RF and Algorithmic Considerations for Practical MIMO Wireless Implementation

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Abstract – **This paper discusses several practical issues pertaining to multiple-input multiple-output (MIMO) system implementation and operation. The presentation focuses on signal coupling in integrated RF front ends and closely-spaced antennas, the behavior of realistic channels with practical antenna geometries, and important considerations relating to channel estimation and feedback. These issues are explored using a combination of detailed modeling and simulation, channel measurements, and system implementation using a real-time MIMO communication platform.**

Index Terms – **Antenna array mutual coupling, MIMO systems, Polarization, Information rates**

I. Introduction

A large volume of research focused on multiple-input multiple-output (MIMO) wireless communication systems has demonstrated the performance potential of this technology. Much of the analysis and development resulting from these research activities, however, assume ideal behavior of the radio-frequency (RF) subsystems and propagation channel and neglect practical requirements for MIMO algorithm implementation. When implementing a MIMO system that must operate under realistic conditions, these practical issues must be considered and properly incorporated into the design.

This paper discusses some of these practical issues concerning MIMO system implementation and operation. Specifically, we focus on signal coupling in integrated RF front ends and closely-spaced antennas, the behavior of realistic channels with practical antenna geometries, and important considerations relating to channel estimation and feedback of this information to the transmitter. These issues are explored using a combination of detailed modeling and simulation, channel measurements, and system implementation using a real-time MIMO communication platform.

II. Coupling in MIMO RF Sub-Systems

In many applications, nodes within a MIMO-enabled network may consist of mobile and portable devices with a relatively small area for antenna placement. Therefore, mutual coupling created by the closely-spaced antenna elements must be considered in the design and will generally impact the performance. Furthermore, traditional practice dictates that the multiple RF receiver front-ends should not be integrated onto a single substrate due to the high coupling that can occur. However, as demand for the additional communication resources enabled by MIMO processing increases, some level of front-end integration will be required in order to make the technology economically viable. Therefore, it is important to fully understand the performance impacts associated with coupling both at the antenna and RF front-end.

While recent studies have shown how optimal receiver impedance matching can be performed to remove the impact of most coupling phenomena [1], the required matching networks would be complex and impractical for implementation. Our goal is therefore to quantify the performance degradation observed with different levels of coupling for practical matching. To accomplish this, we use a detailed network model of the MIMO system that considers the signal flow from transmit antenna to receiver low-noise amplifier. Fig. 1 shows the block diagram of a MIMO system with the coupled antennas, propagation channel, and receiver front-end. This system, which includes a detailed model of the noise injected in the receiving amplifiers, is analyzed using an S-parameter representation. Using a path-based propagation model to describe the channel between the coupled antennas and full wave finite-difference time-domain method to electromagnetically characterize the antennas, the capacity performance of this system can be formulated based on the combined signal plus noise network analysis [1].

Fig. 2 shows a plot of the MIMO capacity, computed using the water-filling capacity formulation, for two coupled dipoles at both transmit and receive as a function of the receive dipole spacing (the transmit dipoles remain fixed at half-wavelength spacing). The matching networks used either achieve minimum noise figure or maximum power gain for the amplifiers. Furthermore, the plots show the performance obtained with an optimal matching network for the coupled antennas versus what occurs either when no coupling is present or when a sub-optimal

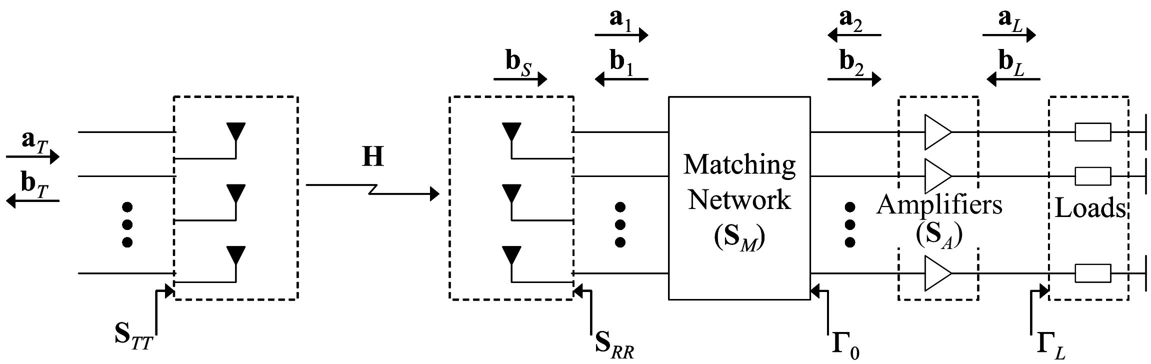

Fig. 1. Block diagram of a MIMO communication system with coupled antennas and receiver front-end.

but practical self-impedance match is assumed. As can be seen, antenna coupling can increase the capacity if a perfect matching network can be used. With a more practical self-impedance match, the performance degradation is negligible for reasonable antenna spacing.

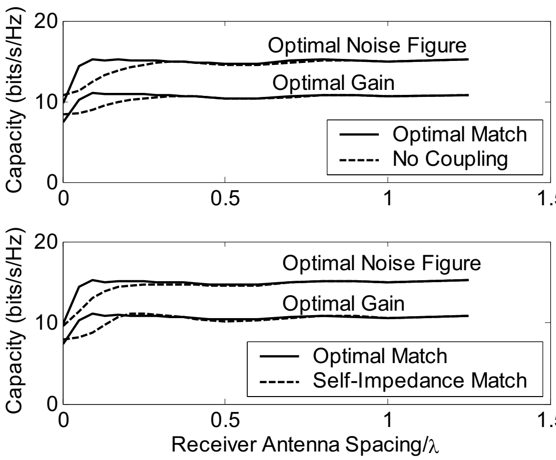

Fig. 2. MIMO capacity versus receiver antenna spacing for two coupled dipoles and different receiver matching assumptions.

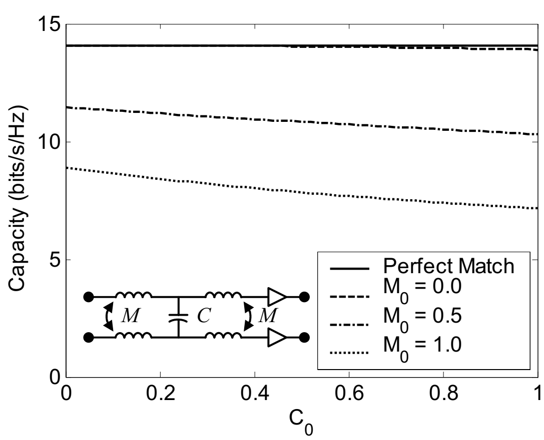

Fig. 3. MIMO capacity versus receive amplifier coupling.

Fig. 3 shows the capacity obtained from the model for a 2×2 system using uncoupled dipoles and coupled receive amplifiers. The network used to model the amplifier coupling is shown in the figure inset, and the results are shown versus normalized capacitance $C_0 = \omega C Z_0$ and mutual inductance $M_0 = \omega M / Z_0$, where ω is the operation frequency and Z_0 is the system impedance. The match is designed assuming no coupling occurs. Also shown is the performance when a perfect matching network is implemented to compensate for the coupling in the amplifiers. As can be seen, the performance degrades due to the impedance mismatch created by the coupling. Therefore, care must be exercised when considering integration of multiple RF front-ends on a single chip.

III. Antenna Polarization

Most theoretical studies assume that the channel provides adequately rich scattering to provide a transfer matrix where all singular values are of similar magnitude so that each antenna provides an independent spatial degree of freedom. In practice, however, time variations in the propagation environment can lead many channel realizations with some small singular values. When implementing a MIMO system, the algorithm must either adapt to this changing channel rank or provide some immunity to its variation. One simple measure that can be taken is to use antennas with different polarization characteristics. Such an arrangement helps maintain the rank of the channel matrix, offering at least two channels even when no scattering is present. However, it must be understood that when cross-polarized scattering is weak (which is commonly observed), the entries in the channel matrix corresponding to transmission on one polarization and reception on another can be small, resulting in decreased capacity due to lower effective signal-to-noise ratio (SNR).

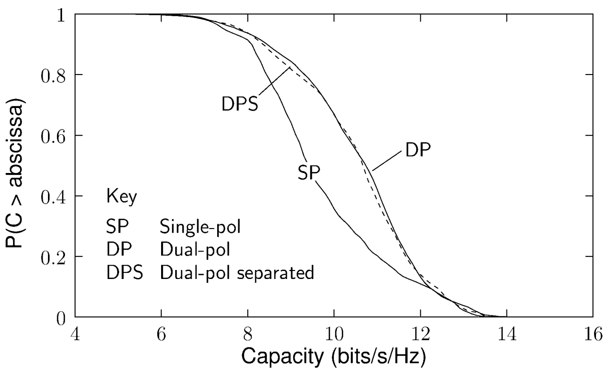

Fig. 4. Measured MIMO capacity complementary cumulative distribution function for a 2×2 MIMO system with different polarization scenarios.

Fig. 4 shows measured capacities (complementary cumulative distribution function) for a 2×2 system employing dual-polarization patch antennas in an indoor environment compared to the capacity in the same environment using two monopole antennas separated by a half wavelength [2]. The statistics were gathered using an ensemble of measurements taken in a variety of locations in a typical university building with laboratories and offices. The capacity resulting when the antennas offering the two polarizations are separated by a half wavelength is also shown. The fact that the polarization diversity offers increased capacity despite the effective decrease in SNR confirms that this arrangement leads to improved behavior in the channel singular values and can be a viable architecture for practical implementation.

IV. Real Time MIMO Communication

While great insight regarding the potential performance of space-time coding techniques can be obtained using simulations in concert with accurate channel models or measured channel data, ultimate performance as well as real-time implementation feasibility must be assessed through experimental prototypes. We have developed a MIMO prototyping platform employing 4 transmit and receive elements (scalable to 8 elements) [3]. A block diagram of the system appears in Fig. 5. The architecture is based on a DSP platform, allowing rapid development of algorithms in C or C++. Embedded PCs are used to simplify the system usability. In this paper, we wish to use this platform to highlight the very practical issue of *Channel State Information* (CSI) that must be considered for real-time implementation.

In environments offering full-rank channel transfer matrices, feeding back CSI from the receiver to the transmitter provides little performance benefit. However, as the channel becomes rank-deficient (has small singular values), the performance of algorithms such as VBLAST [4] that transmit independent streams on all antennas regardless of channel conditions quickly deteriorates. Fig. 6 plots the singular values of a 4×4 channel matrix as well as the symbol error rate (SER) observed on the real-time MIMO system using 16-quadrature amplitude modulation and a bit rate of 1 Mbps in an indoor environment as a function of time. The key behavior observed in this plot is that when the smallest singular value becomes very weak, the SER rises dramatically.

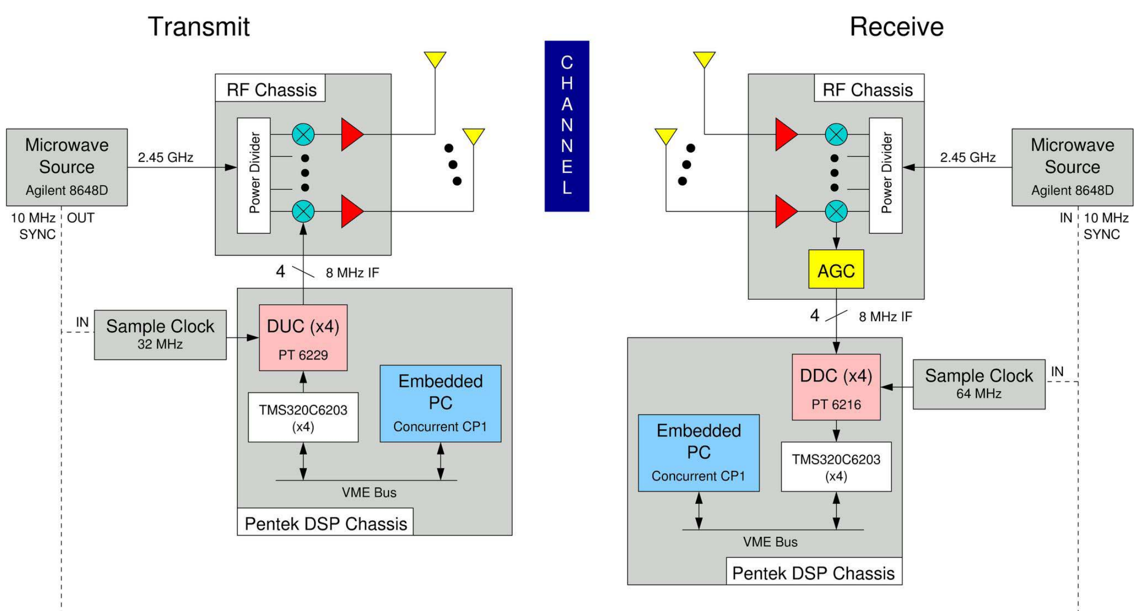

Fig. 5. Block diagram of the real-time MIMO communication system developed at Brigham Young University.

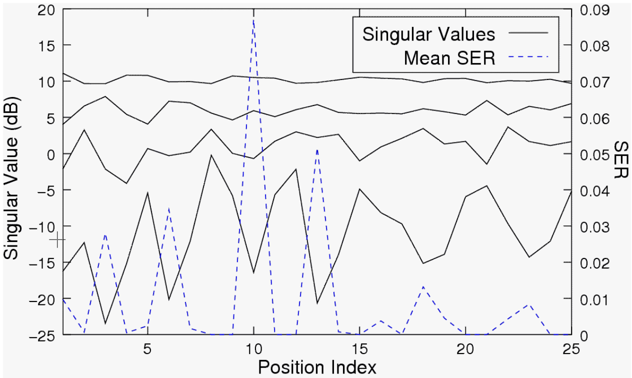

Fig. 6. Measured MIMO capacity complementary cumulative distribution function for a 2×2 MIMO system with different polarization scenarios.

Fig. 7 uses simulation of a VBLAST system to confirm the experimental observations of Fig. 6. In this case, the bit error rate performance of a 4×4 system is simulated for a full rank channel and a rank deficient channel. As can be seen, the bit error rate is unacceptable for the rank deficient case. Since in practical operation, the rank of the channel will typically vary with mobility of one end of the link or with changes to the physical propagation channel, measures must be taken to avoid these periods of poor communication performance. A variety of approaches can be considered for overcoming this difficulty, and the correct one to use depends largely on the application. For example, if it is known that the channel rank will never fall below the value N_R, then only N_R spatially-multiplexed channels can be used with the remaining antennas used for diversity. Alternately, even in scenarios where feedback of the full CSI is impractical, the receiver can simply return the number of usable spatial channels to the transmitter, and the transmitter VBLAST implementation can adapt the number of parallel multiplexed data streams accordingly.

Fig. 7 also shows the behavior when two different training sequence lengths are used in the channel estimation procedure (for full-rank channels), with increased length yielding improved performance. This channel estimation is another practical issue that is important to consider when implementing a prototype system, with tradeoffs existing between training sequence length (which impacts throughput) and error performance.

V. Conclusions

This paper has discussed several practical issues relating to RF and other physical layer aspects of MIMO system implementation. Specifically, the presentation has focused on signal coupling in closely-spaced antennas and integrated RF front ends, the use of polarization to reduce the likelihood of rank deficient channels, and considerations relating to CSI estimation and feedback. Data from simulations, channel measurements, and a prototype real-time MIMO communication system have been used to illustrate the performance under a variety of operating assumptions.

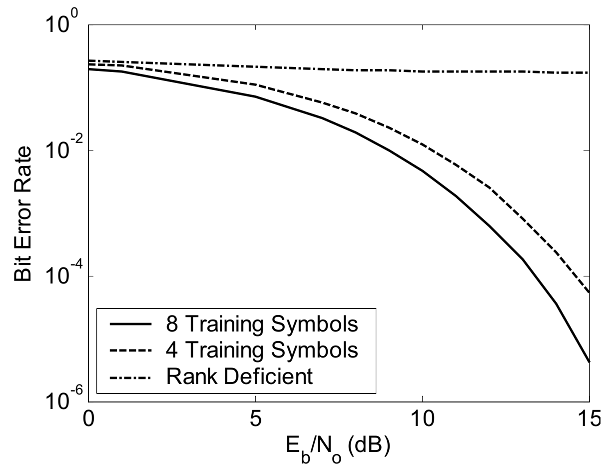

Fig. 7. Simulated 4×4 VBLAST bit error rate performance for full-rank channels with different training sequence lengths as well as for channels that are rank deficient.

Acknowledgement

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