HYBRID TURBO FEC/ARQ SYSTEMS AND DISTRIBUTED SPACE-TIME CODING FOR COOPERATIVE TRANSMISSION

Adrian Agustin, Josep Vidal, Olga Muñoz

Signal Processing in Communications Group
Department of Signal Theory and Communications
Technical University of Catalonia (UPC)
c/ Jordi Girona 1-3, 08034 Barcelona (SPAIN)
Email: agustin@gps.tsc.upc.es
Phone: (+34) 93 401 09 64
Fax: (+34) 93 401 64 47
Office: D5-214

August 2005

Abstract.- Cooperative transmission can be seen as a “virtual” MIMO system, where the multiple transmit antennas are in fact implemented distributed by the antennas both at the source and the relay terminal. Depending on the system design, diversity/multiplexing gains are achievable. This design involves the definition of the type of retransmission (incremental redundancy, repetition coding), the design of the distributed space-time codes, the error correcting scheme, the operation of the relay (decode&forward or amplify&forward) and the number of antennas at each terminal. Proposed schemes are evaluated in different conditions in combination with forward error correcting codes (FEC), both for linear and near-optimum (sphere decoder) receivers, for its possible implementation in downlink high speed packet services of cellular networks. Results show the benefits of coded cooperation over direct transmission in terms of increased throughput. It is shown that multiplexing gains are observed even if the mobile station features a single antenna, provided that cell wide reuse of the relay radio resource is possible.

Keyword list.- Cooperative transmission, Distributed Space-Time Block codes, hybrid ARQ, MIMO and, turbo codes.

1 INTRODUCTION

Wireless networks have been developed in the last decade in order to allow the communications to be "anywhere and any time". However, problems arise in the communications among the mobile users as time-varying fading channels and the shadowing effect. The appropriate method to combat these effects is the use of diversity. Typically, time and frequency diversity have been considered. Moreover, in the last years space diversity [1],[2] using multiple antenna system (MIMO – Multiple Input Multiple Output) has received much attention because it can be combined with other forms of diversity and additionally, offers an increase of the total capacity of the system (tradeoff diversity-multiplexing gain [3]). MIMO systems have been suggested to increase the channel capacity linearly with the minimum number of transmitting and receiving antennas. Another form of space diversity is achieved by exploiting the antennas of multiple terminals (relays) to combat the fading due to the multipath and shadowing propagation. It is usually known as the relay channel. Initially, the relay channel was studied in [4] for the degraded Gaussian channel assuming that one relay receives and transmits simultaneously (full duplex). Recently, an extension of the relay channel for multi-node networks named cooperative diversity [5], [6] has been proposed. The cooperating users create a "virtual array" through distributed transmissions [7-9]. This way, the paradigm of source-destination communication is changed to source-relay-destination, where the role played by the relay may be dummy (as in amplify and forward retransmission – A&F [6],[9]) or smart (when the relay decodes, re-encondes conveniently and forwards – D&F [6],[10]). In the later case, taking into account Forward Error Correcting (FEC) codes, a new mode of cooperation is possible depending on the data transmitted by the relay [11-13]. It is named coded cooperation and in this mode the relay transmits incremental data of the received packet in order to improve the multiplexing, coding and/or the diversity gains at destination. In general, cooperative transmission may in fact be seen as a distributed space-time coding (DSTC) technique [14].

Due to practical considerations in the design of RF equipment, the physical channels considered at the reception and retransmission of the relay are usually assumed orthogonal, i.e TDD mode. In [15] it is shown that the total capacity is similar to the case where the relays works in a full duplex mode (receives and transmits simultaneously). It has been proved that these schemes are able to provide diversity gains, though at the expense of an increased utilisation of the radio resources [6][9][11][15][17] (two transmissions, for instance from source to relay and/or destination and from relay to destination). However, it is possible to achieve multiplexing gain as the equivalent "virtual" MIMO system by a convenient reuse of the relaying channel when it is considered cell-wide [17][18]. In this case the presence of many simultaneous players in the communication link suggest the use of distribute transmission-reception schemes [19][20]. These features of the cooperative transmission have been analysed in a preliminary work [20] where it has been demonstrated that MIMO multiplexing gains for the downlink are achievable when single antenna receivers are considered.

Among the plethora of possibilities in the design of these systems, we aim at the evaluation of coded cooperative transmission, considering STBC in combination with forward error correction (FEC) codes and retransmissions [13], for the possible adoption as a way to improve the performance of the downlink high speed packet service in cellular networks (in particular for UMTS, High Speed Data Packet Access, HSDPA) when the MS features only one receiving antenna. Adaptive modulation and coding (AMC) and Automatic Repeat reQuest (ARQ) procedures are considered, as important features of the HSDPA.

Retransmission schemes may be designed in multiple ways, depending on the activity of the relay [6]: the relay terminal may either always retransmit or do it only when the packet at the destination terminal is received in error (*incremental retransmission*). For the D&F case, the relay may further decide to retransmit or not the received packet when the relay itself receives it in error (*selective retransmission*). Moreover, if the relay terminal incorporates multiple antennas, this message may further be space-time block coded (STBC) with the same code as used by the source terminal or with a suitable one (e.g. maximizing the mutual information or the SNR at the destination). In addition to these attributes, when the relay decides to retransmit [21], it may do it by providing the destination user with a repeated message (as in HARQ type I, *chase combining*) or with a re-encoded message [11-13] (as in HARQ type II, *code combining*). In both cases, the retransmission may effectively be considered a reconfigurable scheme that accommodates different error protection capabilities (enhancing the transmission rate) depending on the channel state. In principle, if well designed, they allow near-capacity rates at the expenses of increased delay [22].

In order to obtain throughput figures which closely approach true MIMO performance with single antenna mobile terminals the Rate Compatible Punctured - Turbo-Codes (RCPTC) [22] and Hybrid Automatic Repeat reQuest (HARQ) strategies are considered. RCPTC allow us to select different codeword rates whereas HARQ strategies are responsible of packet retransmissions. In case of HARQ-II (*code combining*) the length of retransmission is an important point to be considered in the maximization of the obtained throughput. It is also shown that for medium ranges of SNR, the throughput is affected by the use of suboptimum linear receivers (MMSE or zero forcing) compared to approximate ML receivers [19], [23].

The contents of this work are organised as follows: Section 2 describes briefly the cooperative transmission for a single user and how it is applied to a centralized cellular system with one hop in order to improve its performance. Section 3 presents different cooperative strategies considered for the evaluation of the downlink coded cooperative transmission. Additionally, this section also describes the Rate Compatible Punctured Turbo

Codes (RCPTC) and how are applied to the BS and RS in order to improve the coding gain by the cooperative transmission. Section 4 is devoted to show the results in terms of throughput for the different strategies using different constellation size, ARQ protocol, receiver and length of retransmission (for HARQ-II). Finally, section 5 presents the conclusions and guidelines for system designer.

2 COOPERATIVE TRANSMISSION

We consider an application of the cooperative transmission to a centralized cellular system in the downlink. The cooperative scheme is based on orthogonal access (i.e. TDMA) between the DL and the RL. The selected protocol for the downlink is the protocol-II shown in [12]. The BS transmits the signal to the MS in a DL slot (solid lines in figure 1). This signal is also received by the RS (a role played by another MS or a lamp-posted relay). Eventually, the RS will retransmit the received signal to the MS in the RL slot (dashed line in figure 1).

In the sequel, the signal model for the single user cooperative transmission will be described, standing out the benefits of the cooperation and the different modes of operation (decode and forward or amplify and forward). Finally, it is presented a method allowing improved performance of the cooperative transmission when applied to a cellular system.

2.1 Single user link capacity

In order to define the signal model let *M*, *R* and *N* denote the number of antennas at BS, RS and MS, respectively. In the following $\mathbf{H}_0$, $\mathbf{H}_1$ and $\mathbf{H}_2$ will represent the channel matrices containing the channel coefficients in the direct link (BS to MS), the 1st hop (BS to RS) and the 2nd hop (RS to MS) also named the relay link (RL). The channel coefficients will include a path loss component and a zero-mean complex Gaussian component accounting for the Rayleigh fading. For the A&F approach, the signals received at the MS, during the downlink

(DL) slot and the relay link (RL) slot can be gathered into a single vector expression, as

$$\begin{bmatrix} \mathbf{y}^{(DL)} \\ \mathbf{y}^{(RL)} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_0 \\ \mathbf{H}_2\mathbf{G}\mathbf{H}_1 \end{bmatrix} \mathbf{x} + \begin{bmatrix} \mathbf{I}_N & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_2\mathbf{G} & \mathbf{I}_N \end{bmatrix} \begin{bmatrix} \mathbf{n}^{(DL)} \\ \mathbf{n}_r^{(DL)} \\ \mathbf{n}^{(RL)} \end{bmatrix} \tag{1}$$

where $\mathbf{x}$ is the transmitted signal, $\mathbf{G}$ is a linear combining matrix at the RS, $\mathbf{I}_N$ denotes the NxN identity matrix. Finally $\mathbf{n}^{(DL)}$ and $\mathbf{n}_r^{(DL)}$ are the noise vectors received at the MS and RS during the DL slot, while $\mathbf{n}^{(RL)}$ is the noise vector at the MS during the RL slot. Finally, (1) can be written in a more compact way as follows,

$$\mathbf{y} = \mathbf{H}_{AF}\mathbf{x} + \mathbf{n}_b \qquad \mathbf{R}_{bb} = \begin{bmatrix} \sigma_{MS}^2\mathbf{I}_N & \mathbf{0} \\ \mathbf{0} & \sigma_{RS}^2\mathbf{H}_2\mathbf{G}\mathbf{G}^H\mathbf{H}_2^H + \sigma_{MS}^2\mathbf{I}_N \end{bmatrix} \tag{2}$$

with $\mathbf{R}_{bb}$ the covariance matrix of the noise $\mathbf{n}_b$. Note that (1) can be seen as a M×2N MIMO system with a noise covariance matrix $\mathbf{R}_{bb}$, except for the fact that two time slots are used to complete the transmission of symbols in **x.**

Two different possibilities exist for the DF approach, using Repetition code (D&F-RC) or using Unconstrained Code (D&F-UC) [24]. For both possibilities, the signal received at the RS during the downlink (DL) slot is,

$$\mathbf{y}_r^{(DL)} = \mathbf{H}_1\mathbf{x}^{(DL)} + \mathbf{n}_r^{(DL)} \tag{3}$$

On the other hand, the signal received at MS during the DL and RL for the D&F-UC can be modelled as,

$$\begin{bmatrix} \mathbf{y}^{(DL)} \\ \mathbf{y}^{(RL)} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_2\sqrt{\frac{P_r}{P_{BS}}} \end{bmatrix} \begin{bmatrix} \mathbf{x}^{(DL)} \\ \mathbf{x}^{(RL)} \end{bmatrix} + \begin{bmatrix} \mathbf{n}^{(DL)} \\ \mathbf{n}^{(RL)} \end{bmatrix} = \mathbf{H}_{DF-UC} \begin{bmatrix} \mathbf{x}^{(DL)} \\ \mathbf{x}^{(RL)} \end{bmatrix} + \begin{bmatrix} \mathbf{n}^{(DL)} \\ \mathbf{n}^{(RL)} \end{bmatrix} \tag{4}$$

where the signal transmitted by the RS, $\mathbf{x}^{(RL)}$, does not need to be linearly related to the signal transmitted by the BS $\mathbf{x}^{(DL)}$ in the DL. P_r and P_{BS} denote the power transmitted by the RS and the BS respectively. This system is similar to a (M+R)×2N MIMO system.

Whereas for the D&F-RC, the received signal is,

$$\begin{bmatrix}\mathbf{y}^{(DL)}\\ \mathbf{y}^{(RL)}\end{bmatrix}=\begin{bmatrix}\mathbf{H}_0 & \\ \mathbf{H}_2\sqrt{\frac{P_r}{P_{BS}}} & \end{bmatrix}\begin{bmatrix}\mathbf{x}^{(DL)}\\ \mathbf{x}^{(RL)}\end{bmatrix}+\begin{bmatrix}\mathbf{n}^{(DL)}\\ \mathbf{n}^{(RL)}\end{bmatrix}=\mathbf{H}_{DF-RC}\begin{bmatrix}\mathbf{x}^{(DL)}\\ \mathbf{x}^{(RL)}\end{bmatrix}+\begin{bmatrix}\mathbf{n}^{(DL)}\\ \mathbf{n}^{(RL)}\end{bmatrix} \tag{5}$$

this system is similar to a M×2N MIMO system. Note that in all cases the number of antennas is doubled, at the expenses of an increased use of physical resources.

For the case without CSI at the transmitter and assuming an isotropic transmission, the maximum achievable rate of the different protocols is given by,

$$I_{DL}=\log_2\det\left(\mathbf{I}_N+\frac{P_{BS}}{M}\mathbf{R}_{nn}^{-1}\mathbf{H}_0\mathbf{H}_0^H\right) \tag{6}$$

$$I_{AF}=\frac{1}{2}\log_2\det\left(\mathbf{I}_{2N}+\frac{P_{BS}}{M}\mathbf{R}_{bb}^{-1}\mathbf{H}_{AF}\mathbf{H}_{AF}^H\right),\quad \mathbf{R}_{bb}=\begin{bmatrix}\sigma_{MS}^2\mathbf{I}_N & \mathbf{0}\\ \mathbf{0} & \sigma_{RS}^2\mathbf{H}_2\mathbf{G}\mathbf{G}^H\mathbf{H}_2^H+\sigma_{MS}^2\mathbf{I}_N\end{bmatrix} \tag{7}$$

$$I_{DF-UC}=\frac{1}{2}\min\left(\log_2\det\left(\mathbf{I}_R+\frac{P_{BS}}{M}\mathbf{R}_n^{-1}\mathbf{H}_1\mathbf{H}_1^H\right),\log_2\det\left(\mathbf{I}_{2N}+\frac{P_{BS}}{M}\mathbf{R}_n^{-1}\mathbf{H}_{DF-UC}\mathbf{H}_{DF-UC}^H\right)\right) \tag{8}$$

$$I_{DF-RC}=\frac{1}{2}\min\left(\log_2\det\left(\mathbf{I}_R+\frac{P_{BS}}{M}\mathbf{R}_n^{-1}\mathbf{H}_1\mathbf{H}_1^H\right),\log_2\det\left(\mathbf{I}_{2N}+\frac{P_{BS}}{M}\mathbf{R}_n^{-1}\mathbf{H}_{DF-RC}\mathbf{H}_{DF-RC}^H\right)\right) \tag{9}$$

From the above equation two points have to be emphasized. The decode and forward methods ((8) and (9)) have a performance dependent on the link quality between the BS and RS. On the other hand, the factor ½ in (7),(8) and (9) accounts for the use of two transmission instances per transmitted symbol. Despite of these points cooperative transmission can achieve better performance than direct transmission (6) for certain cases. Figure 2 presents the performance of these protocols in a symmetric scenario (all the links with the same average signal to noise ration (SNR)). We have considered M=2, R=2 for decode and forward protocols (in order to avoid bad link quality between BS and RS when all the SNR of the links are equal), R=1 for amplify and forward and N=1, antennas for the BS, RS and MS, respectively. Note that with this configuration the cooperative transmission are similar to “virtual” 2x2 and 4x2 MIMO systems for the A&F and D&F-RC and for

D&F-UC, respectively. However there is a factor ½ that will penalise their performance. In Figure 2-left, the 10^{-3}-outage mutual information is depicted vs. different SNR and for the different methods. It can be seen how decode and forward protocols achieve always better performance than direct link, however the A&F protocol only for certain SNR values (factor ½ has been considered). Figure 2-right shows the performance of the different protocols in terms of the ergodic capacity. It can be observed that the cooperative methods achieves a performance worse than direct transmission but similar.

Results of the cooperative protocols can be improved if we are able to avoid the factor ½ present at (7),(8) and (9). In that case the cooperative results have to be multiplied by 2, improving the direct link in terms of outage and ergodic capacity and obtaining the "virtual" MIMO systems described previously. That option is possible by a suitable cellular reuse of the relay channel.

2.2 Cellular reuse of the relay channel

In order to improve the cooperative transmission the reuse of the relay link is required, allowing multiple simultaneous transmissions from RSs to MSs, [18]. The cooperative transmission procedure operates as follows: firstly, during the downlink slots, the BS transmits the information to the MSs. This information is also received by its associated RSs, (solid lines in figure 3). Secondly, during the relay slot, all the RSs transmit to MSs the information received in the downlink transmission (dashed lines in figure 3). Figure 3 also shows the frame composition for 2 cooperating users (3 slots are needed). Note that now the reuse factor is 2/3 instead of 1/2 for single user cooperation. As it was pointed in [18],[20] in order to achieve capacity improvement a high reuse of the relay link slot is necessary to compensate for the use of one slot for the relay transmissions (Π close to 1, in figure 3). Note that in that case the performance of the "virtual" MIMO systems (doubling the receiving antennas) can be achieved. For this reason it is important to equip the BS with at least M=2N antennas in order to maximize the multiplexing gain capacity of the new system. Moreover the assumption of a symmetric scenario (all the links with the same SNR) will help us to improve the reuse of the relay link channel because of the RS is close to the MS. Additionally, in the symmetric scenario the D&F methods must have R=2N antennas in order to avoid the bad link quality of the BS-RS link, (8) and (9).

Results obtained in [20] show an important capacity gain when using cooperative transmission provided that the power transmitted by the relays is appropriately adjusted. In this work a high cellular reuse of the relay slot will be assumed, which implies that the observed performance scales within the cell for a moderate number of users.

Note that this environment is different from that one described in [8] where both the power and the duration of the time slot devoted to direct transmission and relay transmission are optimized to maximize the throughput. In our case the time is fixed (TDMA) and the power transmitted by the relay is constrained due to the interfering relay channel and obtained by a distributed power control algorithm, i.e. the SNR in the relay channel is adjusted optimally. Moreover, in our case the maximization of the throughput will be obtained by a suitable selection of the codeword rate and HARQ strategy.

3 DOWNLINK CODED COOPERATIVE TRANSMISSION

This section will explain the different strategies proposed to achieve diversity/multiplexing gains in the cooperative transmission. We consider the direct transmission and the use of the A&F or D&F for the cooperative strategies. In both cases, different distributed space-time block coding methods may be adopted, for diversity, multiplexing or a trading between both gains. Additionally a brief introduction to the Rate Punctured Turbo-Codes (RCPTC) will be done in sub-section 2, necessary for a better understanding about the structure of the transmitted data, explained in sub-section 3. Finally, in sub-section 4, describes the retransmission procedure.

3.1 Distributed space-time block codes

Distributed space-time block codes are based on the space-time block codes applied to distributed antennas. We have considered space-time codes based on Linear Dispersion Codes (LDC) [25]. These codes disperse the energy of the transmitted symbols both in the spatial and in the temporal domain. A LDC builds a block, **S**, for each Q symbols as follows,

$$\mathbf{S} = \sum_{q=1}^{Q} \left(\mathbf{A}_q \alpha_q + j\mathbf{B}_q \beta_q \right) \tag{10}$$

with (α_q, β_q) the real and imaginary parts of the q-th symbol and $\{\mathbf{A}_q,\mathbf{B}_q\}$ the dispersion matrices (DMs). DMs are a set of $M\times T$ matrices, with T the number of channel uses per block and M the number of transmitting antennas. Formulation of (10) also subsumes different Space-Time techniques as VBLAST and Orthogonal codes. In any case, the symbol rate transmission is $R=(Q/T)$ symbols/s/Hz. The relation that allows working with a linear receiver is,

$$Q = \min(M, N)T \tag{11}$$

In the distributed space-time codes, the distributed antennas use different parts of the DMs as is shown in figure 4. The distributed space-time block coding transmission schemes that have been considered in the rest of the paper are detailed below. In each case, the rationale for adoption and the benefits that may be obtained are analysed. In all cases the MS is assumed to use a single antenna (despite of this it is possible to achieve high capacity gains thanks to the cooperation), while the RS may feature one or two antennas.

- **Non-Cooperative (NC).** This is a reference case to which we may compare the performance of a cooperative scheme. RS is not operating and system can be considered as 2x1 MIMO system. For this case, the Alamouti STC (1 symbol/channel use) is used.

- **Cooperative A&F (C-A&F).** In the relay link slot the RS transmits the received signal with an amplifying factor to the MS. The system can be approximated as a 2×2 "virtual" MIMO system using only R=1 antenna, (1). Two different STC have been considered in order to obtain the multiplexing or the diversity gain of a MIMO system:
    - *Diversity Gain.-* Alamouti STC (code rate is 1)
    - *Multiplexing Gain.-* VBLAST STC (code rate is 2)

  For both cases the messages are only encoded in the BS, as a typical MIMO system, and the RS selects the proper amplifying factor and transmits the same received message.

- **Cooperative D&F (C-D&F)**. Here the RS decodes the received signal, re-encodes the information and retransmits it to the MS. We have considered R=2 antennas (avoids bad BS-RS link quality in symmetric scenarios). This implies a dense deployment of lamp-post relay terminals. In the same way as in the previous scheme, the multiplexing and the diversity gain have been analysed.
    - *Diversity Gain.-* Also the Alamouti STC (code rate is 1) has been considered here. Additionally, the RS can select from two possible policies to achieve the diversity gain:
        a) *Selective Transmission*.- The RS transmits only if it decodes correctly the packet
        b) *Persistent Transmission*.- The RS always retransmit (all bits are retransmitted even if they are decoded in error)

In order to maximise capacity, RS and BS should transmit uncorrelated (and ideally Gaussian) symbols, although related to the same message. This can be done by transmitting different parity data from the BS and RS when a convolutional or Turbo code is selected [11]. Further on, this process will be explained in more detail.

o <u>*Multiplexing Gain.-*</u> A different STC is selected to achieve the multiplexing gain. In [24] it was shown the two different options for the C-D&F with different capacity values.

a) *Repetition Code (RC).-* The BS and RS use the same message using the same STC. In this case the VBLAST STC is considered (virtual 2x2 MIMO system, (5)).

b) *Unconstrained Code (UC).-* The whole system can be seen as a virtual (M+R)×2N system, (4). In this case a STC designed for 4×2 MIMO system has been considered, the QOD codes [26]. The BS uses the part of the STC related to the first M antennas and the RS uses the remaining data, see how the dispersion matrices of the STC are divided between distributed antennas in figure 4.

For this strategy STCs allowing linear decoding of the transmitted symbols have been considered. Since the selected STCs are designed for MIMO systems with 2 receiving antennas and the MS only has N=1 actual antenna, it needs both transmissions (BS to the MS and RS to the MS, therefore, 2 “virtual antennas”) to be able to decode the message. For this reason the RS must transmit the same message as the BS, although it can use another part of the DM of the STCs as in the UC, see figure 4. In other words, *persistent transmission* from the RS is required.

- **Mixed Coding Cooperative D&F (Mixed C-D&F).** The RS also has R=2 antennas. This strategy tries to exploit the *diversity gain*, transmitting uncorrelated symbols from BS and RS, and the *multiplexing gain*, selecting a linear rate 2 space-time code. Here it is considered that the systematic data part of the message uses the VBLAST STC and the parity data uses the Alamouti STC. With this configuration the MS can linearly decode the parity information independently (recall that N=1 antenna). The parity information transmitted by the BS and by the RS is different in order to improve the coding gain. Finally to decode the message, the MS needs the transmissions from the BS and the RS to decode the systematic information and finally the whole message.

3.2 Rate Compatible Punctured Turbo-Codes (RCPTC)

We are considering that the STC are fed by channel codes based on the turbo principle. Figure 5 shows the general structure of the parallel Punctured Turbo Codes [27]. These are parallel concatenated convolutional codes in which the information bits are first encoded by a RSC (Recursive Systematic Convolutional) encoder, and (after passing through an interleaver) encoded again by a second RSC. Finally, the codewords are composed by the raw bits sequence (systematic data) and the parity check sequences from the two RSC. The rate of this code is approximately 1/3 (if some tail bits are taken into account). The system can be generalized to achieve rate 1/n by adding more interleavers-plus-RSC blocks (see Figure 5).

Additionally, a family of RCPTC [22] can be obtained by puncturing the coded bits of rate 1/3. Where each output bit stream is obtained using a puncturing pattern with period p, which is represented by the $3 \times p$ sized **P** matrix with ones and zeros. Ones represent the position of the bits to be transmitted and zeros correspond to erased bits. The first row is representative of the systematic part, while the second and third correspond to the parity symbols. Note its applicability to incremental retransmission of the packets when different puncturing matrices are considered (each generated bit stream will contain some uncorrelated data).

We may associate the same or distinct puncturing matrices to the BS and the RS, and to each of the retransmissions. For instance, in HARQ-I the initial transmission and all retransmissions use the same puncturing matrix, while these are different in HARQ-II. Figure 5 also shows an example of two different puncturing matrices of rate ½ and ¼ p=6 (superscripts indicate the number of the retransmission). $\mathbf{P}^{(1)}$ transmits all the systematic information and different parity, whereas $\mathbf{P}^{(2)}$ transmits less parity (rows 2 and 3). The puncturing matrices are designed in such a way that all the symbols of a high rate punctured code are used by the lower rate codes, that is, the higher rate codes are embedded in the low rate codes. In this way, the transmitter needs only transmit supplementary code symbols to get a lower rate code.

3.3 Code structure for the transmitted data

The use of the RCPT codes allows us to evaluate the different cooperative schemes presented before with different rates and parity information transmitted from the BS or RS, by a proper selection of the puncturing matrices. A description of how RCPT codes are combined with DSTBC for the different strategies is given in the sequel.

- **Non-Cooperative.**. The STC used is the Alamouti code, as it was mentioned in section 3.1. The BS uses the frame structure of type I presented in figure 6. For this case the amount of data of systematic and parity data information is the same, as it indicates the selected puncturing matrix, see figure 6-right, providing rate ½. Systematic and parity symbols are concatenated.

- **Cooperative Amplify and Forward**. For the C-A&F the encoding process is only performed in the BS, because the RS retransmits the received signal with a proper amplifying factor to the MS. For this reason the structure of the transmitted data is similar to the non-cooperative strategy, frame structure of type I, see figure 6. When the *diversity gain* is considered, the Alamouti code is applied to the systematic and parity parts of the frame structure, whereas VBLAST code is used for the *multiplexing gain* case. Let us recall that the MS is able to linearly demodulate the symbols transmitted because of the transmissions received from the RS and the BS.
- **Cooperative Decode & Forward**. In this strategy the RS re-encodes the received signal before retransmission, for this reason the encoded process carried out at the BS and RS could be different.

  A) *Diversity Gain*. In order to achieve this gain the objective is to work with a STC designed for a MISO system (Alamouti code) and transmit uncorrelated symbols from the BS and RS which can be independently decoded by the MS (N=1). To accomplish this objective different puncturing matrices for the BS and RS are considered. The BS uses the frame structure of type I and the RS uses the frame structure of type II, both shown in figure 6. In this case there are different parity bits transmitted from the RS to the MS. Additionally the amount of parity data in the RS transmission is larger than BS transmission, (see the puncturing matrices depicted at the right of the frame structure in figure 6)

  B) *Multiplexing Gain.* The difference from the previous case is the DSTBC selected. Now we consider STBC designed for MIMO systems with 2N receiving antennas. Additionally, in order to perform a linear detection of the transmitted symbols, the RS has to transmit exactly the same symbols as the BS. For this reason, the BS and RS must have the same puncturing matrix and therefore the same frame structure, (type I in this case, see figure 6). Moreover, there are two different possibilities to achieve this gain, the Repetition Code, where the BS and RS use the same STBC (designed for M×2N MIMO system), or the Unconstrained Code, where the BS and RS use different parts of a STBC (designed for (M+R)×2N MIMO system, see figure 4).

- **Mixed Cooperative D&F**. This strategy is designed to achieve the multiplexing gain but taking into account also the diversity gain. The main idea of this strategy is that the systematic information will use a STBC designed for MIMO system with 2N receiving antennas, for instance the VBLAST code. The systematic information transmitted by the BS and RS has to be the same for a linear decoding at the MS. For this reason the BS uses the frame structure of type I and the RS uses the frame structure of type III presented in figure 6, note that the puncturing matrices transmit the same systematic data (see row 1). However, the parity data uses a STC designed for a MISO system, therefore for this part of the information the puncturing rows selected in the BS and RS are different (see in figure 6-right the 2^{nd} and 3^{rd} rows of the puncturing matrices associated to the frame structure of Type I and III). Therefore the BS and the RS are transmitting uncorrelated symbols. Additionally, the MS can decode independently the parity data from the BS and RS due to the Alamouti STC.

3.4 ARQ protocol

The ARQ protocol considered here it is based on the Selective-Repeat scheme [21], as in HSDPA. Conventional ARQ protocols can be divided into two classes, Pure-ARQ and Hybrid ARQ protocols [21]. The difference between them is the task performed in the receiver and the type of the message transmitted. For the cooperative and non-cooperative strategies, only the MS informs to the BS if it has decoded the packet correctly (ACK) or wrongly (NACK). In the sequel the process for the different ARQ methods is described:

A. *Pure-ARQ*. If a packet is wrongly decoded, the MS asks for a retransmission. The BS transmits the same packet again. Then the MS discards the previous packet and tries to decode the new one.

B. *HARQ-I*. This protocol considers all the received packets (the same packet) and combines them using the Maximal Ratio Combining (MRC) technique (*chase combining*). Therefore, the SNR of the packet to decode is increased in each retransmission.

C. *HARQ-II*. When the BS has to retransmit a packet, this protocol adds new *redundancy* (new parity bits) by changing the puncturing matrix (*code combing*). The MS considers all the previous packets and builds a larger one with more *redundancy*. The MS tries to decode this new packet. With this protocol the *coding gain* is increased in each retransmission. In the case where some data is transmitted again, then the MRC technique has to be considered.

4 JOINT PROTOCOL AND DSTBC EVALUATION

Under the assumption that the re-use of the relay link is high, only the cooperative scheme of one user has been considered. This is a relevant assumption for a correct interpretation of the results below. If K users are transmitting simultaneously in the relay slot, the throughput figures need to be scaled by K/(K+1). Therefore, the throughput values below assume K>>1, (note that for 9 users, the total throughput has to be scaled by 0.9). A symmetric scenario has been fixed for simulations, each link have the same average SNR. The results analysed in terms of throughput are divided in 7 sections, in order to evaluate separately, the effect of the selected ARQ protocol for D&F transmission, the performance of the Non-Cooperative transmission, the effect of cooperative D&F transmission, the effect of cooperative A&F transmission, the effect of cooperative Mixed D&F and finally the comparison between linear vs. non-linear receivers.

4.1 Configuration

In Table I the main parameters of the simulation has been summarized. The channel coefficients include the zero-mean complex Gaussian component accounting for the Rayleigh fading. The Zero-Forcing receiver (for the Alamouti STC) and the list Sphere Decoder [28] followed by a max-log MAP turbo decoder [29] have been considered.

The different strategies are compared in terms of throughput versus SNR, that is, expected number of correctly decoded information bits per channel use,

$$\eta = E\{\eta_{inst}\} = E\left\{\frac{N_{bits}}{N_{tx}N_{ch}}\right\} \quad \text{[bits/channel use]} \tag{12}$$

with N_{bits} the number of the transmitted bits, N_{tx} the number of transmissions from the BS to MS required to receive the packet correctly and N_{ch} the number of channel uses. Only the channel uses in the link BS-MS have been considered. To evaluate the throughput, every packet is transmitted until it is correctly decoded or a maximum number of 10 re-transmissions are employed. After this, the packet is considered in error and produces an instantaneous throughput value η_{inst}=0.

For the HARQ-II protocol up to 3 different puncturing matrices have been defined in the BS and other 3 for the RS (for Cooperative D&F and Mixed D&F). As we have fixed the maximum number of re-transmissions to 10, the puncturing matrices have to be used several times. In that case, this protocol uses the MRC technique to combine the different packets. Additionally, because of the use of a simple turbo code of rate 1/3 sometimes it is not possible to send 10 retransmissions containing only “new” parity bits.

4.2 Effect of the ARQ protocol in cooperative D&F

In this subsection we present the throughput performance for the C-D&F strategy under the different ARQ protocols. In figure 7, the throughput obtained for the C-D&F (RS always transmit, *persistent transmission*) is depicted for the different ARQ protocols. Different codeword rate has been selected (from 1 (*uncoded*) to 1/3). It is shown that for a given codeword rate, see for instance ¾ (*right-triangle*), the worst performance (at low SNR) is obtained for Pure-ARQ. The HARQ-I improves throughput and the best operation (though the gains are not really significant) is obtained for HARQ-II. Additionally, for the HARQ-II protocol the throughput can be improved by decreasing the length of the retransmissions, because it can efficiently adapt to the channel state, see Figure 8. Note that for a SNR of 10 dB and code rate 1, there is an improvement of 0.9 bit/s/Hz between partial (figure 8-right) and full slot retransmission (figure 8-left), and for SNR=4 dB and code rate ¾ the difference is about 0.3 bit/s/Hz. It is important to remark the effect obtained at low SNR, where the full-slot retransmission is better than partial slot option because of the fixed number of transmissions. The reason for this behaviour is the following: given the same number of transmissions the full slot option can transmit more symbols (systematic or parity) than the partial slot mode.

4.3 Non-Cooperative MIMO transmission

Figure 9, shows the performance in terms of Throughput and Average Number of Transmissions (ANT) when the Alamouti ST code has been selected for the Non-Cooperative MIMO transmission. The retransmission scheme selected is the HARQ-II, because it was shown in the previous sub-section to be the best one in terms of throughput. Non-Cooperative throughput results will be taken as relevant reference for the cooperative case presented in the following sections (let us recall that the BS is using M=2 antennas and the MS is using N=1 antenna).

4.4 Performance of the cooperative D&F transmission

- Diversity Gain

The average throughput of the cooperative transmission may be compared to the average capacity of an ideal 2×2 MIMO system using 4QAM. For full diversity, we use the Alamouti ST code and assume two possible policies for the RS: *selective transmission*, the RS transmits only if it decodes correctly the packet, figure 10-left and *persistent transmission*, the RS always transmits figure 10-right. Additionally, it is shown how the RS may transmit regardless of erroneous reception without deteriorating the performance. That is because we are using the Alamouti code (optimum for 2x1 MIMO system) in the BS-RS link (2x2 MIMO system), thus RS can decode correctly most of the time. Both strategies improve the throughput of the non-cooperative scheme (around 2-3 dB, see figure 9). Moreover it is important to emphasize that only the channel uses between BS-MS have been considered to evaluate the throughput. In the case where the channel uses between RS-MS will also be considered, the selective transmission (only when the packet is correctly decoded) will exhibit an improved performance with respect to the persistent transmission policy. However, the exact evaluation of this gain entails the definition of cell-wide radio resource management strategies which fully exploit this behaviour.

- Multiplexing Gain

In the previous case, the selected STBC, does not fully achieve the multiplexing gain of a "virtual" MIMO system. Therefore, two new STBC are considered to test how much of this mux-gain may be achieved, the *VBLAST-C-D&F-RC* and *QOD–C-D&F-UC*, in figure 11-left and 11-right, respectively. It is shown that both codes achieve the capacity of a 2×2 MIMO system for high SNR values (QOD code presents a tighter performance) although for low SNR values the throughput is worse than in the previous cases, figure 9 and 10. This may be explained by the fact that we have traded mux-gain by diversity gain. This effect could be used efficiently in the dynamic control of the link by selecting the rate of the STC according to the state of the cooperative link. Figure 11 also shows that at low values of SNR the D&F-RC improves the D&F-UC (unlike what happens at high SNR region). This is because of the split of the ST codes between the BS and the RS. For D&F-RC we use VBLAST code at the BS, optimum for 2×2 MIMO system (BS-RS), whereas for the D&F-UC the BS uses a part of a QOD (designed for a 4×2 MIMO system, see figure 4) and the resulting ST code for the BS-RS link is not necessarily the optimum one.

4.5 Performance of the cooperative A&F transmission

In this section the A&F case is considered using the Alamouti code (*diversity gain*) and VBLAST code (*multiplexing gain*) ST codes (see results in figure 12-right). In this case distributed ST code cannot be considered because RS retransmits the received signal as it is received (including noise). This system is more similar to a "conventional" MIMO system because the ST codes are only applied at the BS. Notice that the performance is worse (around 1.5 dB) than D&F-RC case (figure 12-left) but it should be remarked that, in this situation, the RS can work with only R=1 antenna (moreover, the symmetric case is not the best scenario for the A&F; it requires a good link BS-RS or RS-MS so as not to amplify too much noise, see figure 13, where the SNR between RS-MS has been increased 3 and 6 dB over the SNR of the other links for A&F and D&F using Alamouti STC. Results show that C-A&F can improve the results obtained by the C-D&F). This system also outperforms the non cooperative system (see figure 9).

In figure 12 the trade-off between diversity and multiplexing gain is shown for the D&F and A&F. For low SNR values the Alamouti STC is better, whereas for high SNR the VBLAST code is more useful. This is again suggesting that the rate of the STBC should be a parameter to be used in link adaptation.

4.6 Performance of the cooperative mixed D&F transmission

The cooperative Mixed D&F combines the multiplexing gain with the diversity gain, by transmitting the systematic information using the VBLAST and the parity information with Alamouti. Figure 14-right shows the obtained throughput using this strategy. Results show that mixed strategy obtains good throughput results for high SNR values, nevertheless for low SNR the results are worse than Non-Cooperative, see Figure 9. Results are quite similar than the D&F-RC (VBLAST) (see figure 14-left). Additionally, it should be noted that the code rate is defined as the number of systematic bits over the parity bits, and for the mixed strategy, the effect of the rate ¾ is saturated at 2.4 (different value of D&F figure 14-left). This is due to the different channel uses assigned for systematic part (VBLAST–2 bits/s/Hz) and the parity part (Alamouti–1 bit/s/Hz).

4.7 Linear *vs* Non-linear Receivers

Finally, in this section a comparison between linear (Zero Forcing) and non-linear (list-SD) decoders is presented. Figure 15 shows the different performance of the receivers when a non-orthogonal STC (VBLAST in this case) is considered. It can be seen a difference around 4 dB at 2.5 bits/s/Hz. Therefore, the use of non-linear receivers is recommended for non-orthogonal STC.

5 CONCLUSIONS

In this paper the cooperative transmission applied in the downlink has been investigated, using different schemes that combine ARQ, STBC and turbo codes to achieve results close to the true capacity of the system. It has been shown that cooperation outperforms the direct transmission in terms of throughput when a high re-use of the relay link is considered. Additionally, different ARQ protocols have been considered and Hybrid protocols have shown better performance than Pure ARQ. For medium to high SNR values, the HARQ-II with partial slot retransmission seems to be needed to achieve better throughput results.

The following conclusions may be drawn :

a) It has been shown that C-D&F (RS decodes the received data) is the best cooperative strategy in terms of throughput. For low SNR values a strategy exploiting the diversity gain (Alamouti) is the best, and hence, the selection of the rate for the STBC seems to be a useful strategy.

b) For the symmetric scenario (and since we have only considered the channel uses between BS and MS) the use of selective transmission does not seem to offer significant gains, that is, transmissions from the RS always seem to be rewarding even of some errors are encountered.

c) Whereas for medium and high SNR values, strategies using the multiplexing gain with distributed Space-Time codes (RC, UC or Mixed C-D&F) are better in terms of throughput than the Non-Cooperative, the best is the C-D&F-UC. This result has to be considered for the BS in order to maximize the user throughput, i.e., again it is necessary a suitable selection of the STC depending on the channel state.

d) Additionally, the analysis for the A&F also has considered. Slight SNR losses are observed with respect to C-D&F, but there are two points to emphasize, it only uses 1 antenna at the RS (in the D&F R=2 are required) and the symmetric configuration (equal average SNR in all links) is slightly penalising its performance. Moreover, if other scenarios are considered (asymmetric) the C-A&F can achieve better throughput results than the C-D&F, see figure 13. For these reasons this strategy shows a good compromise between the performance and the complexity at RS.

e) Finally, a comparison between linear (ZF) and non-linear (list-SD) receivers has analysed. Differences around 4 dB have been found when non-orthogonal STC are considered. Therefore, the use of non-linear receivers seems to be required for the cases where the non-orthogonal STC are used.

6 ACKNOWLEDGMENTS

This work has been carried out in the framework of the EC-funded project ROMANTIK (IST-2001-32549) and supported by Spanish and Catalan Government Grants: TEC 2004-04526 and TIC2003-05482 and 2001SGR-00268

7 REFERENCES

[1] I.E.Telatar, Capacity of Multi-antenna Gaussian Channels, European Transactions on Telecommunications, vol 10, pp 585-595, Nov/Dec 1999.

[2] G.Foschini, M.J.Gans, On limits of wireless communications in a fading environment when using multiple antennas, Wireless Personal Commun, vol 6, nº 3, pp 311-335, 1998.

[3] L.Zheng, D.N.C. Tse, Diversity and Multiplexing: A fundamental tradeoff in Multiple Antenna Channels, IEEE Trans. on Information Theory, vol 49, nº 5 May 2003.

[4] T.M.Cover, A.A.El Gamal, Capacity Theorems for the Relay Channel, IEEE Trans. on Information Theory, vol 25, nº 5, pp 474-584, September 1979.

[5] A.Sendonaris, E.Erkip, B.Aazhang, User Cooperation Diversity-Part I: System Description, IEEE Trans. on Comm, vol 51, nº 11, November 2003.

[6] J.Laneman, D.N.C. Tse, G.W.Wornell, Cooperative diversity in wireless networks: Efficient protocols and outage behaviour, IEEE Trans. Inform. Theory, vol 50 nº 12, pp. 3062 – 3080. December 2004.

[7] M.Dohler, Virtual Antenna Arrays, PhD Thesis, King's College London, 2003.

[8] M.Dohler et al, State by stage detection of distributed space-time block encoded relaying networks, Proc of Personal Indoor and Mobile Radio Communications (PIMRC), September 2004, Barcelona (SPAIN)

[9] A. Wittneben, B.Rankov, Impact of cooperative relays on the capacity of rank deficient MIMO channels, Proceedings of IST Summit 2003.

[10] R. Nabar, H. Bölcskei, F. Kneubühler, Fading Relay Channels: Performance Limits and Space-Time Signal Design, IEEE Journal Selected Areas Comm, vol 22, no 6, Aug 2004.

[11] M.C.Valenti, B.Zhao, Distributed Turbo Codes: Towards the Capacity of the Relay Channel, Proc. Of IEEE Vehicular Technology Conference (VTC), October 2003, Orlando (USA).

[12] A.Nosratinia, T.E.Hunter, A.Hedayat, Cooperative Communication in Wireless Networks, IEEE Communications magazine, October 2004

[13] T.E. Hunter, A. Nosratinia, Performance Analysis of Coded Cooperation Diversity, Proc. of ICC 2003, vol 4, pp 2688-2698

[14] J.N.Laneman, G.W.Wornell, Distributed Space-Time Coded protocols for exploiting Cooperative Diversity in Wireless Networks, IEEE Trans. on IT, vol 49, nº 10, October 2003.

[15] A.Host-Madsen, On the Capacity of the Wireless Relaying, Proceedings VTC 2002-Fall. Vol 2, September 2002, pp – 1187-1191.

[16] B.Wang, J.Zhang, A.Host-Madsen, On the capacity of MIMO Relay channels, IEEE Trans. On IT, vol 51, nº 1, January 2005. pp 29-43.

[17] S.Barbarossa, G. Scutari, Cooperative diversity through virtual arrays in multihop networks, ICASSP 2003, Hong-Kong, April 2003.

[18] G.Scutari, S. Barbarossa, D. Ludovici, Cooperation diversity in multihop wireless networks using opportunistic driven multiple access, Proceedings of SPAWC 2003, Rome (Italy), June 2003.

[19] S.Barbarossa,G.Scutari, Distributed Space-Time Coding strategies for wideband multihop networks: Regenerative vs non-regenerative relays, Proceedings of ICASSP 2004,May 17-21, Montreal, (Canada)

[20] A.Agustin, O.Muñoz and J.Vidal, A game theoretic approach for cooperative MIMO schemes with cellular reuse of the relay slot, Proc. ICASSP 2004, May 17-21, Montreal (Canada)

[21] D.J.Costello, J.Hagenauer, H.Imai, S.B.Wicker, Applications of Error-Control Coding, IEEE Trans. Inform. Theory, vol 44, nº 6, October 1998, pp 2531-2560.

[22] D.N. Rowitch, L.B. Milstein, On the Performance of Hybrid FEC/ARQ systems using rate compatible Punctured Turbo (RCPT) Codes, IEEE Trans on Comm, vol 48, no 6 June 2000.

[23] O.Damen, A. Chkeif, J. Belfiore, Lattice Code Decoder for Space Time Codes, IEEE Comm Letters, vol 4, no 5, 2000, pp 161-163.

[24] D.Pérez-Palomar, A.Agustin, O.Muñoz, J.Vidal, Decode-and-Forward Protocol for Cooperative Diversity in Multi-Antenna Wireless Networks, Proc. IEEE CISS-04, March 2004, Princeton, (USA).

[25] B.Hassibi, B.M.Hochwald, High-rate codes that are linear in space and time, IEEE Trans. on IT, vol 48, pp 1804-1824, July 2002.

[26] A.Agustín,A.Pagès-Zamora,J.Vidal,LDC consruction with a defined structure, VTC Fall-03, Orlando (USA), October 2003.

[27] J. P.Woodard, L. Hanzo, Comparative Study of Turbo Decoding Techniques: An overview, IEEE Trans. Vehic. Techn., vol 49, no 6, November 2000.

[28] B.M.Hochwald, S.ten Brink, Achieving Near-Capacity on a Multiple Antenna Channel, IEEE Trans. Comm. March 2003.

[29] J.Vogt, A.Finger, Improving the max-log-MAP turbo decoder, Electronics letters 2000, vol 36 nº 23.

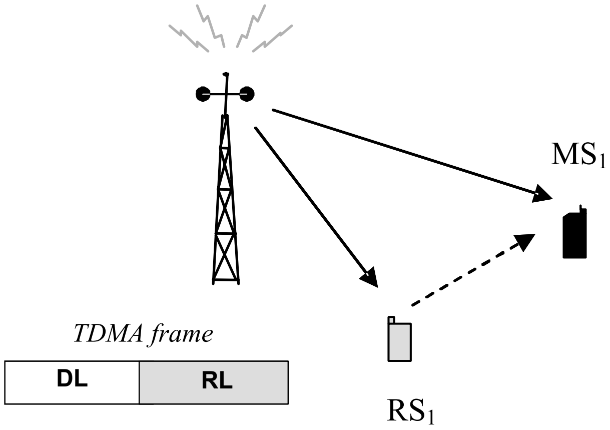


Figure 1 – Single user cooperative transmission. Solid line: transmissions in the DL. Dashed line: transmissions in the RL.

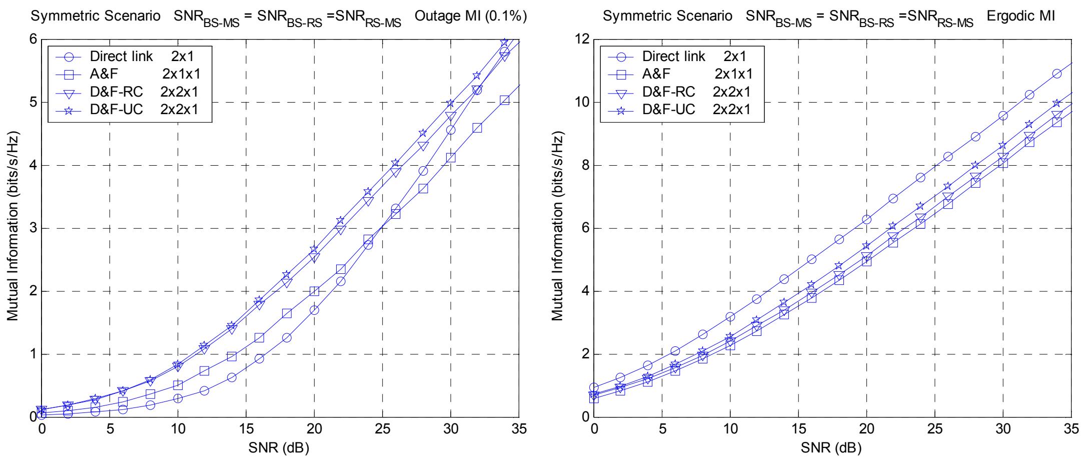


Figure 2 –(Left) 10^{-3} outage capacity and (right) ergodic capacity for the 2x1 direct transmission, A&F (2x1x1), D&F-RC(2x2x1) and D&F-UC(2x2x1). Symmetric scenario (equal SNR at all links is considered).

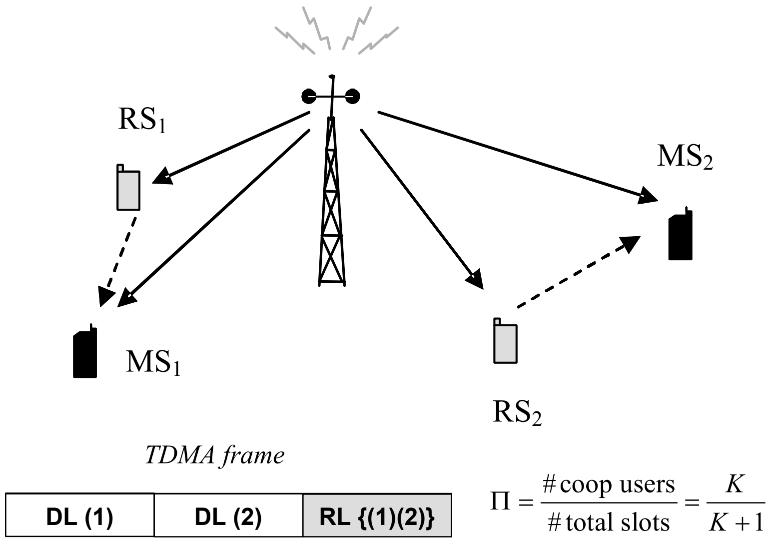


Figure 3- DL cooperative transmission scheme for 2 users. Solid line: transmissions in the DL. Dashed line: transmissions in the common RL

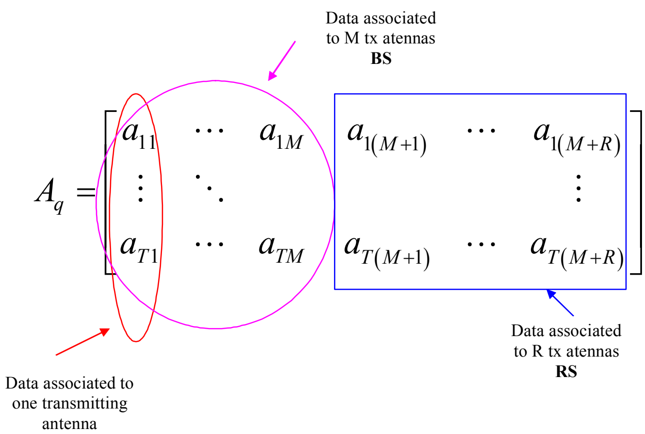
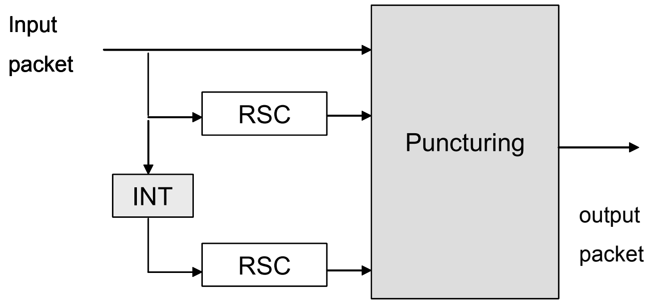


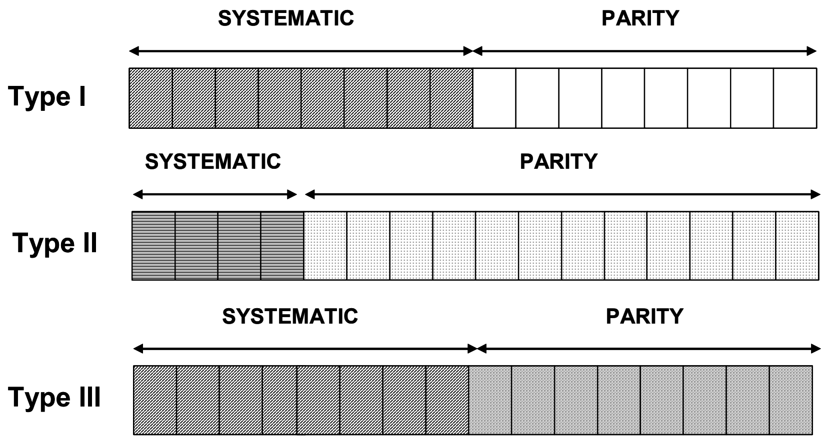
Figure 4- Division of a Space-Time Matrix between the BS and RS for D&F-UC. Different columns of a STBC are associated to the BS and to the RS, for high incorrelation between the symbols transmitted by each of them



$$\mathbf{P}_{1/2}^{(1)} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}$$

$$\mathbf{P}_{1/4}^{(2)} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

Figure 5 - Punctured turbo code encoder



$$P_{BS\_1/2} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}$$

$$P_{RS\_1/2} = \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 & 0 \end{bmatrix}$$

$$P_{RS\_1/2} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$$

Figure 6 – Different frame structure and puncturing matrices associated to BS and RS transmissions. Different textures indicate different puncturing matrices.

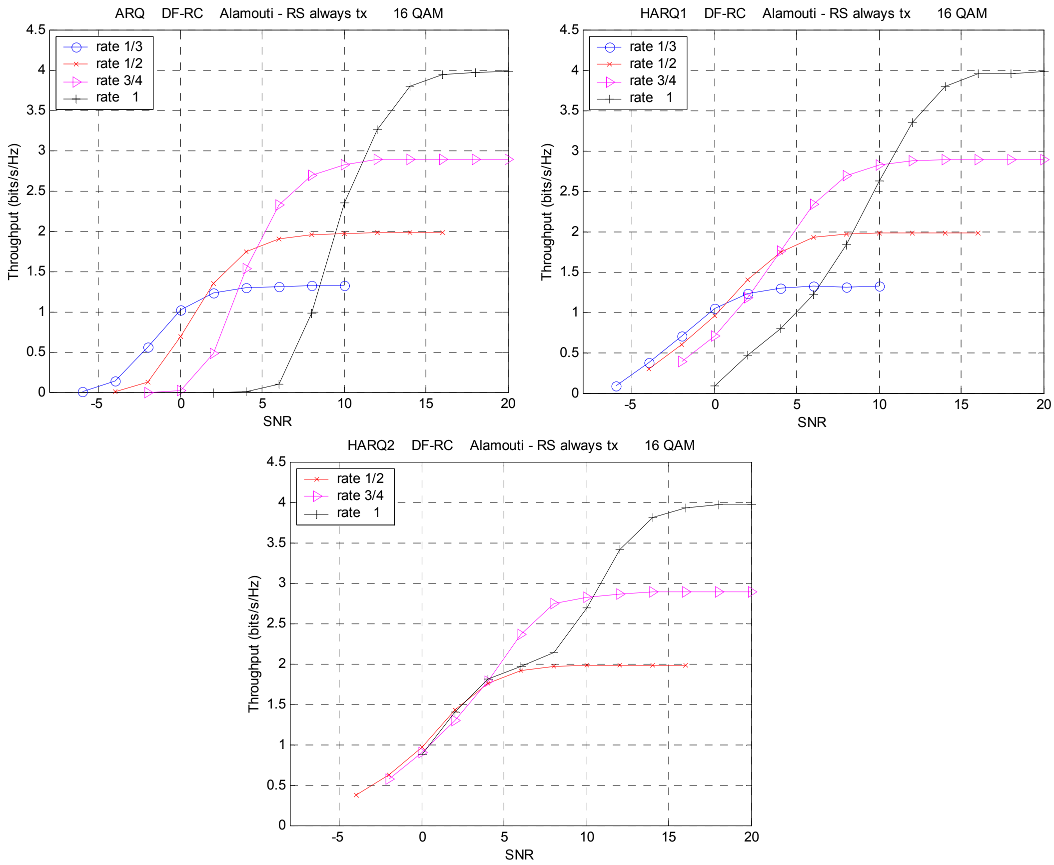


Figure 7 – Throughput performance for different Pure-ARQ (left-above), HARQ-I (right-above) and HARQ-II (below) for the cooperative D&F (diversity gain) where the RS always transmits. 16 QAM. Alamouti STC. ZF - receiver

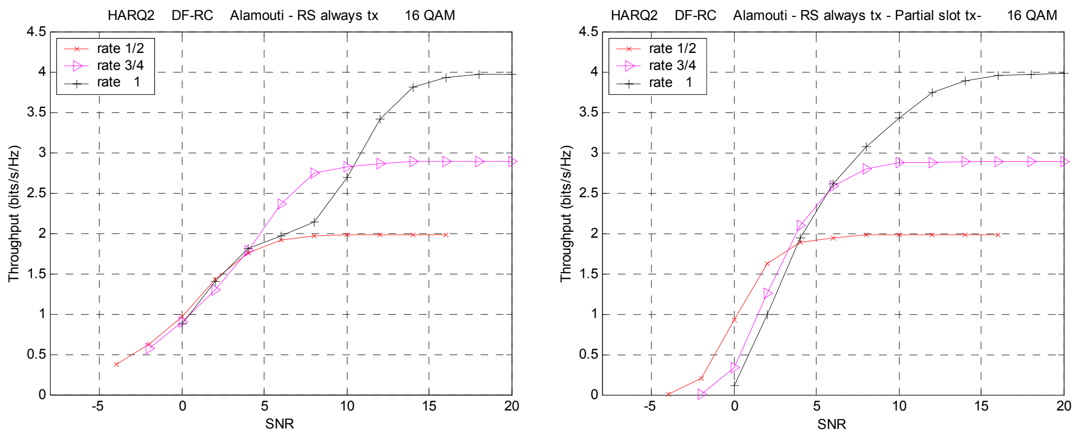


Figure 8 – Effect of the length of the transmissions for the HARQ-II, full slot (left) and partial slot retransmission (right). C-D&F (diversity gain) where the RS always transmits. ZF-receiver.

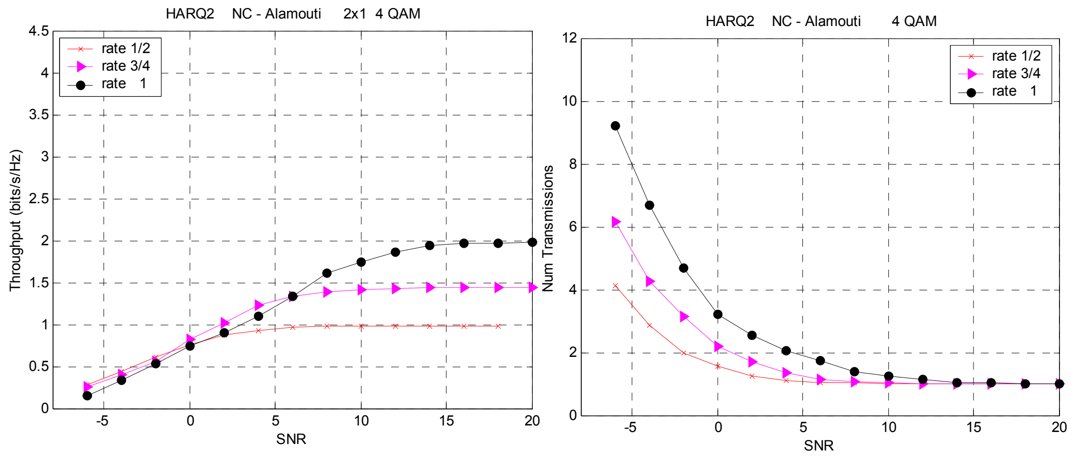


Figure 9 – Throughput (left) and average number of transmissions (right) for non-cooperative scheme using HARQ-II and codes RCPT with rates {1/2 , ¾ ,1}, 4 QAM. ZF-receiver

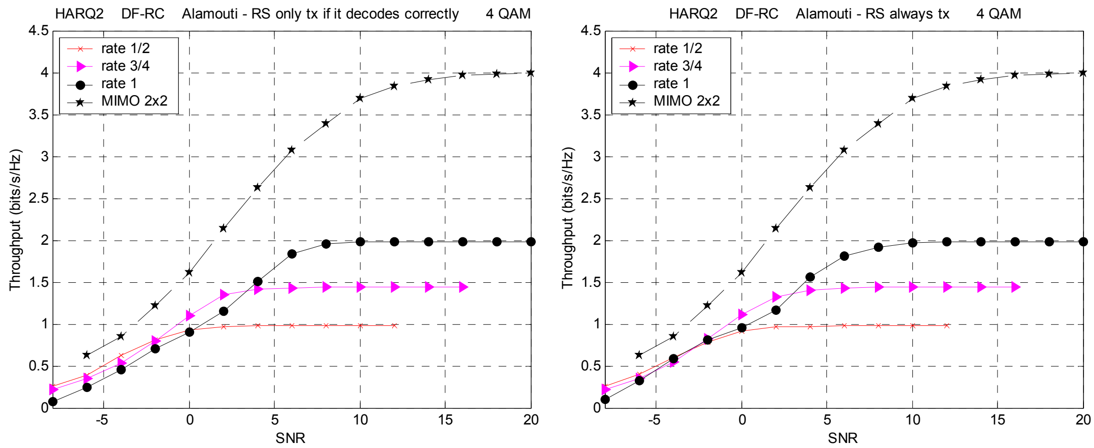


Figure 10- Throughput for C-D&F scheme with HARQ-II with RCPTC of rates {1/2, ¾,1}. Selective transmission (left) and RS always transmit (right). ZF-receiver

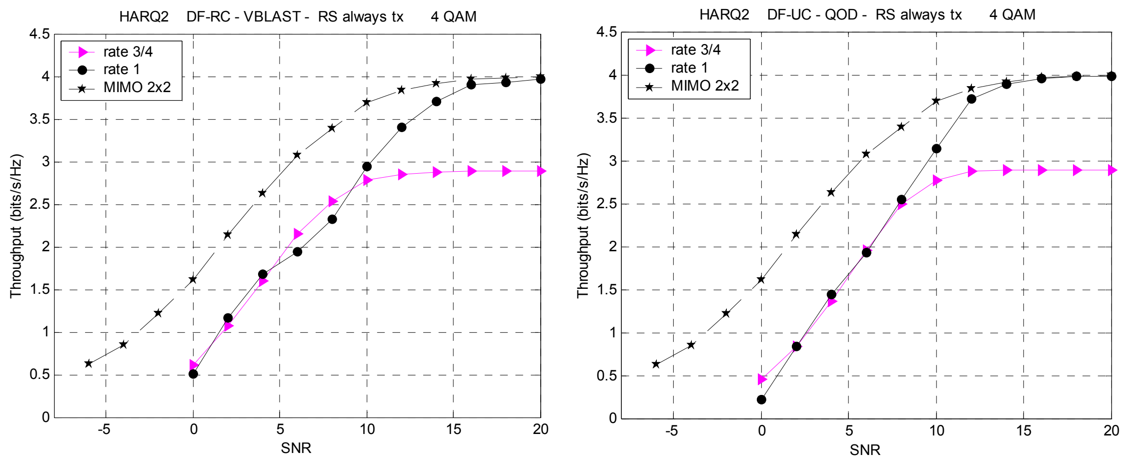


Figure 11- Throughput for C-D&F scheme with HARQ-II with RCPTC of rates {3/4,1} using VBLAST (left) and QOD (right) STC. List-SD receiver.

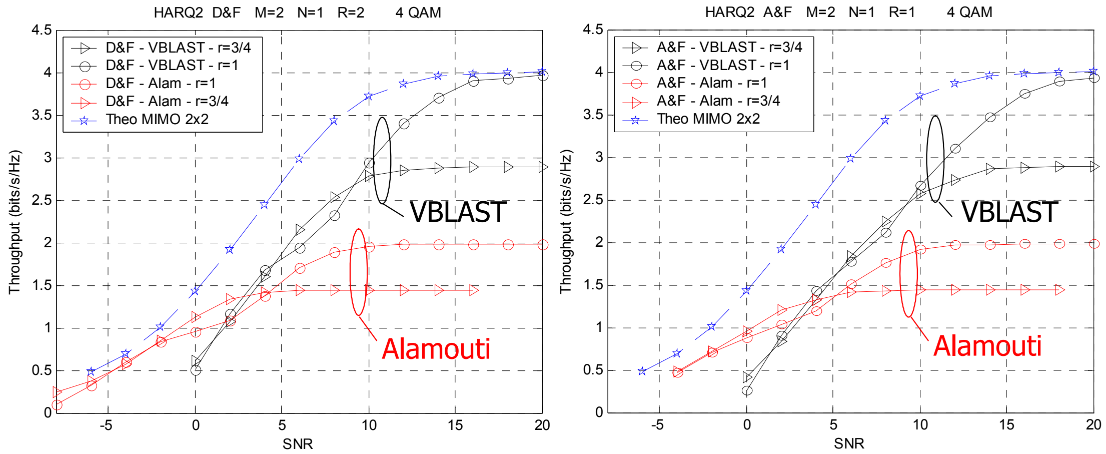


Figure 12 - Throughput for C-D&F (left) and C-A&F (right) schemes with HARQ-II with RCPTC of rates {3/4, 1} using VBLAST (list-SD) and Alamouti STC (ZF)

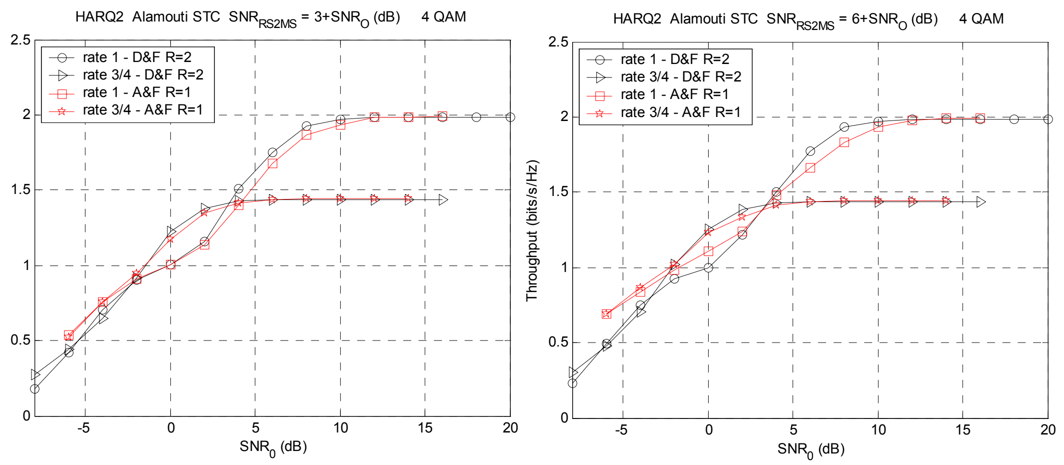


Figure 13 - Throughput for C-D&F and C-A&F schemes with HARQ-II with RCPTC of rates {3/4, 1} using Alamouti STC (ZF), for $SNR_{RS2MS}=3+SNR_0$ (left) and $SNR_{RS2MS}=6+SNR_0$ (right). $SNR_{BS2RS}=SNR_{BS2MS}=SNR_0$.

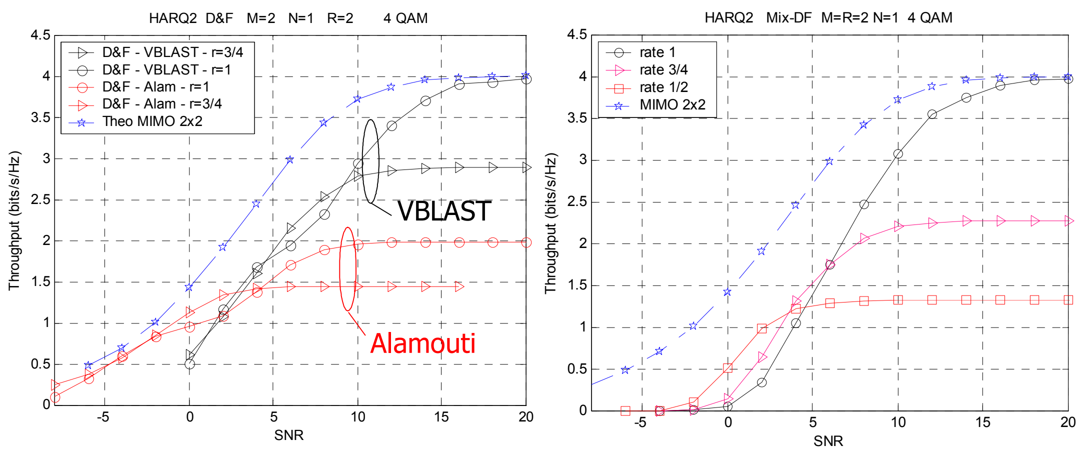


Figure 14 - Throughput for C-D&F (left) and C-Mixed D&F (right) schemes with HARQ-II with RCPTC of rates {3/4, 1} using VBLAST and Alamouti STC

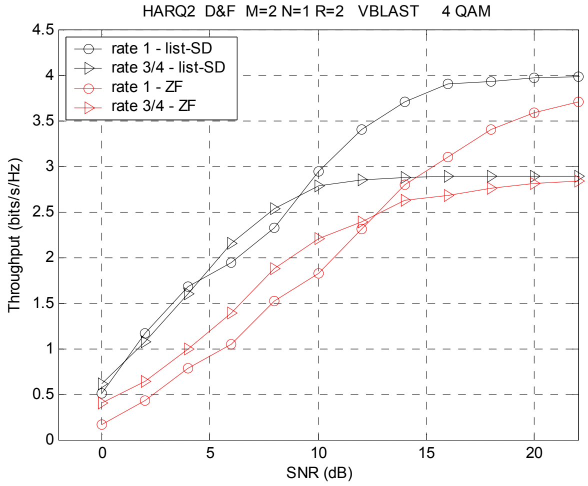


Figure 15 - Throughput for C-D&F schemes with HARQ-II with RCPTC of rates {3/4,1} using VBLAST with the list-SD and the ZF receiver.

Scenario	*Symmetric SNR configuration for all links involved in the cooperative transmission*
Channel	*Rayleigh flat fading channel*
STC	*Alamouti, VBLAST, QOD*
FEC codes	*Turbo Codes (1/3) with S-random interleaver*
Constellation	*4-QAM and 16-QAM*
Receiver	*Zero-Forcing, list-Sphere Decoder*
ARQ	*Pure-ARQ, HARQ-I, HARQ-II*
Length of Re-tx	*Full slot and Partial Slot (1/4)*
Max. tx per message	*10*

Table I .- Configuration of the simulations