Chapter 7

Measurement Results

Multiple-input multiple-output systems have been proposed to increase the data rate of mobile wireless communications. Theoretical analyses have shown that this capacity gain may be significant, but is dependent on favorable propagation conditions between the transmitter and receiver. The measurement campaign described in Chapter 6 was designed to observe the capacity gain in the propagation conditions of an indoor office-building environment. Measurements included three locations in Durham Hall on the Virginia Polytechnic Institute and State University campus in Blacksburg, Virginia. The results of this measurement campaign are reported in this chapter and demonstrate the significance of data produced by the constructed measurement system.

7.1 Capacity

Theoretical studies have predicted that multi-element arrays can provide a multiplicative gain in system capacity above single-antenna systems. Capacity was calculated from measured data using Equation (3-13), with a system-SNR of 20dB and n_T equal to sixteen. The single-antenna system was used as a baseline capacity, calculated with an n_T of one. To maintain a constant transmitted power between systems with different values of n_T, the single-antenna system was calculated with a ρ_{SYS} sixteen times larger than the sixteen-transmitter system. With this adjustment, the capacity of the single-antenna system is equivalent to the minimum theoretical capacity of the sixteen-antenna system, approximately 10.6 bits/sec/Hz.

This potential gain is dependent on both the propagation environment and the design of the antenna arrays. In an attempt to isolate these two variables, measurements were conducted in both a free-space environment and an office-building environment. The free-space measurement was described in the calibration section and measures the minimum capacity, as limited by the antenna arrays. Measurements in the office-building environment predict the capacity available to a system with similar antenna arrays and in similar propagation conditions as those found in the measurements. Data from these environments are presented in the following section.

7.1.1 Free Space Calibration

The ideal free space environment, measured with an ideal system, produces an all-ones H-matrix and results in the minimum theoretical MEA capacity. Non-ideal characteristics of the measurement system increase the minimum measurable capacity by introducing noise or amplitude variations in the received signal tones. The result of this calibration measurement represents the minimum capacity that can be measured by the system when implemented with the antenna arrays specified in Chapter 4.

The non-ideal characteristics of this measurement system were addressed in Chapter 5 and will be reiterated here to substantiate the measurement results. The measurement system contains both horizontally and vertically polarized antenna elements. Although polarization diversity provides an extra degree of freedom in propagation measurements, this antenna arrangement effectively divides the system into two non-interfering measurement systems and raises the minimum capacity observable with the system. From Equation (3-13), it can be calculated that the theoretical capacity of two independent eight-antenna systems is 19.3 bits/sec/Hz.

In addition, internally generated noise produces an exaggerated MEA capacity value in the recorded data. By limiting the signal-to-noise ratio of the recorded data to 30dB, the error due to noise is limited to 2bits/sec/Hz at the minimum capacity value. This error was predicted in simulations at Lucent Technologies, as described in Chapter 4, and verified in the wired-keyhole calibration measurement. Internally generated noise increases the minimum measurable capacity from the theoretical value by 2bit/sec/Hz.

Additional non-ideal characteristics of the antenna arrays can further raise the minimum capacity. The minimum MEA capacity signifies that the loss between each pair of transmitter and receiver antenna-elements is equal, producing an all-ones H-matrix. This all-ones matrix can only be produced with ideal antenna arrays, in which each element has an equal gain, the same polarization and a flat gain pattern. The finite and varied beamwidth of each antenna element and the gain ripple in each element's main beam produce variations in the gain between each pair of transmitter and receiver antennas. Because this unspecified gain can not be normalized in the measured data, these antenna characteristics can raise the minimum measurable capacity. The antenna pattern characteristics of measured array-elements are reported in Chapter 4.

The free-space measurement was conducted in the parking lot at the front of Durham Hall, and the location contained many non-ideal characteristics. Although scattering objects were distant from both arrays and from the line-of-sight path, distant scatterers represent a finite source of error in the measured data by varying the propagation loss between antenna-element pairs. A more accurate measurement could be conducted in an anechoic chamber and would produce a lower minimum observable capacity.

The measurement location and procedure were described in Chapter 5. Approximately one thousand H-matrices were recorded in the free-space measurement, with minimum, mean and maximum capacity values of 37.9, 38.5 and 39.2 bits/sec/Hz. With an uncertainty of 2bits/sec/Hz produced with a signal-to-noise ratio of 30dB, this range of values is acceptable for a steady-state environment. The mean value is considered the minimum observable system capacity obtainable with this measurement system.

The significance of this result is apparent when compared with the theoretical range of capacity values. The minimum theoretical capacity of 10.6bits/sec/Hz represents the single-antenna system. This capacity is produced in a keyhole propagation environment, where all propagation channels are fully correlated and only one transmitter antenna can be effectively utilized for data communication. The maximum MEA capacity of 106.5bits/sec/Hz represents the highest capacity obtainable with sixteen transmitter antennas and a 20dB SNR. With this theoretical range, a value of 38.5bits/sec/Hz represents a gain of approximately 360% over the minimum capacity, or 36% of the maximum MEA capacity. The free-space measurement demonstrates that, even in the least favorable environment, the potential capacity of a communication system with these antenna arrays is increased by a factor of three above the single-antenna system.

7.1.2 Indoor Office-building

In each indoor environment, between four and six measurements were conducted with receiver locations, as detailed in Chapter 6. At each location, the receiver array was arranged at nine points and pointed in four directions, producing a total of 36 data points at each location. Ten seconds of continuous data was recorded for data point, from which approximately 1000 values of capacity were calculated. The average capacity for each ten-second measurement is depicted in Figures (7-1), (7-2) and (7-3). Each capacity value is represented by a bar and grouped according to the location of the receiver array and its direction, North, South, East and West. The location indices refer to the numbering in Figures (6-4), (6-8) and (6-11). The red bars signify invalid measurements, in which the average signal-to-noise ratio was insufficient for accurate calculations.

Measured capacity ranged from 44.9bits/sec/Hz in the hallway environment to 85.3 bits/sec/Hz, in the cubicles. These values represent a 420% and 800% capacity gain above the single-antenna system. In addition, the gain of these results over the free-space environment suggest that characteristics of the propagation environment significantly affect the capacity of an MEA system. The average capacity observed in the hallway, lecture hall and cubicle environments were 69.5, 74.8 and 76.0 bits/sec/Hz, respectively.

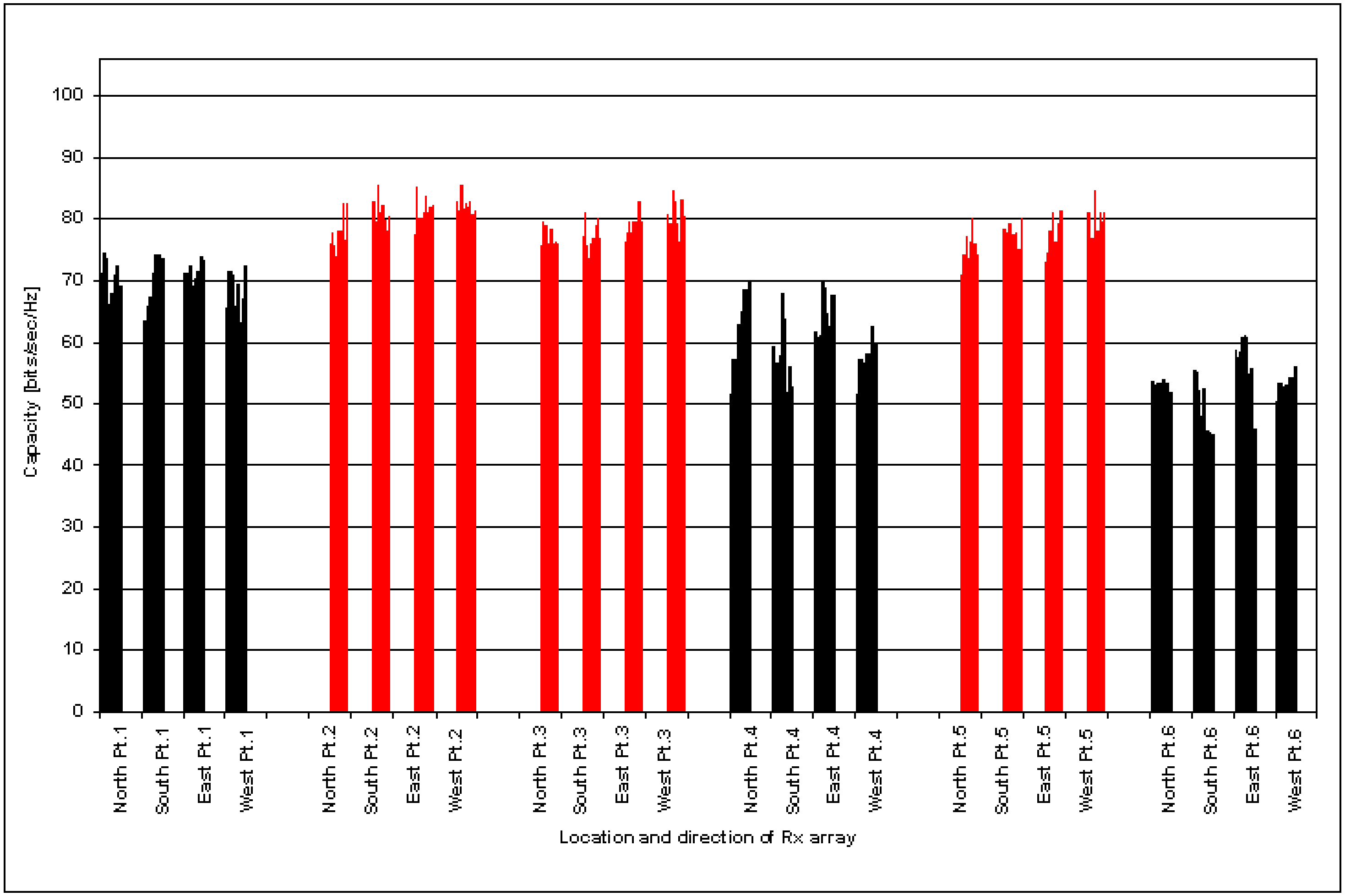

Figure 7-1: Capacity Data – Hallway Environment

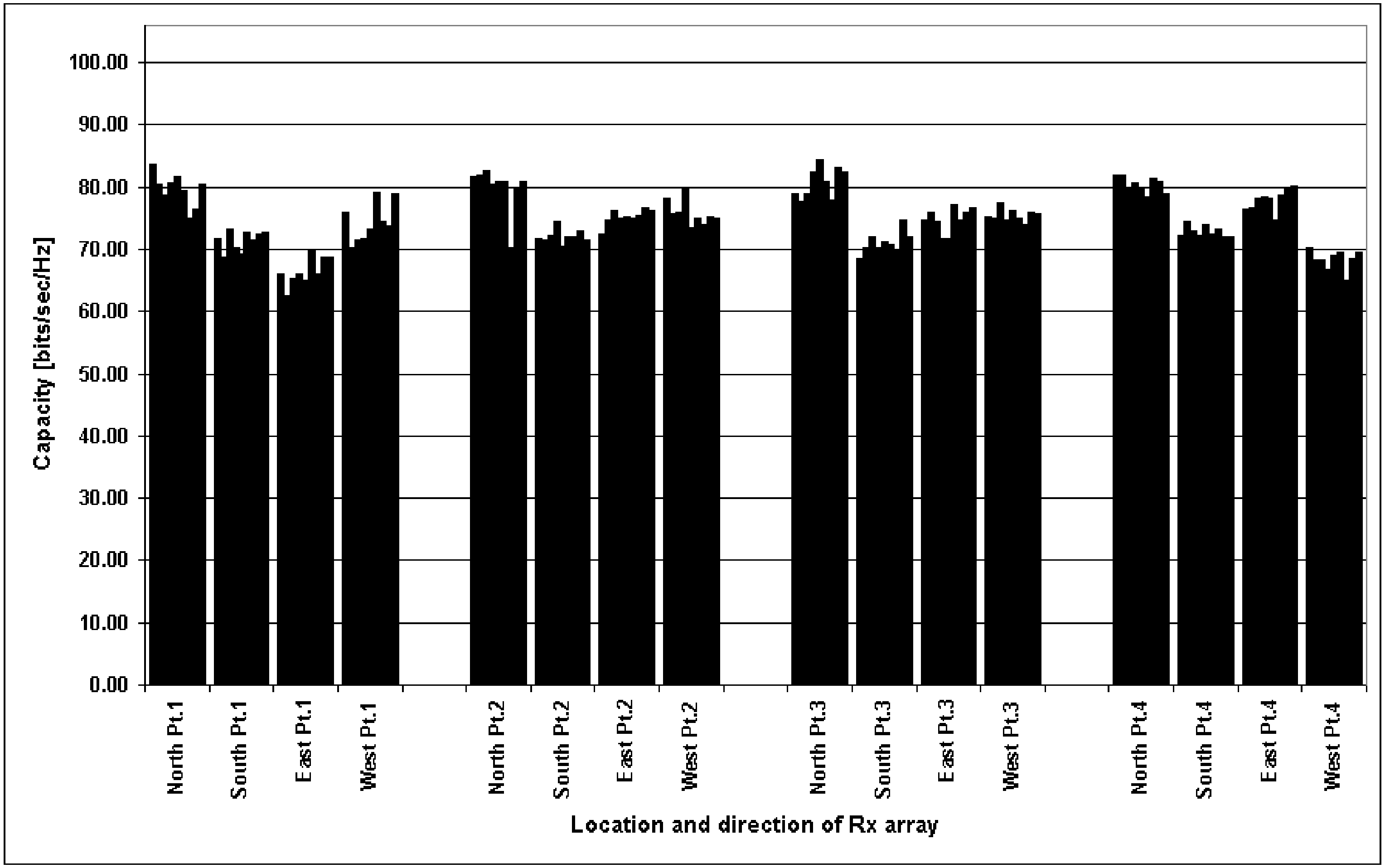

Figure 7-2: Capacity Data – Lecture hall

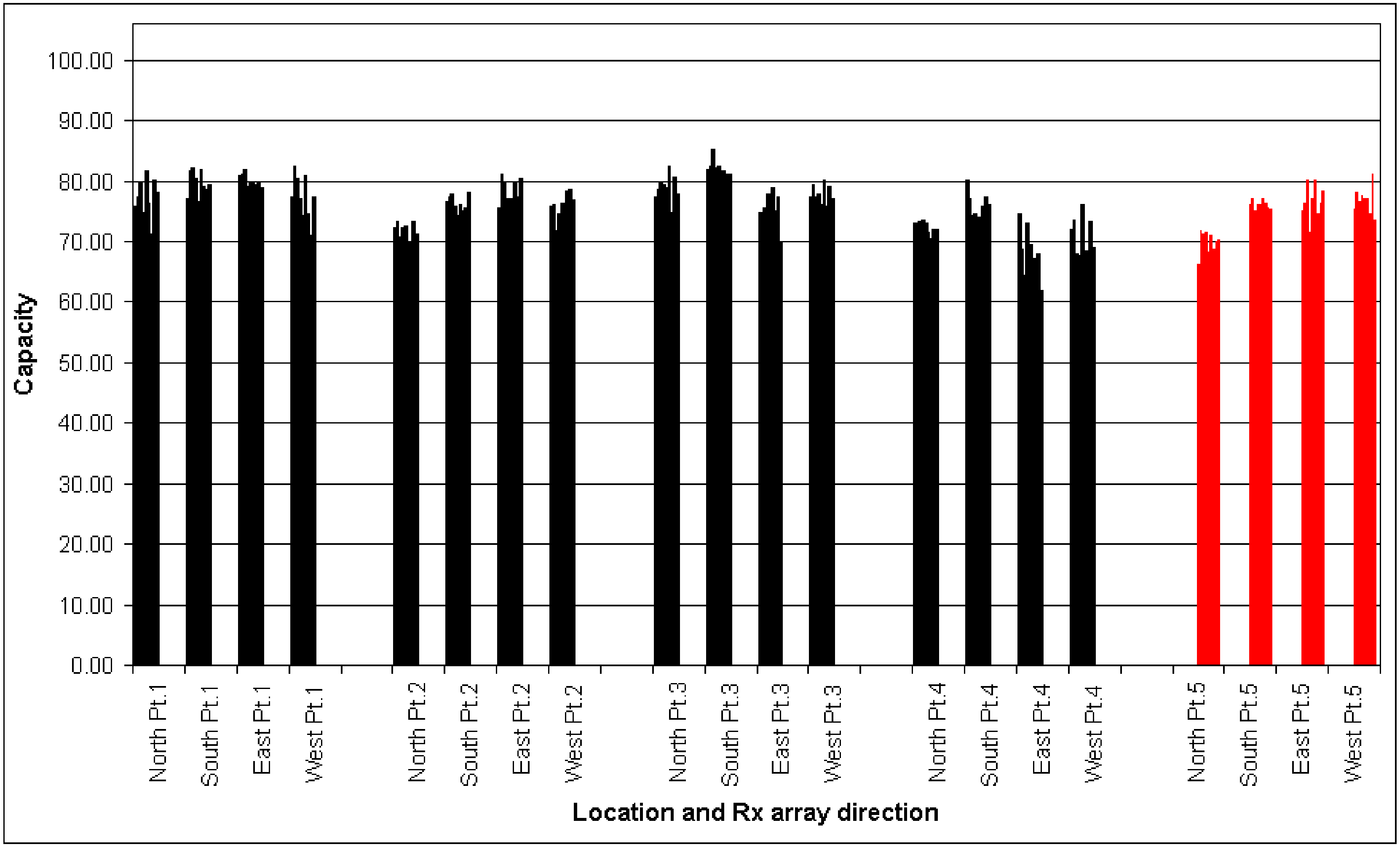

Figure 7-3: Capacity Data – Partitioned Room (Cubicles)

Two significant trends were observed in the capacity data. In the hallway, capacity was found to decrease as the transmitter-receiver separation increased. The transmitter-receiver distance was measured as 34', 53.5' and 71.5' at points 1,4 and 6, and the average capacity at each point was 69.5, 60.3 and 53.0 bits/sec/Hz, respectively. These values represent the capacity as averaged over each measurement and receiver-array direction in the nine-point grid.

The trend between capacity and the transmitter-receiver separation may be explained by the reduction in beamwidth of the received signal as the distance increases. In a narrow and empty hallway, the beamwidth of the received signal is limited by the dimensions of the walls, floor and ceiling and the distance between the transmitter and receiver arrays. As the beamwidth was reduced, the gains of propagation channels may have become more correlated, reducing the MEA capacity. This hypothesis is supported by the scenario in which the transmitter-receiver separation is infinitely large compared to the width and height of the hallway. A hallway of infinite length could be considered a keyhole environment, which produces the all-ones H-matrix and the minimum MEA capacity. The keyhole environment was described in Chapter 3 and theoretically analyzed in [39].

A significant trend observed in the Lecture Hall data pertains to the direction of the receiver array. In each receiver location the maximum capacity was obtained when the receiver array was facing North, away from the transmitter. Significant values of capacity are stated in Table (7-1), and represent the capacity averaged over all measurements from a nine-point grid.

Table 7-1: Selected values of capacity measured in the lecture hall, averaged over the nine-point grid in each receiver location. Capacity is stated with the units of [bits/sec/Hz].

Rx array location	Maximum capacity	2^{nd} highest capacity	Minimum capacity
Point 1	79.6 (North)	74.4 (West)	66.5 (East)
Point 2	80.0 (North)	75.8 (West)	72.1 (South)
Point 3	80.8 (North)	75.5 (East)	71.1 (South)
Point 4	80.4 (North)	78.0 (East)	68.3 (West)

This trend of maximum and minimum capacity values may demonstrate the relationship between capacity and the presence of scattering objects in the beamwidth of the receiver array. The absence of scattering objects in the free-space environment produced a minimum capacity, and the presence of scatterers increases the system capacity, as described in Chapter 3. In the lecture hall the walls, desks and chairs scatter the transmitted signal, producing multiple signal paths between the transmitter and receiver array. The capacity of the system may increase with the number of paths which fall inside the beamwidth of the receiver array. When the receiver faced toward the transmitter, the chairs and desks between the two arrays acted as scattering objects. When the receiver faced North, the transmitted signal reflected off of the rear wall, as well as the chairs and desks, producing a larger number of significant signal paths. This increase in the number of propagation paths may account for the increase in system capacity observed in the lecture hall data. For each measurement location, the maximum capacity was observed with the receiver array facing North, away from the transmitter array. In addition for points 2 and 3, when the receiver was located in the middle of the room, the minimum capacity was observed when the receiver array pointed South, towards the transmitter. For the remaining two points, the minimum capacity was obtained when the array was pointed toward the center of the room, and away from the closest walls. The relationship between MEA capacity and the orientation of the receiver array may demonstrate the affect of scattering objects on array systems.

7.2 Capacity of Sub-arrays

Analyses can isolate sub-arrays in the H-matrices of the previously reported data and predictions of system capacity can be extended to communication systems with a smaller number of transmitters. For example, a sub-array may be isolated which includes only horizontally polarized antennas, or horizontally polarized antennas at the transmitter and vertically polarized antennas at the receiver. In addition, analyses can concentrate on arrays with adjacent elements or distantly spaced antennas. By recorded measurement data from a large number of antenna elements, the investigator can predict the capacity of many smaller systems in the subsequent data processing.

The two sub-arrays analyzed in this investigation are characterized by their element-spacing. The *middle sub-array* represents the propagation channels between transmitter and receiver array-elements 6,7,10 and 11, and the *corners sub-array* includes the channels between antenna-elements 1,4,13 and 16. These element numbers correspond to the indices specified in Figure (4-5). The middle and corners subarrays are depicted in Figures (7-4) and (7-5), and the distance between diagonal elements on each sub-array measures one wavelength and three wavelengths, respectively. For each of the subarrays, data was copied from the elements in the original H-matrices to form a size 4x4 H-matrix for each of these sub-arrays.

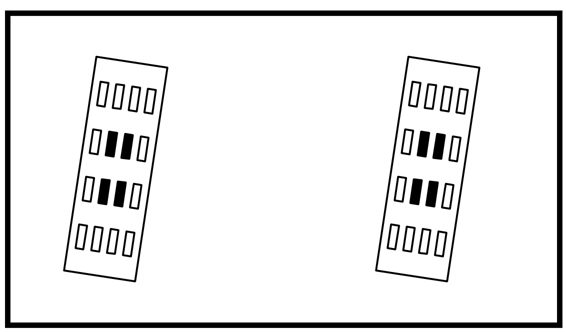

Figure 7-4: The middle subarray consists of the shaded antenna elements. Both the transmitter and receiver arrays are depicted.

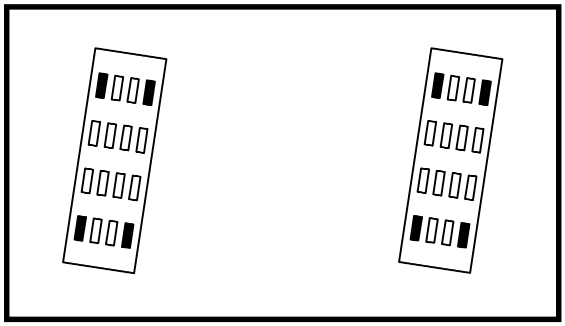

Figure7-5: The corners subarray consists of the shaded antenna elements. Both the transmitter and receiver arrays are depicted.

For selected measurements, the MEA capacity of the sub-arrays was computed using Equation (3-13), with n_T equals four and a system SNR of 20dB. A four-transmitter system with a 20dB average signal-to-noise ratio has one quarter of the SNR produced in a 16-transmitter system and obtains a lesser capacity. The minimum and maximum theoretical capacity of a four-transmitter system are 8.6 and 26.6 bits/sec/Hz, as calculated with the all-ones and identity H-matrices.

Figures (7-6) and (7-7) depict the measured values of capacity of the middle sub-array and corners sub-array for the Hallway environment. The analysis focused on this environment, because of the strong trend observed in previous data. As in the previous capacity plots, the data is organized by Rx array direction and location indices specified in Figure (6-4). In addition, the minimum, average and maximum statistics of the capacity values measured at these points are specified in Table (7-2). Invalid measurements are indicated in red.

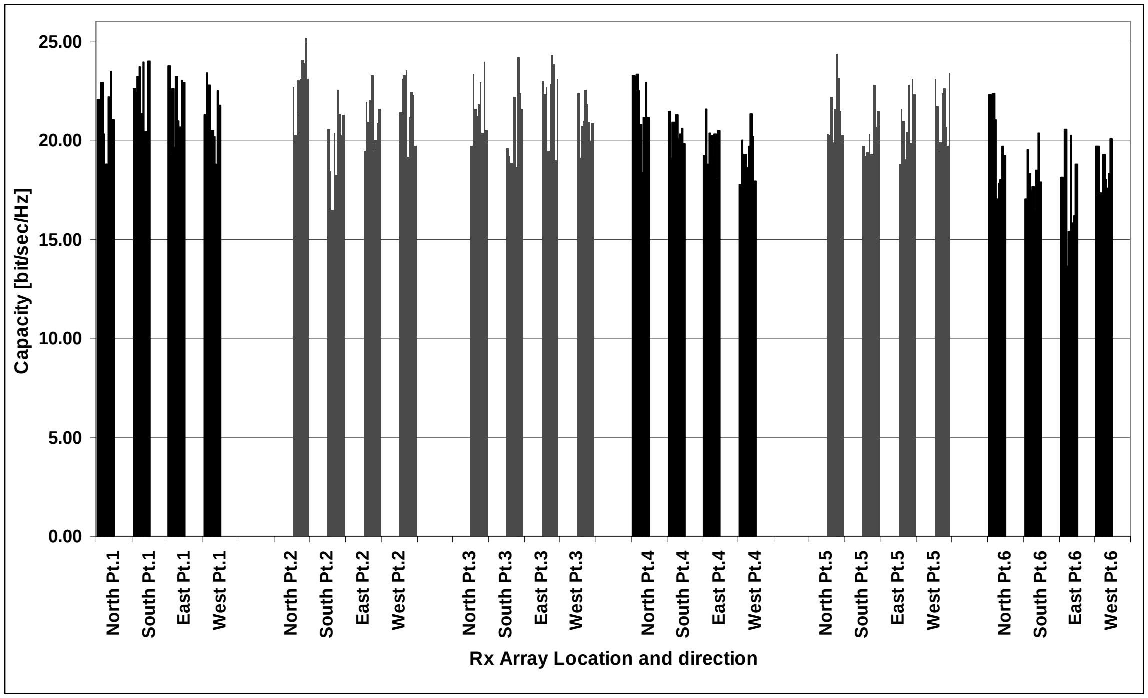

Figure 7-6: Capacity of the middle sub-array – Hallway environment

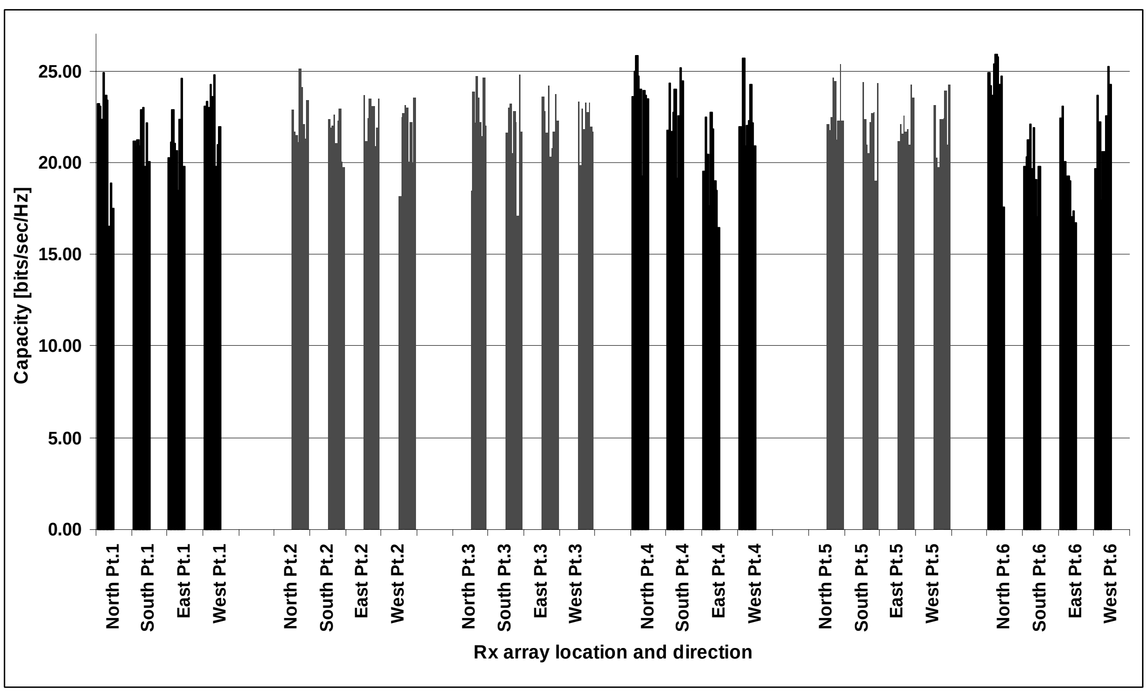

Figure 7-7: Capacity of the corners sub-array – Hallway environment

Table 7-2: Capacity statistics of the middle and corners subarrays at points one and six in the hallway environment. Capacity is expressed as [bits/sec/Hz]

	Minimum	Average	Maximum
Middle subarray – Point 1	18.8	21.7	23.9
Middle subarray – Point 6	13.7	18.5	22.4
Corners subarray – Point 1	16.5	21.7	24.9
Corners subarray – Point 6	16.7	21.3	25.9

The relationship between the transmitter-receiver distance and MEA capacity is apparent in the middle subarray data, but not in corners subarray. The average capacity of the middle subarray is reduced by approximately 15% as the distance between arrays is increased from 34 to 71.5 feet. The corners subarray does not exhibit this change over the same distances. These observations suggest that the corners subarray is not affected by the dimensions of the hallway. A capacity of 21.7 bits/sec/Hz may be the nominal value obtained with two closely-spaced four-element arrays. The capacity is then degraded as the distance between the arrays grows beyond a threshold value, where the threshold is determined by the dimensions of the arrays. This hypothesis is only vaguely demonstrated by the data produced in this campaign, and could be the basis of further investigation.

7.3 Cross-Correlation of Channel Gains

In addition to capacity, the cross-correlation between two channel gains was calculated for several of the propagation channels in each measurement. The calculation of the correlation-coefficient introduced in Chapter 3 compares the fading gains of a pair of channels and has a range from zero to one. This calculation uses data from all nine points in a measurement location to produce a single correlation value. Significant data from these calculations is presented in this section.

The correlation coefficient was calculated for each pair of co-polarized propagation channels for the middle and corners subarrays. The average correlation coefficient for each group from hallway measurements one and six are shown in Figures (7-8) and (7-9). These measurement locations most distinctly illustrate the relationship between system capacity and cross-channel correlation. The correlation coefficients were grouped into three categories, depending on the type of diversity provided. Two propagation channels provide either receiver diversity, transmitter diversity or “total diversity”. In this analysis, total diversity is produced when two channels share neither common transmitter nor common receiver antenna elements, and is indicated as “Tx+Rx diversity” in the figures.

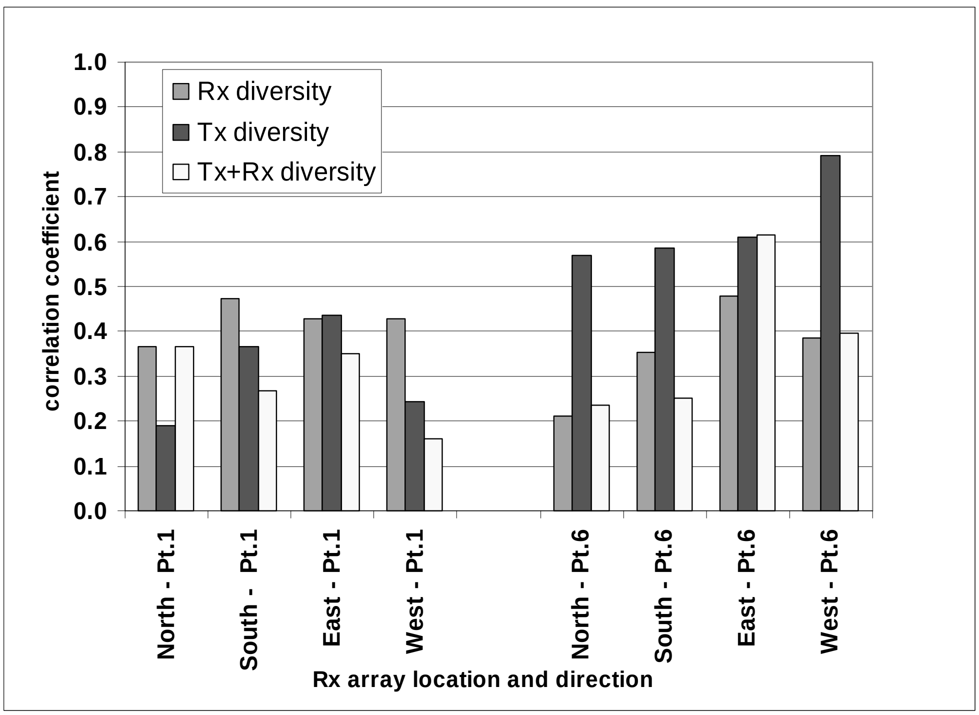

Figure 7-8: Correlation coefficients produced from the middle-elements subarray

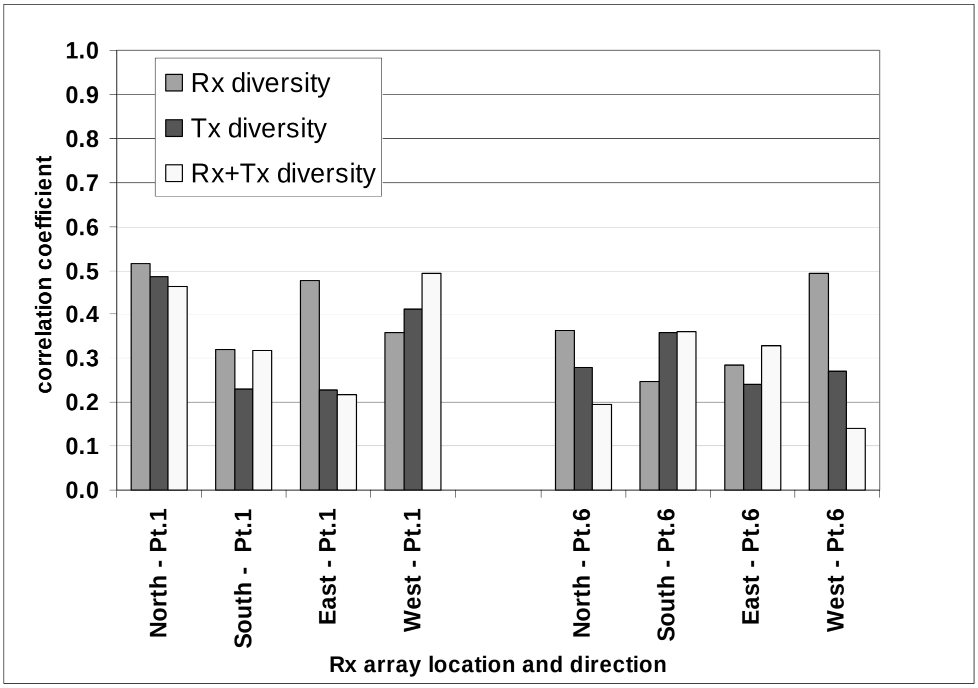

Figure 7-9: Correlation coefficients produced from the corner-elements subarray

The correlation coefficient data reflected a dependence on the transmitter-receiver separation, similar to previous capacity data. The relationship was most apparent in propagation channels which produced the transmitter diversity. Table (7-3) lists the mean correlation-coefficient of for both subarrays at points one and six. The correlation between elements in the middle-subarray increased significantly with a larger distance between arrays. The corners subarray produced equivalent correlation values at both distances.

Table 7-3: Significant values of the correlation-coefficient from points one and six in the hallway environment

	Point 1	Point 6
Middle subarray	0.31	0.64
Corners subarray	0.34	0.29

These results suggest that the correlation and capacity data recorded in this campaign is consistent with theoretical analyses. As described in Chapter 3, an increase in MEA capacity may be observed when the cross-correlation between propagation channels is reduced. This inverse relationship was observed in the channels that provide transmitter diversity. The absence of a more defined trend in the receiver diversity channels may be attributed to the loose relationship between the MEA capacity and the cross-correlation. The MEA capacity depends on the correlation between every propagation channel defined by the array-elements. Due to the complexity of the problem, an explicit relationship involving individual channels could not be defined in this thesis.

In addition, the error margin of the cross-correlation calculation may be too large to demonstrate a definitive trend. Two assumptions were described in Chapter 3, which limit the accuracy of the calculation. The propagation channel must remain static for the duration of the measurement, and a large number of independent samples must be recorded. In this campaign, only 36 observations were recorded at each location of the receiver array. The assumptions could not be verified with this number of samples. If a significantly larger number of continuous samples had been recorded, these assumptions could have been verified as demonstrated in Lee's investigation [17].

7.4 Summary

This chapter described significant data observed in the measurement campaign. One value of MEA capacity was calculated from each H-matrix recorded by the system. These values represent the potential data-rate of a system with an average signal-to-noise ratio of 20dB, sixteen transmitter array-elements and sixteen receiver array-elements. These capacity values were reported in Figures (7-1), (7-2) and (7-3). As discussed in Chapter 3, the minimum and maximum theoretical capacity values for a system with an n_T of sixteen and a 20dB signal-to-noise ratio are 10.6 and 106.5 bits/sec/Hz. Capacity values between 44.9 and 85.3 bits/sec/Hz were measured in this campaign.

In addition, the MEA capacity was calculated for two subarrays. By omitting various elements in the recorded H-matrices, subarrays can be built from the original sixteen-by-sixteen size H-matrix. These subarrays can be input into Equation (3-13) to predict the capacity of smaller systems. Capacity was calculated for two subarrays with an element-spacing of one wavelength and three wavelengths. These results were compared to previous results.

The measured data was also used to calculate the correlation coefficients for many pairs of propagation channels. This calculation compares the gains of two propagation channels from many independent samples. Independent samples were obtained by moving the receiver antenna by a small amount between measurements. This method of measurement has not been analyzed and the accuracy of the resulting data is questionable. It was shown that the general trend of specific results was consistent with theory. The measurement procedure required for accurate correlation data may be a good topic for further investigation.

The data presented in this chapter demonstrates the ability of the constructed measurement system to produce significant results. The system can produce estimates of capacity for communication systems with a variety of antenna arrays. With an acceptable measurement procedure, the system can also observe the cross-correlation of the gain between two propagation channels. While values of the correlation coefficient were not observed below 0.1 in the office-building environment, measurements with this system conclude that MEA systems may achieve a significant capacity gain over single-antenna systems in the indoor office-building environment.

Chapter 8

Conclusion

8.1 Accomplishments

Propagation measurements can provide an accurate characterization of the fading channels between two antenna arrays. The multi-element array (MEA) capacity describes the potential data-rate of a communication system in the measured environment, and the cross-correlation between two channels indicates their similarity. Engineers can use these parameters in the design of diversity or space-time communication systems. From estimates of correlation, an engineer can calculate the diversity gain for a proposed multiple antenna system and use this value in predicting system design parameters, such as the minimum detectable signal power. Correlation measurements can also verify the accuracy of theoretical channel models, which often include broad mathematical assumptions. The MEA capacity can be used to predict the data-rate of a space-time system, or compare the efficiency of a system at various locations. The data produced in propagation measurements can be valuable in the design of a communication system.

A measurement system was built in this thesis work, which simultaneously measures the fading gains of 256 propagation channels. The propagation channels are defined by sixteen-element arrays at the transmitter and receiver. The gain of each channel is sampled independently and recorded as an element of an H-matrix. The multi-element array capacity and the cross-correlation are computed from H-matrices to provide a statistical analysis of the propagation environment.

The measurement system consists of sixteen independent signal chains in both the transmitter and the receiver. A carrier wave signal is emitted from each transmitter antenna, and a sampled waveform is recorded from each receiver antenna. By emitting a distinct frequency from each transmitter antenna, the receiver can use the Fourier transform calculation to separate the transmitted signals from the sampled waveform. Using the assumption of constant transmitter amplitudes, the channel gains can be estimated from this received spectrum and used to calculate MEA capacity and cross-channel correlation. The transmitted frequencies are restricted to a 32kHz bandwidth, at 2111MHz, to preserve a narrowband channel model in these calculations.

The accuracy of this measurement system was limited by the linearity, noise and coupling of the sixteen signal chains. A rigorous suite of calibration measurements was performed to verify the integrity of the recorded data. Measurements observed the gains of each chain, the coupling between chains and the sensitivity and dynamic range of the receiver. In addition, the system was tested with wired propagation environments, and the measured data was compared to ideal results. The gain patterns of individual antenna-elements were measured in an anechoic chamber and the system was tested in a free-space environment to observe the effects of the non-ideal arrays. A daily calibration was designed to normalize the data from each measurement and counter the effects of aging and temperature variation. The signal-to-noise ratio of each transmitted signal was required to be at least 30dB in the recorded data to accurately calculate the MEA capacity. The system was found to achieve this goal with an acceptable range of transmitter-receiver distances for indoor measurements.

In addition to the construction of the system, a measurement campaign was conducted to demonstrate its operation. Measurements were performed in three rooms of Durham Hall on the Virginia Polytechnic Institute and State University campus. These rooms represent a sample of the indoor office-building environment and data was recorded with the receiver placed at different locations in each room. In the post-processing, the MEA capacity was calculated for the sixteen-transmitter sixteen-receiver system, as well as two systems with smaller arrays. The variations of the capacity calculation demonstrate that the system is capable of predicting the capacity for a number of systems from a single measurement. Also, the cross-correlation between channel gains was calculated for many of the measured propagation channels. The measurement campaign demonstrated the use of the system to characterize the propagation environment, in terms of the MEA capacity and cross-correlation parameters.

8.2 Suggestions for Further Research

Throughout this thesis work, it was observed that a number of improvements could be implemented to more accurately measure the propagation environment. In particular, two aspects of the system and subsequent measurement campaign were most apparent. In measuring the antenna patterns of the individual array-elements, it was found that signals from one element may couple into adjacent elements or radiate from the array's ground plane. This coupling could degrade the accuracy of the correlation measurements. In addition, the validity of using a nine-point grid to record independent observations of the propagation environment is questionable. Data was recorded in a static environment and independent measurements were obtained by manually moving the receiver short distances in a grid formation. This measurement procedure could be improved to obtain a larger number of observations, and this data can be analyzed to confirm the assumptions made in the correlation-coefficient calculation. Both of these issues are complex and their analysis could involve a substantial amount of work.

This system was fitted with non-ideal antenna arrays and the arrays' characteristics may restrict the applicability of the measured results. The shape, size and array elements were specified by Lucent Technologies in an effort to imitate a predicted communication system. Mutual coupling between array elements can raise the minimum measurable value of cross-correlation, and reduce the maximum capacity limit. Without a focused analysis on the affects of coupling between elements, the results produced with these arrays can not applied to a generic communication system. The results reported in this thesis apply to systems with similar antenna arrays as those utilized in the measurements. An effort to construct arrays with minimal coupling between elements could be the topic for further research.

Two assumptions were stated in Chapter 3, which affect the calculation of the correlation coefficient. Each of these assumptions requires a substantial amount of investigation before the accuracy of cross-correlation measurements may be ascertained. The first assumption involves the number of observations recorded in each measurement location. Nine observations of the propagation channel were recorded and input into the correlation calculation. This number may not be sufficient to produce accurate results. The second assumption states that the propagation channels must not change significantly between measurements. The receiver was moved short distances to obtain independent observations of a channel. The distance between points in the nine-point grid was assumed small as compared to the transmitter-receiver separation, but no analysis was conducted to verify this assumption. A thorough verification of these assumptions and the design of a more rigorous measurement procedure would require a significant amount of work. This research could serve as the topic of further investigations.

8.3 Closing

Multi-element array systems may hold the potential for an increased data-rate and more efficient communications. A measurement system has been built in this thesis work which can be beneficial in the design of diversity or space-time communication systems. The performance of the system was verified through calibration measurements and the system's operation was demonstrated in a measurement campaign.

References

[1] Selingo J., “Squeezing Ever More From the Cellphone Spectrum”, *The New York Times*, February, 14, 2002.

[2] *Trends in Telephone Service*, Federal Communications Commission, Common Carrier Bureau, August 2001, www.fcc.gov/ccb/stats.

[3] Prasad R., *Third Generation Mobile Communication Systems*, Boston: Artech House, 2000.

[4] *International Conference on 100 Years of Radio*, Conference Publication No. 411, 1995, Institute of Electrical Engineers, London, pg. 44-90.

[5] Proakis J.G., *Digital Communications*, New York: McGraw Hill, Inc., 1995, Chapters 1,5,7,9,12.

[6] Sedra A.S., Smith K.C., *Microelectronic Circuits*, New York: Oxford University Press, 3rd edition, 1991.

[7] Jakes W.C., *Microwave Mobile Communications*, New York: IEEE Press 1974, Chapters 1,5,6.

[8] Razavi B., *RF Microelectronics*, New Jersey: Prentice Hall, 1998.

[9] Beach, M.A., McNamara, D.P., Fletcher,P.N., “MIMO–A Solution for Advanced Wireless Access”, *11th International Conference Antennas and Propagation*, April 2001, Conf. Pub No. 480, pg. 231-235.

[10] Foschini G.J., “A Layered Space-Time Architecture for Wireless Communication in a Fading Environment When Using Multi-Element Antennas”, *Bell Labs Technical Journal*, Autumn 1996, pg. 41-59.

[11] Rappaport T.S., *Wireless Communications: Principles and Practice*, New Jersey: Prentice-Hall Inc, 1996, Chapters 3,4,6,8.

[12] Jakes W.C. Jr., "A Comparison of Specific Space Diversity Techniques for Reduction of Fast Fading in UHF Mobile Radio Systems", *IEEE Transactions on Vehicular Technology*, Vol.VT-20, No.4, Nov. 1971, pg. 81-92.

[13] Parsons J.D., Henze M., Ratcliff P.A., Withers M.J. "Diversity Techniques for Mobile Radio Reception" *IEEE Transactions on Vehicular Technology* Vol.VT-25, No. 3, Aug 1976, pg. 75-84.

[14] Tarokh V., Seshadri N., Calderbank A.R., "Space-Time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction", *IEEE Transactions on Information Theory*, Vol. 44, No. 2, March 1998, pg. 744-765.

[15] Lee W.C.Y., "Antenna Spacing Requirement for a Mobile Radio Base-Station Diversity" *The Bell System Technical Journal*, Vol. 50 No. 6, 1971, pg. 1859-1876.

[16] Lee W.C.Y, "Mobile Radio Signal Correlation Versus Antenna Height and Spacing", *IEEE Transactions on Vehicular Technology*, Vol. VT-25, No. 4 Aug. 1977, pg.290-292.

[17] Lee W.C.Y., "Effects on Correlation Between Two Mobile Radio Base-Station Antennas", *IEEE Transactions on Communications*, Vol. Com-21, No. 11, Nov. 1973, pg. 1214-1224.

[18] Lee W.C.Y., "Mobile Radio Performance for a Two Branch Equal-Gain Combining Receiver with Correlated Signals at the Land Site", *IEEE Transactions on Vehicular Technology*, Vol. VT-27, No. 4, Nov. 1978, pg. 239-243.

[19] Taga T., "Characteristics of Space-Diversity Branch Using Parallel Dipole Antennas in Mobile Radio Communcaitions", *Electronics and Communications in Japan*, Part 1, Vol. 76, No. 9, 1993, pg. 55-66.

[20] Brennan D.G., “Linear Diversity Combining Techniques”, *Proceedings IRE*, Vol. 4, No. 6 June 1959, pg. 1075-1102.

[21] Corazza G.E., Degli-Esposti V., Frullone M., Passerini C., Riva G., “Performance Evaluation of Space Diversity in Indoor Communications Using a Ray-Tracing Propagation Model”, *PINRC*, 1995, pg. 408-413.

[22] Ebine Y., Yamada Y., “A Vehicular-Mounted Vertical Space Diversity Antenna for a Land Mobile Radio”, *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 2, May 1991, pg. 420-425.

[23] Vaughan R.G., Anderson J.B., “Antenna Diversity in Mobile Communications”, *IEEE Transactions on Vehicular Technology*, Vol. VT-36, No. 4, Nov. 1987, pg. 149-172.

[24] Durgin G.D., Rappaport T.S., “Theory of Multipath Shape Factors for Small-Scale Fading Wireless Channels”, *IEEE Transactions on Antennas and Propagation*, Vol. 48, Issue 4, May 2000, pg.682-693.

[25] Naguib, A.F., Seshadri, N., Calderbank, A.R., “Applications of Space-Time Block Codes and Interference Suppression for High Capacity and High Data Rate Wireless Systems” *Conference Record of the Thirty-Second Asilomar Conference on Signals, Systems and Computers*, 1998, Vol.2, pg.1803-1810

[26] Naguib, A.F., Seshadri, N., Calderbank, A.R., “Increasing data rate over wireless channels”, *IEEE Signal Processing Magazine*, Vol17, Issue 3, May 2000, pg. 76-92.

[27] Bolcskei H., Paulraj A., “Performance of Space-Time Codes in the Presence of Spatial Fading Correlation”, *IEEE Records on the Thirty-Fourth Signals, Systems and Computers Conference*, 2000, Vol. 1, pg. 687-693.

[28] Uysal M., Georghiades C.N., “Effects of Spatial Fading Correlation on Performance of Space-Time Codes”, *Electronic Letters*, Feb. 2001, Vol 37, No. 3, pg. 181-183.

[29] Kreyszig E., *Advanced Engineering Mathematics*, New York: John Wiley & Sons, 2nd edition, 1962.

[30] Golden G.D., Foschini C.J., Valenzuela R.A., Wolniansky P.W., "Detection Algorithm and Initial Laboratory Results Using V-BLAST Space-Time Communication Architecture", *Electronics Letters*, Jan. 1999, Vol. 35, No. 1, pg. 14-16.

[31] Bevan D., Tanner R., "Performance Comparison of Space-Time Coding Techniques" *Electronic Letters*, Sept. 1999, Vol. 35, No. 20, pg. 1707-1708.

[32] Papoulis A., *Probability, Random Variables, and Stochastic Processes*, New York: McGraw-Hill Inc., 3rd edition, Chapters 4,7,9.

[33] Therrien C.W., *Discrete Random Signals and Statistical Signal Processing*, New Jersey: Prentice Hall, 1992, Chapters 2,4.

[34] Zepernick H-J, "Wysocki T.A., Multipath Channel Parameters for the Indoor Radio at 2.4GHz ISM Band", *IEEE 49th Vehicular Technology Conference*, Vol.1, 1999, pg. 190-193.

[35] Stark H., Woods J.W., *Probability, Random Processes, and Estimation Theory for Engineers*, New Jersey: Prentice Hall, 1986, 2nd edition.

[36] Couch L.W.II, *Digital and Analog Communication Systems*, New Jersey, Prentice Hall, 1997, 5th edition, ch.1.

[37] Horn R.A., Johnson C.R., *Matrix Analysis*, United Kingdom: Cambridge University Press, 1985, pg. 12.

[38] Pinsker M.S., *Information and Information Stability of Random Variables and Processes*, Holden-Day, Inc., San Fransisco, 1960, Chapter 10.

[39] Chizhik D., Foschini G.J., Valenzuela R.A., "Capacities of multi-element transmit and receive antennas: Correlations and keyholes", *Electronic Letters*, Vol. 36, No. 13, June 2000, pg. 1099-1100.

[40] Horowitz P, Winfield H., *The Art of Electronics*, Cambridge: Cambridge Univ. Press, 2nd edition, Chapter 9.

[41] Tang C-C, Lu W-S, Van L-D, Feng W-S, Liu S-I, "A 2.4-GHz CMOS Down-Conversion Double Balanced Mixer with Low Supply Voltage", T*he International Symposium on Circuits and Systems (ISCAS)*, Sydney, May 2001.

[42] Krauss H.L., Bostian C.W., Raab F.H., *Solid State Radio Engineering*, New York: John Wiley & Sons, 1980, Chapter 7.

[43] Stutzman W.L., Thiele G.A., *Antenna Theory and Design*, New York: John Wiley & Sons, 1981, pg. 385-390.

[44] National Instruments, *LabVIEW User Manual - version 6.0*, July 2000.

[45] Brigham E.O., *The Fast Fourier Transform and Its Applications*, New Jersey: Prentice Hall, 1988, Chapters 2,5.

[46] National Instruments, "Continuously Acquire Analog Input Data and Graph Results Using a Circular Buffer – Example VI", *http://zone.ni.com*, Jan 2000.

[47] Oppenheim A.V., Schafer R.W., *Discrete-Time Signal Processing*, New Jersey: Prentice Hall, 2nd edition, Chapter 10.

[48] Proakis J.G., Manolakis D.G., *Digital Signal Processing: Principles, Algorithms, and Applications*, 3rd edition, 1996, Chapter 8.

[49] Smith S.W., *The Scientist and Engineer's Guide to Digital Signal Processing*, California Technical Publishing, 1997. Chapter 9.

[50] Wepman J.A., Hoffman J.R., "RF and IF Digitization in Radio Receivers: Theory, Concepts, and Examples", *NTIA Report 96-328*, U.S.Dept. of Commerce, March 1996, pg. 15.

[51] Agilent Technologies, *Agilent 8648A/B/C/D Signal Generators: Data Sheet*, USA, 2000.

[52] “Virginia Tech to Dedicate Durham Hall and Dover Lab”, September 2001, *Virginia Tech News Bureau Website,* www.technews.vt.edu/Archives/2001/Sept/01343.html.

Vita

Jason Aron was born in North Carolina in 1977 and spent much of his early life in New York, North Carolina and Basel, Switzerland. In 1995 he enrolled in the Moore School of Electrical Engineering at the University of Pennsylvania. His undergraduate coursework and technical projects encompassed the fields of solid-state devices, electromagnetics and communication systems, and throughout this period the author traveled extensively in the USA, Europe and Israel. In 1998, he interned at the Center for Collaborative Manufacturing at Purdue University and developed intra-company tools to improve the efficiency of teams operating across corporate boundaries. After graduating in May 1999 with a Bachelor of Science in Electrical Engineering and a minor in Mathematics, the author continued his education of wireless communication systems at the Virginia Polytechnic Institute in Blacksburg, Virginia.

In Virginia, the author studied hardware design and communication systems theory. Concurrent with his graduate studies, he worked as a teaching assistance during his first semester in graduate school, and in the following semesters as a research assistant in the Mobile and Portable Radio Research Group. In the summer of 2000 he worked as an intern in the wireless communications research department of Bell Laboratories and assisted in the development of radio-wave propagation measurements for space-time applications. Following the internship, Bell Laboratories funded the author's graduate research to build a measurement system for the same project. After completing his coursework and research, he moved to San Diego, California to start work at Kyocera

Wireless Corporation, where he is currently employed. He completed his Masters thesis in California and graduated from Virginia Tech in April 2002. At Kyocera Wireless the author designs RF hardware for cellular phone applications. His technical interests include the hardware and hardware/software interface of wireless systems and efficient design methods.