CLOSED-LOOP HYBRID MIMO SYSTEM WITH JOINT TRANSMIT ANTENNA AND MODE SELECTION BASED ON CAPACITY MAXIMIZATION

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ABSTRACT

We present a new hybrid multiple input multiple output (MIMO) system combining spatial multiplexing and transmit diversity at different levels. The inner core of the transmit processing is responsible for space-time coding with variable rate-diversity control. The outer core is composed of two (coarse) precoding matrices acting as transmit antenna and mode selection matrices. Exploiting the structure of these selection matrices, a capacity maximizing selection criterion is proposed to optimize the hybrid transmission mode jointly with the transmit antenna mapping. Simulation results show that the proposed hybrid system offers significant capacity gains over its open-loop counterpart and outperforms pure antenna selection and pure mode selection based systems.

1. INTRODUCTION

Performance enhancements of MIMO systems in terms of higher spectral efficiencies and lower error rates can be achieved with "closed-loop" transmission by means of linear precoding [1]. In its general form, linear precoding consists in applying a linear transformation on the input data streams before its transmission over the wireless channel. The design of the precoder needs knowledge about the channel state information, which is generally conveyed from the receiver to the transmitter using a feedback control channel. A very attractive and simple approach to linear precoding relies on the use of limited feedback [2]. These techniques are based on the quantization of the instantaneous channel information at the receiver followed by its conveyance to the transmitter using a low-rate feedback channel. Some closed-loop MIMO techniques operate by selecting the multiplexing factor (number of data streams) and/or the transmit antenna subset for spatial multiplexing systems with linear receivers [3–7].

For instance, a multimode precoding that adapts the best antenna subset and the constellation of each data stream is proposed in [7]. In [8], the quantization of the principal components of the MIMO channel subspace in the angular domain is proposed. Most of existing limited feedback approaches are only focused on pure spatial multiplexing and do not consider multilayered space-time transmission in the form of hybrid combinations of spatial multiplexing and transmit diversity. In [9, 10], adapting the transmission mode from instantaneous channel knowledge is possible by a dual-mode switching between different transmit schemes such as beamforming, spatial multiplexing and transmit diversity.

In this work, we propose a space-time MIMO system consisting of hybrid combinations of spatial multiplexing and transmit diversity at different levels while using spatially precoded transmission. The transmit preprocessing is composed of two (coarse) precoding matrices acting, respectively, as a *mode selection matrix* and an *antenna selection matrix*. The first selection matrix specifies the hybrid transmission mode to be used (among a finite set of possibilities) by controlling the partitioning of the transmit antennas into transmit layers. The second selection matrix maps the transmit layers to a subset of transmit antennas. For the proposed system, we address the problem of jointly selecting the hybrid transmission mode and antenna subset for a fixed data rate. Specifically, we propose to jointly find the antenna and mode selection matrices that best match the MIMO channel eigenstructure based on a capacity maximizing criterion. The flexibility to support hybrid modes with different levels of multiplexing and diversity is an innovation aspect of the proposed system.

This paper is organized as follows. Section 2 presents the baseline system model. In Section 3, we describe the proposed hybrid MIMO system. In Section 4, the joint transmit antenna and mode selection problem is formulated. Section 5 contains our simulation results and the paper is concluded in Section 6.

Notations: The notation and some definitions used throughout this work are now defined. Scalar variables are denoted by lower-case letters $(a, b, \ldots, \alpha, \beta, \ldots)$, vectors are written as boldface lower-case letters $(\mathbf{a}, \mathbf{b}, \boldsymbol{\alpha}, \boldsymbol{\beta}, \ldots)$, matrices correspond to boldface capitals $(\mathbf{A}, \mathbf{B}, \ldots)$, and $\mathbf{A}^T$ is the transpose of $\mathbf{A}$. $\mathbf{e}_i^{(I)}$ denotes a unit vector of dimension I with an entry equal to 1 at the i-th position and 0's elsewhere. The ceiling operator $\lceil x \rceil$ returns the smallest integer above x. The matrix operator $D_i(\mathbf{A})$ forms a diagonal matrix holding the i-th row of $\mathbf{A}$ on its diagonal.

2. BASELINE MODEL

Consider a linearly precoded MIMO wireless communication system with M_T transmit antennas and M_R receive antennas, transmitting M_S independent data streams. Uniform linear arrays of antennas are considered at each link end. Assume that redundant transmission in the joint space-time domain is used (e.g. by means of space-time block coding/spreading), where P denotes the code length, *i.e.* the number of channel uses of the space-time code. Define K as the number of useful information symbols contained in a data stream. The transmission of each data stream is organized into K data blocks of P symbol periods each. The k-th data block of the discrete-time baseband received signal can be modeled by the following input-output relation:

$$\mathbf{X}[k] = \mathbf{H}\mathbf{F}\overline{\mathbf{S}}[k] + \mathbf{V}[k], \quad k = 1, \ldots, K. \tag{1}$$

where $\mathbf{X}[k] \doteq [\mathbf{x}[k,1], \ldots, \mathbf{x}[k,P]] \in \mathbb{C}^{M_R \times P}$ is the received signal matrix collecting the signal received by the M_R receive antennas during P symbol periods, $\mathbf{H} \in \mathbb{C}^{M_R \times M_T}$ is the MIMO channel matrix, $\mathbf{F} \in \mathbb{C}^{M_T \times M_S}$ is the linear precoder mapping M_S data streams to M_T transmit antennas, $\overline{\mathbf{S}}[k] \doteq \kappa(\mathbf{s}[k]) \in \mathbb{C}^{M_S \times P}$ denotes the k-th space-time codeword, and $\kappa(\cdot)$ represents the space-time encoding function, and $\mathbf{V}[k] \doteq [\mathbf{v}[k,1], \ldots, \mathbf{v}[k,P]] \in \mathbb{C}^{M_R \times P}$ is the additive noise matrix with variance σ_v^2. The total transmitted signal power is equally divided across the M_T transmit antennas and satisfies the constraint $\|\mathbf{F}\overline{\mathbf{S}}[k]\|_F^2 = 1$, where $\|\cdot\|_F$ is the Frobenius norm.

3. HYBRID SPACE-TIME MIMO SYSTEM

We propose a space-time MIMO system consisting of hybrid combinations of spatial multiplexing and transmit diversity at different levels while using spatially-precoded transmission. The end-to-end transmit processing maps M_S independent data streams across a set of M_V active transmit antennas, with $M_S \leq M_V \leq M_T$. These M_V transmit antennas are partitioned into M_S disjoint antenna groups, also herein referred to as "layers", where the r-th layer has α_r (not necessarily neighboring) transmit antennas, $r = 1, \ldots, M_S$. Each layer transmits a precoded version of a different data stream. In its general form, the space-time signal generation is represented by a cascade of three processing stages:

1. The M_S input data streams are precoded by $\mathbf{G} \in \mathbb{C}^{M_V \times M_S}$ yielding M_V output data streams;
2. The M_V data streams are space-time coded using a code matrix $\mathbf{W} \in \mathbb{C}^{P \times M_V}$;
3. The resulting signal is assigned to a subset of M_T transmit antennas using $\mathbf{F} \in \mathbb{C}^{M_T \times M_V}$.

The inner core of the transmit processing is represented by $\mathbf{W}$ while the outer core is represented by $\mathbf{G}$ and $\mathbf{F}$. The inner core $\mathbf{W}$ is responsible for space-time coding and allows to control the number of channel uses (code length) of the space-time code. The matrix $\mathbf{F}$ determines which M_V (out of M_T) transmit antennas are selected or, alternatively, how these M_V antennas are mapped to the M_S transmit layers. On the other hand, $\mathbf{G}$ defines the number of transmit antennas $\alpha_1, \ldots, \alpha_{M_S}$ associated with the M_S layers, while precoding across each layer.

Starting from the same general assumptions as those of the baseline model, we now formulate the proposed hybrid MIMO system. The output of the first linear precoding stage, represented by $\overline{\mathbf{s}}[k] \in \mathbb{C}^{M_V}$, is given by:

$$\overline{\mathbf{s}}[k] = \mathbf{G}\mathbf{s}[k]. \tag{2}$$

The space-time codeword $\overline{\mathbf{S}}[k] \in \mathbb{C}^{M_V \times P}$ is generated by spreading $\overline{\mathbf{s}}[k]$ across P symbol periods using the code matrix as follows:

$$\overline{\mathbf{S}}[k] = \kappa(\mathbf{W}, \overline{\mathbf{s}}[k]) = \Big[D_1(\mathbf{W})\overline{\mathbf{s}}[k], \ldots, D_P(\mathbf{W})\overline{\mathbf{s}}[k]\Big]. \tag{3}$$

The transmitted signal matrix $\mathbf{U}[k] \in \mathbb{C}^{M_T \times P}$ is obtained after the second linear precoding stage, *i.e.*:

$$\mathbf{U}[k] = \mathbf{F}\overline{\mathbf{S}}[k]. \tag{4}$$

Combining (2), (3) and (4), we finally obtain a compact input-output relation

$$\mathbf{X}[k] = \mathbf{H}\mathbf{U}[k] + \mathbf{V}[k], \tag{5}$$

where

$$\mathbf{U}[k] = \mathbf{F} \cdot \kappa(\mathbf{W}, \mathbf{G}\mathbf{s}[k]) \tag{6}$$

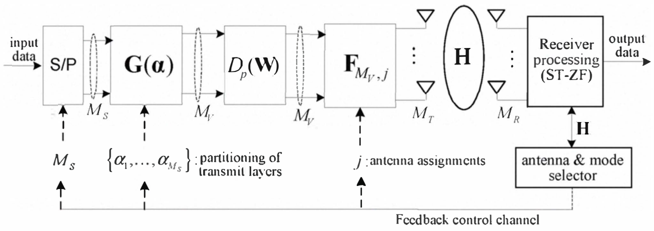

Fig. 1. Block-diagram of the closed-loop hybrid MIMO system using joint transmit antenna and mode selection.

is the k-th transmitted signal matrix, expressed in terms of the three transmit processing operations $(\mathbf{F}, \mathbf{W}, \mathbf{G})$ characterizing the proposed hybrid MIMO system.

In this work, we assume that both precoding matrices $\mathbf{G}$ and $\mathbf{F}$ have a "canonical" structure, *i.e.* they are full column-rank matrices composed of 1's and 0's. Under this particular structural assumption, $\mathbf{G}$ reduces to a *mode selection matrix* that determines the number M_S of layers as well as how the M_V active transmit antennas are partitioned into these M_S layers. This is equivalent to choosing the partitions $\alpha_1, \ldots, \alpha_{M_S}$. For each choice, a different transmission mode arises. As a quick example, for $M_V = 3$, one can partition the three transmit antennas into three different manners: i) three groups of one transmit antenna; ii) two groups of one and two antennas; iii) a single group of three antennas. It is worth noting that $\mathbf{G}$ only specifies the hybrid transmission mode to be used. The mapping of transmit layers to transmit antennas is indeed the role of $\mathbf{F}$, which acts as a *antenna selection matrix* that maps the M_S transmit layers to a subset of M_V antennas. Finally, the code matrix $\mathbf{W}$ allows to control the number of channel uses (code length) of the space-time code while ensuring orthogonality or, at least, a maximum uniform angular separation between the transmitted signals.

Figure 1 depicts the block-diagram of a hybrid MIMO system with closed-loop transmission, with $\mathbf{G}$ and $\mathbf{F}$ acting as transmit antenna and mode selection matrices, respectively. In the following, the structure of each block is detailed.

3.1. Outer core structure

As we have mentioned in the previous section, by focusing on the problem of jointly selecting the transmission mode and the antenna mapping, we propose simple designs for the outer core structure of the proposed MIMO system, which are represented by $\mathbf{G}$ and $\mathbf{F}$.

The following assumptions are satisfied by the mode selection matrix $\mathbf{G}$:

(*A.1*) The rows of $\mathbf{G}$ are unit vectors belonging to the canonical set $\{\mathbf{e}_1^{(M_S)}, \ldots, \mathbf{e}_{M_S}^{(M_S)}\}$.

(*A.2*) $\mathbf{G}$ is a block diagonal matrix composed of M_S mutually orthogonal diagonal blocks, the r-th block containing α_r identical unit rows, as follows:

$$\mathbf{G} = \begin{bmatrix} \mathbf{1}_{\alpha_1} & & & \\ & \mathbf{1}_{\alpha_2} & & \\ & & \ddots & \\ & & & \mathbf{1}_{\alpha_{M_S}} \end{bmatrix}, \tag{7}$$

with

$$\alpha_1 \leq \alpha_2 \leq \cdots \leq \alpha_{M_S}, \tag{8}$$

so that the following structural constraint holds:

$$\mathbf{G}^T\mathbf{G} = \text{diag}(\alpha_1, \ldots, \alpha_{M_S}) = \text{diag}(\boldsymbol{\alpha}), \tag{9}$$

with

$$\sum_{r=1}^{M_S} \alpha_r = M_V, \tag{10}$$

where $\mathbf{1}_{\alpha_r}$ is the "all-ones" vector of dimension α_r, $r = 1, \ldots, M_S$, and $\boldsymbol{\alpha} \in \mathbb{C}^{M_V}$ is the *generating vector* of the mode selection matrix $\mathbf{G}$. This generating vector defines the partition structure of the transmit array into the M_S transmit layers. Different choices of $\boldsymbol{\alpha} = [\alpha_1, \ldots, \alpha_{M_S}]$ in accordance with the design rules (7)-(9), yield different hybrid transmission modes in between orthogonal transmit diversity and spatial multiplexing.

Example ($M_V = 3$): For this system configuration, we may have i) a hybrid mode transmitting three data streams with one transmit antenna per data stream which means that $(\alpha_1, \alpha_2, \alpha_3) = (1, 1, 1)$, corresponding to a three-antenna spatial multiplexing; or ii) a hybrid mode transmitting two data streams, one associated with a single antenna and the other associated with two transmit antennas, *i.e.* $(\alpha_1, \alpha_2) = (1, 2)$. This corresponds to a particular hybrid combination of spatial multiplexing and transmit diversity.

As mentioned before, the canonical precoder $\mathbf{F}$ is an antenna selection matrix which selects M_V (out of M_T) transmit antennas to transmit the M_V virtual (space-time coded) data streams. Therefore, $\mathbf{F}$ can be defined as a subset of M_V columns of $\mathbf{I}_{M_T}$.

3.2. Inner core structure

The code matrix $\mathbf{W} \in \mathbb{C}^{P\times M_V}$ is used to encode the input symbols in the space-time domain. The role of this matrix is to jointly rotate the elements of the extended symbol vector $\overline{\mathbf{s}}[k] = [\overline{s}_1[k], \ldots, \overline{s}_{M_V}[k]]^T \in \mathbb{C}^{M_V}$ defined in (2) so that orthogonality between any two symbols $\overline{s}_i[k]$ and $\overline{s}_j[k]$, $i \neq j$, is ensured (when $P \geq M_V$) or, at least, a maximum angular separation between any two of them is ensured (when $P < M_V$). A possible structure for such a rotation matrix is given by the following Vandermonde matrix:

$$[\mathbf{W}]_{p,m} \doteq \frac{1}{\sqrt{P}} e^{j\frac{2\pi}{M_V}(p-1)(m-1)}. \tag{11}$$

Since $M_S \leq M_V$, we have M_S useful information symbols being transmitted during P symbol periods, and the code rate is given by:

$$B = \left(\frac{M_S}{P}\right) \log_2(\mu) \text{ bits per channel use (pcu)}, \tag{12}$$

where μ is the modulation cardinality.

4. JOINT TRANSMIT ANTENNA AND MODE SELECTION

In this section, a new transmit signal design approach is proposed for the hybrid MIMO system characterized by (5) and (6). We address the problem of jointly selecting the transmit antenna subset and the space-time transmission mode to be used, particular cases of which are full spatial transmit diversity and full spatial multiplexing. Specifically, the joint transmit antenna and mode selection problem consists of selecting the best precoder pair $(\mathbf{F}, \mathbf{G})$ from a finite set of admissible structures known at both transmitter and receiver, which maximize some performance criterion for a fixed rate. In this case, a few feedback information bits are required for selecting $\mathbf{F}$ and $\mathbf{G}$ from their associated codebooks.

Note that choosing the transmission mode implies choosing the multiplexing factor M_S of the system. In order to keep a fixed rate of B bits pcu regardless of the chosen M_S, we may adjust the modulation cardinality μ, or the code length P or, yet, both of them following (12). In order words, a multimode (modulation and code) rate adaptation is possible.

4.1. Mode selection codebook

Recall that $\mathbf{G}$ is completely specified by its associated generating vector $\boldsymbol{\alpha}$. This means that optimizing the 1's and 0's structure of $\mathbf{G}$ is equivalent to optimizing the generating vector $\boldsymbol{\alpha}$. Let us define $\mathcal{G}_{M_V}$ as the *mode selection codebook* of possible generating vectors satisfying the design constraints (7)-(9). We propose an interpretation of $\boldsymbol{\alpha}$ as a *partition* of M_V. A partition is a way of writing an integer M_V as a sum of positive integers where the order of the addends is not significant [11]. Let us define $Q(M_V, M_S)$ as the number of partitions of M_V into M_S elements, representing the number of possible ways to partition M_V transmit antennas into M_S groups, each one associated with a different data stream. For instance, $[1\ \ 1\ \ 2]$ is a partition of $M_V = 4$ transmit antennas into $Ms = 3$ independent data streams, while $[2\ \ 2]$ is a partition of $M_V = 4$ transmit antennas into $M_S = 2$ data streams.

Applied to our context, for a fixed M_V, we define the *mode selection codebook* $\mathcal{G}_{M_V}$ as an ordered set of N_Q partitions, where N_Q is the sum of possible partitions of M_V transmit antennas into r antenna groups, $r = 1, \ldots, M_V$, *i.e.*:

$$N_Q = \sum_{r=1}^{M_V} Q(M_V, r). \tag{13}$$

For a fixed M_V, we can use the following recurrence relation to calculate $Q(M_V, r)$ (see details in [11]):

$$Q(M_V, r) = Q(M_V - 1, r - 1) + Q(M_V - r, r), \tag{14}$$

with $Q(M_V, r) = 0$ for $r > M_V$, $Q(M_V, M_V) = 1$ and $Q(M_V, 0) = 0$. Therefore, the number N_Q denote the total number of possible transmission modes arising for a fixed number M_V of active transmit antennas. This number includes, in addition to pure multiplexing and pure diversity modes, all the hybrid combinations of them. All these modes belong to our mode selection codebook.

Based on the parameterization of the mode selection precoder $\mathbf{G} = \mathbf{G}(\boldsymbol{\alpha})$, the elements of the mode selection codebook $\mathcal{G}_{M_V}$ can be represented by the N_Q possible partitions that can be formed from the generating vector $\boldsymbol{\alpha}$. We assume that the $\mathcal{G}_{M_V}$ can be written as an ordered partition set:

$$\mathcal{G}_{M_V} = \left\{\boldsymbol{\alpha}_{M_V,1}, \ldots, \boldsymbol{\alpha}_{M_V,i} \ldots, \boldsymbol{\alpha}_{M_V,N_Q}\right\},$$

where $\boldsymbol{\alpha}_{M_V,i}$ is the i-th transmission mode in this ordered set. In the following, we provide examples of some mode selection codebooks based on the generating vectors parameterization:

$$\begin{aligned}
\mathcal{G}_1 &= \{\alpha_1\} = \{1\} \\
\mathcal{G}_2 &= \{\boldsymbol{\alpha}_{2,1}, \boldsymbol{\alpha}_{2,2}\} = \{[2],\ [1\ \ 1]\} \\
\mathcal{G}_3 &= \{\boldsymbol{\alpha}_{3,1}, \boldsymbol{\alpha}_{3,2}, \boldsymbol{\alpha}_{3,3}\} = \{[3],\ [1\ \ 2],\ [1\ \ 1\ \ 1]\}, \\
\mathcal{G}_4 &= \{\boldsymbol{\alpha}_{4,1}, \boldsymbol{\alpha}_{4,2}, \boldsymbol{\alpha}_{4,3}, \boldsymbol{\alpha}_{4,4}, \boldsymbol{\alpha}_{4,5}\} \\
&= \{[4],\ [1\ \ 3],\ [2\ \ 2],\ [1\ \ 1\ \ 2],\ [1\ \ 1\ \ 1\ \ 1]\}.
\end{aligned}$$

Note, for instance, that codebooks $\mathcal{G}_3$ and $\mathcal{G}_4$ contain, respectively, two and three hybrid modes in between pure multiplexing and pure diversity. Indeed, as the number M_V of active transmit antennas increases, additional hybrid modes appear.

4.2. Antenna selection codebook

The problem of antenna selection consists of selecting M_V (out of M_T) transmit antennas to transmit M_S space-time coded data streams. We define the antenna selection codebook $\mathcal{F}_{M_V}$ as the set of $\binom{M_T}{M_V}$ matrices taken by selecting M_V columns of the identity matrix $\mathbf{I}_{M_T}$. For each M_V, $\mathcal{F}_{M_V}$ can be written as an ordered set of matrices:

$$\mathcal{F}_{M_V} = \left\{ \mathbf{F}_{M_V,1}, \ldots, \mathbf{F}_{M_V,j}, \ldots, \mathbf{F}_{M_V,\binom{M_T}{M_V}} \right\},$$

where $\mathbf{F}_{M_V,j}$ is the j-th antenna mapping.

Maximum capacity selection: It is known that a capacity-optimal transmit signal design is achieved by means of the water-filling solution provided that the MIMO channel eigenstructure is known at the transmitter [12]. Despite its optimality, this solution supposes "reciprocity" between the forward and reverse channels and generally requires a large amount of feedback. Here, we consider a sub-optimal approach by assuming equal power allocation across the M_V active transmit antennas.

Let us consider the proposed space-time MIMO system using the i-th transmission mode parameterized by $\boldsymbol{\alpha}_{M_V,i}$ and j-th antenna mapping $\mathbf{F}_{M_V,j}$. The instantaneous MIMO channel capacity in terms of bits/s/Hz can be expressed as:

$$\begin{aligned} &C_{i,j}(\mathbf{H}, \boldsymbol{\alpha}_{M_V,i}, \mathbf{F}_{M_V,j}) \\ &= \log_2 \det \left(\mathbf{I}_{M_R} + \frac{\rho}{M_V} \mathbf{H}\mathbf{Z}_{i,j}(\boldsymbol{\alpha}_{M_V,i}, \mathbf{F}_{M_V,j})\mathbf{H}^H \right), \end{aligned}$$

where ρ is the signal-to-noise (SNR) ratio, and the precoder-dependent term

$$\begin{aligned} &\mathbf{Z}_{i,j}(\boldsymbol{\alpha}_{M_V,i}, \mathbf{F}_{M_V,j}) \\ &= \mathbf{F}_{M_V,j}\mathbf{G}(\boldsymbol{\alpha}_{M_V,i}) \underbrace{D_p(\mathbf{W})D_p^*(\mathbf{W})}_{I_{M_V}} \mathbf{G}^T(\boldsymbol{\alpha}_{M_V,i})\mathbf{F}^T_{M_V,j} \\ &= \mathbf{F}_{M_V,j}\mathbf{G}(\boldsymbol{\alpha}_{M_V,i})\mathbf{G}^T(\boldsymbol{\alpha}_{M_V,i})\mathbf{F}^T_{M_V,j}, \end{aligned} \tag{15}$$

$p = 1, \ldots, P$, is constructed from the i-th mode selection precoder $\mathbf{G}(\boldsymbol{\alpha}_{M_V,i})$ and from the j-th antenna selection precoder $\mathbf{F}_{M_V,j}$, with $1 \leq i \leq N_Q$, $1 \leq j \leq \binom{M_T}{M_V}$. Due to the unit-norm structure of $\mathbf{W}$, there is no dependence of $\mathbf{Z}_{i,j}(\boldsymbol{\alpha}_{M_V,i}, \mathbf{F}_{M_V,j})$ on $\mathbf{W}$.

Let us define i^* and j^* as the optimal mode and antenna selection precoder indexes that maximize $C_{i,j}(\mathbf{H}, \boldsymbol{\alpha}_{M_V,i}, \mathbf{F}_{M_V,j})$. The selection criterion solves the following optimization problem:

$$(i^*, j^*) = \arg \max_{1\leq i \leq N_Q,\, 1 \leq j \leq \binom{M_T}{M_V}} C_{i,j}(\mathbf{H}, \boldsymbol{\alpha}_{M_V,i}, \mathbf{F}_{M_V,j}). \tag{16}$$

The number of bits required to select the optimal transmission mode and the optimal transmit antenna subset to be used can be written in terms of M_T and M_V, as:

$$N_B = \left\lceil \log_2 \left(\left(\sum_{r=1}^{M_V} Q(M_V, r) \right) + \binom{M_T}{M_V} \right) \right\rceil. \tag{17}$$

5. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed hybrid MIMO system when operating in open-loop and in closed-loop. For open-loop settings, some performance comparisons consider a fixed configuration for the antenna and mode selection matrices $\mathbf{F}$ and $\mathbf{G}$. Whenever $\mathbf{F}$ and/or $\mathbf{G}$ are fixed, we have:

$$\mathbf{F} = \begin{bmatrix} \mathbf{I}_{M_V} \\ \mathbf{0}_{(M_T - M_V)\times M_V} \end{bmatrix}, \quad \mathbf{G} = \mathbf{I}_{M_V}. \tag{18}$$

This combined setting corresponds to conventional spatial multiplexing (SM), where the first M_V transmit antennas are always selected to transmit M_V independent data streams. Our comparisons also shows the average performance of a "random selection" approach where $\mathbf{F}$ and/or $\mathbf{G}$ are randomly selected at each Monte Carlo run from their associated codebooks.

We compare the capacity performance of the hybrid MIMO system under open-loop and closed-loop transmissions. In Figure 2, we investigate the empirical cumulative distribution function (CDF) of capacity for a system with $M_T = 4$, $M_V = 3$ and $M_R = 3$ operating in open-loop and closed-loop for two SNR values: 10dB and 20dB. In the open-loop case, $\mathbf{F}$ and $\mathbf{G}$ are randomly selected from their associated codebooks. In this figure, we use dashed lines to denote the closed-loop system and solid lines for the open-loop one. As can be seen, a closed-loop hybrid system with joint transmit antenna and mode selection performs considerably better than its open-loop counterpart. Considering the 10% outage capacity, the gain exceeds 3 bits/s/Hz for SNR=10dB and 6 bits/s/Hz for SNR=20dB.

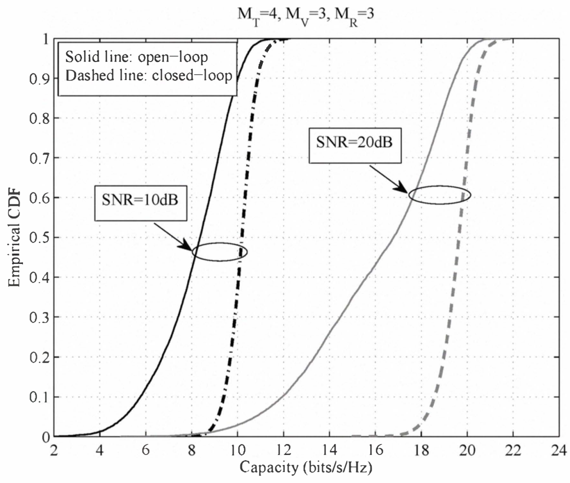

Fig. 2. Capacity results for $M_T = 4, M_V = 3, M_R = 3$: Random selection vs. joint antenna and mode selection.

In Figure 3, we evaluate the impact of using mode selection in addition to antenna selection. We consider a system with $M_T = 6$, $M_V = 4$ and $M_R = 3$ and the SNR is set to 10dB. When transmit antenna selection is used, the 10% outage capacity increases more than 2 bits/s/Hz w.r.t the open-loop system. Note that an additional gain of almost 2 bits/s/Hz is provided by the joint transmit antenna and mode selection approach.

The average bit-error-rate (BER) performance of the hybrid MIMO system using joint transmit antenna and mode selection has also been evaluated using the max-min singular value selection criterion and a space-time zero forcing (ST-ZF) receiver. The formulation of the max-min selection criterion and that of the ST-ZF receiver have been suppressed due to lack of space. Each plotted BER curve is an average over 10^4 Monte Carlo runs. The number of received data blocks is fixed to $K = 50$. At each run, the transmitted symbols are drawn from a pseudo-random sequence composed of BPSK, QPSK or QAM symbols. The modulation is adapted as a function

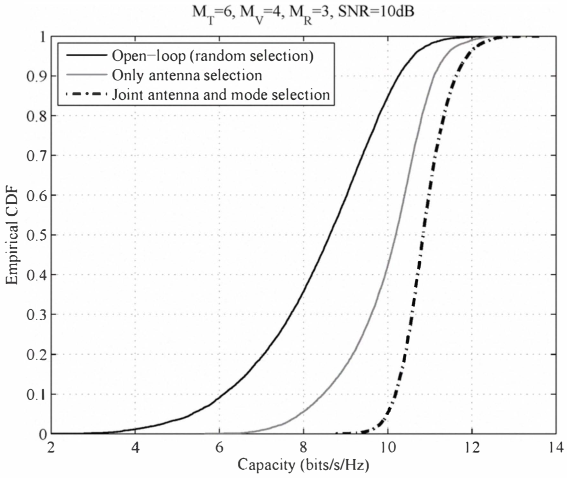

Fig. 3. Capacity results for $M_T = 6, M_V = 4, M_R = 3$ and SNR=10dB: Impact of joint antenna and mode selection.

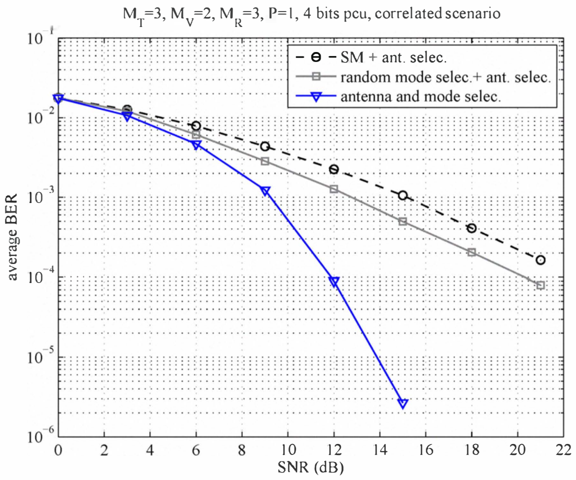

Fig. 4. BER performance for $M_T = 3, M_V = 2, M_R = 3$ and $P = 1$ in a scenario with transmit and receive correlation.

of M_S in order to keep a fixed data rate regardless of the used transmission mode. In Figure 4, we investigate the impact of using mode selection in addition to transmit antenna selection in a system configured with $M_T = M_R = 3$, $M_V = 2$ and $P = 1$ operating under both transmit and receive spatial correlation. The transmit and receive correlation matrices are given by [13]:

$$\mathbf{R}_T = \begin{bmatrix} 1 & 0.2e^{0.86\pi j} & 0.8e^{-0.26\pi j} \\ 0.2e^{-0.86\pi j} & 1 & 0.2e^{0.86\pi j} \\ 0.8e^{0.26\pi j} & 0.2e^{-0.86\pi j} & 1 \end{bmatrix}. \quad (19)$$

$$\mathbf{R}_R = \begin{bmatrix} 1 & 0.91e^{j\pi/2} & -0.69 \\ 0.91e^{-j\pi/2} & 1 & 0.91e^{j\pi/2} \\ -0.69 & 0.91e^{-j\pi/2} & 1 \end{bmatrix}. \quad (20)$$

The hybrid system with a random mode selection provides a slight improvement over pure spatial multiplexing with transmit antenna selection. A significant BER improvement is obtained when the transmit antenna subset and the hybrid mode are jointly optimized.

6. CONCLUSION

We have proposed a hybrid MIMO system allowing to optimize both the transmission mode and the transmit antenna assignments based on the instantaneous MIMO channel using a limited feedback based capacity-maximizing selection. Contrary to existing approaches, which are limited to pure spatial multiplexing, pure transmit diversity or simple direct combinations of both techniques, the proposed system takes into account all possible hybrid transmission modes arising for a fixed number of transmit antennas. Our simulation results corroborate the performance gains of the joint transmit antenna and mode selection approach over open-loop transmission and closed-loop systems based only on transmit antenna selection. Next steps to be taken include the use of other selection criteria to optimize the antenna and mode selection matrices and, possibly, the use of cross-layer approaches.

7. REFERENCES

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