Iterative array level optimization of MIMO antennas

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Abstract

Multiple-input-multiple-output systems have gained importance in the last decade due to their ability to provide improved capacity as compared to their SISO counterparts. System optimization promises further improvement in the capacity. The optimization can be either optimization of detection algorithms or optimizing the hardware designs. Starting with the network level MIMO model which includes the affect of mutual coupling and antenna correlation and an extended MIMO transmission model considering polarization, antenna efficiency, radiation pattern for capacity we analyze some simple antenna configurations for MIMO. This paper analyses the affect of each of the parameters on capacity obtained by using single dipole and three PIFA antenna configurations. Further antenna optimization for capacity including noise and interference will be presented at the conference

1. Introduction

Multiple input multiple output (MIMO) systems have gained importance in the field of wireless communication and ad-hoc networks because of their promise to achieve high capacity and increased throughput. Froschini [1] predicted a linear increase in capacity with the number of antennas for rich multipath channels. Experimental characterization and model development have shown that the ideal linear capacity increase is not achievable in practice due to a number of factors including correlation of the communication channel, mutual coupling between the antennas etc [2-4]. The capacity also depends on the type of channel state information (CSI) available.

Since MIMO antennas are capable of achieving higher capacity as compared to their SISO counterparts, they have been considered for handheld devices. However the limited size of handheld devices poses a significant challenge for multiple antenna array design and analysis. The large number of antennas needed to achieve high capacity cannot fit on the small size of handheld devices without significant mutual coupling. For high MIMO capacity it is preferred to have independent multipath channels which are achieved by increasing spacing between antennas. This is achievable at the base station but in the case of small handheld devices this is not possible. Taking this into account a network theory for MIMO system was first proposed by Jensen [2]. The network model described by Jensen and extended by Landon includes the polarization, efficiency, mutual coupling, and correlation on the system capacity. These models are the starting point for the optimization provided in this paper, and a detailed explanation will be provided in section 2.

Noise in a communication system affects the SNR calculation and thus the reliability and data throughput of the system. The noise in the system can be caused by the various components at the transmitter and receiver including the amplifiers, mixers, connectors, transistors and antennas. The environmental noise such as the impulse noise and man-made noise also contributes to the system noise. The other noises that affect the communication system are the phase noise, self noise, colored noise and correlated noise. Interference also plays an important role in the achievable capacity and the SINR (Signal to interference plus noise ratio) calculation. The main sources of interference are the co-channel and adjacent channel interference. The noise and interference in the system affect the system performance and must be incorporated in capacity calculation. Section 3 gives a brief overview of the noise and interference model for network level MIMO communication.

System optimization can be performed at the detector end or at the front end of the receiver. In this paper we concentrate on optimum antenna designs using the network model. There are two approaches that can be adopted for performing optimization. The first one being using CST an EM software which works on the principle of FIT (finite integration technique) and choose the different antenna combinations. Efficiency, polarization, coupling and correlation for the different antenna combinations are obtained and the capacity is calculated. The design that provides optimum capacity is chosen. The second method is optimization using the Genetic Algorithm where we try to optimize the system capacity for one or more of the above stated factors. We have followed the first method in this paper. The results obtained for capacity based on varying efficiency and polarization for four simple antenna combinations is provided in section 4.

2. A comprehensive MIMO signal model

A benchmark for analyzing any communication system is the capacity and the BER. Multiple-input, multiple-output (MIMO) antenna systems can be analyzed using information theoretic as well as using Network theory approach. The network theory approach helps in analyzing the complete system, including minute information like the antenna mutual coupling, polarization, efficiency and correlation. These factors affect the system performance and hence must be considered in the capacity expression. Jensen [5] analyses a MIMO system including the affects of mutual coupling and antenna correlation. The received voltage expression provided by Jensen is :

$$v_R = Z_0^{\frac{1}{2}} S_{21}(I - S_{RR}S_{11})^{-1} S_{RT} a_T \tag{1}$$

where a_T is the incident waves at the transmitter. The block S_H is the channel S parameter and S_M depicts the S-parameter matrix of the receiver matching network. Z_0 is the load impedance. Starting with this expression Landon [6] developed a comprehensive MIMO model which includes the various affects shown in figure 1. In the past all these effects were considered individually, and the model provided by Landon brings these together. The capacity expression using Landon's model is given by:

$$C_E \approx \overbrace{N \log_2\left(\frac{P_T}{M\sigma^2}\right)}^{SNR,N\ pathloss} + \overbrace{\log_2 \underbrace{\prod_{i=1}^{N} e_{cdr,i}}_{\eta_{cd}}}^{efficiency} + \overbrace{\log_2 \left|M_R M_R^H\right|}^{matching} + \overbrace{\log_2 \underbrace{\prod_{i=1}^{N} \frac{PLF_i}{PLF_{ref}}}_{\eta_{PLF}}}^{polarization} + \overbrace{\log_2 \underbrace{\prod_{i=1}^{N} \frac{D_i}{D_{ref}}}_{\eta_D}}^{distributed\ directivity} + \overbrace{\log_2 \left|R_{s-DP}\right|}^{channel\ correlation} \tag{2}$$

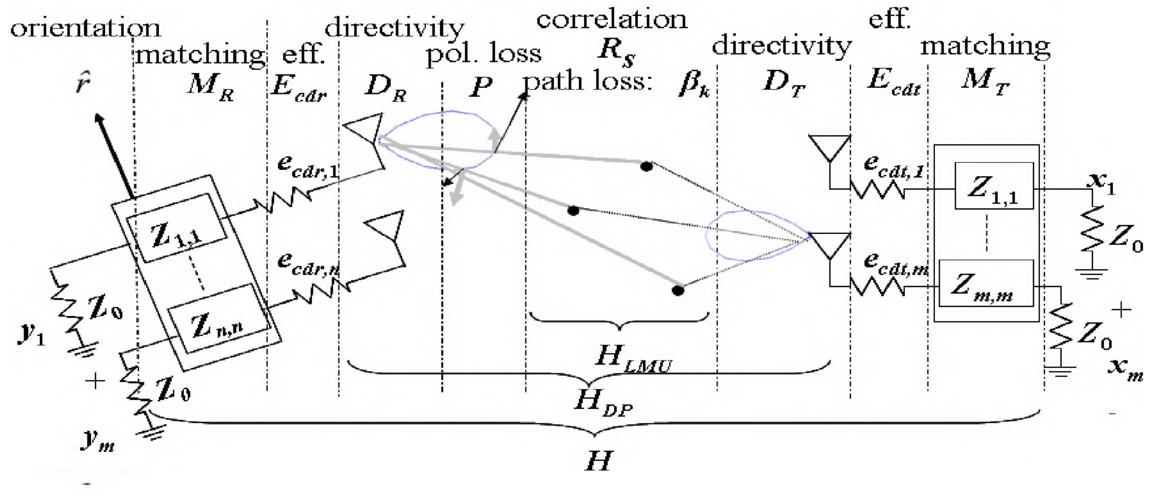

Figure 1: A general MIMO system model. M_R is the n x n impedance matrix describing the receive antenna array with efficiencies E_{cdr}, $e_{cdr,i}$ described at (3). R_s is the spatial correlation of the signals impinging on the receiver—traditionally including the directivity and polarization effects expressed above as D_R and P. Corresponding matrices for the transmit array are subscripted with a T or t, $\hat{r}$ represents the orientation of the receiver. Grouping designator, H_{LMU}, represents a lossless, matched, uncoupled channel matrix and H represents a complete system channel matrix.

This model acts as a starting point for MIMO antenna optimization. This new comprehensive model (and its simplified adaptation for insight) allows us to predict the signal that is transmitted, propagated within the channel, and received as a MIMO capacity. But the true information available in the communication system is a function of both the signal and the noise.

3. Noise and interference model

The capacity of all communication systems is a function of the signal-to-noise-plus-interference ratio (SNIR). The SNIR is also the primary factor controlling the resolution of images, and it is hoped that the technical advancements from this project will also provide a better framework from which to thoroughly evaluate the efficacy of MIMO for breast cancer detection and related medical imagery. Recent advances have provided a detailed understanding of the signals in these complex environments, but models for the noise are still overly-simplified. How noise couples and cross-couples into multiple antennas is intriguing to understand as well as critical for system design. The solid, detailed theoretical framework for noise and interference in complex MIMO channels that is missing today must be accounted for before final optimization of MIMO antennas. This framework is essential to design effective MIMO communication systems. The expression for a simple model in this regard is given by

$$NI = N_{thermal} + N_{mutual} + N_{phase} + N_{time} + N_{environment} + N_{AWGN} + N_{impulse} + N_{manmade} + Interference$$

$$Interference = \sum_{i=1}^{n} y_i \tag{3}$$

y_i is given in expression 2. SNR expression can be written as

$$SNR = \frac{y}{NI} \tag{4}$$

3.4 Optimization

System optimization aims at achieving higher capacity as compared to the existing designs. In MIMO systems the optimization can be performed at the detector by using improved detection algorithms or we can perform front-end optimization. In this section we provide an overview of the front-end optimization and provide some basic antenna designs which can act as starting points for achieving antenna optimization. Equation 2 acts as the main equation for analyzing the capacity. The complete model in (2) includes the effects of polarization, efficiency, channel correlation, antenna coupling etc. on capacity and gives a better system perspective. Each of these factors needs to be analyzed and the capacity for the same must be included. The figure 2a shows three antenna configurations that were used for obtaining capacity for both fixed and oriented configuration. Along with these three antenna configurations we also analyzed four dipole antenna separated by a wavelength. From figure 2b we observe that when the polarization alignment is fixed we simple dipole designs outperform PIFA designs of equal antenna count due to due to improved polarization fidelity and distributed directivity). When the designs are subject to rotation, however, dipoles perform worse than PIFAs and the agile design achieves a performance rivaling that of a non-agile PIFA array with more elements.

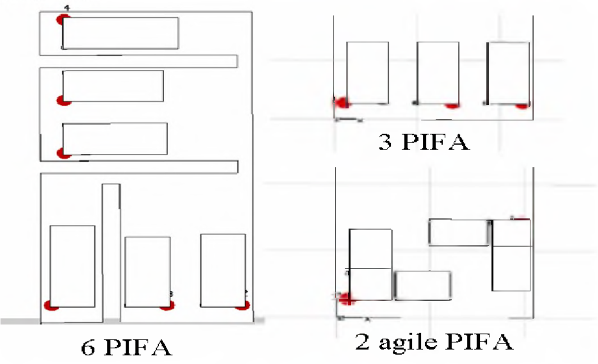

Figure 2a: Antenna configurations.

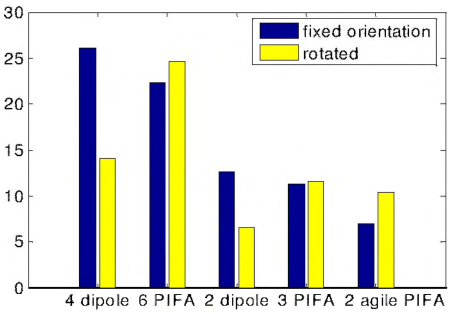

Figure 2b: Capacity for antenna configurations

Table 1: Tabulated capacity and efficiency of each antenna for fixed orientation

	#	C_E	$C_0+\eta$	n	$<D_i>$	$<M_{R,i}>$	$<P_i>$	$<\|R_{s\text{-}DP}\|>$	$<\eta>$
4 corner dipoles	1	12.4	14.1	4	0.98	1.18	1.02	0.99	1.04
2 pifa, 2 dip	2	13.2	14.5	4	0.87	1.26	1.19	0.96	1.06
3 agile switch pifa	3	14.6	16.3	3	1.23	1.90	1.89	0.99	1.64
6 pifas	4	21.0	24.6	6	0.77	2.12	1.25	0.84	1.09

Table 1 summarizes the capacity, efficiency, directivity, mutual coupling for few antenna configurations. This provides the basic antenna selection criteria for MIMO designs. Further designs including antennas with slots and a combination of antennas must be considered and the results for the same will be provided at the conference. All these results have been included for the case where there is no noise. The addition of noise may further deteriorate the system performance and the research in this area is in progress

5. Conclusion

Antenna optimization plays an important role in improving system capacity. The transmission line MIMO equation gives a good starting point for optimization. We compare four different designs for obtaining capacity for a fixed and rotated configuration and show that the rotated antenna gives better capacity. The comparison table provided in the last section when extended with all the antenna combinations will help the designer select the optimum design for MIMO communication. Once these optimum antenna combinations are obtained we can apply GA (Genetic Algorithm) concepts and improve the designs.

7. References

[1] G.J. Foschini, M.J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Pers. Commun.*, vol. 6, pp. 311-355, Mar 1998.

[2] M.A. Jensen, J.Wallace, "A Review of Antennas and Propagation for MIMO Wireless Communications," *IEEE Transactions on Antennas and Propagation*, vol. 52, pp. 2810-2824, Nov 2004.

[3] D. Gesbert, M. Shafi, D. Shiu, P. J. Smith and A. Naguib, "From theory to practice: an overview of MIMO space-time coded wireless systems," *IEEE J. Select. Areas Commun.*, vol. 21, pp. 281-302, Apr. 2003

[4] Tse, P. Viswanath, *Fundamentals of Wireless Communication*, Cambridge University Press, 2004.

[5] Jon W. Wallace and Michael A.Jensen " Mutual coupling in MIMO wireless systems: A rigourous Network Theory Analysis", IEEE Transactions on Wireless Communication, VOL. 3, No. 4, pp 1317-1325,July 2004

[6] David Landon "Polarization misalignment and the design and analysis of compact MIMO arrays", Thesis, Fall 2007