CHAPTER 10
CONCLUSIONS AND FUTURE WORK

10.1 Conclusions

This dissertation reported results of an investigation into the performance of antenna arrays that can be mounted on handheld radios. Handheld arrays show great promise for improving the coverage, capacity, and power efficiency of wireless communication systems. As shown in Chapter 8, the signals received by the antennas in these handheld antenna arrays can be combined to provide 7-9 dB diversity gain against fading at the 99% reliability level in non line-of-sight multipath channels. Thus, peer-to-peer systems of handheld transceivers that use antenna arrays can achieve reliability comparable to systems of single-antenna handheld units, with only one-fifth the transmitter power, resulting in lower overall power consumption and increased battery life. Through the use of adaptive beamforming techniques, a handheld radio with an antenna array can receive a desired signal while rejecting interfering signals that occupy the same frequency and time, but have different spatial or polarization characteristics. This can allow more than one user to share the frequency and time channel within a cell, in spatial-division multiple access (SDMA) or a combination of SDMA and code division multiple access (CDMA). Commercial cellular and PCS systems in which the handheld units are equipped with array antennas can use SDMA or SDMA/CDMA to serve more subscribers within the constraints of limited frequency spectrum. In military systems, the interference rejection capability of handheld arrays can provide protection against hostile jammers.

The investigations reported in this dissertation have shown that two-element arrays with closely spaced elements can provide substantial diversity gain of 7 to 9 dB in non line-of-sight Ricean fading multipath channels (see Section 8.4). This means that if handheld antenna arrays are used with receive diversity combining, the power of the transmitting base station or peer handheld unit can be reduced by 7-9 dB from the power required to maintain a comparable level of reliability in a system that uses single-antenna handheld radios. This represents a significant savings in power, and a substantial reduction in interference to nearby co-channel units. In addition, as reported in Sections 9.6-9.9, four-element arrays of closely spaced elements used with adaptive beamforming algorithms were shown to provide 25 dB or more of interference rejection in the presence of a single interferer. This interference rejection capability could potentially allow two separate spatial channels to coexist in the same time/frequency channel, doubling system capacity.

Chapters 2-5 included background information that provides a context for the development of the hardware and software testbed and simulator, and the investigations described in later chapters.

Background information on mobile communication systems was provided in Chapter 2. Basic types of systems were described, and radio wave propagation at microwave frequencies was discussed, including multipath propagation that can cause severe fading of a received signal. In addition, a brief discussion of polarization was included. Important concepts such as frequency reuse, modulation, and multiple access techniques were also introduced in Chapter 2.

Chapter 3 presented antenna arrays and beamforming concepts that can be applied to improve the performance of mobile communication systems. First, the pattern of an array with arbitrary geometry and elements was derived. Phase and time based approaches for scanning the main beam of an array were described and compared. Fixed beam forming techniques that are used in switched-beam arrays and angle diversity systems were also discussed. Optimum beamforming, adaptive algorithms that iteratively approximate the optimum beamforming solution, and the effect of array geometry and element patterns on optimum beamforming performance, were also discussed in Chapter 3.

Chapter 4 described proposed applications of array antennas such as those described in Chapter 3 to improve performance of wireless communication systems. Proposed strategies for coverage and capacity improvement using switched-beam and adaptive arrays were discussed. These include range extension, interference rejection/reduction, and spatial division multiple access (SDMA). Antenna arrays can also be used for multipath fading mitigation and direction finding, and these topics were briefly discussed. Multipath fading mitigation using handheld antenna arrays was further investigated in Chapter 8. Possible ways that existing systems can evolve to incorporate the benefits of array antennas were also described, along with issues that affect successful integration and deployment of array antennas in wireless communication systems.

Chapter 5 introduced a category of adaptive arrays known as polarization-sensitive (dual- or multi-polarized) arrays, and described ways in which they could be used to improve performance of wireless systems. The concepts of diversity and reuse, both of which may be possible with multi-polarized arrays, were reviewed. Previous research into polarization-sensitive or dual-polarized arrays, and cross-polarized interference cancelers (XPICs) was reviewed. Possible deployments of polarization sensitive adaptive arrays in base-mobile and peer-to-peer mobile communication systems were discussed. The performance of dual- and multi-polarized arrays had only been simulated in free space up to this point. Performance of these arrays in multipath channels had not been investigated previously, but was investigated as part of the handheld adaptive antenna array experiments reported in Chapter 9.

Chapters 2 through 5 provided background on mobile communication systems, array antennas, and potential applications of array antennas to improve the performance of mobile communication systems.

The emphasis of the remainder of the dissertation was to investigate the performance of handheld antenna arrays used with diversity combining (for mitigation of fading due to multipath), and with adaptive beamforming (for interference rejection). While some research had been done on diversity combining in handheld radios, no investigation had explicitly considered the antenna pattern effects due to mutual coupling of closely spaced antennas. The use of adaptive beamforming at handheld radios is a novel area of research that offers many of the possible benefits that can be obtained using base station arrays as discussed in Chapter 4. The possibility of adaptive beamforming at the mobile was first discussed in 1988 [10.1], but only one limited investigation has been reported, in a 1999 conference paper [10.2]. To support the diversity combining and adaptive beamforming investigations, an RF testbed and a software modeling package were developed. These systems were described in Chapter 6 and Chapter 7 respectively. The investigation of diversity, including spatial, pattern, and polarization effects, was discussed in Chapter 8 and the investigation of interference rejection using co-polarized and multi-polarized handheld adaptive arrays was discussed in Chapter 9.

Chapter 6 described the handheld antenna array testbed (HAAT), a portable narrowband RF measurement system that was developed to investigate performance of handheld antenna arrays, including dual- and multi-polarized arrays, for diversity combining and interference rejection. The HAAT was developed jointly by the author and J. Randall Nealy, who was also primarily responsible for the hardware development. The hardware and software components of the system, and typical operational scenarios were described in Chapter 6.

This dissertation includes the following contributions. First, as described in Chapter 7, the vector multipath propagation simulator (VMPS), a software package for modeling the transmission of polarized waves in multipath environments, was developed. Geometrically based vector channel models had been developed previously for use in investigations of diversity combining and adaptive beamforming in mobile communication channels [10.3]-[10.5]. However, these models did not include the effects of polarization of transmitted waves or the patterns, polarizations, and orientations of the transmitting and receiving antennas. An extended model was needed to support the investigation of polarization diversity and beamforming using dual- or multi-polarized arrays. Chapter 7 describes a framework that was developed for modeling multipath propagation including these polarization and antenna effects. This framework formed the basis for the VMPS software. VMPS uses polarization-sensitive vector channel models, and can model the effects of antenna pattern, polarization, and orientation, channel characteristics, and interference scenarios. The transmitters and/or receivers in these simulations may be mobile. This feature is essential for realistic simulation of multipath fading, and also allows simulation of the performance of adaptive beamforming algorithms in dynamic channels. VMPS was used to model propagation of polarized waves in a free-space interference scenario in Chapter 9, and it may be used more extensively in future investigations to test array configurations in scenarios that cannot be easily duplicated with available experimental hardware.

Second, a methodical experimental investigation of spatial, polarization, and pattern diversity for handheld radios was conducted. This investigation was described in Chapter 8. The effect of mutual coupling on the patterns of closely spaced antennas was modeled and measured, and the effect of the distorted patterns on the theoretical envelope correlation was shown. Over 800 experiments were performed in peer-to-peer multipath scenarios using the handheld antenna array testbed (HAAT). The results showed that substantial diversity gains of 7-9 dB could be achieved at the 99% reliability level in non line-of-sight rural, suburban, urban, and indoor channels that were characterized by Ricean fading with specular-to-random power ratio K ranging from 0.4 to 2.0 or –4 to +3 dB. These diversity gains were achieved even when using arrays with small antenna spacings of 0.15 to 0.3 wavelengths. In the 1800 MHz PCS band, this corresponds to an antenna spacing of 2.5 to 5 cm (1 to 2 in.), and such arrays would be small enough to fit on a small handheld phone operating in this band.

Chapter 9 presented the third contribution, the most extensive investigation yet reported of adaptive beamforming using handheld antenna arrays. The investigation used small four-element antenna arrays that were mounted on a receiver that could be carried like a mobile phone. This investigation showed that a high degree of interference rejection was possible, indicating that in a system using handheld radios equipped with adaptive arrays, more than one user can share a frequency and time channel. This can be done through the spatial-division multiple access (SDMA) scheme described in Chapter 2 and Chapter 4 or a combination of SDMA and code division multiple access (CDMA) as discussed in Chapter 4. This capacity improvement would allow a commercial mobile communication system to support more users than a conventional system using the same limited frequency spectrum, resulting in increased revenues. The interference rejection capability of handheld adaptive arrays also provides protection against jamming in military scenarios.

The investigation described in Chapter 9 consisted of experiments in rural, suburban, and urban channels with two mutually interfering transmitters. Controlled experiments with a receiver that was stationary or moving at a uniform speed on a linear positioner showed that mean SINR for the desired signal could be improved from about 0 dB before beamforming to 25 to 50 dB after beamforming. Similar improvements in SINR were seen at lower cumulative probabilities of 0.1% to 10%. In multipath channels, these performance levels were achieved even when there was no separation between the transmitters in azimuth angle as seen from the receiver, and no difference in the orientations of the two transmitting antennas. Additional measurements were performed in which the receiver was hand-carried at walking speeds in peer-to-peer and microcell scenarios. The mean SINR improvement in the peer-to-peer scenario was approximately 30 dB, and the mean SINR after beamforming was 12-16 dB in the microcell scenario. The low SINR in the microcell scenario is partly due to the low SNR caused by attenuation of the signal over the longer propagation path. In the multipath channels measured, a dual- or multi-polarized antenna array provides no more than a 3 dB advantage over a co-polarized array, indicating that in these channels polarization flexibility can be helpful but is not critical.

10.2 Future Work

There are numerous opportunities for research on handheld adaptive arrays in addition to the investigations presented in this dissertation. For example, the interference rejection capability of conformal array configurations that can be deployed on very small handsets has not yet been investigated. This is an important area of investigation since handsets are being made smaller.

In addition, the effects of the operator's head and hand on the performance of adaptive beamforming with handheld arrays can be studied more extensively. Gain imbalance between antennas in an array can result either when different types of antennas are used or when one or more antenna is covered by the user's head or hand. The resulting power imbalance can degrade the performance of the array, and this should also be investigated. These investigations would aid in the design of practical antenna configurations that work well under typical operating conditions. The new indoor range in the Virginia Tech Antenna Laboratory as well as the HAAT could be used in such investigations.

The investigation presented in this dissertation considered 4-element arrays operating in the presence of a single interferer. It is also desirable to understand array performance in multipath fading channels as a function of the number of elements and number of interferers. HAAT and VMPS could be used in such an investigation. Such an investigation would help to determine the minimum number of elements that an array must have to operate satisfactorily in a given interference scenario, or the worst-case interference that can be overcome with a specific antenna configuration. This information can be used in system planning to gain maximum advantage from the handheld adaptive arrays.

More extensive experiments can be conducted using candidate handset array configurations in a microcell scenario in which the transmitters use power amplifiers to improve the SNR, and therefore the measurable interference rejection, at the receiver. This will give a more accurate idea of the interference rejection that can be achieved in an operational system.

The experiments reported in this dissertation involved narrowband CW signals. Emerging wireless communication systems, however, use bandwidths of up to 5 MHz. The performance of handheld antenna arrays in wideband systems is expected to be similar to narrowband performance in some channels but may be substantially different from narrowband performance in channels that have delay spreads on the order of a chip or symbol period. Further experiments are needed to quantify wideband performance of handheld adaptive arrays, and to verify the applicability of handheld antenna arrays to wideband systems. Experiments similar to those described in this dissertation must be performed using a wideband testbed, such as the VIPER system that is currently operational and undergoing further development at Virginia Tech. With wideband signals, additional beamforming algorithms may be used, such as decision-directed algorithms or algorithms that use knowledge of a spreading code.

Validation of the VMPS modeling software is in progress, using data reported in this dissertation. Once validated for multipath channels, VMPS can be used in future investigations using both narrowband and wideband signals.

From a theoretical perspective, it may be possible to relate a suitable measure of spatial-polarization signature differences between signals to the SINR that is achieved by an adaptive beamformer. Both simulated and experimental data, including data from the experiments reported in this dissertation, can be analyzed to investigate this relationship.

Further work is also required to devise implementation and transition strategies and to quantify the effects of handheld adaptive arrays on coverage, reliability, spectral efficiency, and power efficiency of peer-to-peer and cellular wireless communication systems. The tradeoffs between the cost of deploying handheld adaptive arrays and their benefits for system performance must also be investigated to determine what types of wireless communication systems are good candidates for deployment of handheld adaptive arrays.

References

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