Capacity Enhancement via Multi-Mode Adaptation in Spatially Correlated MIMO Channels

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Abstract—**We consider a low-complexity adaptive MIMO transmission approach for spatially correlated channels. The proposed scheme adaptively switches between different transmission *modes* depending on the changing channel conditions, as a means to enhance system capacity. Each mode is a combination of a transmission technique (ie. statistical beamforming, double space-time transmit diversity and spatial multiplexing) and a modulation/coding scheme. We first motivate our adaptive algorithm by deriving new closed-form capacity expressions, and demonstrating significant information theoretic improvements over non-adaptive transmission. We then present a practical method to switch between different modes, based on the channel statistics. Our approach is shown to yield significant improvements in spectral efficiency for typical channel scenarios.[1]**

I. Introduction

The performance of multiple-input multiple-output (MIMO) wireless communication systems can be improved by exploiting partial or full channel knowledge at the transmitter. When instantaneous channel knowledge is available, adaptive schemes have been proposed to switch between transmit diversity and spatial multiplexing schemes as a means to improve error rate performance [1]. Other adaptive approaches have been designed based on time/frequency selectivity indicators [2]. Alternatively, the *spatial selectivity* of the channel, defined as in [3], can be exploited to switch between different MIMO schemes. It is now well-known that the capacity [4] and error rate performance [5] of MIMO systems depend on the spatial characteristics of the propagation environment (ie. angle spread, number of scatterers, angle of arrival/departure) [6, 7]. This dependence is typically revealed through the eigenvalues of the transmit and receive spatial correlation matrices [8], which give an indication of the channel spatial selectivity.

In this paper we exploit knowledge of the spatial selectivity in a low-complexity adaptive MIMO transmission scheme as a means to improve system performance. The proposed scheme switches between statistical beamforming (BF), double space-time transmit diversity (D-STTD) and spatial multiplexing (SM) depending on the estimated channel quality (partially revealed through the spatial selectivity information). To motivate the scheme, we first derive some new closed-form capacity results which show an explicit dependence on the eigenvalues of the spatial correlation matrices. We then demonstrate the significant information theoretic improvements which are obtained by adapting based on this spatial selectivity information. We finally present a practical adaptive algorithm that switches between different transmission *modes*, by using the information of the spatial correlation matrices and the average signal to noise ratio (SNR). This practical approach yields significant spectral efficiency improvements over non-adaptive transmission in typical channel scenarios.

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II. System and Channel Models

We consider a narrowband MIMO system employing N_t transmit and N_r receive antennas modelled (for each channel use) by

$$\mathbf{y} = \sqrt{\frac{E_s}{N_t}}\,\mathbf{H}\mathbf{x} + \mathbf{n} \tag{1}$$

where $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ is the receive signal vector, $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ is the transmit signal vector subject to the power constraint $\mathcal{E}\{||\mathbf{x}||_2^2\} = N_t$, and $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is the zero-mean additive Gaussian noise vector with covariance matrix $\mathcal{E}\{\mathbf{n}\mathbf{n}^H\} = N_o\mathbf{I}_{N_r}$. Also, $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ is the spatially correlated Rayleigh MIMO channel matrix modelled as

$$\mathbf{H} = \mathbf{R}^{1/2}\mathbf{Z}\mathbf{S}^{1/2} \tag{2}$$

where $\mathbf{Z} \in \mathbb{C}^{N_r \times N_t}$ contains independent complex Gaussian entries with zero mean and unit variance, and where $\mathbf{S}$ and $\mathbf{R}$ denote the transmit and receive spatial correlation matrices respectively, with eigenvalue decompositions

$$\mathbf{S} = \mathbf{U}_s\mathbf{\Lambda}_s\mathbf{U}_s^H, \quad \mathbf{R} = \mathbf{U}_r\mathbf{\Lambda}_r\mathbf{U}_r^H \tag{3}$$

We assume that $\mathbf{R}$ and $\mathbf{S}$ are normalized Hermitian positive definite matrices with $\mathrm{Tr}(\mathbf{R}) = N_r$ and $\mathrm{Tr}(\mathbf{S}) = N_t$. Moreover, throughout this paper we assume that the receiver has perfect knowledge of the instantaneous channel $\mathbf{H}$, and

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that the transmitter knows only the channel statistics (ie. $\mathbf{S}$ and $\mathbf{R}$). With the above model, the average signal to noise ratio (SNR) per receive antenna is $\gamma_o = E_s/N_o$.

III. Ergodic Capacity for Spatially Correlated MIMO Channels

In this section we present new capacity expressions for the (suboptimal) transmission techniques used by our adaptive algorithm. We first however, review the optimal capacity-achieving transmission strategy when only statistical channel information is available at the transmitter.

A. Optimal Transmission: Statistical Water-Filling (WF)

The ergodic MIMO capacity is given by the well-known formula

$$C = \max_{\mathbf{Q}:\mathrm{tr}(\mathbf{Q})=E_s} \mathcal{E}\left[\log_2\left|\mathbf{I}_{N_r} + \frac{\mathbf{HQH}^H}{N_o}\right|\right] \tag{4}$$

where the maximization is over the set of all power-constrained input covariance matrices $\mathbf{Q}$. Under the assumptions in Section II, the capacity achieving $\mathbf{Q}$ is given by [9]

$$\mathbf{Q}^{\mathrm{opt}} = \mathbf{U}_s \mathbf{\Lambda}_Q^{\mathrm{opt}} \mathbf{U}_s^\dagger \tag{5}$$

where $\mathbf{\Lambda}_Q^{\mathrm{opt}}$ is the diagonal statistical water-filling matrix

$$\mathbf{\Lambda}_Q^{\mathrm{opt}} = \arg \max_{\mathbf{\Lambda}_Q:\mathrm{tr}(\mathbf{\Lambda}_Q)=E_s} \mathcal{E}\left(\log_2\left|\mathbf{I}_{N_r} + \sum_{i=1}^{N_t} \frac{\lambda_{s,i}\lambda_i^Q \mathbf{w}_i\mathbf{w}_i^H}{N_o}\right|\right) \tag{6}$$

where

$$\mathbf{w}_i = \left[\sqrt{\lambda_{r,1}}w_{i,1}, \ldots, , \sqrt{\lambda_{r,N_r}}w_{i,N_r}\right]^T \tag{7}$$

and where $w_{i,j}$ are i.i.d. complex Gaussian random variables with zero mean and unit variance. Also, $\lambda_{s,i}$ and $\lambda_{r,i}$ denote the i^{th} eigenvalue of $\mathbf{S}$ and $\mathbf{R}$ respectively. From (6) and (7) we see that the capacity achieving transmission scheme (defined by $\mathbf{Q}^{\mathrm{opt}}$) depends explicitly on the eigenvalues of the transmit and receive correlation matrices. Unfortunately, for any given $\mathbf{R}$ and $\mathbf{S}$, the calculation of $\mathbf{\Lambda}_Q^{\mathrm{opt}}$ requires numerical optimization which is undesirable when designing practical systems, due to its high computational complexity.

We now present capacity expressions for the low-complexity transmission techniques: BF, SM and D-STTD. In Section IV we compare the capacity of these techniques with the optimal WF capacity (4), and show that adapting between these techniques yields significant capacity improvements over fixed transmission schemes.

B. Statistical Beamforming (BF) with MRC Receiver

In this subsection we derive a new closed-form expression for the capacity of statistical BF transmission in the correlated channel model (2). Note that the capacity for the special case $\mathbf{R} = \mathbf{I}_{N_r}$ was computed in [10]. We assume that the receiver employs maximum ratio combining (MRC). The input covariance matrix for this system is given by

$$\mathbf{Q}^{\mathrm{bf}} = \mathbf{U}_s \mathbf{\Lambda}_{\mathrm{bf}} \mathbf{U}_s^H \tag{8}$$

where

$$\mathbf{\Lambda}_{\mathrm{bf}} = \mathrm{diag}\left(E_s, 0, \ldots, 0\right) \tag{9}$$

Note that the first column of $\mathbf{U}_s$ is the eigenvector corresponding to the largest eigenvalue of $\mathbf{S}$, which we denote $\lambda_{s,\max}$. As mentioned in [9] and [11], statistical BF is in fact optimum (ie. $\mathbf{\Lambda}_{\mathrm{bf}} = \mathbf{\Lambda}_{\mathrm{opt}}$) in the low SNR regime.

Substituting the input covariance (8) and the equivalent channel (2) into (4) gives

$$C_{\mathrm{bf}} = \mathcal{E}\left[\log_2\left|\mathbf{I}_{N_r} + \frac{\mathbf{R}^{1/2}\mathbf{Z}\mathbf{S}^{1/2}\mathbf{U}_s\mathbf{\Lambda}_{\mathrm{bf}}\mathbf{U}_s^H\mathbf{S}^{H/2}\mathbf{Z}^H\mathbf{R}^{H/2}}{N_o}\right|\right]. \tag{10}$$

Next, we use the eigenvalue decompositions in (3). Noting that $\mathbf{U}_s$ and $\mathbf{U}_r$ are unitary, and recognizing that $\mathbf{Z}$ is invariant under unitary transformation, it is easily shown that the BF capacity (10) is equivalent to

$$\begin{aligned} C_{\mathrm{bf}} &= \mathcal{E}\left[\log_2\left|\mathbf{I}_{N_r} + \frac{1}{N_o}\mathbf{\Lambda}_r^{1/2}\mathbf{Z}\mathbf{\Lambda}_s^{1/2}\mathbf{\Lambda}_{\mathrm{bf}}\mathbf{\Lambda}_s^{1/2}\mathbf{Z}^H\mathbf{\Lambda}_r^{1/2}\right|\right] \\ &= \mathcal{E}\left[\log_2\left|\mathbf{I}_{N_r} + \gamma_o\lambda_{s,\max}\tilde{\mathbf{z}}\tilde{\mathbf{z}}^H\right|\right] \end{aligned} \tag{11}$$

where $\gamma_o = E_s/N_o$, $\tilde{\mathbf{z}} = \left[\sqrt{\lambda_{r,1}}\, z_1, \ldots, \sqrt{\lambda_{r,N_r}}\, z_{N_r}\right]^T$, and the z_i's are i.i.d. zero mean unit variance complex Gaussian random variables. Note that the second line in (11) followed by using (9). Invoking the property $|\mathbf{I}_n + \mathbf{AB}| = |\mathbf{I}_m + \mathbf{BA}|$ (for arbitrary $\mathbf{A} \in \mathbb{C}^{n\times m}$ and $\mathbf{B} \in \mathbb{C}^{m\times n}$) in (11) gives

$$C_{\mathrm{bf}} = \mathcal{E}\left[\log_2\left(1 + \gamma_o\lambda_{s,\max}\sum_{i=1}^{N_r}\lambda_{r,i}z_i^* z_i\right)\right] \tag{12}$$

which can be written as

$$C_{\mathrm{bf}} = \mathcal{E}\left[\log_2\left(1 + \frac{\gamma_o\lambda_{s,\max}\eta}{2}\right)\right] \tag{13}$$

with

$$\eta = \sum_{i=1}^{N_r}\lambda_{r,i}\varepsilon_i \tag{14}$$

where the ε_i's are i.i.d. exponentially distributed random variables; such that η is a central quadratic form. Since the exponential distribution is a chi-squared distribution with *even* degrees of freedom, we use a general result from [12] to give the p.d.f. of η as

$$f(\eta) = \sum_{i=1}^{N_r}\prod_{j=1,j\neq i}^{N_r}\left(\frac{\lambda_{r,i}}{\lambda_{r,i} - \lambda_{r,j}}\right)\frac{\exp\left(-\frac{\eta}{2\lambda_{r,i}}\right)}{2\lambda_{r,i}} \tag{15}$$

Using (15), we show in [13] that the expectation (13) can be evaluated as

$$\begin{aligned} C_{\mathrm{bf}} &= -\frac{1}{\ln 2}\sum_{i=1}^{N_r}\left[\prod_{j=1,j\neq i}^{N_r}\left(\frac{\lambda_{r,i}}{\lambda_{r,i} - \lambda_{r,j}}\right)\right. \\ &\quad \left.\times \exp\left(\frac{1}{\gamma_o\lambda_{s,\max}\lambda_{r,i}}\right)\mathrm{Ei}\left(-\frac{1}{\gamma_o\lambda_{s,\max}\lambda_{r,i}}\right)\right]. \end{aligned} \tag{16}$$

where $\mathrm{Ei}(\cdot)$ is the exponential integral.

We clearly see that the BF capacity in (16) is a function of the eigenvalues of the transmit and receive spatial correlation matrices. This expression reveals the dependence of the performance of BF on the long-term spatial characteristics of the channel, which is exploited by our adaptive algorithm.

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C. Spatial Multiplexing (SM) with Linear Receivers

We now derive a new closed-form expression for the capacity of SM transmission with linear receivers. In this case, the input covariance matrix is given by

$$\mathbf{Q}^{\mathrm{sm}} = \frac{E_s}{N_t}\mathbf{I}_{N_t}. \tag{17}$$

For systems with $N_t \leq N_r$, SM transmission with MRC reception is in fact optimum (ie. $\mathbf{Q}^{\mathrm{sm}} = \mathbf{Q}^{\mathrm{opt}}$) in the high SNR regime [14]. Note that, with MRC receivers, closed form capacity results are now available for general correlated Rician MIMO channels [15, 16].

When SM with linear receivers are employed, the MIMO channel is effectively decoupled into N_t parallel streams, for which the capacity is given by [17]

$$C_{\mathrm{sm}} = \sum_{k=1}^{N_t} \mathcal{E}\left[\log_2\left(1+\gamma_k\right)\right] \tag{18}$$

where γ_k is the conditional post-processing SNR for the k-th stream. This is given by

$$\gamma_k = \frac{1}{\left[\left(\mathbf{I}_{N_t} + \frac{\gamma_o}{N_t}\mathbf{H}^H\mathbf{H}\right)^{-1}\right]_{k,k}} - 1 \tag{19}$$

for a minimum-mean square error (MMSE) receiver [18], and

$$\gamma_k = \frac{\gamma_o}{N_t}\frac{1}{\left[\left(\mathbf{H}^H\mathbf{H}\right)^{-1}\right]_{k,k}}. \tag{20}$$

for a zero-forcing (ZF) receiver [18]. Unfortunately, the expectations in (18) cannot be computed in closed-form in general. Hence, for the remainder of this section we consider transmit correlated channels (ie. $\mathbf{R} = \mathbf{I}_{N_r}$) with ZF detection. In this case γ_k has p.d.f. [17]

$$f\left(\gamma_k\right) = \frac{N_t\sigma_{s,k}^2}{\gamma_o}\frac{\exp\left(-\frac{\gamma_k N_t \sigma_{s,k}^2}{\gamma_o}\right)}{\Gamma\left(N_r - N_t + 1\right)}\left(\frac{\gamma_k N_t \sigma_{s,k}^2}{\gamma_o}\right)^{N_r - N_t} \tag{21}$$

where $\sigma_{s,k}^2 = \left[\mathbf{S}^{-1}\right]_{k,k}$. Now using (21) and the relation

$$\sigma_{s,k}^2 = \frac{|\mathbf{S}^{kk}|}{|\mathbf{S}|} \tag{22}$$

where $\mathbf{S}^{kk}$ corresponds to $\mathbf{S}$ with the k^{th} row and column removed, we show in [13] that the SM capacity (18) can be evaluated as

$$C_{\mathrm{sm}} = \sum_{k=1}^{N_t}\frac{\exp\left(\frac{|\mathbf{S}^{kk}|N_t}{|\mathbf{S}|\gamma_o}\right)}{\ln 2} \times \sum_{m=1}^{N_r-N_t+1}\frac{\Gamma\left(m - N_r + N_t - 1, \frac{|\mathbf{S}^{kk}|N_t}{|\mathbf{S}|\gamma_o}\right)}{\left(\frac{|\mathbf{S}^{kk}|N_t}{|\mathbf{S}|\gamma_o}\right)^{m-N_r+N_t-1}} \tag{23}$$

From this final SM capacity expression, as for the BF case, we see a dependence on the eigenvalues of the spatial correlation matrix (ie. through the determinant), which is exploited in our adaptive algorithm.

D. D-STTD with Linear Receivers

We now consider the capacity of D-STTD transmission. Although closed-form analytical results appear difficult to obtain even for the simplest i.i.d. Rayleigh MIMO channels (see below), in this section we derive a new D-STTD capacity expression which is suitable for numerical evaluation.

Consider the D-STTD scheme proposed in [19] where the $N_t = 4$ transmitted symbols (denoted $x_1, \ldots, x_4$ in the following) are encoded over 2 consecutive channel uses. Following [19] we define the stacked signal vectors

$$\bar{\mathbf{y}} \triangleq \begin{bmatrix} \bar{\mathbf{y}}_1 \\ \bar{\mathbf{y}}_2 \\ \vdots \\ \bar{\mathbf{y}}_{N_r} \end{bmatrix} \quad \bar{\mathbf{x}} \triangleq \begin{bmatrix} x_1 \\ x_2^* \\ x_3 \\ x_4^* \end{bmatrix} \quad \mathcal{H} \triangleq \begin{bmatrix} \mathcal{H}_{1,a} & \mathcal{H}_{1,b} \\ \mathcal{H}_{2,a} & \mathcal{H}_{2,b} \\ \vdots & \vdots \\ \mathcal{H}_{N_r,a} & \mathcal{H}_{N_r,b} \end{bmatrix} \tag{24}$$

with $\bar{\mathbf{y}}_m = [y_m(0),\ y_m^*(1)]^T$ and

$$\mathcal{H}_{m,a} \triangleq \begin{bmatrix} h_{m,1} & -h_{m,2} \\ h_{m,2}^* & h_{m,1}^* \end{bmatrix} \quad \mathcal{H}_{m,b} \triangleq \begin{bmatrix} h_{m,3} & -h_{m,4} \\ h_{m,4}^* & h_{m,3}^* \end{bmatrix}. \tag{25}$$

where $h_{i,j}$ denotes the $(i,j)^{\mathrm{th}}$ entry of the MIMO channel matrix $\mathbf{H}$ in (1). It can be shown that the equivalent input-output relation for D-STTD transmission can be given by

$$\bar{\mathbf{y}} = \sqrt{\frac{E_s}{N_t}}\,\mathcal{H}\bar{\mathbf{x}} + \bar{\mathbf{n}} \tag{26}$$

Note that the elements $\bar{\mathbf{y}}_m$ of the (equivalent) received signal vector $\bar{\mathbf{y}}$ contain the signals at the m^{th} receive antenna over the two consecutive symbol time-slots. For more information see [13, 19].

At the receiver we consider low-complexity linear detectors. The post-processing SNR for the k^{th} stream (ie. γ_k) in this case is given by (19) and (20) for MMSE and ZF detection, respectively, but with $\mathbf{H}$ replaced by the equivalent D-STTD channel matrix $\mathcal{H}$ defined in (24).

Using results from [20], the capacity of D-STTD with linear receivers is given by

$$C_{\mathrm{dsttd}} = \mathcal{E}\left[\frac{1}{2}\sum_{k=1}^{N_t}\log_2(1+\gamma_k)\right] \tag{27}$$

where the normalization factor of $\frac{1}{2}$ accounts for the two channel uses spanned by the D-STTD symbols. Unfortunately we cannot easily solve for the expectation in (27) due to the difficulty in obtaining the distribution of γ_k. This difficulty arises since, even in the simplest i.i.d. Rayleigh MIMO case, $\mathcal{H}\mathcal{H}^H$ is not Wishart distributed. We prove in [13] that $\gamma_1 = \gamma_2$ and $\gamma_3 = \gamma_4$ and, moreover, that the random variables γ_k (for $k = 1, \ldots, 4$) are identically distributed. As such (27) can be simplified as[2]

$$C_{\mathrm{dsttd}} = 2\ \mathcal{E}\left\{\log_2\left(1+\gamma\right)\right\} \tag{28}$$

[2]Note that we drop the k subscript since the SNR statistics are identical for each stream.

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IV. Capacity Tradeoffs and Adaptive Switching MIMO Transmission Scheme

In this section we present the theoretical capacity tradeoffs between BF, D-STTD and SM schemes, in spatially correlated channels, and an overview of the adaptive MIMO algorithm.

A. *Tradeoffs between BF, D-STTD and SM*

In Fig. 1 we compare the mean capacity of the optimal statistical WF scheme against the low-complexity BF, D-STTD and SM transmission techniques. Without loss of generality, we show the results for a 4×4 MIMO system. The WF capacity is derived by numerically solving the optimization problem in (6). For BF, D-STTD and SM we use the capacity expressions in (16), (28) and (18), respectively, assuming a ZF receiver for the last two schemes. We present the results for Model F of the IEEE 802.11n wireless local area network standard channel models [21]. As expected from [9, 11], we see that BF achieves the optimal WF capacity in low SNR regime. For high SNRs, WF outperforms SM, which is the best of the low complexity schemes, by approximately 5 dB. We note that, although statistical WF is optimal for all SNRs, WF-based transmission may not be suitable for practical MIMO systems, due to the high computational complexity needed to solve the optimization problem (6).

In Fig. 1 we also show the capacity crossing-points of BF/D-STTD (CP1) and D-STTD/SM (CP2), corresponding to the SNR thresholds of 4 dB and 18.2 dB, respectively. In theory, these SNR thresholds can be exploited to adaptively switch between MIMO schemes. In this way, significant capacity improvements could be obtained (over fixed transmission) over the entire range of SNRs.

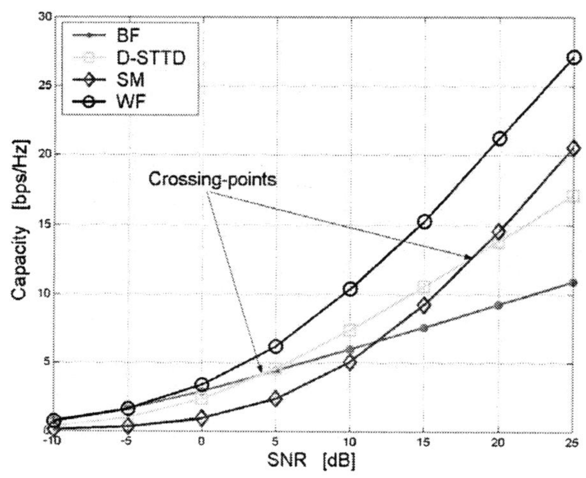

Fig. 1. Mean capacity for BF, D-STTD (with ZF), SM (with ZF) and WF in the IEEE 802.11n channel Model F (NLOS).

Fig. 2 depicts the capacity of statistical BF, D-STTD and SM in Models C and F, described in [21]. Model C is characterized by lower angle spread and number of clusters than F, resulting in higher spatial correlation. For D-STTD and SM we employ a ZF linear receiver. We clearly see that the performance of the various schemes and the crossing-points change from Model C to F, due to the different spatial correlation. For Model C, the two crossing-points CP1 and CP2 occur at the SNR of 8.2 dB and 31.8 dB, respectively. For Model F, the SNR thresholds are 3.7 dB and 18.4 dB, corresponding to CP1 and CP2, respectively. These results suggest that, in addition to the average SNR, a practical MIMO adaptive algorithm should exploit information of the channel spatial correlation as switching criterion across BF, D-STTD and SM, as discussed in the following subsection.

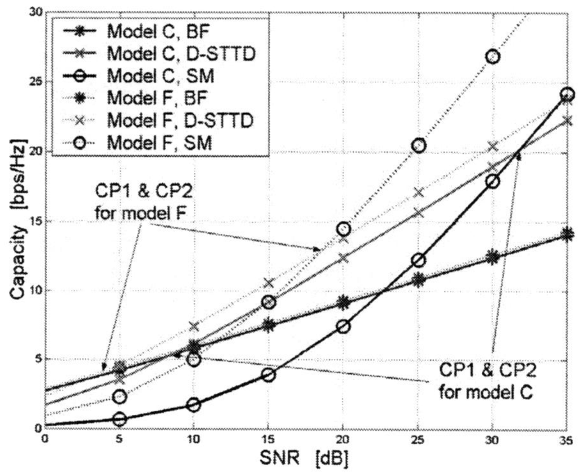

Fig. 2. Mean capacity for BF, D-STTD (with ZF), SM (with ZF) in the IEEE 802.11n channel Models C and F (NLOS). CP1: crossing-point BF versus D-STTD; CP2: crossing-point D-STTD versus SM.

B. *Overview of the Adaptive MIMO Algorithm*

We now describe a practical algorithm for adapting across BF, D-STTD and SM as a function of the spatial selectivity of the channel. The goal of this adaptive method is to enhance the spectral efficiency of the system for a predefined target bit error rate (BER). Hereafter, we briefly review this algorithm, which is described with more details in [22].

We define a set of 12 *modes*, with each mode consisting of a particular MIMO transmission technique (ie. statistical BF, SM, or D-STTD) and modulation/coding scheme (MCS). We employ MRC receivers for BF transmission, and use linear MMSE receivers when operating with SM or D-STTD.

To facilitate mode adaptation based on information of the channel spatial characteristics, our practical approach is to first define a set of *typical* channel models and to empirically pre-compute the error rate performance of the modes in each case. We characterize four typical channel models, with different degrees of spatial selectivity as described in [22], based on the IEEE 802.11n models [21]. These models, along with a corresponding set of SNR thresholds (see below), define a set of *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 spatial correlation matrices. Note that the relative condition number is an indicator of the spatial selectivity of the channel.

Based on the simulated BER performance of the transmission modes in the typical channels, we generate a set of *SNR thresholds*, with each threshold corresponding to the minimum required SNR to achieve the target BER. The SNR thresholds are then stored in a look-up table (LUT). To enable the mode adaptation, our proposed algorithm estimates the link-quality for the current transmission based on the link-quality metrics. These metrics act as inputs into the LUT which selects the mode providing the highest spectral efficiency, while satisfying the predefined target BER.

V. Simulation Results

Fig. 3 demonstrates the achievable spectral efficiency of the proposed adaptive algorithm, as a function of SNR, compared to that of a fixed transmission scheme employing adaptive MCS. Results are presented for a practical 4×4 MIMO system operating in *typical* channel Model 3, as defined in [22], and for a target BER of 0.05.

We clearly see that, for high SNR, the proposed adaptive algorithm yields a spectral efficiency gain of 11 bps/Hz over a fixed BF system with adaptive MCS. We emphasize that the BER for the adaptive scheme remains below the predefined target for all levels of spectral efficiency.

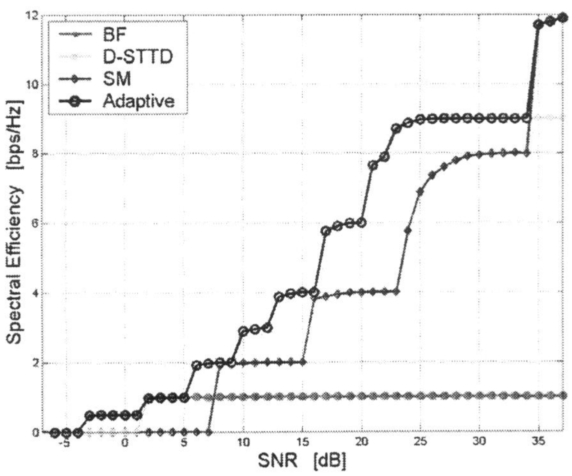

Fig. 3. Spectral efficiency of the adaptive MIMO transmission scheme versus fixed BF, D-STTD and SM with adaptive MCS, in channel "Model 3" in [22].

VI. Conclusions

We presented an adaptive MIMO transmission technique that switches between statistical BF, D-STTD and SM transmission to increase system capacity, by exploiting the spatial selectivity of the channel. We first derived new theoretical capacity expressions for these transmission schemes and showed the dependence of the capacity on the eigenvalues of the channel spatial correlation matrices. We then used these expressions to study the capacity tradeoffs between the schemes in different channel scenarios and to define switching criteria for our adaptive method. Finally, we showed through simulations that our adaptive MIMO algorithm yields significant gain in spectral efficiency over non-adaptive schemes.

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