MIMO Radio Channel Measurements: Performance Comparison of Antenna Configurations

Carol C. Martin, Jack H. Winters   Nelson R. Sollenberger

AT&T Labs - Research
200 S. Laurel Avenue
Middletown, NJ 07748
E-mail: martin@research.att.com

Mobilink Telecom, Inc.
One Arin Park
Middletown, NJ 07748

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 for different antenna configurations using 4 transmit and 4 receive antennas at both the base station and terminal in a mobile environment. We compare results for a base station rooftop antenna array consisting of dual-polarized spatially separated antennas, a vertically-polarized multibeam antenna array, and a dual-polarized multibeam antenna array. 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.**

I. 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 path 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.

In a previous paper [7], we presented initial field test results and provided details on the test system and measurements. Here we extend this study by comparing the increase in capacity for different antenna configurations 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. We considered several different antenna configurations for the base station and terminal. We compare results for a base station rooftop antenna array consisting of dual-polarized spatially separated antennas, a vertically-polarized multibeam antenna array, and a dual-polarized multibeam antenna array. Several antenna configurations were tested for the terminal, including a vertically-polarized antenna array, a dual-polarized array, and combinations of antennas with space, polarization, and pattern diversity. 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, 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. Data was collected along drive routes in a residential area with vehicle speeds on the order of 30 mph and on a highway with speeds of more than 60 mph. To assess performance we evaluated and compared the distributions of the capacity, as well as the fading correlation, 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.

II. TEST SYSTEM

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. (Details on the test system and measurements are presented in [7].) 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.

At the base station, four coherent 1900 MHz receivers were used with real-time baseband processing using 4 TI TMS320C40 DSPs. The receivers sampled the complex-baseband signal at each antenna and recorded the complex correlation of each transmit waveform on each antenna at a rate of 3038 ($\approx$ 24300/8) samples per second.

We considered several different antenna configurations for the base station and terminal (see Fig. 1). The base station rooftop antenna array configurations included dual-polarized spatially separated antennas, a vertically-polarized multibeam antenna array, and a dual-polarized multibeam antenna array. The first configuration (B1) used two dual-polarized antennas (with slant $\pm$45 degree polarization) that were separated by 11.3 feet ($\approx$ 20 wavelengths). This combination of polarization and spatial diversity provided the best performance with 4 antennas in previous field trials of smart antennas [8]. The second (B2) and third (B3) configurations were multibeam antennas. The sec-

0-7803-7005-8/01/$10.00 © 2001 IEEE

TABLE I
FIELD TEST CASES

Case	Base Config.	Terminal Config.
1	B1	T1a
2	B1	T3
3	B1	T1b
4	B1	T2
5	B2	T1b
6	B2	T2
7	B3a	T2
8	B3b	T2

ond configuration was a vertically polarized array, with four 30° beams covering a 120° sector. The third configuration was a dual-polarized (with slant ±45 degree polarization) multibeam antenna, with four 30° beams in each polarization. We chose the 4 beams in two different ways - alternating polarizations (B3a), i.e., +45°, -45°, +45°, -45° for beams 1, 2, 3, and 4, respectively, and the two dual-polarized center beams (B3b) (the mobile was kept within these two beams during the field test).

The laptop-mounted terminal antennas included a vertically-polarized antenna array (T1), a dual-polarized array (T2), and a combination of antennas with space, polarization, and pattern diversity (T3). The antenna elements were spaced half a wavelength apart in configurations T1 and T2. These three configurations are shown in Fig. 1. For configuration T1, there were two types of antennas used: antennas from Ericsson handsets (T1a) and monopole antennas (T1b). Monopole antennas were used for configuration T2 and antennas from Ericsson handsets were used for configuration T3.

Table 1 lists the combination of antenna configurations for which data was collected.

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 a multi-lane highway, 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.

III. MEASUREMENT ANALYSIS METHOD

To evaluate the 16 complex channel measurements (the channels between the 4 transmit and 4 receive antennas), 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

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

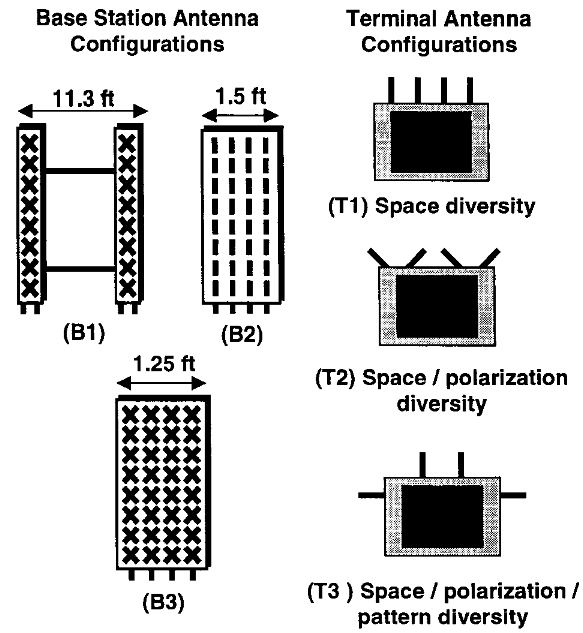

Fig. 1. MIMO antenna configurations.

where det[] denotes the determinant, I is the identity matrix, ρ is the signal-to-noise ratio at each receive antenna, and the superscript $\dagger$ 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

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

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 ρ = 20 dB, the actual capacity is about 3.77 with independent Rayleigh fading for all channels with equal power.

With the multibeam antenna configuration, the equal-power assumption no longer holds, and (2) is no longer valid. Indeed, if one beam receives a signal that is much stronger than the other beams, then from (2) the average capacity will be 1/4 that of the strongest beam, and the normalized capacity will be 4, rather than the correct value of 1. Therefore, for the multibeam configuration, we normalize the capacity by the average capacity of the strongest beam, i.e.,

$$C_n = \frac{\log_2(\det[\boldsymbol{I} + \frac{\rho}{4}\boldsymbol{H}^\dagger \boldsymbol{H}])}{\frac{1}{4}\sum_{i=1}^{4}\log_2(1+\rho H_{ij_{max}})} \tag{3}$$

where j_{max} is the beam with the strongest receive signal, determined as below. Note that in (3) the average capacity is estimated by averaging over 4 channels, rather than 16, and therefore the estimated average has a significant variance about the actual average. This results in an increased spreading of the normalized capacity distribution. Furthermore, this affects the method for choosing the strongest beam. Our computer simulation results show that, with independent Rayleigh fading of equal-power channels, the strongest antenna must be chosen based on the average capacity of each beam with that capacity averaged over at least 20 fades to eliminate the effect of choosing a beam based on short-term fast fading. Otherwise, the calculated average normalized capacity can be significantly reduced. Therefore, in our analysis, we choose the beam with the highest average capacity, with that capacity averaged over 1 second when driving (for pedestrian and indoor tests, the strongest beam was chosen for the entire test).

Computer simulations show that the distribution of the capacity does not vary significantly with averaging [7]. 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.

IV. 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.

With the multibeam antenna, the channel powers can vary substantially, though. Fig. 2 shows the received signal strength versus time for the 16 channels with case 8 and route A. These results show that over route A, the received signal strength in the two center beams differed by as much as 20 dB. However, the received signal strength in the orthogonal polarizations in the same beam were generally nearly equal, although the difference was as much as 4 dB in some cases.

Figure 3 shows the normalized capacity, along with the fading correlation for the transmit and receive antennas, versus time for case 4 and route A. 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, it was only reduced to 3.

The capacity is much lower with the multibeam antennas, though. Figs. 4 to 7 show the capacity and correlation versus time for cases 5 to 8, respectively, with route A. Fig. 4 shows that with the vertically-polarized multibeam antenna, the normalized capacity is usually only slightly higher than one, except for short periods of time where it increases to about 2. This occurs when the terminal is between beams. Note that the correlation is generally higher for some antennas when the capacity is higher, i.e., when the terminal is between beams. This is apparently due to the fact that when the terminal is in one beam, the other beams are mainly receiving noise, which has low correlation with the desired signal in the main beam. Thus, the capacity with the multibeam antenna corresponds to the number of beams with significant received signal power, as expected.

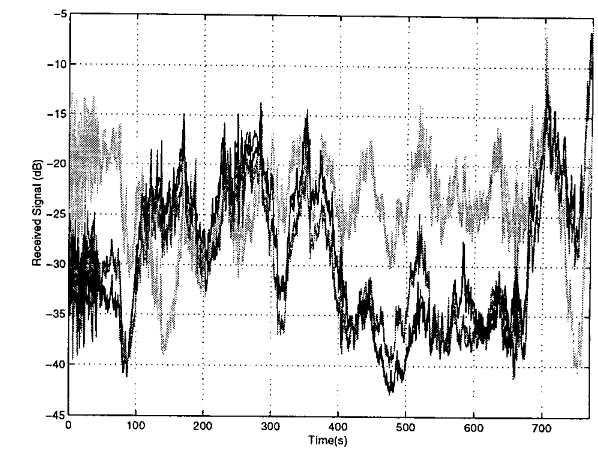

Fig. 2. Received signal strength for all 16 channels with multibeam antenna.

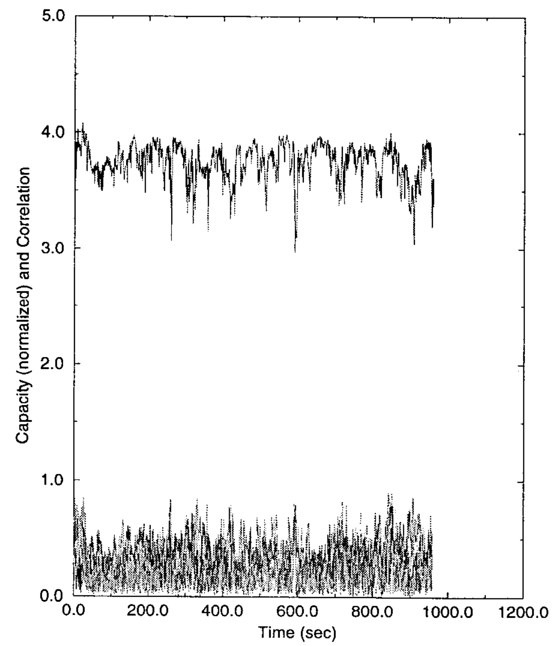

Fig. 3. Measured normalized capacity and correlation versus time for case 4.

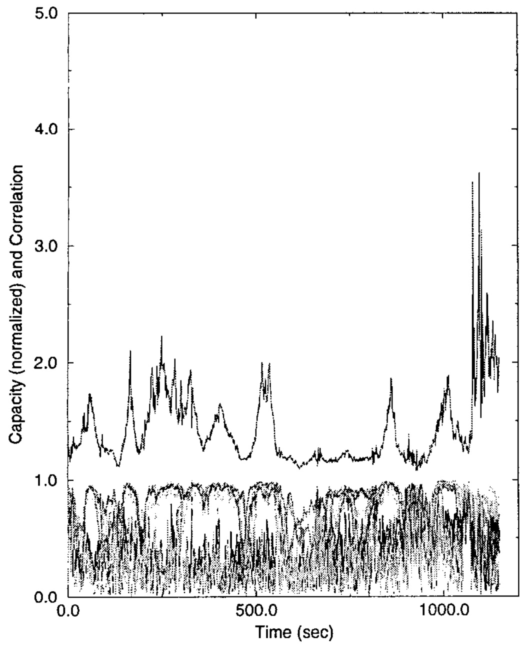

Fig. 4. Measured normalized capacity and correlation versus time for case 5.

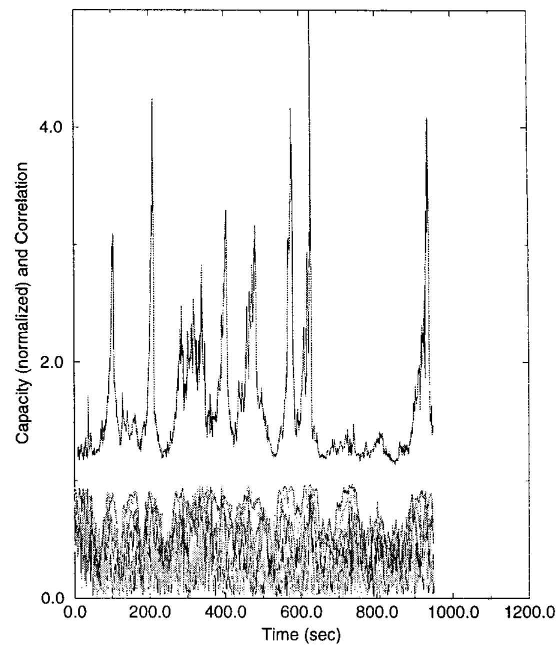

Fig. 6. Measured normalized capacity and correlation versus time for case 7.

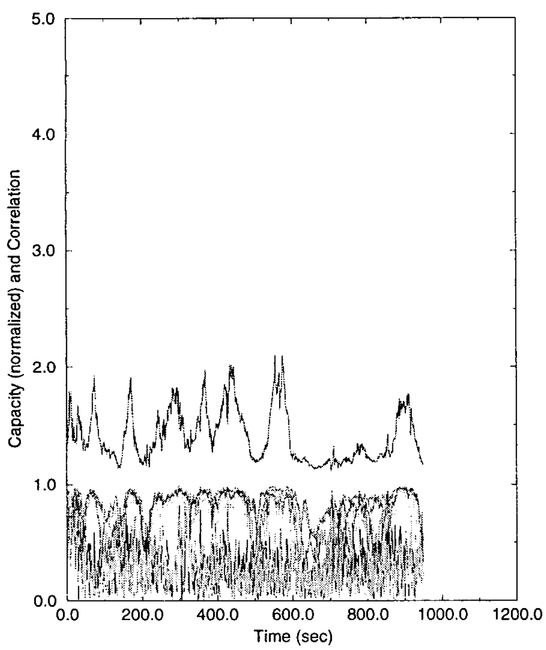

Fig. 5. Measured normalized capacity and correlation versus time for case 6.

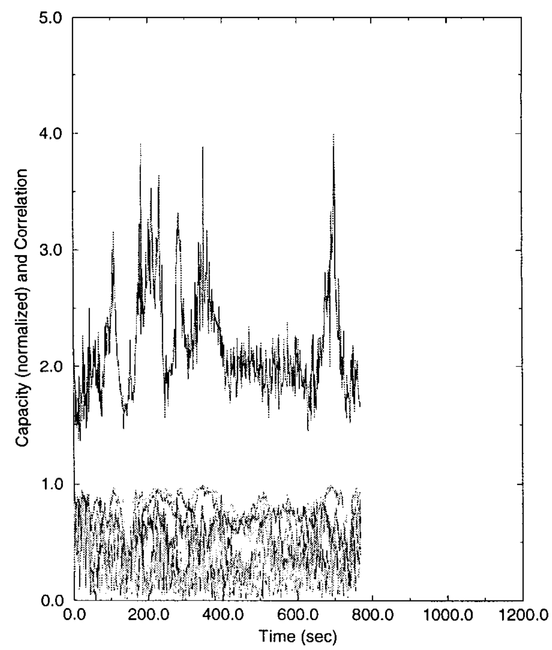

Fig. 7. Measured normalized capacity and correlation versus time for case 8.

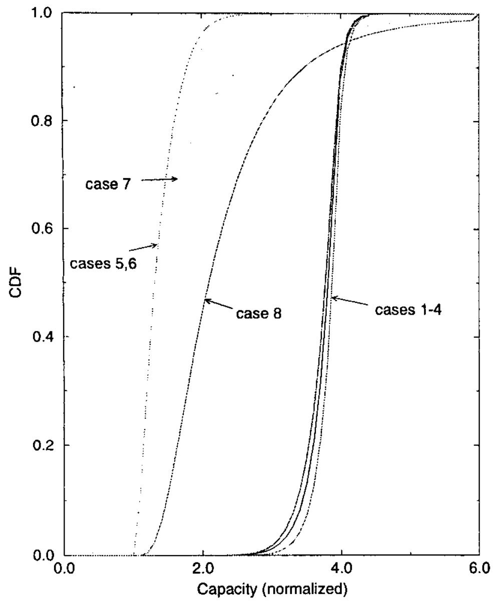

Fig. 8. Normalized capacity distribution for all tests with route A.

Fig. 5 shows the capacity and correlation for spatial and polarization diversity laptop antennas (T2) as compared to the spatial-diversity laptop antennas (T1) used in Fig. 4. As with base station antenna configuration B1 cases 1 to 4, the type of laptop antenna does not have a significant effect on the capacity results.

Fig. 6 shows that, when the adjacent beams are orthogonally polarized, the capacity is still low when the terminal is mainly in one beam, but when the terminal is between beams, the capacity is higher than with the vertically-polarized multibeam antenna. This is apparently due to the fact that the received signals in orthogonally-polarized beams have lower correlation, as seen in the correlation results.

Fig. 7 shows that with dual-polarized beams, the capacity is about 2 when the terminal is mainly in one beam, increasing to 3 or 4 when the terminal is between beams. Note also that in Figs. 4 to 7, the periods of higher capacity, which occur when the terminal is between beams, are at roughly the same points in time, as expected. This was typical of all runs - the repeated results for a given drive route were very similar.

Our results are summarized in Fig. 8, which shows the capacity distribution for all cases with route A. With base station antenna configuration B1, the capacity is close to ideal for all laptop terminal antenna configurations. The vertically-polarized multibeam antenna (cases 5 and 6), however, provides only a small capacity increase (median =1.3). With orthogonally-polarized adjacent beams (case 7), the capacity is slightly higher (median = 1.4), but with dual-polarized beams (case 8), the median capacity increase is greater than 2. (Note that with cases 7 and 8, the capacity sometimes exceeds that of antenna configuration B1, but this is due to the greater error in the average capacity estimation of the multibeam antenna, as discussed earlier).

V. 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, as well as with a variety of laptop antenna configurations. However, with multibeam antennas, the capacity was only slightly greater than one, except when dual-polarized beams were used, which provided an average capacity of about 2. These field test data and results are valuable inputs to the development 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.

Acknowledgments

The authors would like to thank Claes Beckman and Allgon System AB for providing the dual-polarized multibeam antenna used in the field tests.

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," *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] 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.