Adaptive MIMO Transmission Scheme: Exploiting the Spatial Selectivity of Wireless Channels

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***Abstract*— We present a novel adaptive transmission technique for MIMO systems with the aim to enhancing the spectral efficiency for a target error rate performance and transmit power. This adaptive method employs the condition number of the spatial correlation matrix as an indicator of the spatial selectivity of the MIMO channel. The distribution of the condition number is then used to identify the prevailing channel environment. Depending on the identified channel state, our adaptive algorithm chooses the MIMO transmission method, among spatial multiplexing, D-STTD, and beamforming, that maximizes the spectral efficiency. Performance results show significant gains in throughput and reduced error rate compared to conventional fixed transmission schemes.**

I. Introduction

Multiple-input multiple-output (MIMO) is a promising solution to improve the spectral efficiency of next generation wireless communications systems. MIMO technology exploits the spatial components of the wireless channel to provide significant capacity gain and increase link robustness, through multiplexing and diversity techniques. Optimal theoretical trade-offs between multiplexing and diversity schemes were derived in [1]. Practical algorithms to switch across these schemes were proposed in [2], [3]. The link-adaptation algorithm presented in [2] was designed to enhance the spectral efficiency of MIMO systems by switching across transmit diversity (TD) and spatial multiplexing (SM). The switching criterion was based on the signal-to-noise ratio (SNR) information and time/frequency selectivity indicators. This algorithm, however, did not exploit the information about the spatial selectivity of the channel, defined as in [4]. The spatial information of the MIMO channel can be leveraged to further improve the system performance as in [3]. In [3] the condition number of the instantaneous channel matrix was employed as criterion to select between TD or SM schemes. Simulation results showed significant diversity gain, but for a fixed rate transmission.

In this contribution we propose a novel adaptive transmission technique, aiming to enhance the spectral efficiency for a fixed predefined target error rate performance. The key insight of our method is that it is possible to characterize the spatial selectivity of the channel based on a metric derived from the spatial correlation matrices. The proposed algorithm estimates the channel quality and, based on this information, adaptively switches across different MIMO transmission schemes to maximize the throughput for a fixed error rate and transmit power. This adaptive algorithm only tracks the long-term channel statistics. The practical implementation of the algorithm is based on identifying a set of link-quality regions, which represent “typical” (quantized) channel scenarios. These link-quality regions are mapped into a set of transmission modes (defined by a combination of modulation/coding and MIMO transmission schemes) through a look-up table (LUT). Since the adaptation occurs over a long time scale, minimal coordination between the transmitter and receiver is required to feed back the information of the selected mode.

To gain intuition on our proposed method, we consider three different channel scenarios in the context of cellular systems. The first scenario is defined by line-of-sight (LOS) and/or user at the edge of the cell. In this case, since the channel has rank one and/or low SNR, a beamforming scheme would be selected by the adaptive algorithm as a means to increase the robustness of the link. The second channel scenario is poor scattering environment (i.e., low angular spread) and medium SNR, in which few channel eigen-modes are available to transmit parallel streams over the wireless link. In this case, the user would be starved of diversity and would require schemes like double space-time transmit diversity (D-STTD) [5] for additional diversity gain, which results in throughput enhancement. The third channel scenario is a rich scattering environment (i.e., high angular spread) and/or user close to the base station (i.e., high SNR), for which our adaptive algorithm would switch to multiplexing transmission in order to increase spectral efficiency.

This paper is organized as follows. In Section II we present the channel model and the theoretical tradeoff between beamforming and multiplexing schemes, which is the basis of our proposed method. In Section III we first describe the technique employed to estimate the spatial selectivity of the channel. Then, we provide some system specifications and detailed

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description of the adaptive algorithm. Section IV presents some simulation results, showing the significant performance improvement produced by out method. Finally, we draw some conclusions in Section V.

II. Channel Model and Capacity Tradeoffs

In this section we describe the channel model employed in the adaptive algorithm. Then, we provide theoretical analysis on the capacity tradeoff between beamforming and multiplexing schemes.

A. Channel Model

We simulate the MIMO channel according to the clustered channel model proposed by the standard IEEE 802.11n for wireless local area networks (WLANs), described in [6]. We consider a narrowband MIMO system with N_t transmit antennas and N_r receive antennas for which the channel matrix is given by

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

where K is the Ricean K-factor, $\mathbf{H}_{LOS}$ and $\mathbf{H}_{NLOS}$ are the line-of-sight (LOS) and the non-line-of-sight (NLOS) components, respectively. The NLOS channel matrix is defined as

$$\mathbf{H}_{NLOS} = \mathbf{R}_r^{1/2}\mathbf{H}_w\mathbf{R}_t^{1/2} \quad (2)$$

where $\mathbf{R}_t$ and $\mathbf{R}_r$ denote the transmit and receive spatial correlation matrices, respectively, and $\mathbf{H}_w \in \mathbb{C}^{N_r \times N_t}$ is a matrix of complex Gaussian fading coefficients. Different scenarios, characterized by different spatial properties (i.e., angle spread, mean angle of arrival/departure, number of clusters), are defined in [6] and more details will be provided in the next section.

B. Beamforming and Spatial Multiplexing Tradeoffs

Here we make a tradeoff between beamforming (BF) and spatial multiplexing (SM) by identifying the capacity maximizing scheme in different channel scenarios. We first derive the mutual information of BF and SM as a function of the spatial correlation matrices of the channel. Then, we characterize the crossing-point of the two capacity curves in different propagation scenarios.

We consider BF transmission technique, for which perfect channel state information is available at the transmitter (CSIT) and receiver (CSIR). Under these assumptions, the mutual information of the MIMO system is given by [7]

$$C = \log_2\left|\mathbf{I}_{N_r} + \frac{1}{\sigma_n^2}\mathbf{H}\mathbf{Q}\mathbf{H}^H\right| \quad (3)$$

where σ_n^2 is the noise variance, $\mathbf{Q}$ is the covariance matrix of the transmit signal and $\mathbf{H}$ is the MIMO channel matrix generated as in (1). We compute the singular value decomposition of the MIMO channel matrix as $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$. For the CSIT case, the transmit covariance matrix can be decomposed as $\mathbf{Q} = \mathbf{V}\mathbf{\Lambda}_q\mathbf{V}^H$, where $\mathbf{\Lambda}_q$ is the power allocation matrix. With these assumptions, equation (3) becomes

$$C = \log_2\left|\mathbf{I}_{N_r} + \frac{1}{\sigma_n^2}\mathbf{U}\mathbf{\Sigma}\mathbf{\Lambda}_q\mathbf{\Sigma}\mathbf{U}^H\right|. \quad (4)$$

Assuming optimal power allocation with CSIT, we define $\mathbf{\Lambda}_q = \mathrm{diag}(P, 0, ..., 0)$. Then, from equation (4) we derive the instantaneous channel capacity of BF as

$$C_{BF} = \log_2|1 + \gamma\sigma_{max}| \quad (5)$$

where $\gamma = P/\sigma_n^2$ is the SNR and σ_{max} is the maximum eigenvalue of the matrix $\mathbf{H}\mathbf{H}^H$.

For the spatial multiplexing scheme, we assume equal power transmission across all antennas, for which the mutual information is given by [7]

$$C = \log_2\left|\mathbf{I}_{N_r} + \frac{\gamma}{N_t}\mathbf{H}\mathbf{H}^H\right| \quad (6)$$

where γ is the SNR, as before. Assuming zero-mean correlated Rayleigh fading channel as in (2), equation (6) becomes

$$C_{SM} = \log_2\left|\mathbf{I}_{N_r} + \frac{\gamma}{N_t}\mathbf{R}_r^{1/2}\mathbf{H}_w\mathbf{R}_t\mathbf{H}_w^H\mathbf{R}_r^{H/2}\right| \quad (7)$$

which is the instantaneous channel capacity for SM.

Fig. 1 shows the mean capacity for BF and SM, derived from the mutual information in equations (5) and (7). We consider the NLOS channel models B and F described in [6], characterized by low and high angular spreads, respectively. Interestingly, but not surprisingly, the capacity of SM increases from model B to model F, due to the higher angular spread for model F, which produces larger number of eigenmodes in the channel. Contrarily, the angular spread has an adverse effect on the performance of the BF, for which the capacity decreases from model B to model F.

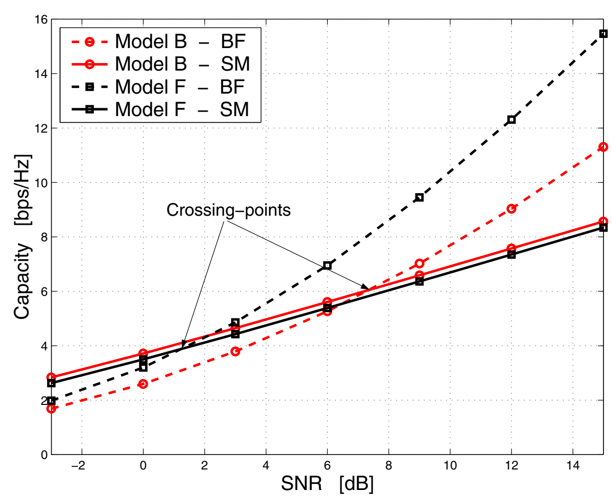

Fig. 1. Capacity crossing points for a MIMO(2, 2) system, with IEEE 802.11n channel models B and F (NLOS).

Moreover, it is possible to characterize the SNR values for which the BF and SM curves cross (or capacity *crossing-points*) over different channel models. These crossing-points are ideal SNR thresholds that could be theoretically exploited to switch across BF and SM schemes as a means to maximize the channel capacity. In the next section we will show how to derive these thresholds for our practical adaptive algorithm. For the channel models B and F the theoretical crossing-points are about 7.3 dB and 1.2 dB, respectively. This suggests that the practical switching criterion of BF and SM has to account for the spatial component (i.e., spatial selectivity) of the MIMO channel, as discussed in the next section.

III. Description of the Adaptive Algorithm

The performance of the MIMO system depends on the characteristics of the propagation environment, as already acknowledged in [7]–[10]. Particularly, it has been proved that capacity [7, p.77] and error rate performance [10] depend on the eigenvalues of transmit/receive spatial correlation matrices, which are a measure of the spatial diversity available in the MIMO channel [11]. This dependence is also shown in equation (7) where we related the MIMO capacity of SM to the spatial correlation matrices $\mathbf{R}_t$ and $\mathbf{R}_r$.

The rank of the matrices $\mathbf{R}_t$, $\mathbf{R}_r$ and $\mathbf{H}$ is essentially determined by the angle spread (AS), number of clusters (N_c), angle of arrival/departure (AOA/AOD) and Ricean K-factor (or LOS component), and can be used as an indicator of the spatial selectivity of the MIMO channel. Note that the spatial selectivity depends also on the antenna array configuration as described in [8], [9], [12]. Without loss of generality, in this contribution we assume a uniform linear array (ULA) with four dipole antennas half-wavelength spaced apart.

In the following subsections we explain our criterion to switch across different MIMO schemes, based on the knowledge of the eigenvalues of the transmit/receive spatial correlation matrices. We also provide detailed description of the proposed adaptive algorithm and the system specifications.

A. Definition of the Link-quality Regions

We characterize four "typical" channel models, with different degrees of spatial selectivity, based on the IEEE 802.11n standard channel models described in [6]. These models are defined as follows:

- **Model 1** (NLOS, High AS): zero-mean correlated Rayleigh fading model, with K$= -\infty$ dB, AS $\in [28^o, 55^o]$, $N_c = 6$ (consistent to "*Model F, NLOS*" in [6]).
- **Model 2** (NLOS, Low AS): zero-mean correlated Rayleigh fading model, with K$= -\infty$ dB, AS $\in [22.4^o, 24.6^o]$, $N_c = 2$ (consistent to "*Model C, NLOS*" in [6]).
- **Model 3** (LOS, Low K-factor): correlated Ricean model with K-factor $K = 2$ dB, AS $\in [22.4^o, 24.6^o]$, $N_c = 2$ (similar to "*Model C, LOS*" in [6]).
- **Model 4** (LOS, High K-factor): correlated Ricean model, similar to "*Model A, LOS*" in [6], but here $K = 6$ dB, AS$= 30^o$, $N_c = 1$.

The combination of these models with different values of SNR thresholds defines the *link-quality regions*. To predict the link-quality region for a given transmission, we employ two *link-quality metrics*: the average SNR and the relative condition number of the eigenvalues of the spatial correlation matrices.

B. Spatial Selectivity Indicator

Different estimators of the channel spatial selectivity have been proposed thus far, based on the singular values of the MIMO channel [3] or the eigenvalues of transmit/receive correlation matrices [11]. In our proposed method we exploit the distribution of the relative condition number of the transmit/receive correlation matrices, defined as

$$D_\lambda = \frac{\lambda_{max}}{\lambda_{min}} \qquad (8)$$

with λ_{max} and λ_{min} being respectively the maximum and minimum eigenvalues of the spatial correlation matrix, and $1 \leq D_\lambda < \infty$.

In Fig. 2 we show the cumulative density function (CDF) of this relative condition number for the four channel models described above. Note that these curves are obtained by simulating the models defined in the previous subsection, with fixed values of AS and random cluster's mean AOAs/AODs, uniformly generated in the range $[0, 2\pi)$.

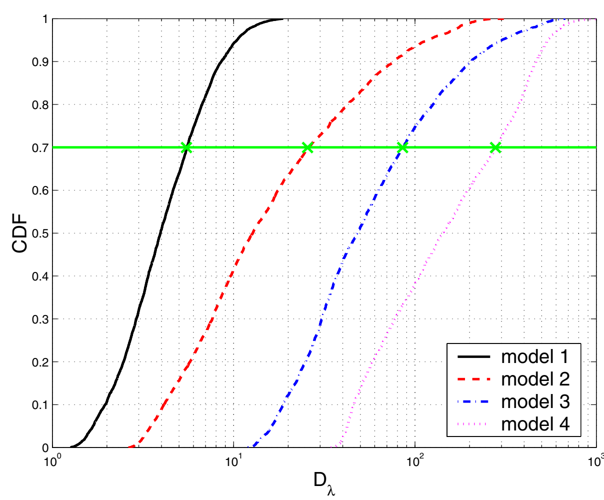

Fig. 2. Cumulative density function (CDF) of the relative condition number of the eigenvalues of the spatial correlation matrix.

Given the fact that the CDF curves in Fig. 2 are separated across the four defined channel models, it is possible to employ the condition number in equation (8) as an indicator of the channel spatial selectivity. Then, we exploit this information to adapt across different transmission schemes. We empirically choose the threshold of 70% to define four quantized regions as

- **Region 1** (NLOS, High AS): $D_\lambda \in [1, 5.5)$
- **Region 2** (NLOS, Low AS): $D_\lambda \in [5.5, 25.8)$
- **Region 3** (LOS, Low K-factor): $D_\lambda \in [25.8, 85.8)$
- **Region 4** (LOS, High K-factor): $D_\lambda \in [85.8, +\infty)$

where each region defines a "typical" channel scenario, characterized by certain degree of spatial selectivity. The combination of these regions with different quantized values of target

SNR defines the set of feasible link-quality regions employed by our algorithm, as described in the following subsections.

In practical systems, the spatial correlation matrices can be estimated at the transmitter/receiver according to standard techniques described in [13]–[15]. Moreover, the condition number is computed for both transmit and receive spatial correlation matrices. Then, the algorithm may select the highest condition number between the transmitter and receiver to decide the current link-quality region.

C. MIMO Transmission Modes

The proposed adaptive algorithm uses a combination of modulation/coding schemes (MCS) and practical MIMO transmit/receive techniques. We consider three common MIMO transmission schemes:

- **Beamforming** (BF) with MRC receiver
- **Double space-time transmit diversity** (D-STTD) with minimum mean squared error (MMSE) receiver
- **Spatial multiplexing** (SM) with equal power allocation across the transmit antennas and MMSE receiver

We choose these schemes since they provide increasing data rates for a fixed error rate performance and for a fixed number of transmit/receive antennas. Moreover, they are being actively considered by different standards bodies such as 3GPP and IEEE 802.11n, as reported in [5], [16]–[18]. Note that in time division duplex (TDD) systems, exploiting upling/downlink channel reciprocity, BF does not require any feedback information like the open loop schemes D-STTD and SM. In frequency division duplex (FDD) systems, limited feedback techniques [19] can be applied to reduce the complexity of BF scheme.

To enable transmission over the wireless link, we define eight combinations of modulation/coding schemes, according to the standard IEEE 802.11a [20]. The combination of the 3 MIMO schemes with these 8 MCSs results in a total of 24 different transmission modes, from which we select a subset of 12 modes (including "mode 0", meaning no transmission in case the target error rate is not satisfied by any of the schemes).

D. Building up the Look-up Table

The spectral efficiency and error rate performance of the MIMO transmission modes aforementioned are a function of the characteristics of the propagation environment, as it was already acknowledged in [7], [10]. Unfortunately, it is not possible to derive in closed-form the error rate performance of these transmission modes as a function of the SNR, in different Ricean channel models. Therefore, we simulate the error rate performance for all the feasible link-quality regions previously defined and build up a look-up table (LUT). This LUT maps the channel quality information (i.e., SNR and spatial selectivity) into error rate performance.

In Fig. 3 we show the bit error rate (BER) for the various MIMO transmission schemes as a function of the SNR in different channel models. These simulations are carried out employing the MCS number 4 as in [20]. It is possible to see that for a fixed channel model, each MIMO scheme requires a minimum value of SNR (or *SNR threshold*) in order to satisfy a predefined target BER. These SNR thresholds are empirically derived by simulations and stored in the LUT. Note that, for a given MIMO scheme, the SNR thresholds vary as a function of the channel model, as shown in Fig. 3.

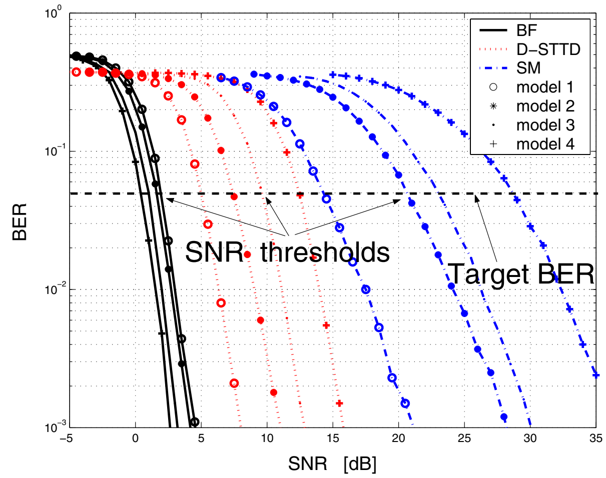

Fig. 3. Bit error rate (BER) for BF, D-STTD and SM with QPSK modulation and convolutional code with rate 3/4, in different channel models. Spectral efficiency: 1.5 bps/Hz for BF, 3 bps/Hz for D-STTD and 6 bps/Hz for SM.

In our simulations we fix the target BER to 5%, however, different targets may be chosen depending on the system. For each channel model, we heuristically choose the 12 modes (out of the 24 modes available in the systems) corresponding to the lowest SNR threshold for a given transmission rate.

E. Adaptive Switching Criterion

Our proposed method adaptively selects the optimal transmission mode that maximizes the throughput (or spectral efficiency) for a predefined target error rate, depending on the current channel condition. To enable this mode adaptation, the proposed algorithm estimates the link-quality for the current transmission based on the average SNR information and the spatial selectivity indicator. These metrics are the inputs to the LUT, used to select the mode providing the highest throughput for the predefined target error rate. When the mode selection is done at the receiver, only a low-rate feedback channel is needed to convey this information to the transmitter.

IV. Simulation Results

Finally, we show the performance of the proposed algorithm in terms of capacity and SNR gains. Without loss of generality, we present the results for a practical 4×4 MIMO system. However, these results can be extended to different numbers of antennas and different transmission schemes.

Fig. 4 shows the spectral efficiency, as function of the SNR, achievable through our adaptive algorithm versus methods using fixed MIMO transmission schemes with adaptive MCS. These results are derived for channel "model 1", but they can be extended to other channel models, as well. In Fig. 4 it is possible to see that for high SNR, a system employing the proposed adaptive algorithm would produce gain in spectral efficiency of 13.5 bps/Hz, compared to a system employing BF scheme (with adaptive MCS). Note that for the adaptive method as the spectral efficiency increases the BER always remains below the predefined target.

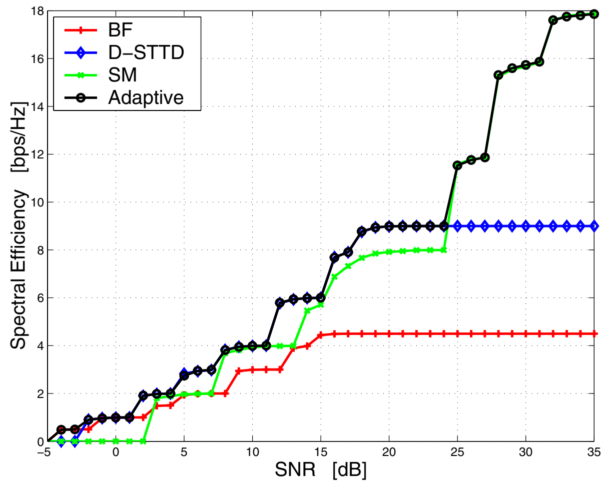

Fig. 4. Spectral efficiency of the adaptive MIMO transmission scheme versus fixed BF, D-STTD and SM with adaptive MCS, in channel "model 1".

In Fig. 5 we compare the BER performance of the proposed adaptive algorithm against fixed transmission schemes in channel "model 4". For medium SNR, a system employing the proposed adaptive technique would provide about 8 dB gain in SNR compared to a system using fixed SM scheme. This gain is shown in Fig. 5 by the thicker BER curves, corresponding to different MCSs for BF and SM that provide the same transmission rate. Note that the BER curve for the adaptive scheme always remains below the predefined target.

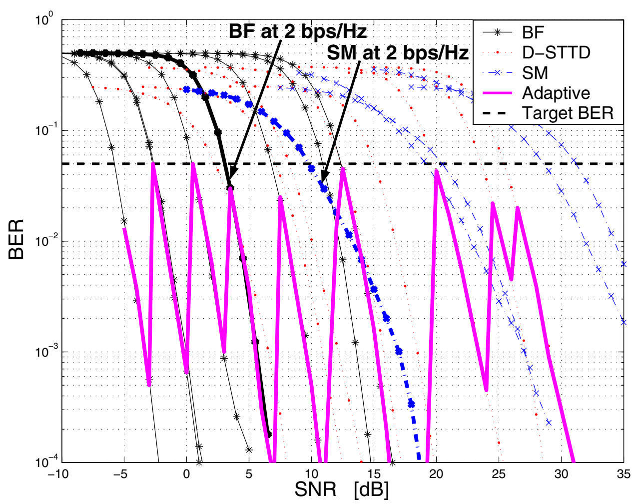

Fig. 5. Bit error rate (BER) of the adaptive MIMO transmission scheme versus fixed BF, D-STTD and SM with different MCS, in channel "model 4".

V. Conclusion

We presented a novel adaptive technique to switch across different MIMO transmission schemes as a means to enhance the spectral efficiency of the system for a fixed predefined target error rate. The algorithm employs average SNR information and channel spatial selectivity indicator to adapt different MIMO schemes to the changing channel conditions. Our proposed transmission technique provides significant gain in SNR and spectral efficiency, depending on the channel conditions. Given these gains and its low complexity, our proposed method is suitable for practical MIMO communication systems, particularly in the context of IEEE 802.11n, IEEE 802.16 and 3GPP standards.

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