Adaptive Switching between Spatial Diversity and Multiplexing: a Cross-layer Approach

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***Abstract*— In this paper, we propose a cross-layer approach to solve the problem of switching between multiplexing and diversity modes in an HSDPA context. In particular, three transmission modes are considered: diversity, spatial multiplexing and a hybrid diversity/multiplexing mode. The main purpose of this work is to achieve the maximum possible data rate according to scenario conditions rather than minimize the symbol error rate. To do that, both the transmission mode and the modulation scheme are jointly selected aimed at maximizing link layer throughput. Hence, a cross-layer methodology is addressed in the sense that physical layer parameters are adjusted with the aim of improving *link* layer performance. Computer simulation results show the considerable performance gains of the proposed cross-layer approach for which computational complexity still remains affordable.**

***Index terms*— Diversity, spatial multiplexing, cross-layer, MIMO, adaptive modulation.**

I. INTRODUCTION

MIMO techniques are aimed at either enhancing diversity or providing spatial multiplexing capabilities. Spatial diversity provides a means to improve link reliability. On the contrary, the multiple paths provided by such MIMO schemes are used in a spatial multiplexing context to transmit independent information streams.

Most of current research in MIMO is focused on making use of only one approach, but, recently, studies that combine both schemes have appeared in the literature [1]. In that direction, a system based on switching between multiplexing and diversity is proposed in [2]. According to instantaneous channels conditions, the transmission mode is switched in order to minimize the resulting Symbol Error Rate (SER). For a *constant* data rate, it was shown that by choosing the best mode for a given channel realization, better results can be obtained than with the original approaches separately. In order to improve granularity in terms of SER, a third transmission mode that combines the advantages of both MIMO approaches was included in [3]. In particular, four transmit antennas are considered and the D-STTD technique [4], which consists in transmitting an independent Alamouti scheme in each pair of transmit antennas, is taken as the hybrid mode.

On the other hand, switching between transmission modes can be used in order to increase the data rate. For instance, in [5], those transmission modes that maximize the spectral efficiency for a pre-determined target SER are selected according to channel conditions. That is, the selection algorithm chooses the transmission mode with the highest data rate for which the resulting SER is below a specific threshold.

However, in practical communications systems, link quality is determined not only by the performance of the physical layer procedures but, also, by the specific protocols used in upper layers (such as Automatic Repeat Request (ARQ)). Some optimization criteria aimed at maximizing link layer throughput, are presented in [6] [7], showing considerable improvement with respect to conventional physical layer-oriented designs.

In this paper, a system capable of adaptively switching between multiplexing and diversity is proposed. The purpose of this work is to achieve the maximum possible throughput according to scenario conditions, rather than minimize the overall SER. In particular, by considering constant transmit power, data rate is adapted by jointly selecting the transmission mode and the modulation scheme. To do that, in a practical system (as HSDPA), where all the system characteristics are specified, an appropriate optimization criterion is directly the maximization of the link layer throughput instead of the selection of the maximum transmission data rate subject to SER constraints. Hence, we address a cross-layer (CL) methodology in the sense that physical layer parameters are adjusted aimed at improving *link* layer performance.

This paper is organized as follows. In Section II, we describe the signal and system model. In section III, the different transmission modes available at the Base Station are presented. Then, we explain the proposed cross-layer switching criterion in Section IV. Simulation results are discussed in Section V and, finally, we close the paper with the conclusions section.

II. SIGNAL AND SYSTEM MODEL

Consider an HSDPA transmission link between an M-antenna Base Station (BS) and an N-antenna User Equipment (UE), and assume an ideal spreading/despreading process (see Figure 1). By stacking T consecutive data samples, the received vector at the i-th sensor, ($\mathbf{r}_i = [r_i(1), .., r_i(T)]^T$), can be written as:

$$\mathbf{r}_i = \mathbf{S}\mathbf{h}_i + \mathbf{n}_i \quad (1)$$

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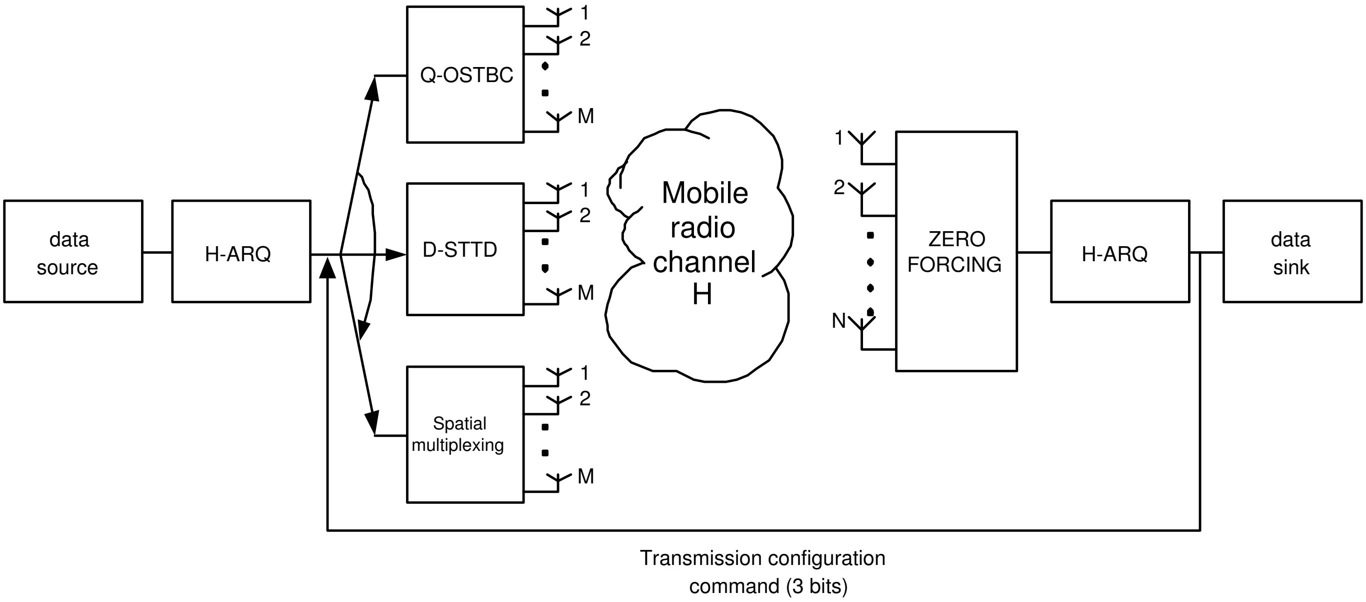

Fig. 1. Block diagram of a MIMO communication system with an adaptive switching of the transmission mode.

where $\mathbf{S}$ is the $T \times M$ symbol matrix that describes the transmission block code, according to the modulation scheme (R), $\mathbf{h}_i = [h_{i_1}, .., h_{i_M}]^T$ is the channel vector corresponding to the i-th receiver, and $\mathbf{n}_i$ stands for an additive Gaussian noise vector of complex, random variables with zero mean and variance σ^2 (accounting for both intra- and inter-cell interference, since long scrambling codes are used). The channel impulse response is assumed to exhibit block Rayleigh flat-fading characteristics (2 ms frames, with pedestrian users moving at 3 km/h). Besides, it is also considered that perfect Channel State Information (CSI) is available at the receive side, where, in order to keep computational complexity moderate, a Zero-Forcing (ZF) detection scheme is used for all the transmission modes. Channel knowledge is used at the receiver to jointly estimate both the optimal transmission mode and modulation scheme maximizing link layer throughput according to the H-ARQ strategy under consideration (see section IV). Once the transmission configuration is selected, a low-rate error-free feedback channel is utilized to convey this information to the transmitter.

At the transmit side, power is evenly distributed among transmit antennas, that is, proportional to $1/M$. In order to properly analyze the different transmission modes with a minimum number of receive antennas at the UE, the number of transmit and receive antennas will be set to $M = N = 4$. The reason for that being that an even number of transmit antennas $M \geq 4$ is required for the D-STTD scheme at the transmit side, whereas at the receiver, a number of antennas $N \geq M$ is needed for the spatial multiplexing mode.

At the link level, a Type III Hybrid-ARQ is adopted [8]. In particular, in order to minimize signalling and buffering requirements at the UE, the N Stop-and-Wait (NSAW) with chase combining method is used [9]. Regarding the packet combining, this is done by simply averaging soft symbols at the output of the ZF scheme [10]. Therefore, the resulting symbol estimates after $p-1$ consecutive retransmissions can be expressed as:

$$\mathbf{y}_p = \frac{1}{p}\sum_{i=1}^{p} \mathbf{y}_{ZF,i} \tag{2}$$

where $\mathbf{y}_{ZF,i}$ denotes the *soft-symbol* vector at the output of the ZF scheme at the i-th transmission.

III. TRANSMISSION MODES

This section is devoted to present the different transmission schemes available at the Base Station. The corresponding signal-to-noise ratio for each transmission scheme is also given since this expression will be used in the next section to derive the link layer throughput.

A. Diversity mode

A Quasi-Orthogonal STBC (Q-OSTBC) code is considered for the diversity mode. Although full diversity is not obtained, this strategy is adopted since full rate ($r = 1$) is achieved. Moreover, better performance than with orthogonal designs is obtained over the low-SNR range[1] [11]. The symbol block matrix, $\mathbf{S}$ is given by:

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_2^* & -s_1^* & s_4^* & -s_3^* \\ s_3^* & s_4^* & -s_1^* & -s_2^* \\ s_4 & -s_3 & -s_2 & s_1 \end{bmatrix} \tag{3}$$

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[1] Notice that, the diversity mode will be usually selected in the low-SNR region.

For the ease of notation, the received signal can be rewritten as:

$$\mathbf{y}_i = \mathbf{H}_i \mathbf{s} + \mathbf{v} \tag{4}$$

where vectors $\mathbf{y}_i$ and $\mathbf{v}_i$ have been redefined as:

$$\begin{aligned} \mathbf{y}_i &= [r_{i_1}, r_{i_2}^*, r_{i_3}^*, r_{i_4}] \\ \mathbf{v}_i &= [n_{i_1}, n_{i_2}^*, n_{i_3}^*, n_{i_4}]^T \end{aligned} \tag{5}$$

respectively, and $\mathbf{H}_i$ stands for the equivalent space-time channel matrix:

$$\mathbf{H}_i = \begin{bmatrix} h_{i_1} & h_{i_2} & h_{i_3} & h_{i_4} \\ -h_{i_2}^* & h_{i_1}^* & -h_{i_4}^* & h_{i_3}^* \\ -h_{i_3}^* & -h_{i_4}^* & h_{i_1}^* & h_{i_2}^* \\ h_{i_4} & -h_{i_3} & -h_{i_2} & h_{i_1} \end{bmatrix} \tag{6}$$

As commented in the previous section, a ZF detector is adopted in all the transmission modes. Prior to detection, the received signal at the different branches are match-filtered and coherently combined:

$$\mathbf{z} = \sum_{i=1}^{N} \mathbf{H}_i^H \mathbf{y}_i = \left[\sum_{i=1}^{N} \mathbf{H}_i^H \mathbf{H}_i \right] \mathbf{s} + \sum_{i=1}^{N} \mathbf{H}_i^H \mathbf{v}_i \tag{7}$$

After that, the transmitted symbols can be estimated as:

$$\hat{\mathbf{s}} = \left[\sum_{i=1}^{N} \mathbf{H}_i^H \mathbf{H}_i \right]^{-1} \mathbf{z} = \mathbf{s} + \left[\sum_{i=1}^{N} \mathbf{H}_i^H \mathbf{H}_i \right]^{-1} \sum_{i=1}^{N} \mathbf{H}_i^H \mathbf{v}_i \tag{8}$$

The signal-to-noise ratio corresponding to the k-th symbol can be estimated as:

$$\rho_k = \frac{E\left[|s_k|^2 \right]}{\sigma^2 \left\| \mathbf{w}_k \right\|^2} \qquad k = 1, 2, \ldots, M, \tag{9}$$

where w_k stand for the row vector in matrix $\mathbf{W}$:

$$\begin{aligned} \mathbf{W} &= \left[\sum_{i=1}^{N} \mathbf{H}_i^H \mathbf{H}_i \right]^{-1} \sum_{i=1}^{N} \mathbf{H}_i^H \\ &= \begin{bmatrix} \mathbf{w}_1^T \\ \mathbf{w}_2^T \\ \mathbf{w}_3^T \\ \mathbf{w}_4^T \end{bmatrix} \end{aligned} \tag{10}$$

When considering an NSAW hybrid ARQ strategy in combination with a chase-combining scheme, ρ_k will ultimately depend on the actual number of recombined soft-symbol packets. Hence, the effective SNR can be expressed as $\rho_{k,p} = \alpha^{p-1} p \rho_k$, where p is the accumulated number of transmissions and α is the chase-combining efficiency that models the combining gain loss respect to the theoretical model [12]. Notice that, from a maximum number of packet transmissions (P) on, the effective SNR no longer improves and, thus, it is needed to limit the number of packet transmissions ($p \leq P$).

Since all the row-vector norms are identical [13], the signal-to-noise ratio corresponding to the diversity mode can be written as:

$$\rho_{\text{DIV},p} = \alpha^{p-1} p \frac{E\left[|s_k|^2 \right]}{\sigma^2 \left\| \mathbf{w}_1 \right\|^2} \tag{11}$$

It is worth noting that, the vector norm can be computed without resorting to any matrix inversion (details are omitted here for brevity, see [13]).

B. Hybrid mode

The hybrid mode is based on transmitting four different symbols during two consecutive time intervals. Then, at the expense of half diversity gain, data rate is doubled ($r = 2$). In particular, a D-STTD scheme is adopted, which results in the following symbol block:

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_2^* & -s_1^* & s_4^* & -s_3^* \end{bmatrix} \tag{12}$$

Therefore, the equivalent space-time channel matrix can be written as:

$$\mathbf{H}_i = \begin{bmatrix} h_{i_1} & h_{i_2} & h_{i_3} & h_{i_4} \\ -h_{i_2}^* & h_{i_1}^* & -h_{i_4}^* & h_{i_3}^* \end{bmatrix} \tag{13}$$

As in the diversity mode, the ZF detector is used. Hence, expressions (7) and (10) are still valid but taking into account the new matrix $\mathbf{H}$ expression given by (13).

Again, no matrix inversion is required to compute the vector norms [13], but, in this case, vector norms are related by pairs. That is:

$$\begin{aligned} \left\| \mathbf{w}_1 \right\|^2 &= \left\| \mathbf{w}_2 \right\|^2 \\ \left\| \mathbf{w}_3 \right\|^2 &= \left\| \mathbf{w}_4 \right\|^2 \end{aligned} \tag{14}$$

Therefore, two different SNR expressions exist for the hybrid transmission mode:

$$\rho_{\text{HYB},1,p} = \alpha^{p-1} p \frac{E\left[|s_k|^2 \right]}{\sigma^2 \left\| \mathbf{w}_1 \right\|^2} \quad \rho_{\text{HYB},2,p} = \alpha^{p-1} p \frac{E\left[|s_k|^2 \right]}{\sigma^2 \left\| \mathbf{w}_3 \right\|^2} \tag{15}$$

C. Spatial multiplexing mode

In this mode, four symbols are transmitted in parallel in each time-slot ($r = 4$):

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \end{bmatrix} \tag{16}$$

and, consequently, not transmit spatial diversity can be expected (for a $M = N = 4$ configuration).

The corresponding space-time channel matrix can be expressed as:

$$\mathbf{H}_i = \begin{bmatrix} h_{i_1} & h_{i_2} & h_{i_3} & h_{i_4} \end{bmatrix} \tag{17}$$

and expressions (7) and (10) can also be used to obtain the SNR:

$$\rho_{\text{MULT},k,p} = \alpha^{p-1} p \frac{E\left[|s_k|^2 \right]}{\sigma^2 \left\| \mathbf{w}_k \right\|^2} \qquad k = 1, 2, 3, 4 \tag{18}$$

IV. FAST ADAPTIVE SWITCHING BASED ON CL DESIGNS

We start by deriving a closed-form expression for the link-layer throughput. By taking into account the specific modulation scheme and the transmission mode in use, a closed-form expression for the instantaneous SER can be obtained:

$$\begin{aligned} &\mathrm{SER}_{\mathrm{DIV},p} = \gamma(\rho_{\mathrm{DIV},p}, R) && \\ &\mathrm{SER}_{\mathrm{HYB},k,p} = \gamma(\rho_{\mathrm{HYB},k,p}, R) && k = 1,2 \\ &\mathrm{SER}_{\mathrm{MULT},k,p} = \gamma(\rho_{\mathrm{MULT},k,p}, R) && k = 1..4 \end{aligned} \tag{19}$$

From that, we can derive an expression for the (uncoded) packet-error rate (PER) of an $L{\cdot}M$-symbol packet, according to the transmission mode:

$$\mathrm{PER}_{\mathrm{DIV},p} = 1 - (1 - \mathrm{SER}_{\mathrm{DIV},p})^{L} \tag{20}$$

$$\mathrm{PER}_{\mathrm{HYB},p} = 1 - \left[\prod_{k=1}^{2} (1 - \mathrm{SER}_{\mathrm{HYB},k,p})\right]^{L} \tag{21}$$

$$\mathrm{PER}_{\mathrm{MULT},p} = 1 - \left[\prod_{k=1}^{4} (1 - \mathrm{SER}_{\mathrm{MULT},k,p})\right]^{L} \tag{22}$$

Notice that, packet size is constant for the three transmission modes but, as reflected in the above expressions, the number of redundant symbols increases when spatial diversity is introduced.

Finally, by estimating the average number of transmissions as:

$$E[p]{=}(1 - \mathrm{PER}_1) + \sum_{p=2}^{P}\left[p(1 - \mathrm{PER}_p)\prod_{t=1}^{p-1}\mathrm{PER}_t\right] \tag{23}$$

where PER_i must be appropriately chosen according to the corresponding transmission mode (equations (20)-(22)), the link layer throughput can be easily obtained:

$$\eta_{N-SAW}\left(\mathbf{m}\right) = \frac{N_{SAW}}{W}\frac{l \cdot r \cdot b}{E[p]} \tag{24}$$

where W stands for the round-trip delay expressed in number of slots, N_{SAW} accounts for the number of concurrent SAW processes, l is the ratio of information bits per packet and b the number of bits per symbol, according to the modulation scheme in use. Therefore, the optimization process consists in jointly selecting the transmission mode *and* the modulation scheme that maximize this expression. Notice that only three bits[2] are required to convey that information to the transmitter via feedback channel.

Given the highly non-linear nature of the optimization problem, an exhaustive search is considered. Contributions to computational complexity mainly arise from the computation of the instantaneous signal-to-noise ratio expressions (equations (11), (15) and (18)) required for SER estimation, rather than from the scoring part. However, for the spatial multiplexing case, a reduced-complexity version was developed by the authors in [14]. On the other hand, no matrix inversion is required for the Q-OSTBC and D-STTD schemes.

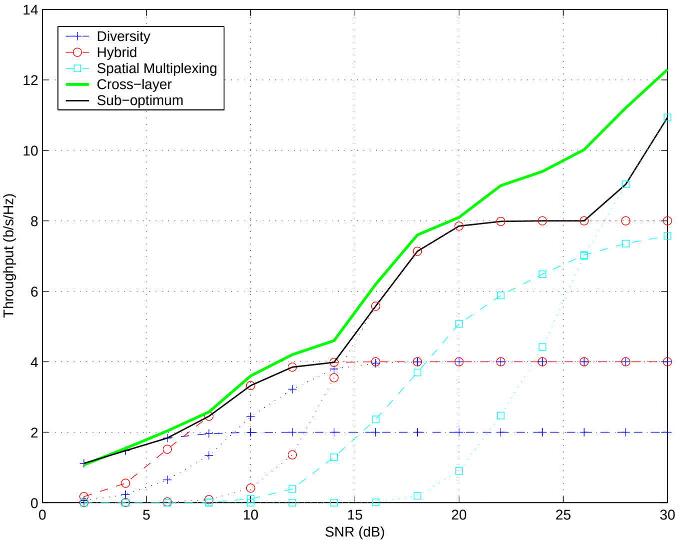

Fig. 2. Link layer throughput vs. average SNR for the different transmission schemes. (Solid lines: switching approaches, dashed lines: QPSK, dotted lines: 16-QAM)

Alternatively, when the receiver computational requirements are further limited, a *sub-optimum* approach based on the scenario statistics can be adopted. That is, the average link layer throughput is pre-computed for the different transmission modes and modulation schemes. Then, a set of thresholds for the average SNR can be established. By doing so, the transmission mode and constellation size can be selected at the BS according to the long-term average SNR of the system.

V. SIMULATION RESULTS

In an HSDPA context, frames for data bursts are divided into three slots, where three packet blocks of length $L = 160$ symbols are allocated. As far as computer simulations are concerned, round-trip delay is assumed to be equal to $W = 3$ slots and, thus, the number of concurrent SAW processes is adjusted to $N_{SAW} = 3$. Information associated to the selected modulation scheme and transmission mode will be allocated in the Transport Format and Rate Combination (TFRC) field, as done for HSDPA coding-and-modulation modes, to be conveyed over an error-free feedback channel to the transmit side in a scenario of low mobility terminals ($v_{UE} = 3$ km/h). Transmission mode and modulation scheme configurations will be updated on a frame-by-frame basis, at most. The number of receive antennas and the maximum number of transmit antennas are equally set to $N = M = 4$. Concerning the chase combining reliability parameter, α, it was empirically set to 0.74 and 0.72 for QPSK and 16-QAM, respectively, this setting the maximum number of packet transmissions to $P = 4$.

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[2] In this work, three transmission modes and two modulation schemes (QPSK and 16-QAM) are considered, i.e. six transmission configurations are available at the transmitter.

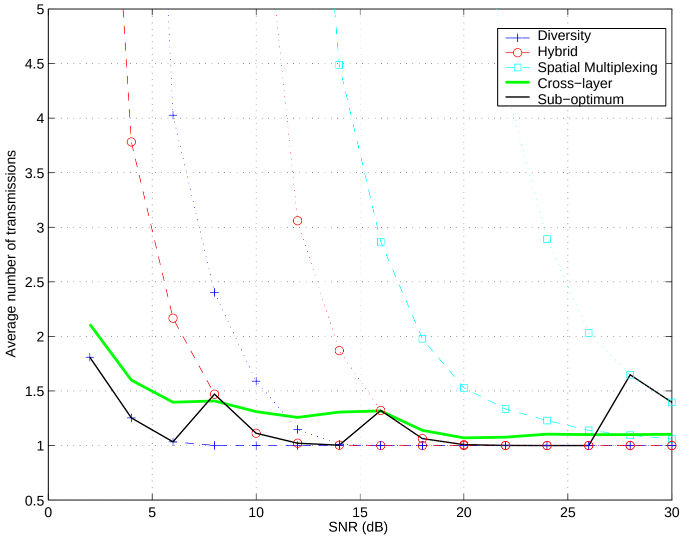

Fig. 3. Average number of transmissions vs. average SNR for the different transmission schemes. (Solid lines: switching approaches, dashed lines: QPSK, dotted lines: 16-QAM)

Figure 2 is devoted to show how both the proposed cross-layer design and the sub-optimum approach make the most of the different transmission modes and modulation schemes as a function of the long term average SNR. Clearly, considerable performance gains can be obtained with an adaptive switching approach with respect to using the original schemes separately. It is also clear that, for the whole range of SNR, superior performance gain is obtained with the fast adaptive cross-layer technique since this approach takes advantage of those instantaneous scenario conditions that allow higher throughput. Finally, one can observe that in terms of transmission delay (see Fig.3), the CL approach in combination with H-ARQ mechanisms provides a means to effectively keep the number of $individual$ packet transmissions low for the whole range of signal to noise ratios (less than 2).

VI. CONCLUSIONS

In this paper, a cross-layer design to switch between multiplexing and diversity was derived. In order to obtain a customized design for an HSDPA system, an algorithm that jointly selects the optimal transmission mode and the modulation order maximizing the link layer throughput expression was adopted. It was mentioned that computational complexity considerations are not restrictive in practical systems, but, still, in order to decrease receiver requirements, a statistical sub-optimum approach was also derived. Regarding system performance, both the proposed approaches were shown to exhibit superior performance in comparison with the original MIMO techniques separately. Particularly, a considerably gain was obtained with the fast adaptive cross-layer technique since instantaneous variations of the scenario conditions are taken into account.

Future work in the field will encompass an extension to multi-user scenarios and the study of the proposed transmission schemes in more realistic environments. For instance, scenarios where the correlation between transmit antennas is not neglected, or where effects such as errors or delay are introduced in the feedback channel.

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