Characterization of a Wideband Adaptive-MIMO Antenna

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Introduction

Multiple-Input Multiple-Output (MIMO) systems are potentially able to give a dramatic gain in spectral efficiency [1]. However, achieving this potential generally requires a large number of transceivers at both ends of the communication system [2]. A simple and effective suboptimal solution which uses a smaller number of active elements and several parasitic elements terminated in controllable impedances was proposed in [3]. The antenna, referred to as an Adaptive MIMO (AdaM) Antenna, is simple, low-cost, and effective in many multipath propagation scenarios.

The goal of this paper is to carefully explore the potential performance of the AdaM antenna in a set of realistic environments and over wideband operation based on experimental measurements of a prototype antenna. The results demonstrate that, when compared to a system using a traditional receive array, a 2×2 MIMO system using an AdaM receive antenna can achieve the same spectral efficiency with a significant average transmit power reduction and that the AdaM antenna enables the MIMO system to more effectively use the available frequencies in a wideband scenario.

AdaM Antenna Modeling

The analysis given in [3] provides a detailed description of the effect of the parasitic elements on the channel matrix. To use this representation to characterize a wideband system we sub-divide the band of interest in K smaller sub-bands over which the combined antenna and propagation response can be considered "flat" and equal to the response at the sub-band center frequency f_k. Shannon's channel capacity C_k [4] for the k-th sub-band is then given as

$$C_k = \sum_{i=1}^{r_k} \log_2 \left(1 + \frac{P_T \Sigma_{i,k} \alpha_{i,k}}{\sigma^2_{\eta,k}} \right), \quad \text{[bit/s/Hz]} \tag{1}$$

where P_T is the total transmitted power, $\Sigma_{i,k}$ is the square of the ith singular value of the matrix $\mathbf{H}(f_k)$, r_k is the rank of $\mathbf{H}(f_k)$, $\sigma^2_{\eta,k}$ is the variance of the additive white Gaussian noise at the receiver in the kth sub-band, and $\alpha_{i,k}$ is the fraction of the total transmitted power P_T allocated to the ith spatial channel of the kth sub-band. The overall maximum throughput of the MIMO channel for the wideband system becomes

$$R_{max} = \sum_{k=1}^{K} C_k \Delta f, \quad \text{[bit/s]} \tag{2}$$

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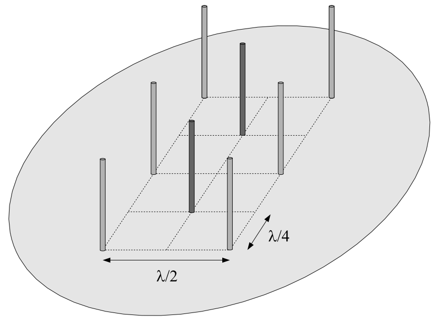


Figure 1: Parasitic MIMO antenna: dark gray - active elements; light gray - parasitic elements.

where Δf is the bandwidth of each sub-band. Because the impedance on the parasitic elements modifies $\Sigma_{i,k}$, it is possible to choose a loading configuration (using, for example, a genetic algorithm) that maximizes the capacity.

Measurement Results

Measurements have been performed using a wideband 8×8 MIMO channel sounder [5]. The prototype AdaM antenna consists of eight wire monopole antennas which resonate at 2.55 GHz (see Fig. 1). The two inner and six outer wires represent the active and parasitic elements, respectively. The controllable loads are based on a Philips BAP63 pin diode, with the impedance changed by changing the driving voltage from 0V (OFF) to 5V (ON). A control system switches through all possible impedance states for the six parasitic elements during a measurement. Reference measurements use a two-element array of monopole antennas with half-wavelength spacing, which is identical to the AdaM array with the parasitic elements removed. The transmit antenna is identical to the reference array, while either the reference or AdaM antenna is used at the receiver.

For each measurement location, one measurement is performed for each receiver array type. The measurement of the wideband 2×2 MIMO channel was carried out using an excitation signal consisting of 30 frequency tones spaced by 1 MHz with a center frequency of 2.55 GHz. The chosen spacing is sufficient to sound the channel correctly since the measured correlation bandwidth is approximately 5 MHz. Each measurement therefore produces 30 2×2 channel matrices, or one for each frequency. The capacity is then constructed by choosing the power allocation coefficients $\alpha_{i,k}$ using the waterfilling [4] solution for the 60 singular values resulting from the 30 channel matrices. When considering the AdaM antenna, this algorithm must be applied for *each* parasitic termination combination to determine the loading which maximizes the system capacity. Since there are six parasitic antennas each with two possible states, a full measurement consists of $2^6 = 64$ channel measurements.

Once we have acquired the channel matrices for the reference antenna and the 64 different termination combinations for the AdaM antenna, we must effectively compare the relative performance of these different systems. To do this, we compute the value of P_T/σ_η^2 in (1) required to achieve a value of $R_{max} = 300$ Mbit/s in

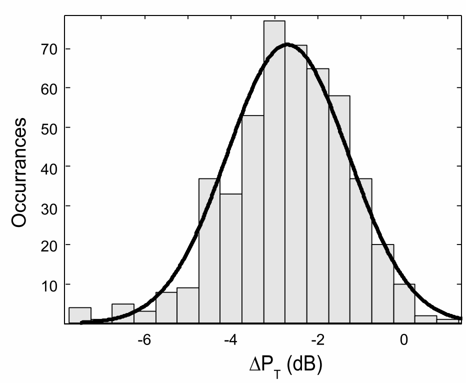


Figure 2: The distribution of the ratio ΔP_T over all measurement scenarios.

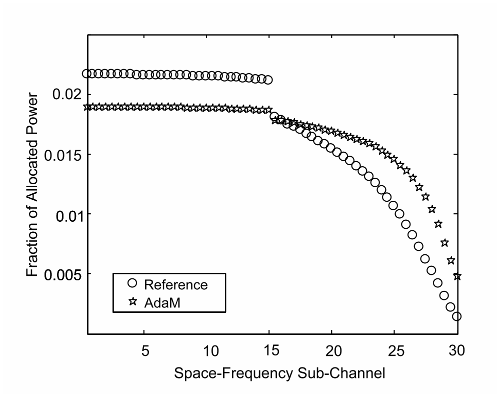
(2) for each configuration, where we have assumed that the noise power is equal across the bandwidth so that $\sigma_{\eta,k} = \sigma_\eta$ for all k. The value of this ratio for each AdaM configuration relative to that for the reference antenna system is then used as a metric for evaluation. If a particular configuration can achieve the specified rate with lower transmit power P_T, then this is an effective gain to the system. Numerically, we evaluate the ratio

$$\Delta P_T = \frac{(P_T/\sigma_\eta^2)_{\text{AdaM}}}{(P_T/\sigma_\eta^2)_{\text{reference}}}, \tag{3}$$

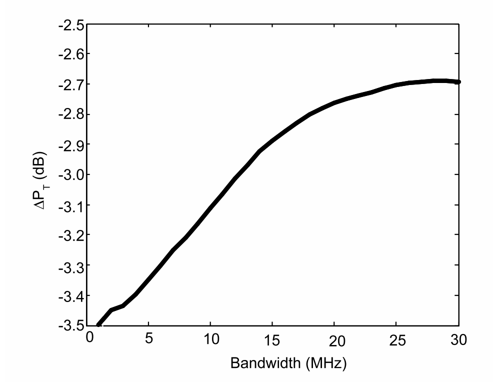
where the subscripts 'AdaM' and 'reference' indicate the antenna configuration used.

Fig. 2 shows a histogram of ΔP_T constructed from all measurements along with the best fitting Gaussian distribution (mean 2.7, standard deviation 1.4). The Gaussian appears to fit the distribution relatively well. The power reduction achieved by the AdaM antenna is greater than 1 dB, 1.7 dB, and 2.7 dB for 90%, 75%, and 50% of the cases, respectively. It is worth noting that the AdaM antenna requires more power than the reference antenna in only 6 out of 494 cases (1.2%).

By exploring the power allocation coefficients $\alpha_{i,k}$ constructed from the waterfilling solution, we can gain some insight into the operation of the AdaM antenna. Fig. 3(a) plots the average of these coefficients over all measurements. As can be seen, the AdaM antenna allows more effective use of a larger number of space-frequency sub-channels, a condition which leads to improved capacity (or, in this case, reduced power for the same throughput). Fig. 3(b) shows the power reduction averaged over all measurements as a function of the operation bandwidth. When the bandwidth is narrow, the beamforming achieved by the optimal loading of the AdaM antenna achieves a power reduction of 3.5 dB. As the bandwidth is increased, the loading may not be as effective over the entire band, resulting in the observed decrease in power reduction. It is important to point out, however, that the degradation in power reduction is only 0.8 dB as the bandwidth is increased from 1 MHz to 30 MHz, indicating that the optimal loading works well over reasonable operation bandwidths. This is an important consideration for practical implementation of AdaM antennas.



(a) Average of the alpha coefficients



(b) Power reduction vs. bandwidth

Figure 3: Average of the alpha coefficients and power reduction vs. operation bandwidth.

Conclusion

We have experimentally investigated the use of AdaM antennas in a wideband communication system. For a 2×2 MIMO system with 30 MHz operation bandwidth at 2.55 GHz, the results show that the AdaM antenna facilitates a power reduction of 2.7 dB (on average). The results also show that the performance remains strong over a relatively wide bandwidth. Because the parasitic elements have been used only at the receiver, the results in [3] suggest that improved performance is possible when the AdaM is used at both ends of the link. Future work includes the use of miniaturized electronically controlled parasitic antennas using a mixture of space and polarization diversity for Wi-Fi and Wi-Max applications.

References

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