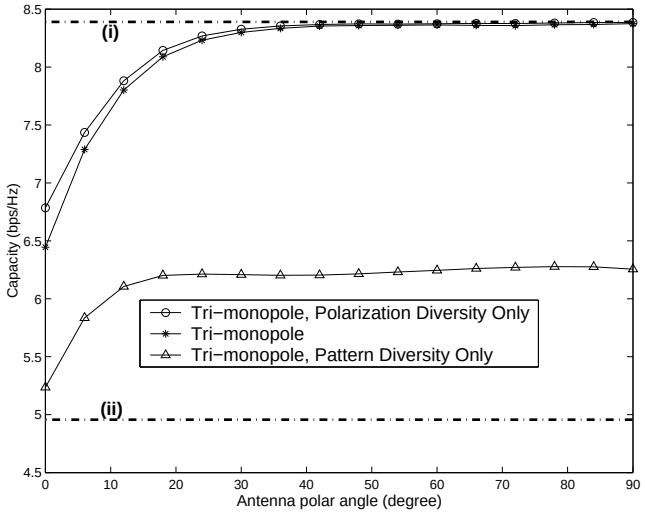


Fig. 3. Channel capacity of a 3×3 MIMO system with different diversity schemes. Average receiver SNR 10 dB. (i) Capacity of 3×3 Rayleigh channel, (ii) Capacity of 3×1 Rayleigh channel.

The propagation environments for the MS are simulated in three scenarios: indoor, outdoor dense urban and outdoor suburban. For indoor, the angular spectrum of incident waves is assumed to have a uniform elevation spectrum $\theta \in [0, 180^\circ)$ and a uniform azimuth spectrum $\phi \in [0, 360^\circ)$. For outdoor dense urban, the angular spectrum of incident waves is limited to a uniform elevation spread of 30° about the horizontal plane, with a uniform azimuth spectrum. For outdoor suburban, the incident waves are also assumed to have a uniform elevation spread of 30° about the horizontal plane, but with a Laplacian azimuth spectrum of $\sigma_\phi = 5^\circ$ [19] and the main azimuth direction randomly selected in $[0, 360^\circ)$.

IV. Results

Fig. 2 illustrates the dependence of channel capacities on the slanting angle ω of the MS monopoles in different propagation environments. We assume perfect transmit power control, hence a normalized channel. Suppose $\rho = \frac{P}{n_T N} = 10$ dB, where P, n_T and N are as defined in (1). Note that the difference of receive branches is considered in the transfer matrix $\mathbf{G}$. With a normalized $\mathbf{G}$, ρ is the average SNR over all receive antennas. We observe that in rich scattering environments such as indoor or outdoor dense urban, the decorrelation of signals at local antennas can be achieved with moderate slanting angle ($\omega > 20^\circ$), and the channel capacity approaches the capacity of an uncorrelated 3×3 Rayleigh channel. In the suburban environment with small azimuth spread, the capacity performance is degraded modestly.

In addition to the polarization difference among the receive antennas, the angular patterns in the principal polarization are also different. Since antenna pattern diversity and polarization diversity are always coupled in practice, the simulation developed here offers a tool to examine which one is more essential in contributing to the capacity gain. We carry out the simulation by deviating from the NEC antenna radiation model to two ideal models:

- *Polarization-Diverse Only*: We use the antenna polarizations from the NEC model, but set the angular patterns to be isotropic in radiation intensity. That is, we substitute $\frac{\mathbf{A}_i(\Omega)}{|\mathbf{A}_i(\Omega)|}$ and $\frac{\mathbf{A}_j(\Omega)}{|\mathbf{A}_j(\Omega)|}$ for $\mathbf{A}_i(\Omega)$ and $\mathbf{A}_j(\Omega)$ in (2), respectively.
- *Pattern-Diverse Only*: We use the pattern differences in radiation intensity, but no polarization diversity. That is, we substitute $|\mathbf{A}_i(\Omega)|$ and $|\mathbf{A}_j(\Omega)|$ for $\mathbf{A}_i(\Omega)$ and $\mathbf{A}_j(\Omega)$ in (2), respectively.

Fig. 3 compares the MIMO channel capacity of the tri-monopole antennas with those from the polarization-diverse-only and the pattern-diverse-only models. Indoor environment is simulated to maximize the effects of different diversity factors. We observe that the channel capacity of the polarization-diverse-only model is very close to that of the actual tri-monopole system. The capacity of the pattern-diverse-only model, on the other hand, is much lower. Thus, it is indeed polarization diversity that accounts for most of the capacity increase in antenna-diverse MIMO systems. This confirms the assumption by Andrew et. al in [7].

Finally, we compare the capacity of the tri-monopole system to that of the idealized tri-dipole model used in previous works. Three electrically short dipoles are orthogonally collocated in the ideal tri-dipole model, where the antenna radiation pattern of a vertical dipole ($\omega = 0$) is $\mathbf{A}(\Omega) = \sin(\theta)\hat{\mathbf{a}}_\theta$. The mutual coupling between local antennas and the casing effect are not considered. In the outdoor dense urban environment, the slanting angle of antennas that maximizes the channel capacity can be calculated as $\omega^* \approx \frac{1}{2}\cos^{-1}\left(-\frac{\pi+15}{7\pi+9}\right) = 62.9^\circ$. This agrees with the simulation result in Fig. 4. In the outdoor suburban environment with Laplacian azimuth spectrum, $\mathbf{\Psi}_r$ can not be exactly an identity matrix due to the asymmetry of the weighted correlations. Therefore, the channel capacity can not reach the capacity of the uncorrelated 3×3 Rayleigh channel, as shown in Fig. 4. One observation from Fig. 4 to Fig. 2 is that practical antennas with mutual coupling and

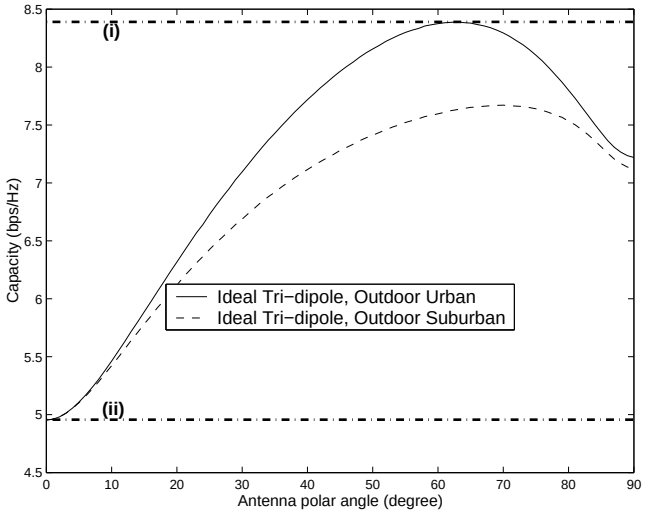


Fig. 4. Channel capacity of a 3×3 MIMO system with antenna polarization diversity (ideal model). Average receiver SNR 10 dB. (i) Capacity of 3×3 Rayleigh channel, (ii) Capacity of 3×1 Rayleigh channel.

casing effects can provide large capacity increase with less constraint on antenna configurations than the idealized tri-dipole system.

V. Conclusions

We presented a simulation study of MIMO channel capacity as a function of antenna configurations and propagation environments. For a size-constrained receiver, antenna polarization diversity provides local decorrelation, hence increased channel capacity. We focused on a simple yet realistic tri-monopole antenna structure, and took into account of all the mutual coupling and casing effects using full-wave electromagnetic simulation. We found that: 1) The tri-monopole antennas can provide a large channel capacity that approaches the capacity of the uncorrelated Rayleigh channel. The increase is especially pronounced when the mobile is in a rich-scattering environment. 2) Although the decorrelation of received signals is due to a combination of antenna polarization and pattern diversity, the capacity gain is mainly attributed to the polarization diversity. 3) The tri-monopole antennas with mutual coupling and casing effects can provide large capacity increase with less constraint on antenna configurations than the idealized tri-dipole system. Further research will be conducted on polarization-diverse MIMO systems using improved propagation models and relaxing the channel normalization assumption. This will involve more sophisticated models of the channel matrix.

References

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Commun.*, vol. 6, no. 3, pp. 311–335, Mar. 1998.

[2] I. E. Telatar, "Capacity of multi-antenna gaussian channels," *Eur. Trans. Telecommun.*, vol. 10, no. 6, pp. 585–595, 1999.

[3] D.-S. Shiu, G. J. Foschini, M. J. Gans, and J. M. Kahn, "Fading correlation and its effect on the capacity of multielement antenna systems," *IEEE Trans. Commun.*, vol. 48, no. 3, pp. 502–513, Mar. 2000.

[4] C. B. Dietrich, K. Dietze, J. R. Nealy, and W. L. Stutzman, "Spatial, polarization, and pattern diversity for wireless handheld terminals," *IEEE Trans. Antennas Propagat.*, vol. 49, no. 9, pp. 1271–1281, Sept. 2001.

[5] P. Kyritsi, D. C. Cox, R. A. Valenzuela, and P. W. Wolniansky, "Effect of antenna polarization on the capacity of a multiple element system in an indoor environment," *IEEE J. Select. Areas Commun.*, vol. 20, no. 6, pp. 1227–1239, Aug. 2002.

[6] R. U. Nabar, H. Bölcskei, V. Erceg, D. Gesbert, and A. Paulraj, "Performance of multiantenna signaling techniques in the presence of polarization diversity," *IEEE Trans. Signal Processing*, vol. 50, no. 10, pp. 2553–2562, Oct. 2002.

[7] M. R. Andrews, P. P. Mitra, and R. deCarvalho, "Tripling the capacity of wireless communications using electromagnetic polarization," *Nature*, vol. 409, pp. 316–318, Jan. 2001.

[8] T. Svantesson, "On capacity and correlation of multi-antenna systems employing multiple polarizations," in *IEEE Int. Antennas Propagat. Symp. Digest*, June 2002, pp. 202–205.

[9] D. D. Stancil, A. Berson, J. P. Van't Hof, R. Negi, S. Sheth, and P. Patel, "Doubling wireless channel capacity using co-polarised, co-located electric and magnetic dipoles," *IEE Electron. Lett.*, vol. 38, no. 14, pp. 746–747, July 2002.

[10] J. B. Andersen and B. N. Getu, "The MIMO cube – a compact MIMO antenna," in *The 5th Int. Symp. on Wireless Personal Multimedia Communications*, Oct. 2002, pp. 112–114.

[11] G. J. Burke and A. J. Poggio, *Numerical Electromagnetics Code (NEC) – Method of Moments*. Lawrence Livermore National Laboratory, 1981.

[12] H. Xu, M. J. Gans, N. Amitay, and R. A. Valenzuela, "Experimental verification of MTMR system capacity in controlled propagation environment," *Electron. Lett.*, vol. 37, no. 15, pp. 936–937, July 2001.

[13] 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, no. 2, pp. 335–343, Mar. 2003.

[14] D. Gesbert, H. Bölcskei, D. A. Gore, and A. Paulraj, "Outdoor MIMO wireless channels: model and performance prediction," *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 1926–1934, Dec. 2002.

[15] J. W. Wallace and M. A. Jensen, "Modeling the indoor MIMO wireless channel," *IEEE Trans. Antennas Propagat.*, vol. 50, no. 5, pp. 591–599, May 2002.

[16] W. C. Jakes, *Microwave Mobile Communications*. John Wiley and Sons, New York, 1974.

[17] D. Chizhik, F. Rashid-Farrokhi, J. Ling, and A. Lozano, "Effect of antenna separation on the capacity of BLAST in correlated channels," *IEEE Commun. Lett.*, vol. 4, no. 11, pp. 337–339, Nov. 2000.

[18] T. Su, K. Dandekar, and H. Ling, "Simulation of mutual coupling effect in circular arrays for direction finding applications," *Microwave Optical Tech. Lett.*, vol. 26, pp. 331–336, Sept. 2000.

[19] K. I. Pedersen, P. E. Mogensen, and B. H. Fleury, "Spatial channel characteristics in outdoor environments and their impact on BS antenna system performance," in *Proc. IEEE Veh. Technol. Conf.*, May 1998, pp. 719–723.