Smart Antenna for Handsets

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Abstract

This paper describes a Texas Instrument (TI) sponsored research carried out jointly by the Virginia Tech Antenna Group (VTAG) and the Mobile Portable Radio Research Group (MPRG) at Virginia Polytechnic Institute and State University. The research is focused on determining the feasibility of smart transmit and receive handset antennas. The goals are to show reduced power consumption, improved capacity and better link reliability. The research topics include developing new smart antenna algorithms and evaluating link reliability and capacity improvement. A comprehensive set of spatio-temporal vector channel measurements has been collected in order to assess the performance of the smart antenna in real environments. Data collection was performed with four array hardware testbeds developed at Virginia Tech and they are: Handheld Antenna Array Testbed (HAAT), MPRG Antenna Array Testbed (MAAT), VIPER, and Transmit Diversity Testbed (TDT).

Transmit diversity algorithms for both flat fading and frequency selective channel using an IMT-2000 type-signal are being evaluated with the Transmit Diversity Testbed. Different spatio-temporal structures are being studied for wideband receiver array applications.

1.0 Introduction

Smart antennas hold promise of providing significant performance improvement in third generation handheld radios. The Mobile and Portable Radio Group (MPRG) and the Antenna Group (VTAG) at Virginia Tech are teamed to investigate key aspects of smart handset-antennas for Texas Instruments. This includes collecting antenna and propagation measured data, evaluating diversity and adaptive algorithms, simulating overall system performance, and quantifying basic phenomena that impact handsets with smart antennas. Since beginning this project in July 1998, we have created three tools, a Handheld Antenna Array Testbed (HAAT), a Vector Multipath Propagation Simulator (VMPS), and a wideband Vector ImPulsE Response measurement system (VIPER). We have used these tools along with the MPRG Antenna Array Testbed (MAAT) to gain an understanding of the propagation environment as perceived by an array of antennas at the handset. This information has been used to predict the performance of smart antennas employed at the handset.

Extensive measurements at 2.05 GHz indicate that gains in the link budget of 7-9 dB at the 99% reliability level can be realized in narrowband systems for outdoor and indoor non line-of-sight environments. These gains can be achieved by using small antenna arrays with diversity or adaptive combining at the handset, for antenna separations of 0.15 wavelength or greater. Additional measurements indicate that a single interfering signal can be reduced by 25-40 dB using adaptive beamforming algorithms. Thus substantial improvements in reliability, system capacity, and transmit power savings are possible.

This paper provides a summary of milestones achieved during a 2-year project with Texas Instrument [1], [2]. It contains descriptions of the hardware testbeds, propagation measurements and demonstrations, as well as plans for future research.

2.0 System Development

2.1 Handheld Antenna Array Testbed (HAAT)

The HAAT system was developed to evaluate the performance of various antenna configurations in diversity combining and adaptive beamforming experiments. Figure 2 shows a typical experimental scenario using the HAAT system. The receiver mixes the signals from two or more receiver channels down to baseband. These signals are recorded on digital audiotape for off-line processing using the appropriate algorithms. The receiver is moved along a 2.8-meter track at constant speed simulating a person walking. A small hand-held radio type unit holds two antennas. The spacing and orientation of the antennas is varied. The system has the following features:

- 2.05 GHz CW signal(s)
- 2 transmitters
- 1 receiver (2 channels, expanding to 4)
- 2.8 meter linear track continuously collected data, processed off line
- battery operated system, highly portable
- realistic operating scenarios for the handheld receiver.

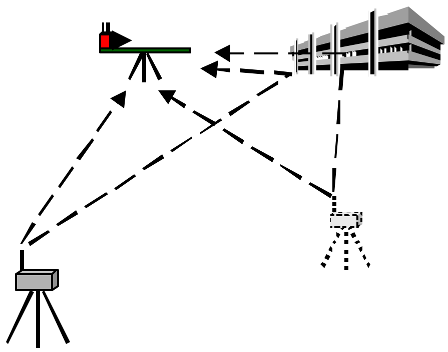

Figure 1 A typical experiment using the HAAT in a multipath environment. One transmitter is used for diversity combining experiments. A second transmitter can be used for interference rejection experiments using adaptive beamforming algorithms.

2.2 MPRG Antenna Array Testbed (MAAT)

The MAAT shown in Figure 2 has many of the same characteristics as the HAAT but has more channels and is capable of much larger bandwidths. It is, however, somewhat bulky and difficult to move to various sites. The MAAT operates at 2.05 GHz with a sinusoidal or modulated signal. The bandwidth is set now at 100 kHz but can be extended to 1 MHz with modifications. The MAAT is capable of digital real-time beamforming and angle-of-arrival estimation.

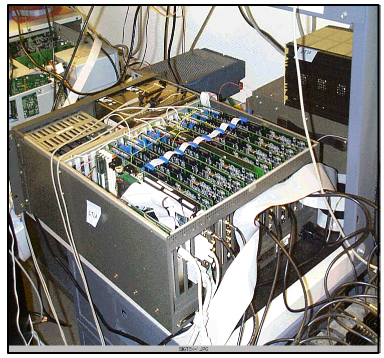

Figure 2: The MAAT consists of eight Harris 40214 Programmable Direct Digital Downconverters and eight C54x DSPs.

MAAT experimental results confirm the occurrence of transmit and receive reciprocity, i.e., the functional roles of the transmit and receive antennas are interchanged. This allows simplification of the experimental collection to prove smart transmit antennas. It also allows data collected to support smart receive antennas to be used for interpreting the performance of smart transmit antennas.

2.3 Vector ImPulsE Response Measurement System (VIPER)

A software-defined, wideband vector channel measurement receiver was developed. VIPER also supports transmit and receive diversity measurements. The VIPER receiver is capable of receiving signals up to 400 MHz in bandwidth and processing these signals in software. The receiver serves as a testbed for smart antenna algorithms and performs the function of a multipath measurement system for comparing antenna algorithm performance results in multiple radio channel environments. Figure 3 below shows the photograph of the VIPER RF front-end section. A four-channel oscilloscope is used for the sampling system, and the computer acquires all signal information from this oscilloscope.

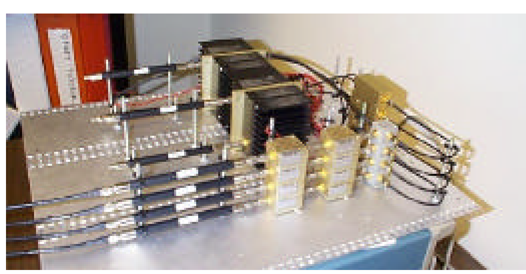

Figure 3 VIPER RF front-end section

VIPER has been designed to implement processing functions in software with minimal RF hardware. Figure 4 below shows a block diagram of the receiver hardware. A single-stage down-conversion is performed, and IF signals are sampled at 1 giga-sample per second for each of the four channels. The samples are stored in RAM and processed by the computer.

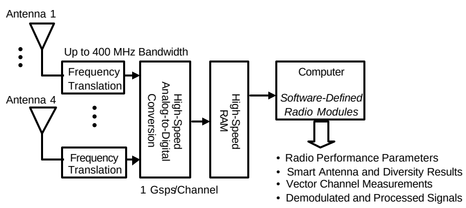

Figure 4. VIPER system diagram

The VIPER software is responsible for acquiring, processing, and recording received signals and displaying measurement or algorithm results. The software has evolved over the past year to include the following modules:

- Antenna diversity and diversity gain processing
- Measurement of time dispersion characteristics (multipath) of radio channels
- Implementation of smart antenna algorithms developed in MATLAB
- Power, time-domain, and spectrum measurement
- Acquisition and recording of raw received signals
- Playback of recorded signals for developing and testing new algorithms

2.4 Wideband Transmit Diversity Testbed

A wideband transmitter has been designed and built for the wideband diversity and channel measurement experiments. The transmitter is based on an FPGA with on-board EEPROM that defines the PN and data sequences. The current implementation of the transmitter allows the PN chip sequence to run as high as 25 Mcps, but future implementations will use the FPGA IC's full capability to run a PN sequence at 100 Mcps. This high chip rate is required for detailed measurements of multipath radio channels, but lower chip rates will be used during diversity experiments for producing signals similar in bandwidth to those of 3G wireless systems.

2.5 Vector Multipath Propagation Simulator (VMPS)

The Vector Multipath Propagation Simulator (VMPS) was developed to function in conjunction with experimental measurements in either narrowband or wideband signal environments. The complete radio channel can be modeled with this simulator including antenna and propagation effects. Experimental results can be used to optimize the models implemented in VMPS. The goal is to study and isolate the effects of such parameters as antenna pattern and spacing, multipath, interference, algorithm performance, and others.

A receiver system with up to 8 antennas can be modeled with the VMPS simulator. Up to 6 transmitters can be activated and placed at arbitrary locations around the receiver. Multipath propagation is simulated by inserting scatterers at locations chosen by users or determined from built-in models. Transmit power and reflection coefficient of the scatterers can be varied and line of sight can be turned on or off. The combination of all these features allows for the simulation of a wide variety of channel conditions.

The simulator can model the performance of several diversity schemes such as spatial, polarization, pattern, and angle diversity. Diversity gains of 7-11 dB have been obtained from VMPS at the 99% level for two antenna elements in non-line of sight urban propagation environments using maximal ratio combining. These simulation results agree with measurements performed under similar propagation conditions using the HAAT system. VMPS can also evaluate the performance of broadband communication systems that use spatial-temporal arrays, spatial arrays, tapped delay line equalizers, or a single antenna receiver under different scenarios of interference and multipath.

4.0 Measurements

Extensive measurements have been carried out with the developed hardware testbeds. These measurements include diversity measurements at the handset, effect of antenna element spacing and operator tissue on diversity, adaptive beamforming, angle of arrival, verification of channel reciprocity, and wideband vector channel measurements.

Sample diversity measurements for an outdoor non-line-of-sight channel are presented in figures 5 and 6. Figure 5 shows correlation coefficient versus antenna spacing. Note that correlation is well below 0.7, which is good for achieving improvement due to diversity. Figure 6 shows diversity gain as a function of antenna spacing. There is about 9 dB of gain for 99% reliability and about 5-dB gain for 90% reliability almost independent of spacing down to 0.1 wavelengths.

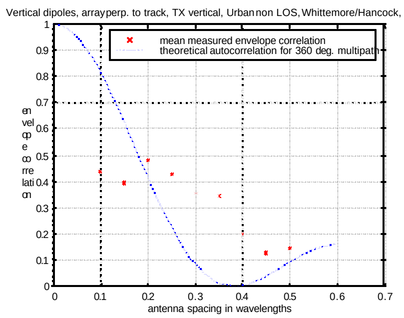

Figure 5: Envelope correlation coefficient versus antenna spacing for spatial diversit y measurements in an urban, non-LOS environment.

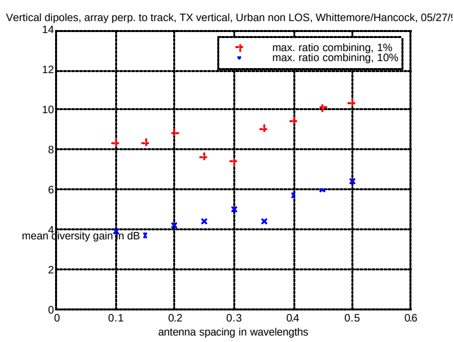

Figure 6 Mean diversity gain vs. antenna spacing for spatial diversity measurements in an urban, non-LOS environment.

HAAT system was used to study different types of diversity implementation that included spatial, polarization and pattern diversity. Table 1 presents a summary of diversity results for urban non-LOS channel. Table 2 shows results from experiment with a human operator. Note that the operator's head near the antennas causes only a small degradation in performance gains from diversity.

Table 1:

Type	Envelope Correlation	Power Imbalance, dB	Gain, MRC,dB	Gain, Select, dB
Spatial	0.12-0.49	0.7-4.4	7.4-10.4	6-9
Polarization	0.31	0.4	9.2	7.8
Pattern	0.13-0.08	5.6-6.2	9.2-11.2	7.9-9.7

Table 2:

	Envelope Correlation	Power Imbalance	Diversity gain, MRC	Diversity gain, Selection
w/operator	0.31	0.4 dB	10.6 dB	9.4 dB
w/o operator	0.44	0.5 dB	8.8 dB	7.1 dB

Extensive investigation was performed on 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. The adaptive beamforming investigation consisted of over 250 experiments in rural, suburban, and urban channels with two mutually interfering transmitters. Controlled experiments provided a performance improvement of 25 to 50 dB with a least-squares constant modulus algorithm (LSCMA). 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 37-41 dB, and the mean SINR after beamforming was 21-27 dB in the microcell scenario. The lower 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.

MAAT system was used to carry out angle of arrival measurements, adaptive interference cancellation algorithms for a spread spectrum system (low bandwidth), and multi-spectral vector channel measurements based on a frequency sweep over 10 MHz bandwidth. The multi-spectral measurements reveal the flat fading nature of an indoor channel and a frequency selective fading nature for an outdoor to indoor channel.

The VIPER was used to initiate a series of wideband vector channel measurements for a variety of channels (indoor, outdoor, etc.) with a bandwidth commensurate with IMT-2000 bandwidth. Initial experiments were performed in an indoor environment.

5.0 Transmit diversity research

This section describes Virginia Tech's recent activities on transmit diversity at the handset. It involves investigation of the different aspects of this form of diversity. Transmit diversity is employed by transmitting the symbol sequence over all the elements of an antenna array at the transmitter. The problem is defined to maximize signal to noise (SNR) at the receiver subject to constant transmit power. Different algorithms were proposed and techniques devised to implement transmit diversity at the handset for a flat fading channel. The techniques involved using a complex weight vector at the transmitter to scale the symbols through different antenna elements. The proposed techniques were compared with respect to maximum achievable SNR and the convergence behavior. The techniques include early-late technique, subspace technique, gradient-based approach, and least-square (LS) technique.

The techniques were tested through simulations and results showed that the LS technique provided the most promising solution for a flat fading channel. Simulations indicate that 2-6 dB of performance gain for a 2-element array, and 5-12 dB of performance gain for a 4-element array compared to a single antenna system is possible for indoor environments. Feedback and latency issues associated with these proposed algorithms were studied. Simulations show that a coarse magnitude and phase quantization of the complex weight vector is possible with only slight performance degradation. The suitability of these algorithms with respect to their implementation in WCDMA standard of IMT-2000 was also studied. The channel structures and the signal format of WCDMA can accommodate the algorithms.

6.0 Transmit diversity demonstration

The feasibility of the transmit diversity system was demonstrated by a hardware implementation. The setup consisted of a 2-element wideband transmit diversity testbed and VIPER as the receiver. The gain of one element was held constant while the phase of the other element was varied in discrete steps. Signal strength was measured for each phase setting and the setting providing the maximum power was identified and relayed back to the transmitter. Signal strength measurements were also done for individual antenna elements and performance of the diversity system was compared to those of single antenna system. Initial results show that an improvement of 3-4 dB is possible at 1% level of cumulative distribution function (CDF) plots.

7.0 Conclusions

This paper has described Virginia Tech's research on smart handset antennas. Different testbeds have been developed and propagation experiments have been carried out with these testbeds. Channel measurements indicate performance improvement of diversity system over single antenna system. Narrowband measurements indicate up to 40 dB of interference rejection can be obtained using adaptive beamforming techniques with a four-element array. Similar gains should be possible for wideband systems using appropriate algorithms. Wideband diversity experiments are underway with the VIPER system. Transmit diversity has been investigated for a flat fading channel and different algorithms have been proposed and verified by simulation. Transmit diversity has been demonstrated with a wideband signal in an indoor environment. Building on our experience with VIPER, a wideband handheld antenna array testbed with continuous data collection capability can be rapidly developed to support experiments to evaluate the performance of adaptive beamforming at the handset with wideband signals.

8.0 References:

[1]. "Summary of the First Year of Work with Virginia Tech's Smart Handset-Antenna Research for Texas Instruments", Technical report submitted to TI, 1999.

[2]. "Summary of the Second Year of Work with Virginia Tech's Smart Handset-Antenna Research for Texas Instruments", Technical report submitted to TI, 2000.