CHAPTER 1
INTRODUCTION

As wireless communication systems evolve, service quality and capacity are of primary importance. To ensure reliable communication over a mobile radio channel, a system must overcome multipath fading, polarization mismatch, and interference. The trend towards low power hand held transceivers increases all of these challenges. Even as more spectrum is allocated, demand for higher data rate services and steadily increasing numbers of users will motivate service providers to seek ways of increasing the capacity of their systems.

Antenna arrays can improve reliability and capacity in two ways. First, diversity combining or adaptive beamforming techniques can combine the signals from multiple antennas in a way that mitigates multipath fading. Second, adaptive beamforming using antenna arrays can provide capacity improvement through interference reduction. The use of adaptive arrays is an alternative to the expensive approach of cell splitting, which increases capacity by increasing the number of base station sites. Most adaptive arrays that have been considered for such applications are located at the base station and perform spatial filtering. They cancel or coherently combine multipath components of the desired signal and null interfering signals that have different directions of arrival from the desired signal.

Multi-polarized adaptive arrays, sometimes called polarization-sensitive adaptive arrays, can also match the polarization of a desired signal or null an interferer having the same direction of arrival as the desired signal, if the two signals have different polarization states. If base stations or mobile units in a peer-to-peer system can match the polarization states of hand-held transceivers, link quality and reliability will be enhanced, and power consumption in the hand-held units will be reduced, increasing battery life. It is possible that 100% or greater increase in system capacity can be achieved through a combination of spatial and polarization reuse. Because they offer large untapped potential performance gains, multi-polarized adaptive arrays should be studied extensively to determine what performance improvements are feasible. Currently, however, little is known about the performance of multi-polarized adaptive arrays in mobile communication systems.

Multi-polarized arrays have been considered as a means of rejecting jammers in military applications [1.1]-[1.3]. The potential of multi-polarized arrays for interference rejection in wireless communication systems has been investigated in recent years [1.3]-[1.6]. This research indicates that 20 to 35 dB of interference rejection is possible if interfering and desired signals differ in either polarization state or angle of arrival. However, neither measurements nor simulations have been reported that show the performance of multi-polarized adaptive arrays in typical mobile multipath channels.

Some researchers have proposed diversity combining at handheld radios and shown that significant performance gains can be achieved. The use of adaptive antennas on handheld radios is a new area of research. In 1988, Vaughn [1.7] concluded that with then-current technology, adaptive beamforming would work for units moving at pedestrian speeds but would be difficult for high-speed mobile units. In 1999, Braun, et al. [1.8] reported experiments in which data was recorded using a two-element handheld antenna array, and processed using diversity and optimum beamforming techniques. While this was the first publication of its kind, some assumptions were made in the experiments and data processing that limit the applicability of the results.

This dissertation evaluates the performance improvement that can be achieved using co-polarized and dual-polarized antenna arrays at handheld receivers. This was done by measuring and modeling the performance of small handheld array configurations to determine the degree of diversity gain and interference rejection they can provide in typical mobile radio channels. Multi-polarized geometrically based multipath propagation models were developed for use in this study. A software package, the vector multipath propagation simulator (VMPS) was developed that can model the transmission, reflection, and reception of polarized waves and account for the effects of element and array pattern and orientation. Design guidelines for multi-polarized arrays and recommendations for their integration into new wireless communication systems are presented based on the results of this study. An overview of the dissertation follows.

Chapter 2 describes mobile radio fundamentals. Basic types of systems are described in Section 2.1. The concept of frequency reuse is presented in Section 2.2. In Section 2.3, radio wave propagation at microwave frequencies is discussed. Propagation effects discussed include large-scale path loss, shadowing, and multipath. Polarization concepts are introduced in Section 2.4. They are important because many wireless communication systems are characterized by random polarization states due to the random orientations with which users hold the portable handsets. Modulation, reuse, and multiple access techniques are described in Sections 2.5 and 2.6.

Antenna arrays using adaptive beamforming techniques can reject interfering signals having a direction of arrival different from that of a desired signal. Multi-polarized arrays can also reject interfering signals having different polarization states from the desired signal, even if the signals have the same direction of arrival.

Chapter 3 presents essential concepts in antenna arrays and beamforming. In Section 3.1 the pattern of an array with general geometry and elements is derived. Scanned arrays are discussed in Section 3.2. Phase and time scanning approaches are described and compared. Section 3.3 discusses fixed beam forming techniques that are used in switched-beam arrays and angle diversity systems. The concept of optimum beamforming is introduced in Section 3.4. Section 3.5 describes adaptive algorithms that iteratively approximate the optimum beamforming solution. Section 3.6 describes the effect of array geometry and element patterns on optimum beamforming performance.

Proposed applications of array antennas for wireless communication systems are described in Chapter 4. Section 4.1 discusses strategies that have been proposed for coverage and capacity improvement using switched-beam and adaptive arrays. Multipath fading mitigation and direction finding are briefly discussed in Sections 4.2 and 4.3, respectively. Section 4.4 shows possible ways that existing systems can evolve to incorporate the benefits of array antennas. Section 4.5 mentions some of the issues that affect successful integration and deployment of array antennas in wireless communication systems.

Chapter 5 introduces multi-polarized arrays. Such arrays have been considered for interference rejection, though not in the context of a wireless mobile communication system. Section 5.1 reviews the concepts of diversity and reuse. Previous research into multi-polarized or dual-polarized arrays, and cross-polarized interference cancelers (XPICs) is reviewed in Section 5.2. Section 5.3 discusses possible deployments of polarization sensitive adaptive arrays in base-mobile and peer-to-peer mobile communication systems.

A portable RF measurement system was required to allow quantitative evaluation of diversity combining and adaptive beamforming using various array configurations and combining algorithms. Chapter 6 describes the Handheld Antenna Array Testbed (HAAT) system and associated hardware and software. Key features of this system include portability and ability to test hand-held antenna configurations in typical microcellular and peer-to-peer communication scenarios. An overview of the chapter is given in Section 6.1, followed by a system overview in 6.2. Sections 6.3-6.8 discuss the hardware and software components of the system, including transmitters, a linear positioning system, two- and four-channel receivers and data loggers, data processing hardware, and software used to process data and evaluate performance of diversity combining and adaptive beamforming. Sample graphs of the data processing software outputs are also shown. Section 6.9 summarizes the chapter.

Chapter 7 describes the development of multi-polarized vector multipath propagation models. Section 7.1 gives an overview of the chapter. Section 7.2 discusses vector propagation models that have been developed to approximate characteristics of a radio channel, including path loss, shadowing, and multipath effects. Sections 7.3 and 7.4 discuss reflection of polarized waves and the geometrical requirements for extending the current propagation models to include the effects of antenna pattern, antenna orientation, and wave polarization. In Section 7.5, the vector multipath propagation simulator (VMPS) software package is described and an example of its use in a diversity scenario is given.

Chapter 8 reports experiments that examine the diversity dimensions of antenna configurations. These dimensions affect the performance of diversity combining in handheld radios. After the introduction in Section 8.1, Section 8.2 gives an overview of diversity principles with an emphasis on their relevance for handheld diversity antennas. Section 8.3 discusses the experimental configuration, including the HAAT, antenna arrays used, and outputs of the data processing. Section 8.4 presents results of the experiments. Section 8.5 provides conclusions based on the results of the experiments.

In Chapter 9, experiments are described that were performed using the HAAT to investigate adaptive beamforming using several different antenna configurations. Section 9.2 describes indoor measurements that were performed to verify operation of the 4-

channel HAAT receiver and associated processing software. Section 9.3 describes the procedure and antenna configurations used in controlled adaptive beamforming measurements using the linear positioner. Free-space simulations using VMPS were performed as a baseline for comparison with measurement results. These simulations are described and the results are presented in Section 9.4. Sections 9.5 – 9.7 describe controlled experiments using the linear positioner that were performed in rural, suburban, and urban multipath channels. Two sets of outdoor measurements were performed with an operator carrying the 4-channel HAAT receiver as if it were a mobile communication handset. These measurements are reported in Section 9.8 and compare the performance of co-polarized and multi-polarized array configurations in peer-to-peer and microcellular scenarios.

Chapter 10 summarizes the contents of this dissertation and includes a discussion of the results, along with future work to be done in this area of research.

References

[1.1] R. T. Compton, Jr., "On the Performance of a Polarization Sensitive Adaptive Array," *IEEE Transactions on Antennas and Propagation,* Vol. AP-29, No. 5, pp. 718-725, September 1981.

[1.2] R. T. Compton, Jr., "The Tripole Antenna: An Adaptive Array with Full Polarization Flexibility," *IEEE Trans. Ant. Prop.*, Vol. AP-29, No. 6, pp. 944-952, November 1981.

[1.3] R. T. Compton, Jr., "The Performance of a Tripole Adaptive Array Against Cross-Polarized Jamming," *IEEE Trans. Ant. Prop.,* Vol. AP-31, No. 4, pp. 682-685, July, 1983.

[1.4] L. B. Preiser, "Polarization Diversity of the General Nonuniformly Spaced Adaptive Array," *IEEE Antennas and Propagation Society International Symposium*, pp. 553-556, 1988.

[1.5] I. Kaptsis and K. G. Balmain, "Base Station Multi-polarized Adaptive Antenna for Mobile Radio," International Conferenc on Universal Personal Communications, pp. 230-235, 1994.

[1.6] B. Vaidyanathan, M. D. Srinath, and G. D. Mandyam, "Dual Polarized Smart Antenna Beams," *46th IEEE Vehicular Technology Conference*, pp. 1675-1679, 1996.

[1.7] R. G. Vaughn, "On Optimum Combining at the Mobile," *IEEE Transactions on Vehicular Technology*, vol. 37, no. 4, pp. 181-188, November 1988.

[1.8] C. Braun, M. Nilsson, and R. D. Murch, “Measurement of the Interference Rejection Capability of Smart Antennas on Mobile Telephones,” *IEEE Vehicular Technology Conference*, 1999.