Multiple-Input Multiple-Output (MIMO) Radio Channel Measurements and Experimental Implementation for EDGE

Carol C. Martin, Jack H. Winters, Hanks H. Zeng, Nelson R. Sollenberger, Ashutosh Dixit
AT&T Labs - Research
100 Schulz Drive
Red Bank, NJ 07701-7033
martin@research.att.com

Abstract

In this paper we present results from the first field test to characterize the mobile multiple-input multiple-output (MIMO) radio channel. We measured the capacity, normalized to a single antenna system, and fading correlation between antennas of a system with 4 antennas on a laptop computer and 4 antennas at a rooftop base station. The field test results show that close to the theoretical 4 times the capacity of a single antenna system can be supported in a 30 kHz channel with dual-polarized, spatially-separated base station and terminal antennas under a variety of test runs, including suburban drives, highway drives, and pedestrian routes. Therefore, these results show that it may be possible to provide in excess of 1 Mbps in a 200 kHz mobile radio channel (for the 3G wireless TDMA system EDGE) with the appropriate base station antennas. To test the performance of MIMO for EDGE we have built a real-time experimental system with 2 transmitters and a 2-branch receiver. In this paper we describe the system implementation and present simulation results for 2×2 MIMO-EDGE showing only a 2 dB degradation due to channel estimation.

1. Introduction

Multiple antennas at both the transmitter and receiver have the potential to significantly increase the capacity of a wireless communications channel [1, 2, 3]. That is, using multiple-input multiple-output (MIMO) techniques with these antennas, multiple independent channels can be supported in the same bandwidth, but only if the scattering environment is rich enough. Recent research has shown that high theoretical capacity is possible – data rates as high as 40 bits/s/Hz have been demonstrated (in an indoor slow-fading environment) [4]. Experimental measurements have also been made for stationary microcellular systems [5, 6], showing that this multipath environment can support MIMO with 4 transmit and 4 receive antennas unless there is a line-of-sight between the transmit and receive antennas. However, in cellular mobile radio, the channel differs in several important ways from the indoor or stationary-microcellular channel. Therefore, to determine the potential of MIMO techniques for 3G and 4G wireless systems, field tests are needed to characterize the mobile MIMO radio channel in a typical cellular environment.

Currently, 2 receive and 1 transmit antennas are used at most base stations, and a single transmit and receive antenna is used at the mobiles. Smart antenna upgrades being considered include the use of 4 receive and 4 transmit antennas at the base station. The 3G TDMA wireless system EDGE will provide data rates up to 384 kbps to mobile users. Thus, with 4 base station antennas in combination with 4 receive/4 transmit antennas at the mobile, there is the potential to provide data rates up to 4 times [1, 2] that of EDGE ($\approx$1.5 Mbps) with the same total transmit power, if the multipath environment is rich enough.

In this paper we present results from the first field test to characterize the mobile MIMO radio channel. These results show the potential increase in capacity using 4 transmit and 4 receive antennas at both the base station and terminal in a mobile environment. The test system consisted of a 4-branch base station receiver with rooftop antennas and 4 transmitters at the mobile with antennas mounted on a laptop computer. Real-time baseband signal processing at the base station performed timing recovery and symbol synchronization, and calculated and recorded the 4×4 complex channel matrix every 300 μs. Extensive drive tests plus pedestrian and indoor tests were conducted at 1900 MHz from a typical cellular base station site located in a suburban environment.

To test the performance of MIMO for EDGE we have proposed a receiver architecture and implemented a real-

0-7803-6514-3/00/$10.00©2000 IEEE

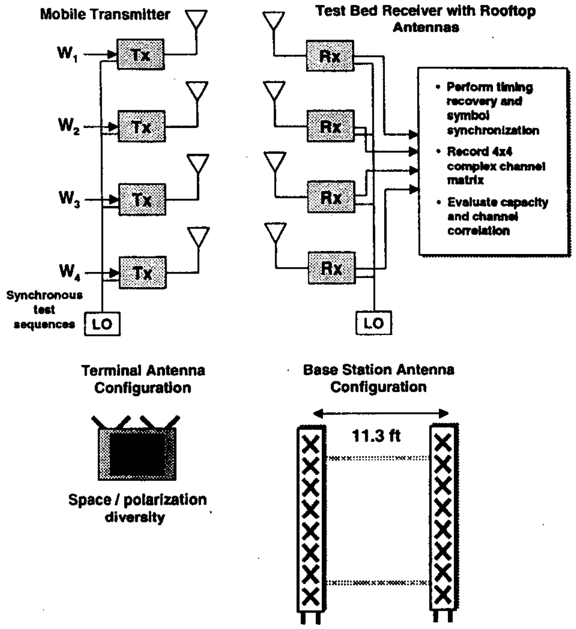

Figure 1. The MIMO channel measurement system.

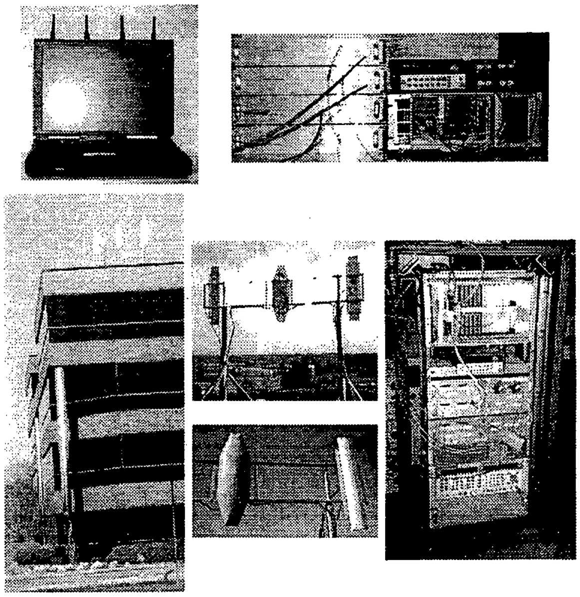

Figure 2. The hardware for the test system: the laptop-mounted terminal antennas, transmitters, roof-mounted antennas, and the receiver system.

time experimental system with 2 transmitters and a 2-branch receiver. In this paper we present simulation results for our 2×2 MIMO-EDGE receiver architecture and describe the experimental system.

In Section 2, we describe the test system and capacity calculation technique. We analyze the measurements in Section 3. (Further details on the test system and measurements are presented in [7].) The MIMO-EDGE real-time implementation is described in Section 4. Conclusions are presented in Section 5.

2. Test System and Measurement Analysis Method

The test system is shown in Figure 1. It consisted of a 4-branch base station receiver with rooftop antennas and 4 transmitters at the mobile with antennas mounted on a laptop computer. The hardware for the test system is shown in Figure 2.

Four coherent 1 watt 1900 MHz transmitters were used to transmit bit and frame synchronous 8-symbol Walsh sequences. A different, orthogonal Walsh sequence was transmitted out of each antenna, with a symbol rate of 24.3 ksymbols per second in a 30 kHz bandwidth (as in IS-136). [1]

The 4-branch base station receiver was similar to that used in previous IS-136 field trials [9, 10]. Four coherent 1900 MHz receivers were used with real-time baseband processing using 4 TI TMS320C40 DSPs. Thus, at this receiver, the sampled complex-baseband signals at each antenna were correlated in the DSPs in real time with each of the 4 Walsh sequences. The complex correlation of each transmit waveform on each antenna was then recorded at 3038 (≈ 24300/8) samples per second.

The base station rooftop antenna array used dual-polarized spatially separated antennas. The base station's two dual-polarized antennas (with slant ±45 degree polarization) were separated by 11.3 feet (≈ 20 wavelengths). This combination of polarization and spatial diversity provided the best performance with 4 antennas in previous field trials of smart antennas [9]. The laptop-mounted terminal antennas included a vertically-polarized antenna array and a dual-polarized array with elements spaced a half wavelength apart.

Drive tests plus pedestrian and indoor tests were conducted at 1900 MHz from the base station site located in a suburban environment. Data was collected along several drive routes including routes in a residential area and on a

---

[1] It was assumed that the data rate and delay spread in the environment was low enough so that the effect of delay spread was negligible. Previous field trials [8] have shown this to be the case.

highway, with vehicle speeds of 30 and 60 mph, and downrange distances between 2 to 5 miles. Pedestrian tests were also conducted by walking with the terminal at several locations and placing it inside a house.

To evaluate the 16 complex channel measurements, we calculated the capacity and fading channel correlation of these results, along with their distributions. Let the measurements at a given time be given by the 4×4 matrix $\boldsymbol{H} = [H_{ij}]$, where H_{ij} is the measurement of the complex channel between the ith transmit and jth receive antenna. The capacity is then given by

$$C = \log_2(\det[\boldsymbol{I} + \frac{\rho}{4}\boldsymbol{H}^\dagger \boldsymbol{H}]) \qquad (1)$$

where $\det[]$ denotes the determinant, I is the identity matrix, ρ is the signal-to-noise ratio, and the superscript † denotes complex conjugate transpose.

Now, we are interested in the capacity increase with MIMO techniques, and therefore we normalize this capacity by the average capacity with a single transmit/receive antenna and the same total transmit power. Since, due to the shadow fading, this average capacity at a given time is unknown, we estimate it by averaging the capacity of all 16 measured channels, i.e., the normalized capacity is given by

$$C_n = \frac{\log_2(\det[\boldsymbol{I} + \frac{\rho}{4}\boldsymbol{H}^\dagger \boldsymbol{H}])}{\frac{1}{16}\sum_{i=1}^{4}\sum_{j=1}^{4}\log_2(1 + \frac{\rho}{4}H_{ij})} \qquad (2)$$

Our computer simulation results show that this normalization works well, as long as the channel powers are approximately equal and the channel correlations are not too high. The results show that at $\rho = 20$ dB, the actual capacity is about 3.77 with independent Rayleigh fading for all channels with equal power.

Computer simulations show that the distribution of the capacity does not vary significantly with averaging. This is because the normalized capacity with 4 transmit/4 receive antennas is already averaged over the four spatial channels, and is in marked contrast to the capacity of a single transmit/receive antenna system where the capacity varies substantially with the Rayleigh fading. Thus, the capacity for pedestrian users does not vary significantly with small changes in position (or with time) and is similar to that of mobile users. In the next section, we present our results for the distribution of the instantaneous normalized capacity, as these results hold for both pedestrian and mobile users.

3. Results

We first verified that the channel powers were approximately equal with the dual-polarized base station and terminal antenna arrays. The results show that the received signal powers generally differ by less than 1-2 dB across the channels, thus confirming that the capacity calculation of (2) will be accurate.

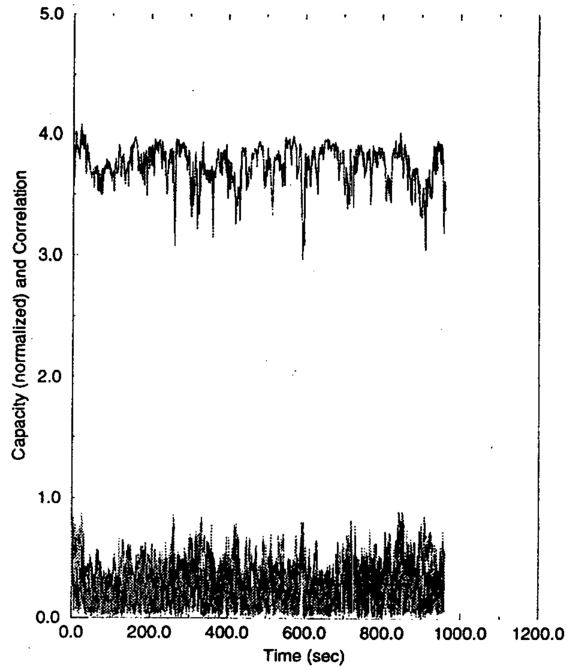

Figure 3. Measured normalized capacity and correlation versus time.

Figure 3 shows the normalized capacity, along with the fading correlation for the transmit and receive antennas, versus time for one of the residential drive routes. The capacity and correlation values were averaged over 1 second. Note that the capacity does not vary significantly and is close to 3.77 even with correlation coefficients as high as 0.5. The measured results show that the capacity does not vary significantly even at slow speeds when there are large variations in the signal level due to Rayleigh fading. On the highway drive route, capacity drops to around 3.0 for short periods of time. These periods are seen to correspond to high signal strength and high correlation, even between terminal antennas, implying that a strong direct ray was present. The results indicate that the multipath environment is rich enough to support 4×4 MIMO in the vast majority of the locations. Even when the capacity was lower, though, it was only reduced to 3.

The above points are illustrated in Figure 4, which shows the normalized capacity distribution for all test runs. The capacity distribution is seen to be close to ideal for all tests. Only in the tail of the distribution, where the CDF is below 0.2, is there significant deviation from ideal for some tests.

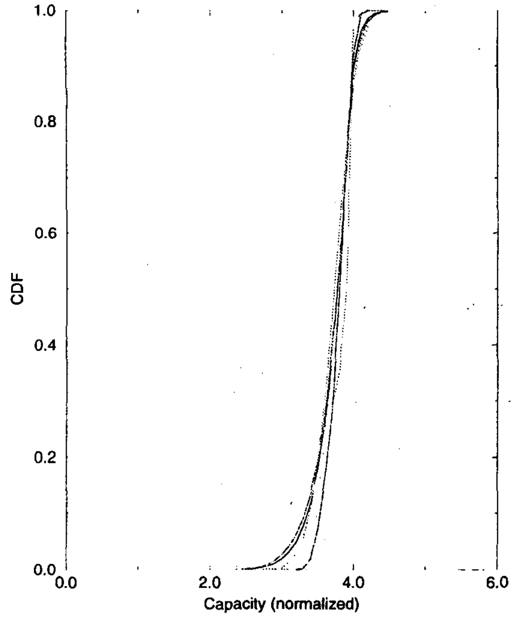

Figure 4. Normalized capacity distribution for all tests.

4. Experimental Implementation for EDGE

These results show that with MIMO techniques it may be possible to substantially increase the data rates in a mobile radio channel for next generation cellular data services. Extending our work on smart antennas for TDMA IS-136 to 3G EDGE, we have implemented a real-time experimental EDGE radio link that supports 2-branch interference suppression for realistic mobile dispersive multipath fading channels. To demonstrate the feasibility and performance of MIMO for EDGE under realistic channel conditions in the laboratory and in the field, we have enhanced the EDGE radio link to support real-time 2×2 MIMO processing.

The MIMO-EDGE receiver architecture is shown in Figure 5. Two independent data streams are transmitted and received by the 2-branch receiver. The MIMO receiver extracts each of the data streams based on the interference suppression approach, treating each signal in turn as a co-channel interferer. The prefilters suppress the interferer and shorten the channel impulse response for the desired signal. The shortened channel is further equalized by the 2-stage soft-output equalizer which is the cascade of a delayed decision-feedback sequence estimator (DDFSE) and a maximum *a posteriori* probability (MAP) estimator. The channel shortening and prefilter design is based on the minimum mean-square error decision-feedback equalization (DFE) rule. In particular, the equalizer is trained as if it was a DFE with the prefilters as the feedforward filters and the shortened channel as the feedback filter. The DFE weights are computed from the MIMO channel impulse responses which are jointly estimated using the least-squares method.

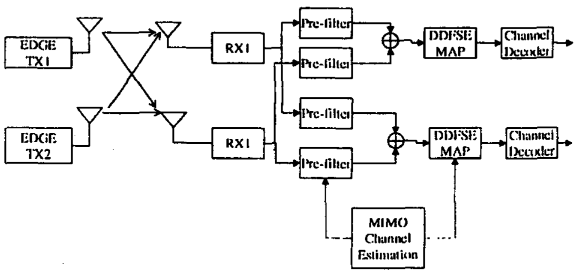

Figure 5. MIMO-EDGE receiver architecture.

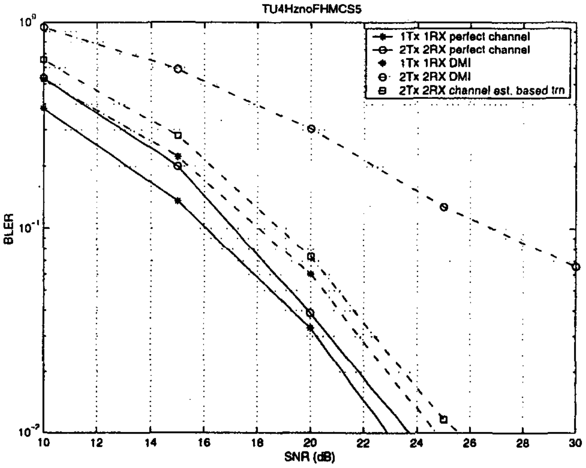

Figure 6. MIMO-EDGE simulation results.

The key added feature to the EDGE 2-branch interference suppression algorithm described in [11, 12], that uses direct matrix inversion (DMI) for equalizer training, is the joint MIMO channel estimator. Figure 6 shows computer simulation results of the block error rate (BLER) versus SNR for 2×2 MIMO, comparing channel estimation based equalization with the DMI approach. Simulations were performed using the GSM typical urban channel profile, 4 Hz Doppler frequency, and the EDGE MCS-5 modulation and coding scheme. For a 10% BLER, the results show a 1 dB loss for the 2×2 compared to the 1 × 1 case assuming perfect channel estimation. The channel estimation based equalization approach performs significantly better than DMI with only a 2 dB degradation due to equalizer training. Further improvement in performance is expected by using successive interference cancellation.

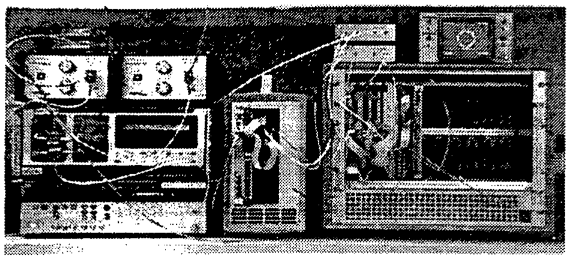

Figure 7. MIMO-EDGE experimental system in the laboratory.

Figure 7 shows the MIMO-EDGE experimental system in the laboratory with the multipath channel fading emulator. The RF sections are not shown in this photograph. From left to right are: (a) the RF channel fading emulator, with an HP synthesizer serving as the fader's local oscillator, noise sources, and attenuators to set SNR levels; (b) the DSP baseband signal processing hardware for the transmitters and 2-branch receiver using VME boards with multiple TI TMS320C40 floating point processors, A/Ds, D/As and clocks; (c) two-channel analog low-pass filter boxes; and (d) an oscilloscope displaying the EDGE 8-PSK signal constellation.

Laboratory tests of the experimental MIMO-EDGE radio modem are in progress. Preliminary results show close agreement to the simulation results. The experimental radio modem will support MIMO real-time field tests in the near future.

5. Conclusions

The field test results show that, with 4 transmit and 4 receive antennas, close to the theoretical 4 times the capacity of a single antenna system can be supported in a 30 kHz channel with dual-polarized, spatially-separated base station and terminal antennas. Results show that for the 4×4 MIMO system the degradation in capacity due to fading correlation is small even with correlation coefficients as high as 0.5. Close to the theoretical 4 times capacity was achieved under a variety of test runs, including suburban drives, highway drives, and pedestrian routes, both close to the base station and inside a house a few miles from the base station. Therefore, it may be possible to provide in excess of 1 Mbps in a 200 kHz mobile radio channel (for the 3G wireless TDMA system EDGE) with the appropriate base station antennas. These field test data and results are valuable inputs to the design, development, and deployment of multi-antenna systems and MIMO adaptive antenna algorithms and show that MIMO techniques could substantially increase the data rate and capacity of future cellular systems.

To test the performance of MIMO for EDGE we have built a real-time experimental system with 2 transmitters and a 2-branch receiver. A key feature of the 2×2 MIMO-EDGE receiver is the joint MIMO channel estimator that shows only a 2 dB degradation due to equalizer training. Field tests of the experimental radio modem will be conducted in the near future.

References

[1] J. H. Winters, "On the capacity of radio communication systems with diversity in a Rayleigh fading environment," *IEEE Journal on Selected Areas in Communications*, June 1987.

[2] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multiple antennas," *Bell Labs Technical Journal*, vol. 1, no. 2, Autumn 1996, pp. 41-59.

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

[4] G. D. Golden, G. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky, "Detection algorithm and initial laboratory results using the V-BLAST space-time communication architecture," *Electronic Letters*, vol. 35, no. 1, Jan, 7, 1999, pp. 14-15.

[5] M. Steinbauer, A. F. Molisch, A. Burr, and R. Thomae, "Channel capacity of MIMO systems based on measurement results," to be presented at *WCNC '00*, September 2000.

[6] J.-P. Kermoal, P. Mogensen, S. Jensen, J. Anderson, F. Frederiksen, T. S. Rensen, and K. Pedersen, "Experimental investigation of multipath richness for multi-element transmit and receive antenna arrays," *Proc. IEEE Veh. Technol. Conf.*, May 2000.

[7] C. C. Martin, J. H. Winters, and N. R. Sollenberger, "Multiple-input multiple-output (MIMO) radio channel measurements," *Proc. IEEE Veh. Technol. Conf.*, September 2000.

[8] C. C. Martin, N. R. Sollenberger, and J. H. Winters, "Field test results of downlink smart antennas and power control for IS-136," *Proc. IEEE Veh. Technol. Conf.*, May 1999.

[9] J. H. Winters and G. D. Golden, "Adaptive antenna applique field test," *Fourth Workshop on Smart Antennas in Wireless Mobile Communications*, Stanford University, July 24, 1997.

[10] R. L. Cupo, G. D. Golden, C. C. Martin, K. L. Sherman, N. R. Sollenberger, J. H. Winters, and P. W. Wolniansky, "A four-element adaptive antenna array for IS-136 PCS base stations," *Proc. IEEE Veh. Technol. Conf.*, May 1997, pp. 1577-1581.

[11] H. Zeng, Y. Li, and J. H. Winters, "A fast selective-direction MMSE timing recovery algorithm for spatial-temporal equalization in EDGE," *Proc. IEEE Veh. Technol. Conf.*, September 2000.

[12] H. Zeng, Y. Li, J. H. Winters, and H. Sadjadpour, "A 2-stage soft-output equalizer for EDGE," *WCNC*, September 2000.