Antenna Selection in MIMO Systems

Shahab Sanayei and Aria Nosratinia, University of Texas at Dallas

ABSTRACT

Multiple-antenna systems, also known as multiple-input multiple-output radio, can improve the capacity and reliability of radio communication. However, the multiple RF chains associated with multiple antennas are costly in terms of size, power, and hardware. Antenna selection is a low-cost low-complexity alternative to capture many of the advantages of MIMO systems. This article reviews classic results on selection diversity, followed by a discussion of antenna selection algorithms at the transmit and receive sides. Extensions of classical results to antenna subset selection are presented. Finally, several open problems in this area are pointed out.

INTRODUCTION

Impressive improvements in capacity and bit error rates (BERs) have motivated the recent interest in multiple-antenna radio systems, also known as multiple-input multiple-output (MIMO) systems. Along with the gains, however, comes a price in hardware complexity. The radio front end has a complexity, size, and price that scales with the number of antennas. It is possible to alleviate this cost and at the same time capture many of the advantages of MIMO systems by a technique known as antenna selection. This article is dedicated to a tutorial overview of MIMO antenna selection methods.

MIMO signaling can improve wireless communication in two different ways: diversity methods and spatial multiplexing. Diversity methods improve the robustness of the communication system in terms of BER by exploiting the multiple paths between transmit and receive antennas. On the receive side, this diversity is similar to that provided by the RAKE receiver. Diversity can also be obtained with multiple transmit antennas, but then one must address the mutual interference of simultaneously transmitting antennas. This leads to a body of work known as *space-time coding*. Defining *diversity order* as the slope of the BER–signal-to-noise ratio (SNR) curve, space-time codes are capable of delivering diversity order of M_rM_t, where M_r and M_t are the number of receive and transmit antennas, respectively.

Another MIMO technique, spatial multiplexing, emerged from the fact that in a rich scattering environment it is possible for the receiver to descramble signals that are transmitted simultaneously from multiple antennas; thus, one is able to send parallel independent data streams and achieve overall system capacities that scale with $\min(M_r, M_t)$. The possibility of a linear capacity growth with the number of antennas has been dazzling, especially knowing that increasing power (SNR) only leads to logarithmic improvements in capacity. These gains arise from resolving parallel spatial paths in the channel, hence the name *spatial multiplexing*. Examples of spatial multiplexing include the Bell Labs Space Time (BLAST) architecture and its variants.

In the following, we present an overview of antenna selection in MIMO systems, in the context of diversity/SNR as well as system capacity.

SNR AND DIVERSITY

This section reviews antenna selection methods that capture diversity and improve the SNR of the system. Diversity refers to the existence of two or more signal paths that fade independently. This happens when the radio channel consists of several paths that are sufficiently separated in space, time, frequency, or (sometimes) polarization. The key idea is that if several paths have channel coefficients that are statistically independent, it is unlikely that they will fade together, so the probability is small that signal strengths will fall below detection threshold.

RECEIVE ANTENNA SELECTION

Diversity via multiple receive antennas is a direct extension of traditional receive diversity ideas, and many of the results in multi-antenna receive diversity are similar to those in the literature on RAKE receivers.

Consider a generalized diversity reception system as depicted in Fig. 1. The receiver sees several versions of the transmit signal, each experiencing a different complex-valued fading coefficient $h_i(t)$ and noise $n_i(t)$. To exploit diversity, these signals must be combined in a gainful manner.

Diversity combining can be classified into three categories. *Selection diversity* chooses the path with the highest SNR, and performs detection based on the signal from the selected path.[1] Maximal ratio combining (MRC) makes decisions based on an optimal linear combination of the path signals. Equal gain combining (EGC) simply

[1] *A suboptimal version of selection diversity, known as scan diversity, tests the paths one by one until one is found with SNR above a predetermined threshold. This path is used for detection.*

adds the path signals after they have been co-phased. A summary and analysis of these methods is given in a classic paper by Brennan [1].

Assume that the path coefficients are independent, identically distributed, with Rayleigh magnitude and uniform phase, with average path SNR of Γ. For our purposes, we are primarily interested in the average receive SNR resulting from optimal selection of one out of M_r path:

$$E[\gamma_s] = \Gamma \sum_{k=1}^{M_r} \frac{1}{k}.$$

Therefore, adding diversity paths leads to diminishing returns in SNR. To be specific, the harmonic sum leads to a logarithmic growth of SNR as the number of paths is increased.

In comparison, MRC and EGC have average receive SNRs that increase linearly with the number of paths, but MRC has higher average SNR (up to 1.05 dB more in Rayleigh fading) [1].

The application of selection combining to receive antenna selection is shown in Fig. 2, where a single receive antenna is chosen from among all antennas. Since only one RF branch is available, we face a dilemma: we need to know all the branch SNRs for optimal selection, but how can we know all SNRs simultaneously when there is only one RF chain? There are several ways to address this problem based on the quasi-stationarity of the channel gains. For example, one may use a training signal in a preamble to transmitted data. During this preamble, the receiver scans the antennas, finds the antenna with the highest channel gain, and selects it for receiving the next data burst.

There are many practical considerations in antenna selection. For example, the optimal choice must be based on the SNR of the received signals, but in practice it is easier to use an envelope detector and select the branch with the highest signal plus noise. The decision can also be made based on either predetection or post-detection signals.

The previous discussion assumed that the receiver has only one RF chain. Quite possibly the number of available RF chains may be more than one, but less than M_r. In that case, a subset of the receive antennas must be selected and their signals combined. This is known as *generalized selection*, and the resulting gains as *generalized selection diversity* (Fig. 3). It is also known as hybrid selection/maximal ratio combining [2]. The combination of the selected paths can be performed via either MRC or EGC. MRC gives better performance, but requires multiplication by complex numbers. EGC is easier, but is less efficient.

For generalized selection diversity, optimal antenna selection is achieved by choosing the L_r branches that have the largest SNR. This is true regardless of whether MRC or EGC is used for combining.

The equivalent SNR of generalized selection combining with MRC has been calculated as

$$\Gamma_{GSC} = \Gamma L\left(1 + \sum_{k=L+1}^{M} \frac{1}{k}\right).$$

We are not aware of a corresponding closed form expression for equal gain generalized selection combining.

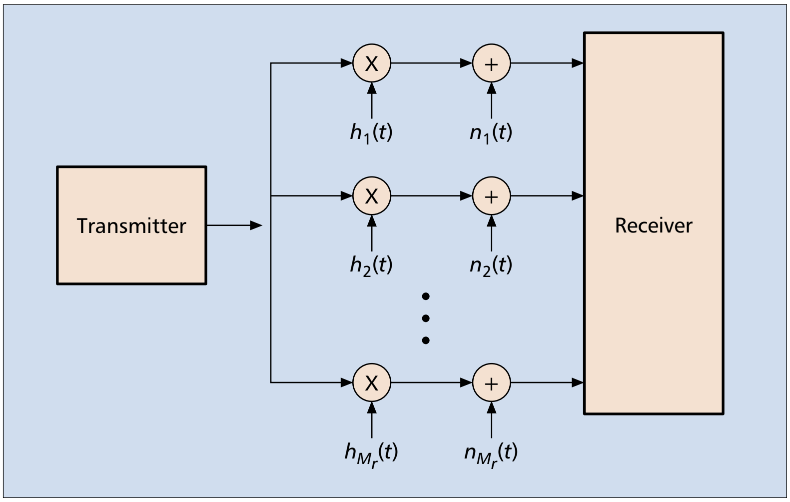

Figure 1. *Receive diversity.*

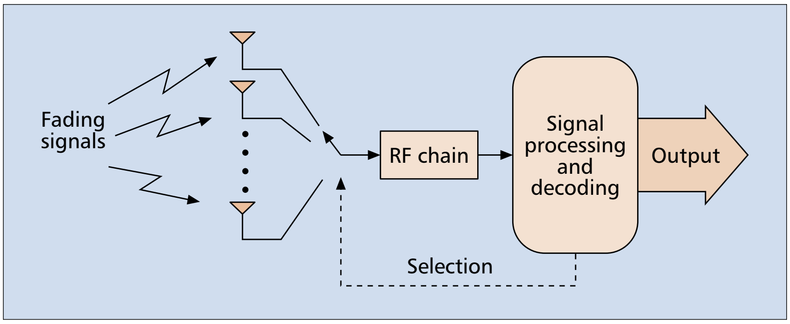

Figure 2. *Receive antenna selection.*

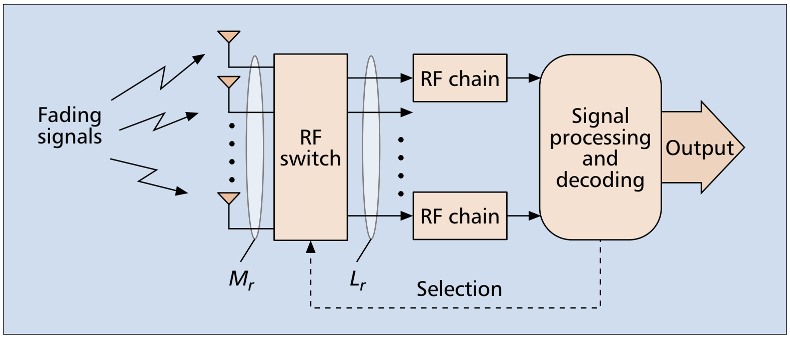

Figure 3. *A generalized selection diversity system.*

Transmit Antenna Selection

Transmit antenna selection, unlike receive selection, requires a feedback path from the receiver to the transmitter (Fig. 4). This feedback rate is rather small, especially for single antenna selection. Aside from that difference, however, transmit antenna selection is very similar to receive antenna selection; the antenna is selected that provides the highest equivalent receive SNR. Therefore, little else need be said about single transmit antenna selection.

To study multiple transmit antenna selection, assume that there are L_t RF chains and M_t antennas ($M_t > L_t$) at the transmitter, and one antenna at the receiver. Then we are faced with

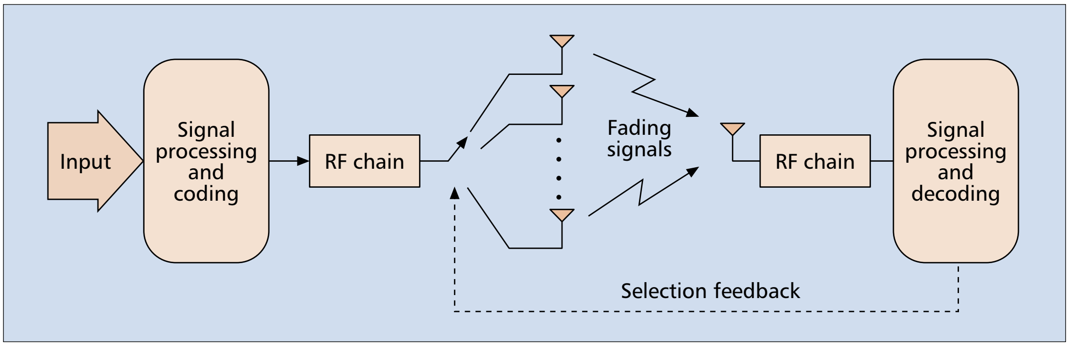

Figure 4. *Transmit antenna selection.*

The basic calculations for diversity reception often assume independent paths, but in practice the paths may be correlated. Spatial correlation reduces the effectiveness of any spatial diversity technique, including selection diversity.

the task of choosing the most suitable L_t out of M_t transmit antennas. Then the phase and amplitude of the transmit signals (subject to power constraints) must be such that their superposition at the receiver results in maximal receive SNR. In this case, one should choose the L_t transmit antennas with the highest channel gain. This method, which is equivalent to beamforming over the selected antennas, is known as *hybrid maximal ratio transmission*.

Hybrid maximal ratio transmission requires the transmitter to know not only the L_t most suitable transmit antennas, but also the (relative) complex-valued channel gains from each transmit antenna to the receiver. Obviously, this needs more feedback than a simple selection diversity.

TRANSMIT/RECEIVE SELECTION

The next step is to apply selection diversity simultaneously to both the transmitter and receiver (Fig. 5). In this scenario, there are M_t transmit and M_r receive antennas. The transmit and receive side have L_t and L_r RF chains, respectively. Therefore, it is possible to transmit L_t parallel data streams, so a space-time code must be used to provide diversity. Denote the overall $M_r \times M_t$ channel matrix by H, and the $L_r \times L_t$ channel matrix representing the selected antennas by $\tilde{H}$. Let us now consider the example of orthogonal block space-time codes.[2] These codes have a very simple decoder and lead to an equivalent single-input single-output (SISO) channel with the equivalent channel gain

$$h_{eq} = \sqrt{\frac{1}{L_t}\sum_{i=1}^{L_t}\sum_{j=1}^{L_t}\left|\tilde{h}_{ij}\right|^2},$$

where $\tilde{h}_{ij}$ are the elements of $\tilde{H}$. The SNR of the equivalent channel is proportional to the Frobenius norm of the selected channel matrix $||\tilde{H}||^2 = \Sigma_{ij}|\tilde{h}_{ij}|^2$. Therefore, joint transmit/receive selection strategies must choose a subset of the rows and columns of H to maximize the sum of the squared magnitudes of transmit-receive channel gains. This is not an easy task; for example, successively choosing the best receivers and then the best transmitters will not necessarily result in an overall optimal choice. In fact, except exhaustive search, no systematic solution to joint transmit/receive antenna selection is currently known. Efficient (optimal or suboptimal) joint selection of transmit and receive antennas remains an interesting open problem.

CHANNEL CHARACTERISTICS AND PERFORMANCE

Diversity combining in the presence of various channel conditions has been the subject of numerous studies. Here we present a brief overview of several main results in the context of selection diversity and generalized selection diversity.

The diversity order provided by all selection methods discussed so far is M_tM_r. That is, both antenna selection and generalized antenna selection, despite different complexities, provide the same diversity order. However, diversity order by itself does not tell the entire story. At a given channel condition, generalized selection has a better performance than single-antenna selection, as one would expect.

Selection diversity techniques require knowledge of channel conditions at the receiver for receive selection and at the transmitter for transmit selection. The estimation and feedback (if required) of channel state information takes some time, and the channel state must remain constant over that period. Therefore, the most widely accepted channel model in this context is the block-fading model.

The performance of selection diversity will suffer if channel state does not remain stationary, or if the estimate of channel state is inaccurate. Very little work has been done in characterizing the performance of antenna selection techniques in the presence of time variations or noisy channel estimates.

The basic calculations for diversity reception often assume independent paths, but in practice the paths may be correlated. Spatial correlation reduces the effectiveness of any spatial diversity technique, including selection diversity. The effects of spatially correlated channels have been studied extensively, showing that the diversity order cannot exceed the rank of the spatial correlation matrix of the channel.

Performance analysis of selection combining and generalized selection combining has been the subject of much research. In particular, Alouini and Simon [3] analyzed the generalized selection combining over Rayleigh fading channels using the moment generating function method, and later [4] extended and simplified the expressions for independent but nonidentically distributed Rayleigh paths. Mallik and Win [5] analyzed generalized selection combining in correlated Nakagami fading. There is a large

[2] *Orthogonal block codes for more than two transmit antennas are limited in that their effective rate is less than one symbol per transmission. Trellis space-time codes and nonorthogonal block codes remove this limitation at the cost of higher receiver computation complexity. For the purposes of this tutorial, we limit the discussion to orthogonal codes.*

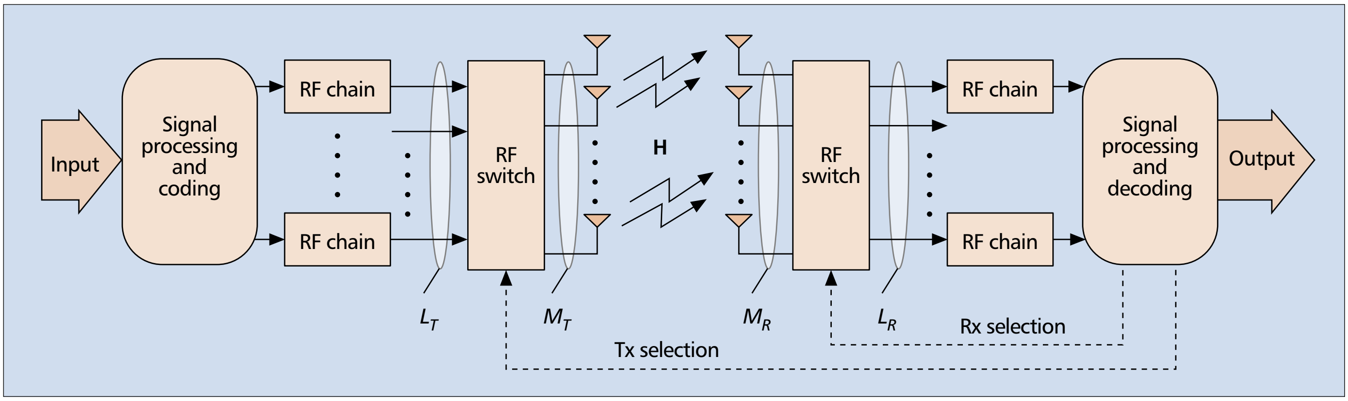

Figure 5. *Antenna selection in MIMO.*

body of work in this area, but further discussion of performance evaluation is beyond the scope of this tutorial.

Spatial Multiplexing and Capacity

As mentioned earlier, in a wireless fading channel with sufficiently rich scattering, it is possible to achieve capacities with MIMO systems that were unthinkable even a decade ago. When the wireless channel has sufficient degrees of freedom, the data streams transmitted from multiple transmit antennas can be separated, thus leading to parallel data paths. The capacity of the radio channel under these conditions grows with $\min(M_t, M_r)$, that is, linearly with the number of antennas. The previous section concentrated on antenna selection in MIMO channels from a diversity or, equivalently, from a BER performance viewpoint. In this section we discuss antenna selection in light of MIMO system capacity in the presence of spatial multiplexing.

We again refer to Fig. 5, a multiple-antenna system with M_t transmit and M_r receive antennas. The channel matrix H is an $M_r \times M_t$ complex valued matrix. We assume a block fading model in which the channel statistics can be Rayleigh or Rician, and the system experiences additive Gaussian noise at the receive antennas. The object is to select the best L_r out of M_r antennas at the receive side and the best L_t out of M_t antennas at the transmit side so that the resulting system capacity is maximized. Assuming equal power transmission from antennas, the capacity as a function of the channel matrix is

$$C = \log\det\left(I + \frac{\rho}{L_t}\tilde{H}^\dagger\tilde{H}\right),$$

where ρ is the receive SNR, $\tilde{H}$ is the $L_r \times L_t$ selected channel matrix, I is the $L_t \times L_t$ identity matrix, and $\tilde{H}^\dagger$ is the Hermitian of $\tilde{H}$.

The ideal antenna selection technique chooses $\tilde{H}$ out of H such that the expression above is maximized.

Receive Antenna Selection

For the case of receive antenna selection, assume we have $M_t = L_t$ transmit antennas and transmit RF chains, M_r receive antennas, and L_r receive RF chains, where $L_r < M_r$. Therefore, the problem is to choose $M_r - L_r$ rows of matrix H to be discarded and arrive at matrix $\tilde{H}$, such that the capacity is maximized. A simple exact solution to this problem is lacking. The only known exact solution is by exhaustive search, which is time consuming. In the following we study two approximate solutions.

Applying the Taylor expansion of $\log(\cdot)$, we find that at low SNR, capacity is proportional to $||\tilde{H}||^2$ (with higher-order terms being negligible). Therefore, at low SNR the antenna selection algorithm can simply maximize the norm of the (selected) channel matrix. Thus, at low SNR, antenna selection for diversity gain and antenna selection for capacity both follow the same strategy [6].

In other circumstances, norm-based selection may not be optimal. Nevertheless, norm-based selection may be used because of its low computational complexity and known statistics [7, 8]. In an attempt to achieve near-optimal selection, Gorokhov [9] suggested a decremental selection algorithm where, starting from the full channel matrix, the rows of H are discarded one by one so that at each step the capacity loss is minimized. Further work [10, 11] showed that an incremental algorithm (instead of a decremental one) leads to less complexity and has almost the same capacity as optimal selection.

An outline of the incremental selection algorithm (for high SNR) is as follows. Start by selecting the row vector with highest norm. At each selection step, project each remaining row vector on the orthogonal complement of the span of the previously chosen vectors, and choose the one whose projection has the largest magnitude. Continue until exactly L_r antennas are selected.

Successive selection is a greedy algorithm for maximizing capacity. As a result, successive selection may not be strictly optimal. However, simulations show that the ergodic capacity of successive selection is indistinguishable from the true optimum. Also, it is shown [11] that successive selection provides the full diversity of the original MIMO system.

Transmit Antenna Selection

In the context of spatial multiplexing (maximizing capacity), transmit antenna selection has many similarities with receive antenna selection.

The main difference, as mentioned earlier, is

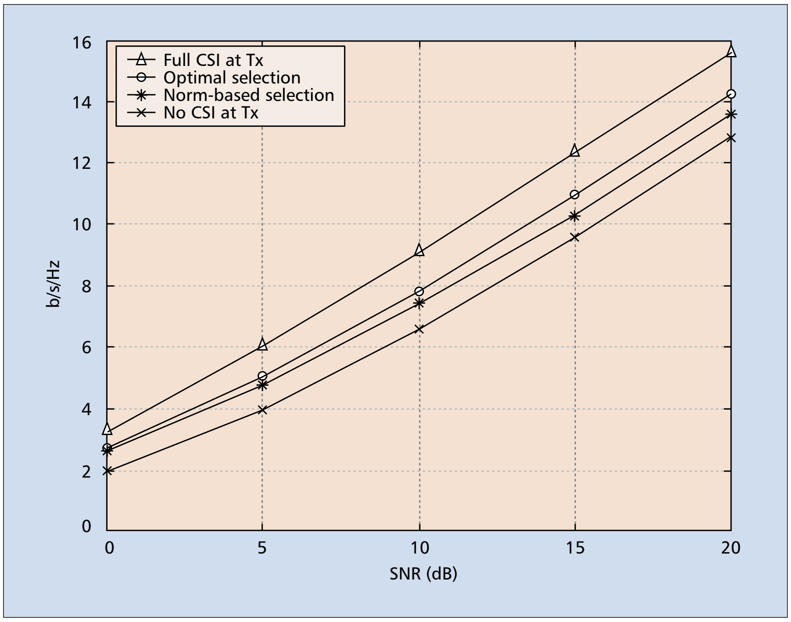

Figure 6. *Capacity of transmit antenna selection for* $M_t = 8$, $L_t = L_r = M_r = 2$. *Optimal selection and successive selection curves are identical.*

that in the case of transmit selection, a feedback path must exist to inform the transmitter which antennas to select. This feedback, in effect, gives the transmitter some information about the state of the channel. It is well known that the capacity of a wireless channel with transmit-side channel state information (CSI) is generally higher than without it. In other words, there is some *excess capacity* generated by the transmitter knowledge of the channel. When the transmitter is fully aware of the channel coefficients, the maximum capacity available in the channel will be attained (through a water-filling strategy).

The feedback required by antenna selection is, of course, only a small fraction of the full channel state information. Full channel state information involves several complex-valued variables, but for transmit selection only on the order of $O(L_t \log M_t)$ bits of feedback information is necessary. Very interestingly, this minimal amount of feedback is sufficient to capture a considerable fraction of the optimal capacity with full CSI (Fig. 6). The excess capacity provided by transmit antenna selection is quantified and analyzed in [6].

Discussion and Conclusion

This article presents an overview of antenna selection in MIMO systems. Antenna selection can reduce hardware complexity and cost, achieve full diversity, and in the case of transmit antenna selection, gain rate (capacity). These objectives can be achieved at an affordable computational cost. There are two main approaches for antenna selection: norm-based selection and successive selection. The former approach is more suitable when SNR is low, whereas the latter suits the high SNR regime. Both methods can be applied for either transmit or receive antenna selection.

Antenna selection has certain inherent limitations. One of the most important limitations arises whenever the system bandwidth is larger than the coherence bandwidth of the channel (i.e., when the channel is frequency-selective). The different response of the channel at different frequencies implies that at each band a different antenna selection is optimal. So whenever the channel is highly frequency-selective, with many uncorrelated frequency bands, antenna selection may not be feasible or useful. However, in moderately frequency-selective channels, antenna selection still provides significant gains.

Antenna selection also presents several practical issues we have overlooked in this introductory tutorial. For example, the RF switches available with current technologies are far from ideal, a fact that may offset some of the advantages of antenna selection. The most important shortcoming of the practical switches is their transfer attenuation, which must be compensated by more power from the output stage amplifier of the transmitter and by a more sensitive low noise amplifier at the receiver.

Finally, we note several open problems in antenna selection. Analysis and code design for antenna selection still requires more investigation. Also, the important problem of optimal joint transmit and receive antenna selection is open. Performance evaluation of antenna selection algorithms when the channel matrix is not perfectly known at the receiver is a seemingly important yet relatively unexplored problem. The combination of antenna selection with space-time signaling schemes has been noted by several investigators, but much work remains in this area, and it is a worthy subject of future research.

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BIOGRAPHIES

SHAHAB SANAYEI [S'04] (shahab.sanayei@student.utdallas.edu) received his B.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1995 and his M.S. degree in electrical engineering from Rice University, Houston, Texas, in 2002. From 1994 to 1997 he was with the Intelligent Systems Laboratory at Sharif University of Technology. From 1997 to 2000 he was an R&D engineer with Towzin Electric Co., Tehran, Iran. Since September 2002 he has been with the Department of Electrical Engineering at the University of Texas, Dallas, where he is currently pursuing his Ph.D. degree in electrical engineering. His research interests include MIMO systems and information theory.

ARIA NOSRATINIA [M'97, SM'04] (aria@utdallas.edu) received his B.S. degree in electrical engineering from the University of Tehran, Tehran, Iran, in 1988, his M.S. degree in electrical engineering from the University of Windsor, Ontario, Canada, in 1991, and his Ph.D. degree in electrical and computer engineering from the University of Illinois at Urbana-Champaign in 1996. From 1995 to 1996 he was with Princeton University, New Jersey. From 1996 to 1999 he was a visiting professor and faculty fellow at Rice University, Houston, Texas. Since 1999 he has been with the faculty of the University of Texas, Dallas, where he is currently associate professor of electrical engineering. His research interests are in the broad area of communication and information theory, particularly coding and signal processing for the communication of multimedia signals. He was the recipient of the National Science Foundation Career award in 2000 and has twice received chapter awards for outstanding service to the IEEE Signal Processing Society.