Multiple-Input Multiple-Output (MIMO) Radio Channel Measurements

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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. For this 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, 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.

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 [7] 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. The base station rooftop antenna array used dual-polarized spatially separated antennas, while several different antenna configurations were considered for the terminal, including a vertically-polarized antenna array and a dual-polarized array. We conducted our tests using a 30 kHz bandwidth, with bit and frame synchronous orthogonal sequences transmitted from each of the 4 transmitters at the mobile. 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. The data

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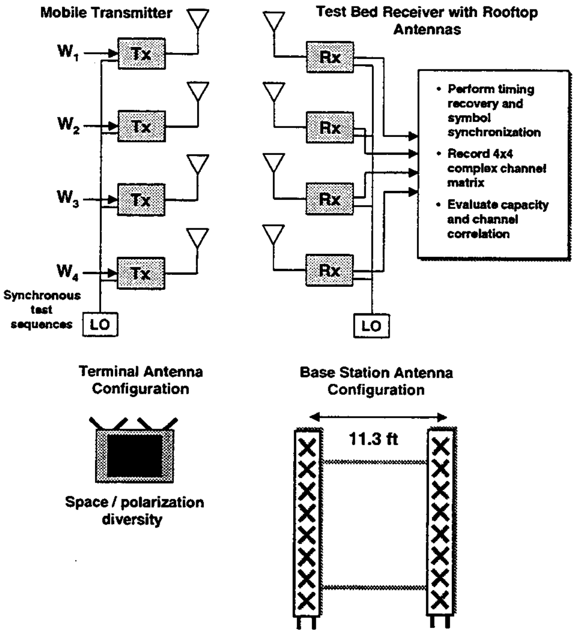

Figure 1. The MIMO channel measurement system.

collected along the same drive routes on separate drive tests was processed to compare the results from different antenna configurations. To assess performance we evaluated and compared the distributions of the capacity, with these configurations.

In Section 2, we describe the test system. We describe the capacity calculation technique in Section 3 and analyze the measurements in Section 4. Conclusions are presented in Section 5.

2. Test System

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 ($\approx$ 24300/8) samples per second.

To verify the performance of this setup under ideal fading conditions, we used Rayleigh fading emulators in the laboratory. Figure 3 shows the laboratory setup, which used all 8 hardware fading emulators that were available. Note that since there are 16 separate channels with our system of 4 transmit and 4 receive antennas, half of the channels had the same fading as the other half. However, this was adequate to verify that the test system impairments were less than the accuracy of the measurements to be reported.

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 ($\approx$ 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. Both simple monopoles and commercial handset antennas were used. In this paper we present the results for the dual-polarized terminal array with monopole elements.

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 3 drive routes: A, B, and parkway. Drive routes A and B are in a residential area with tall trees and an open area with office parks with vehicle speeds on the order of 30 mph and a downrange distance of 2 miles. The parkway drive route is along the Garden State Parkway, with speeds on the order of 60 mph and a downrange distance of about 5 miles. For these routes, the terminal antennas were located inside a van. Pedestrian tests were also conducted by walking with the terminal around the van in a parking lot next to the rooftop antennas and at several locations near to and inside a house located on drive route A.

3. Measurement Analysis Method

As noted above, the test setup collected the 16 complex channel measurements (the channels between the 4 transmit and 4 receive antennas) at a 3.038 ksamples per second rate. To evaluate these measurements, we calculated the capacity and fading channel correlation of these results, along with

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[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.

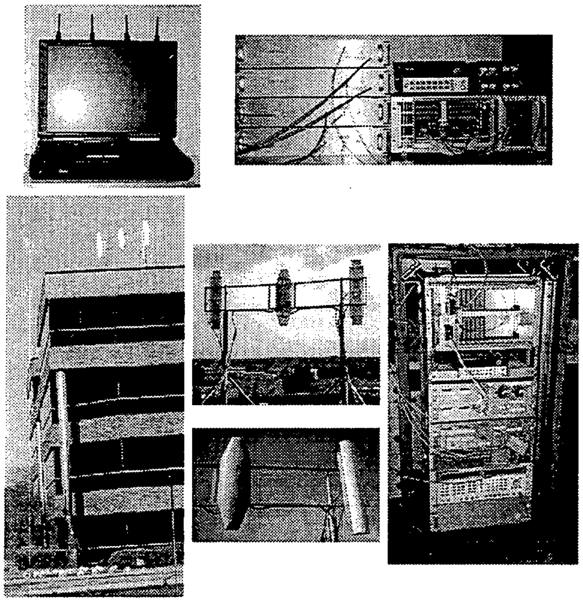

Figure 2. The hardware for the test system: the laptop-mounted terminal antennas, transmitters, roof-mounted antennas, and the receiver system.

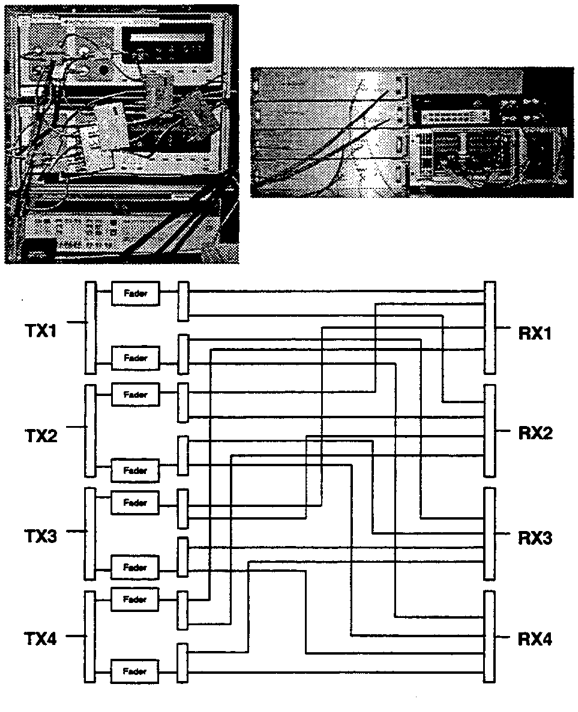

Figure 3. The laboratory test setup.

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

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

where det[] denotes the determinant, ρ is the signal-to-noise ratio, and the superscript † denotes complex conjugate transpose. Note that this capacity is also given by

$$C = \sum_{i=1}^{4} \log_2(1 + \frac{\rho}{4}\lambda_i) \qquad (2)$$

where λ_i is the ith eigenvalue of $\boldsymbol{H}^\dagger \boldsymbol{H}$.

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

$$C_n = \frac{\log_2(\det[1 + \rho \boldsymbol{H}^\dagger \boldsymbol{H}])}{\frac{1}{16}\sum_{i=1}^{4}\sum_{j=1}^{4} \log_2(1 + \rho H_{ij})} \qquad (3)$$

Our computer simulation results show that, with independent Rayleigh fading with equal powers in all channels, the estimated average is nearly identical to the actual average, and the use of the estimated average produces a negligible difference in the distribution of capacity (since 16-fold diversity is used). Thus, this normalization works well, as long as the channel powers are approximately equal and the channel correlations are not too high (these effects are examined below). The normalized capacity does depend on ρ, though. However, our computer simulation results show that the normalized capacity varies only a few percent with ρ for ρ greater than 5 dB, which is the normal cellular operating range. In our analysis, we use a fixed value of ρ (20 dB).[2]

As mentioned above, with 4 transmit/4 receive antennas the capacity should be about 4 times that with a single transmit/receive antenna [2]. Computer simulation results show that at $\rho = 20$ dB, the actual capacity is about 3.77 with independent Rayleigh fading for all channels with equal power.

Next, consider time averaging of the capacity. Figure 4 shows computer simulation results of the cumulative distribution function (CDF) of the normalized capacity averaged over 8 and 128 fades, as well as the instantaneous capacity, with independent-Rayleigh-fading equal-power channels. Note that the distribution of the capacity does not vary

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[2] Furthermore, from our analyses we make relative comparisons of the capacity of different configurations over the same drive routes, and such comparisons should not be affected by the small effect of ρ.

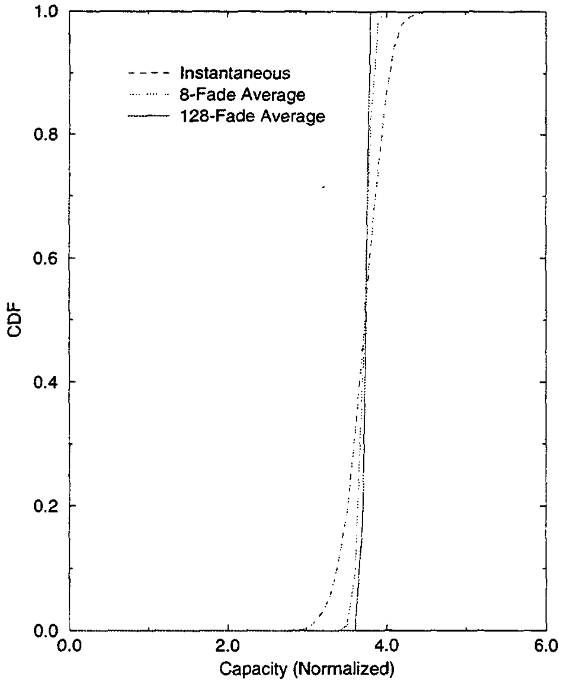

Figure 4. Computer simulation results of the distribution of the normalized capacity averaged over 8 and 128 fades, as well as the instantaneous capacity.

significantly with averaging. The instantaneous normalized capacity distribution is only slightly wider than that for 128 fades (1 second averaging at 30 mph). 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. Thus, 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 (particularly since in the drive tests the vehicle speed varied and was not recorded).

4. Results

We first verified that the channel powers were approximately equal with the dual-polarized base station and terminal antenna arrays. Figure 5 shows the received signal strength versus time for all 16 channels for drive route A. The received signal strength was averaged over 1 second intervals. 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 (3) will be accurate. Note the large variation in signal level particularly at the beginning of the drive route and around 875 seconds due to inadequate averaging of the Rayleigh fading when the vehicle was stationary.

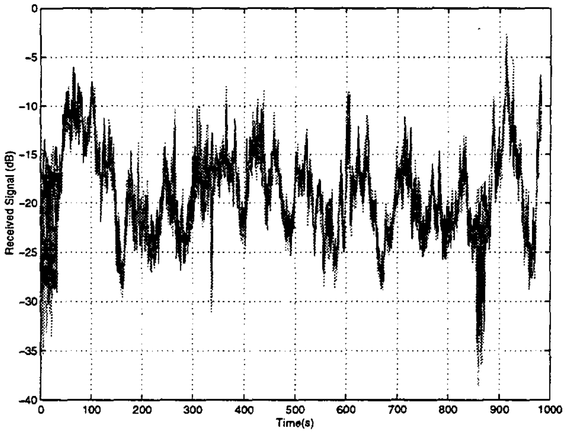

Figure 5. Received signal strength for all 16 channels for drive route A.

Next, consider the variation of the capacity over time for different velocities. Figures 6, 7, and 8 show the normalized capacity, along with the fading correlation for the transmit and receive antennas, versus time for drive route A, parkway, and indoors. Note that the terminal velocity is about 30 mph, 60 mph, and 1 mph, respectively, in these three figures. The capacity and correlation values were averaged over 1 second. Note that as the velocity increases, the capacity changes more slowly with time (due to the averaging of the fast fading). However, the capacity does not vary significantly even at slow speeds when there are large variations in the signal level due to Rayleigh fading. The correlation appears higher indoors than at 30 mph, but this is due to inadequate averaging at slow speeds. In Figures 6 and 8, the capacity varies rapidly with time, but remains close to 3.77 even with correlation coefficients as high as 0.5. However, in Figure 7, the capacity drops to around 3.0 for short periods of time. These periods are seen to correspond to high correlation, even between terminal antennas, implying that a strong direct ray was present. During these periods, the signal strength was also significantly higher, which further indicates the presence of a strong direct ray. This drop in capacity was only seen along the parkway, and not even in

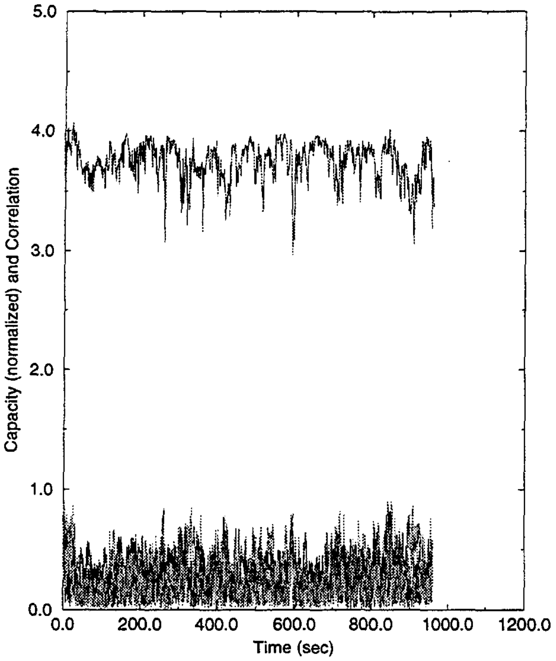

Figure 6. Normalized capacity and correlation versus time for drive route A.

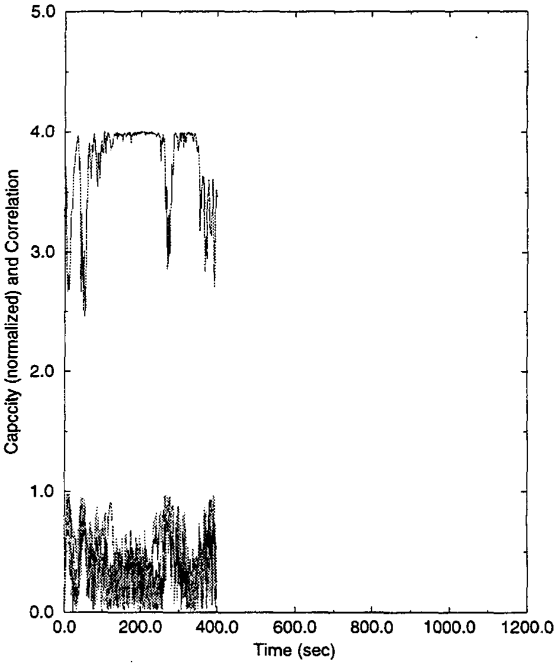

Figure 7. Normalized capacity and correlation versus time for the parkway drive route.

the parking lot below the base station antennas. This indicates 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 9, 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 – in particular, the parkway drive route which is the far left curve.

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.

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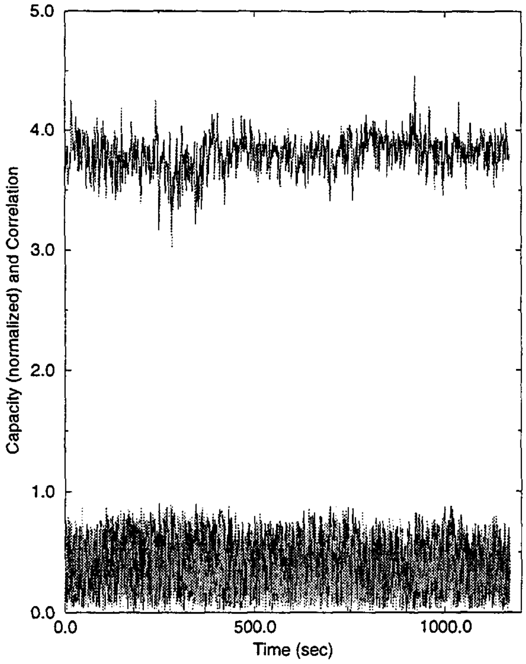

Figure 8. Normalized capacity and correlation versus time for the indoor test.

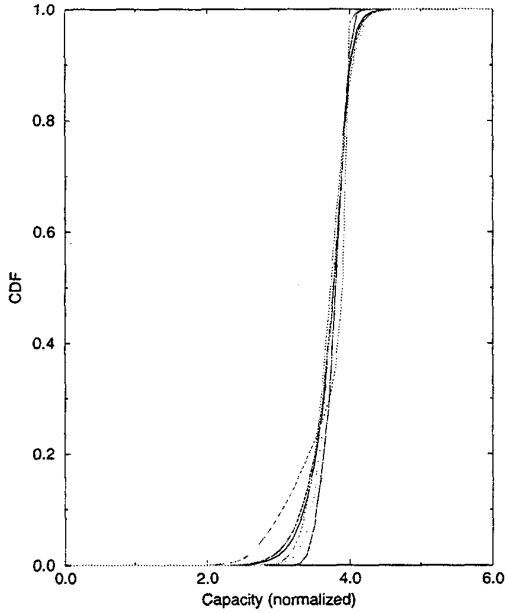

Figure 9. Normalized capacity distribution for all tests.

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