A MIMO System With Multifunctional Reconfigurable Antennas

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***Abstract*—A multiple-input–multiple-output (MIMO) system equipped with a new class of antenna arrays, henceforth referred to as multifunction reconfigurable antenna arrays (MRAAs), is investigated. The elements of MRAA, i.e., multifunction reconfigurable antennas (MRAs) presented in this work are capable of dynamically changing the sense of polarization of the radiated field thereby providing two reconfigurable modes of operation, i.e., polarization diversity and space diversity. The transmission signaling scheme can also be switched between transmit diversity (TD) and spatial multiplexing (SM). The results show that the reconfigurable modes of operation of an MRAA used in conjunction with adaptive space–time modulation techniques provide additional degrees of freedom to the current adaptive MIMO systems, resulting in more robust system in terms of quality, capacity and reliability. A performance gain up to 30 dB is possible with the proposed system over conventional fixed antenna MIMO systems depending on the channel conditions.**

***Index Terms*—Microelectromechanical systems (MEMS), multiple-input–multiple-output (MIMO), multifunction reconfigurable antenna (MRA).**

I. Introduction

WIRELESS communication technology, a fundamental part of modern information infrastructure, is evolving at a frantic pace in order to meet the ever demanding performance characteristics of highly integrated mobile wireless communication devices. The continued increase in demand for various wireless services such as voice, data, and multimedia is also fueling the need for higher data rates. Given that the wireless bandwidth is expensive, emerging technologies that improve spectrum efficiency in wireless systems are becoming a necessity. It was proven that multiple-input–multiple-output (MIMO) systems multiply data throughput, with a simultaneous increase in range and reliability, without consuming any extra bandwidth thereby resulting in improved spectral efficiency [1]. The true benefits of MIMO, however, can be exploited only through a smart design that is able to respond to the wireless channel. The goal is to maximize the resources available in multiple antenna channels by using optimal schemes at all times. In a typical adaptive MIMO system, some of the adjustable parameters are the modulation level, coding rate, and the transmission signaling schemes such as SM, TD, and beamforming. The performance of such an adaptive system can be superior in comparison to that of a nonadaptive one [2], [3]. However, when an inter-disciplinary analysis is performed on the interrelationships of transmission signaling schemes, antenna properties and propagation conditions, it becomes clear that there is an additional room for further exploitation of theoretical gains of the MIMO systems [4]. In today's adaptive MIMO systems the antenna element properties are fixed by the initial design and cannot be changed. In this work, we introduce *an additional degree of freedom* by treating the antenna element properties as an additional component in the joint optimization of the adaptive system parameters. The antenna properties are effectively integrated with the space–time processing techniques and the propagation environment.

The goal of joint optimization of antenna array properties and the associated transmission algorithm can only be achieved if each individual element of the array can be dynamically reconfigured, i.e., a multifunctional reconfigurable antenna (MRA). In short, the adaptive MIMO system introduced in this paper will not be constrained to employ fixed antenna properties over varying channel conditions. This feature will permit the selection of the best antenna properties in conjunction with the adapted transmission scheme with respect to the channel condition.

II. A MIMO System Equipped With MRAA

It has been shown that under certain channel conditions, the use of polarization diversity is beneficial in terms of improving symbol error rate of up to an order of magnitude if the space–time modulation technique employed is spatial multiplexing (SM) [5]. On the other hand, the use of polarization diversity, in general, typically yield performance degradation for transmit diversity (TD) schemes such as Alamouti scheme [5]. Also, some of the practical MIMO systems may require a trade-off between data rate and diversity which translates into switching between SM and TD, respectively. Given that space-time modulation schemes such as SM and TD will perform differently for different channel conditions a switching between SM and TD based on the instantaneous channel state information was recently proposed [6].

A. Background and Motivation

In this work, we have developed a MIMO system that adapts not only the space-time modulation technique but also the antenna properties with respect to channel. It is useful to briefly look into the properties of the channel matrix of a MIMO system

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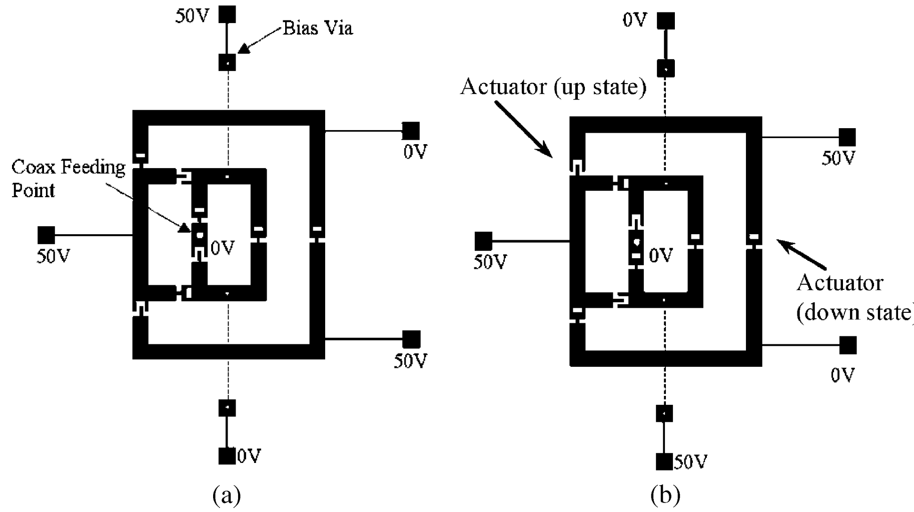

Fig. 1. Top view schematics of MRA spiral corresponding to each reconfigurable mode of operation: (a) left-hand circular polarization and (b) right-hand circular polarization.

consisting of n receive and m transmit MRA's. This channel matrix $\mathbf{H}$ can be given as follows:

$$\mathbf{H} = \begin{bmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nm} \end{bmatrix} \quad (1)$$

where h_{ij} represents the gain from transmit antenna j to receive antenna i. An explicit expression of this gain may be given as follows:

$$\begin{aligned} h_{ij} &= \Gamma_s(\vec{r}_{ij}) \cdot e^{-j\vec{k}\cdot\vec{r}_{ij}} \\ &= \frac{c_{ij}}{r_{ij}} \vec{l}_{eff_j}(\theta_j, \phi_j).C_{pol_{ij}} \vec{l}_{eff_i}(\theta_i, \phi_i) \cdot e^{-j\vec{k}\cdot\vec{r}_{ij}} \end{aligned} \quad (2)$$

In (2), $|\Gamma_s(\vec{r}_{ij})|^2 = P_{R_i}/P_{T_i}$ is the ratio of the power received by receive MRA i to the transmitted power by transmit MRA j. The vector $\vec{r}_{ij}$ represents the path vector from j^{th} transmit MRA to the i^{th} receive MRA, $\vec{k}$ is the wavenumber vector, $\vec{l}_{eff_j}(\theta_j, \phi_j)$ and $\vec{l}_{eff_i}(\theta_i, \phi_i)$ are the normalized vector radiation patterns of jth transmit MRA and i^{th} receive MRA, respectively. $C_{\mathrm{pol}_{ij}}$ represents the polarization coupling factor between the polarization states of the incoming wave launched into channel by jth transmit MRA and that of ith receive MRA, and c_{ij} is a channel dependent propagation parameter. The Shannon capacity of this MIMO system, which equals the maximum data rate that can be transmitted over the channel with arbitrarily small error probability, can be expressed as

$$C = \log_2 \left[\det \left(I_i + \rho \frac{\mathbf{H}.\mathbf{H}^*}{u} \right) \right] = \sum_{k=1}^{u} \log_2 \left(1 + \rho \frac{\lambda_k}{u} \right) \quad (3)$$

where I_i is the i-dimensional identity matrix, ρ represents the signal-to-noise ratio (SNR), * denotes the transpose conjugate, $u = \min(n, m)$, and λ_k is the kth eigenvalue of $\mathbf{H} \cdot \mathbf{H}^*$. From (3), one can see that the capacity will increase if the rank of the MIMO channel, i.e., $\mathbf{H} \cdot \mathbf{H}^*$, is increased. For a MIMO system equipped with MRAs, h_{ij} given by (2) can be optimized (jointly with the transmission signaling scheme with respect to channel) through the reconfigurable parameters of $\vec{l}_{\mathrm{eff}_j}(\theta_j, \phi_j)$, $C_{\mathrm{pol}_{ij}}$ and $\vec{l}_{\mathrm{eff}_i}(\theta_i, \phi_i)$ so that the rank is maximized, thereby the MIMO capacity is increased. This brief analysis given here is the key motivation to employ MRAs with today's adaptive MIMO systems.

B. MRA Spiral

A MRA spiral that is capable of altering the state of polarization of the radiated field between right-hand and left-hand circular polarizations (rhcp and lhcp), thereby providing two reconfigurable modes of operation, has recently been introduced in [7]. The schematic of this antenna is shown in Fig. 1. For the clarity of illustration each configured geometry is depicted separately and MEMS actuators in the up state are shown without metallic membrane. MRA spiral architecture is built on a number of printed rectangular-shaped metal strips interconnected by microelectromechanical systems (MEMS) actuators on a microwave laminate RO4003-FR4 ($\varepsilon_r = 3.38$, $\tan\delta = 0.002$). Judicious activation of interconnecting actuators, that is, by keeping some of the actuators in the up position (zero bias) while activating the rest of them by applying dc bias voltages, allows the MRA spiral to reconfigure its architecture into single arm rectangular spirals with opposite winding sense of the spiral, left or right senses. Accordingly, rhcp and lhcp radiation is achieved over the frequency band of 4–6 GHz. The details on the MEMS microfabrication, theoretical and experimental results of MRA spiral can be found in [7].

C. 2×2 MIMO With MRAA

We propose a 2×2 MIMO system where an MRAA consisting of two MRA spiral antennas is employed both at the transmit and receive ends. Fig. 2 shows the schematic of this system. By changing the sense of polarization of MRA spiral elements in each MRAA, either spatial diversity or polarization diversity scheme can be employed. The system is also able to switch between SM and TD based on the instantaneous channel state information as described in [6]. When TD is selected MRAAs employ the spatial diversity scheme where MRA spiral elements radiate the same sense of polarization. If

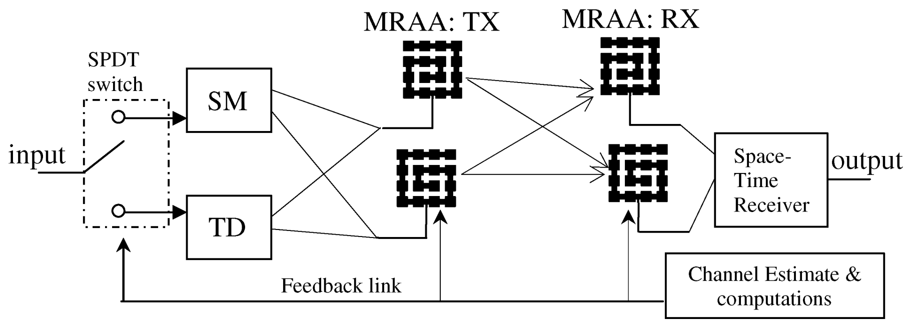

Fig. 2. The schematic of a 2×2 MIMO system employing MRAAs.

thespace–time modulation technique is SM then the MRAAs are reconfigured into the polarization diversity scheme where each MRA spiral radiates the opposite sense of polarization.

III. Results

The 2×2 MIMO channel, $\mathbf{H}$, is modeled as follows [8]

$$\mathbf{H} = \sqrt{\frac{K}{K+1}}\mathbf{H}_{\text{LOS}} + \sqrt{\frac{1}{K+1}}\mathbf{H}_{\text{NLOS}} \quad (4)$$

$$\mathbf{H}_{\text{LOS}} = \begin{bmatrix} 1 & \sqrt{\beta} \\ \sqrt{\beta} & 1 \end{bmatrix} \quad (5)$$

$$\mathbf{H}_{\text{NLOS}} = (\mathbf{R}_{RX})^{1/2}$$

$$\mathbf{H}_{iid}(\mathbf{R}_{TX})^{1/2} = \begin{bmatrix} h_{11} & \sqrt{\alpha}h_{21} \\ \sqrt{\alpha}h_{21} & h_{22} \end{bmatrix} \quad (6)$$

where K is the Ricean factor, α and β are the attenuated cross coupling coefficients for polarization case with respect to channel, i.e., NLOS or LOS. $\mathbf{H}_{iid}$ is the flat-fading Rayleigh component of the MIMO channel. The elements of $\mathbf{H}_{iid}$ are complex Gaussian random variables with zero mean and unit variance. $\mathbf{R}_{RX}$ and $\mathbf{R}_{TX}$ are the receiver and transmitter side correlation matrices, respectively, and given by

$$\mathbf{R}_{RX} = \begin{bmatrix} 1 & r \\ r & 1 \end{bmatrix}, \quad \mathbf{R}_{TX} = \begin{bmatrix} 1 & t \\ t & 1 \end{bmatrix}. \quad (7)$$

In (7), r is the correlation coefficient between two receive antennas, and t is the correlation coefficient between two transmit antennas and they are given as $r = \rho(RX \text{ spacing}) \times \rho(\text{polarization})$, $t = \rho(TX \text{ spacing}) \times \rho(\text{polarization})$. The parameter $\rho(.)$ denotes the real correlation coefficient due to either spacing or polarization between MRA spiral elements of the MRAA. Note that if both MRA spirals have the same polarization, then $\rho(polarization)$ is equal to one. In the simulations, when the polarization scheme is selected, the first transmit and the first receive antennas and the second transmit and the second receive antennas use the same sense of polarization where the polarization of the second antennas are the opposite of the first ones.

In Fig. 3, we provide the simulation results for 2×2 SM-MMSE (minimum mean square error receiver) [8] and 2×2 TD-Alamouti for four different scenarios. The simulation parameters are based on the realistic channel model which was previously proposed for indoor MIMO wireless environments (see [9], for further details). The parameters used for the scenarios are as follows:

Scenario I and III (low-correlation): The spacing between MRA spirals antennas, d, is half-wavelength, i.e., $\lambda/2$. $\rho(d) = 0.3$, $\rho(pol) = 0.3$, $\alpha = 0.5$, $\beta = 0.1$ and $K \in \{0, 10\}$. The MIMO transmission schemes are 2×2 SM-MMSE and TD-Alamouti, respectively.
Scenario II and IV (moderate-correlation): $d = \lambda/4$. $\rho(d) = \sqrt{0.3}$, $\rho(pol) = 0.3$, $\alpha = 0.5$, $\beta = 0.1$ and $K \in \{0, 10\}$. The transmission schemes are 2×2 SM-MMSE and TD-Alamouti, respectively.

Fig. 3(a) and (b) corresponding to the scenarios I and II, show that polarization diversity scheme provides substantial gain, e.g., >20 dB, for SM-MMSE, especially for highly LOS environment ($K = 10$). However it does not introduce any performance loss for NLOS conditions ($K = 0$). On the other hand, TD-Alamouti suffers from changing the polarization of the antennas [see Fig. 3(c) and (d)]. Therefore it is crucial for a multimode system, i.e., a system deploying SM or TD depending upon the instantaneous application needs, to incorporate MRAs to achieve the maximum gains. For example, in a near LOS environment, i.e., $K = 10$, when a high data rate is preferred over diversity gain, SM will be the winning strategy for transmission signaling. Reconfiguring the antenna diversity scheme into polarization diversity by using the proposed spiral MRAA system, more than 20 dB performance gain can be achieved as compared to an antenna array of which properties are fixed by the initial design and cannot be changed. Some multimedia applications, e.g., real time voice transmission, may favor diversity gain over high data rates to maintain robustness. In such a case, TD-Alamouti will be used in conjunction with MRAA that is reconfigured into spatial diversity scheme. In short, these preliminary results show that the proposed 2×2 MIMO system using MRAAs will be very robust against several channel conditions and as the channel becomes more LOS, significant gains can be achieved as compared to adaptive MIMO systems employing fixed-antenna arrays.

IV. Conclusion

Wireless applications that are increasingly bandwidth- and mobility-intensive have driven MIMO research to push against the physical limits of coding and signaling. The multifunctional reconfigurable antenna technology presented in this work greatly impacts adaptive MIMO performance through the capability of dynamically changing antenna properties. The reconfigurable antenna properties integrated with signaling

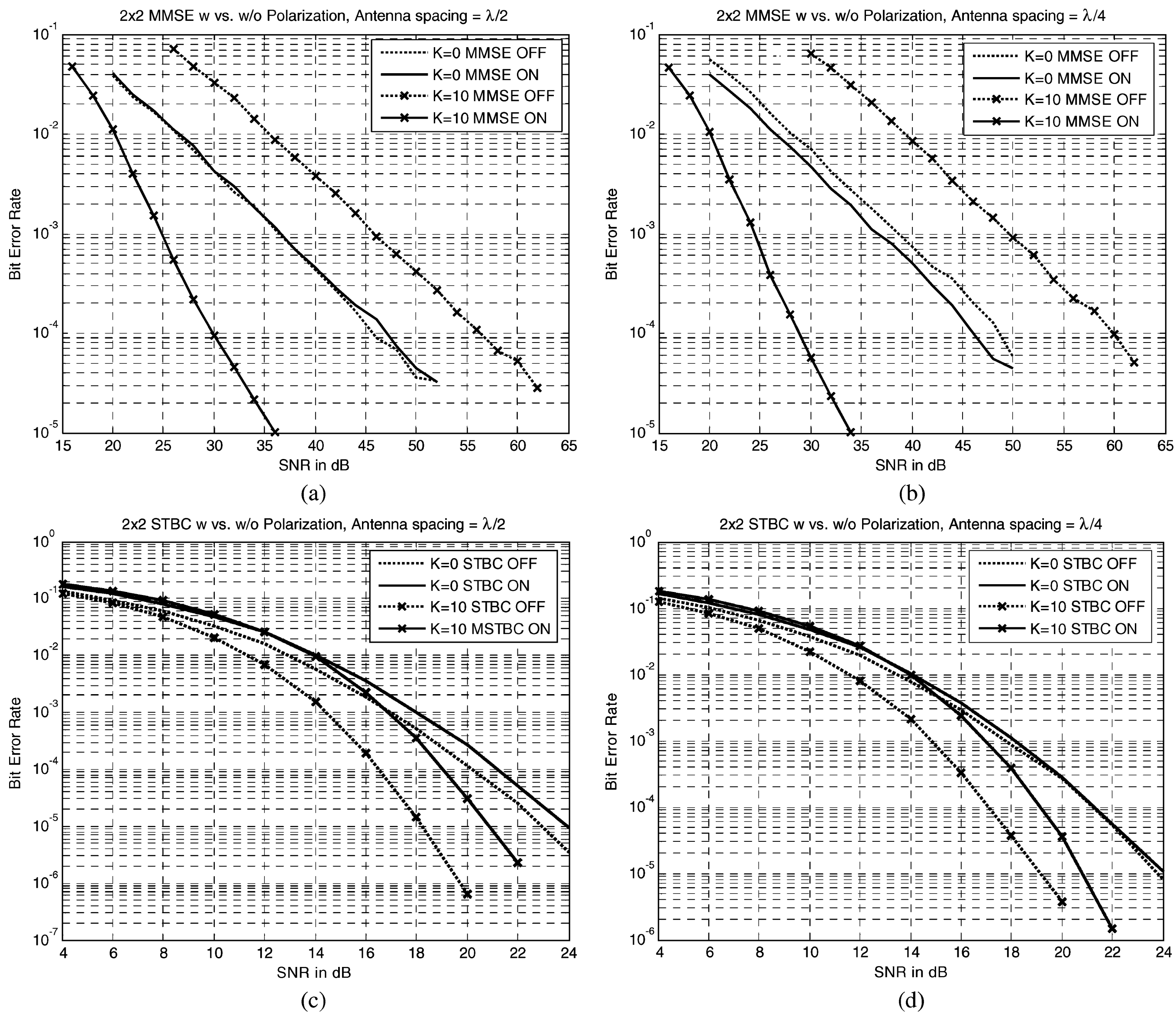

Fig. 3. Bit error rate versus SNR curves for the proposed MIMO system employing MRAA. ("ON" indicates polarization diversity activated, "OFF" indicates polarization diversity deactivated.) (a) SM-MMSE scenario I; (b) SM-MMSE scenario II; (c) TD-Alamouti scenario III; (d) TD-Alamouti scenario IV.

schemes to the propagation environment provides an additional degree of freedom in adaptive optimization. Depending on the channel conditions a performance gain up to 30 dB is possible over existing adaptive MIMO systems. A long awaited design space where interplay between reconfigurable antenna and adaptive signaling feed-back-to-each-other is likely to revolutionize broadband MIMO system design methodology.

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