MIMO Technology for Point-to-Point and Multi-User Wireless Communication *

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1 Introduction

Technology development for multiple input multiple output (MIMO) wireless communication has undergone significant growth over the past several years. While some research questions remain unanswered related to this topic, for the most part the technology currently exists for implementing MIMO in point-to-point links. Using multi-antenna approaches for multi-user networks, however, remains an area of intense investigation. In this paper, we highlight some of our recent research in point-to-point MIMO systems and discuss our current and upcoming work relating to multi-user networks with MIMO enabled nodes.

2 Point-to-Point MIMO Research

Channel Measurement and Modeling: We have conducted an intensive campaign aimed at experimentally characterizing the MIMO multipath channel and capturing our findings in simple yet accurate channel models. To this end, we have constructed and deployed a MIMO channel probing system capable of supporting up to 16 transmit and receive antennas. The system operates at 2.4 GHz and directly measures the channel transfer matrix using simultaneous transmission of pseudo-noise sequences from all antennas and a maximum-likelihood estimation procedure at the receiver. Data collected from this system has been used to examine issues such as: (1) the effect of antenna element spacing, polarization, and directivity on channel capacity, (2) the tradeoff between signal-to-noise ratio and multipath richness on MIMO performance, and (3) the statistical characteristics of the channel matrices for a variety of environments.

Based upon these measurements as well as prior studies on multipath characteristics in wireless channels, we have developed a channel model capable of capturing the statistical behavior observed in the data. This model characterizes the channel by representing each multipath component in terms of its amplitude, arrival time, and departure/arrival angles. Given statistical descriptions of these multipath parameters (based on experimental observations), a double-directional channel impulse response is formed which, when coupled with the antenna responses, is used to construct the narrowband channel matrix. Polarization is included via an empirical fit to the measured data. Extensive studies have shown that this model matches the measured data extremely well both in terms of the channel capacity and the joint statistics of the transfer matrix coefficients.

Channel Capacity: For MIMO systems, the channel is typically taken to be a combination of the antenna arrays with the electromagnetic propagation. However, this metric does not truly offer an upper bound on performance since different antenna configurations might be more suitable for a particular propagation environment. Therefore, we have formulated an *Intrinsic Capacity* bound that considers only the electromagnetic propagation and the apertures within which the arrays are confined. The approach uses a discretization of the currents in the transmit aperture and resulting fields in the receive aperture coupled with a numerical computation of the optimal transmit and receive signal weighting. The resulting capacity provides a bound against which the performance of different antenna geometries can be measured.

In related work, we have developed a complete network theory of MIMO systems which rigorously incorporates the impact of antenna mutual coupling and source/load impedance matching. The approach properly computes the radiated power (which is of course different than the sum of the

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squares of the excitation currents as is usually assumed) for use in the capacity constraint. In addition to providing a complete analysis framework, this study has revealed that mutual coupling can not increase capacity due to *pattern diversity* as is typically assumed, since this pattern diversity is simply the linear superposition of the individual (isolated) patterns of the array elements. However, coupling can increase capacity for certain spacings due to increased effective aperture – the total aperture is greater than the sum of the effective apertures of the elements – for optimal as well as for self-impedance matching to the array at the receiver.

Finally, we have explored the recently-proposed concept of using all six electromagnetic polarizations for communication. The relevant issue becomes the achievable communication performance when the antenna is confined to a single point in space. This study used very basic electromagnetic concepts to show that in reality, the magnetic and electric fields are not independent as has been previously suggested. However, six degrees of communication performance can be obtained using three electric and three magnetic infinitesimal dipoles (under certain propagation conditions). These degrees of freedom stem from three orthogonal radiation patterns coupled with two distinct polarizations. This interpretation of the phenomenon is much more consistent with traditional views concerning the nature of electromagnetic waves.

3 Multi-User MIMO Research

When dealing with multi-user networks, one possibility is to simply use MIMO technology to provide highly spectral-efficient transmissions over each individual link while coordinating all multi-user access using traditional methods. The technology for such an approach, however, is largely in place, and using all spatial degrees of freedom for increasing throughput ignores the possibility of using space-time processing for higher-level network functions such as power control, multiple access, message routing, etc. Future research in this area must examine integrating the space-time processing capabilities of networks with MIMO-enabled nodes to increase overall network capacity and facilitate other aspects of multi-user communication. Some topics relevant to this issue are included below.

Channel Characterization: Simple multi-user network studies assume that the channels between distinct nodes are independent. However, for nodes in relatively close proximity, the multipath structure will likely have strong similarities, leading to some relationship between the resulting channel matrices. We are currently designing a multi-user channel probing system capable of simultaneously constructing the transfer matrices from one node to multiple receiving nodes. Based upon data from this measurement campaign, we will augment existing channel models as appropriate or construct new ones capable of properly representing realistic channels. These channel models will facilitate studies of how space-time processing can be used to suppress multi-user interference as well as provide high spectral efficiency over the network.

Multi-User Space-Time Signaling: While medium access control (MAC) and link-level protocols can control the coordination of multiple nodes, the physical layer must be equipped with effective algorithms for space-time processing, whether it be for spatial division multiple access (SDMA), jammer mitigation, or other functions. We are developing several such approaches for this application. The first is a generalized zero-forcing solution in which a single node can transmit distinct messages to multiple other nodes by ensuring that the transmission for one user is spatially orthogonal to the channels for the other users. Because this algorithm, however, requires that the transmitter possess a significant amount of channel state information (CSI), we are currently exploring a promising class of algorithms that calculate an "optimal" linear precoding by exploiting: 1) CSI (reasonably available via training) at the transmitter, 2) knowledge of the statistical interference environment that the receiver nodes will experience (known at the transmitter since it is producing the interference), and 3) the beamforming algorithm used by each receiver. In this context, "optimal" can take on different meanings depending on the overall algorithm objectives. Furthermore, in a recent collaboration with Bell Laboratories, we have also investigated the dual problem and developed "dirty-paper" transmit algorithms that are near-capacity and much simpler to implement than other proposed approaches that require, for example, complicated nested lattices.