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# Two-Level HARQ for Turbo Coded Cooperation

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**Abstract**—Wireless networks can exploit an implicit distributed diversity by the use of cooperative systems thanks to the broadcast nature of the radio link. Cooperation leads to improvements in terms of throughput and/or performance and decreases the sensitivity to channel variations. In this paper, a practical approach for a two-user cooperative wireless network is proposed based on a particular hybrid automatic repeat request (HARQ) protocol and turbo coded cooperation. In particular, we propose a two-level ARQ protocol where decision on retransmission is conditioned by two levels; first by the feedback from the destination and second by the feedback from the partner node. The proposed two-level ARQ protocol, combined with turbo coded cooperation, is designed to guarantee inter-user channel improvement through the relay-level ARQ, and consequently better overall system performance and higher throughput by controlling retransmission at destination side.

## I. INTRODUCTION

Recently, cooperative communication has emerged as an efficient concept that draws some of the benefits of multiple antenna devices, such as spatial diversity gain over wireless fading channels, without requiring multiple antennas at each node. The simplest cooperative scheme is the relay channel, introduced by van der Meulen in [1]: a source communicates with a single destination with the help of a relay, which assists the source by forwarding extra information to the destination. This forwarding can be performed in several ways. Among them, decode-and-forward [2] is very popular due to its simplicity and performance.

Turbo codes are a natural fit for relay channels, since two codewords are generated (at the source and at the relay). This principle, called *distributed turbo coding* was introduced in [3], where channel coding and cooperation were combined. The relay decodes, interleaves and re-encodes the message prior to forwarding. The overall network can be regarded as a (distributed over space) turbo code. This approach benefits from cooperative diversity, coding and turbo processing gain. This work was later extended to a two-user wireless network in [4, 5], called *coded cooperation*; each user is responsible for transmitting not only its own information, but also some version of the partner information. Therefore, transmitting nodes play both roles: source and relay.

Automatic repeat request (ARQ) techniques can be adopted in cooperative wireless networks to overcome throughput degradation due to the cooperative phase and to strengthen the user-to-relay and user-to-destination links. Several works on ARQ protocols combined with relaying schemes or applied to cooperative users can be found in the literature, e.g. [6–9].

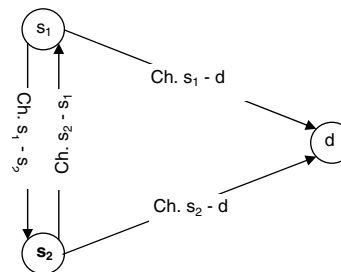


Fig. 1. A three-node cooperative wireless network.

In this paper, we consider ARQ techniques for a two-user wireless network with coded cooperation. The proposed protocols combine the **turbo-based hybrid ARQ (HARQ) protocol** [10] at data link layer and the turbo coded cooperation at physical layer [5]. In particular, we consider three ARQ protocols. A first protocol, called destination-level ARQ, is proposed to avoid the throughput degradation due to the cooperation phase when packets are received correctly at the destination. A similar idea was used in [11] in the context of **relay systems**. A second cooperative ARQ protocol, called relay-level hybrid ARQ, is then addressed to favor cooperation between users by improving the inter-user link channels. Alike the principle of turbo coded cooperation, since two codewords are available at partner node among two successive transmissions, this protocol involves iterative decoding at partner side and, therefore, ensures more cooperation. Finally, a third protocol combining destination-level and relay-level protocols, referred to as two-level ARQ, is proposed. This designation comes from the fact that decision on retransmission at each node is conditioned by two levels: first by the feedback from the destination and second by the feedback from the partner node.

## II. SYSTEM MODEL

We consider the wireless relay network depicted in Fig. 1. Two sources  $s_1$  and  $s_2$  cooperate to transmit statistically independent data to a single destination  $d$ . Source  $s_i$  ( $i = 1, 2$ ) can either transmit its own local information (transmission mode) or help the partner node by relaying its information (relaying mode). We denote by  $\mathbf{u}_{iL}$  and  $\mathbf{u}_{iR}$  the local user data and the relayed user data, respectively, at source  $s_i$ . Both sources are equipped with two recursive convolutional encoders  $\mathcal{C}_a$  and  $\mathcal{C}_b$  of rates  $R_a = 1/2$  and  $R_b = 1$ , respectively.

In the following, we briefly describe the coded cooperation scheme of Fig. 1 when no ARQ is used. We assume time division multiple access (TDMA), therefore all channels are orthogonal. Without loss of generality, we focus on the information generated at node  $s_1$ . The transmission of user data  $\mathbf{u}_{1L}$ , of length  $K$  bits, is performed over two time slots, also called phases. In the first phase, referred to as the *broadcast* phase, source  $s_1$  encodes  $\mathbf{u}_{1L}$  by  $\mathcal{C}_a$  into codeword  $\mathbf{x}_{1L}$ , of length  $N_a = K/R_a = 2K$  bits.  $\mathbf{x}_{1L}$  is augmented with a cyclic redundancy code (CRC) in order to facilitate error detection and transmitted over the wireless channel. For simplicity, in the remainder of the paper, when referring to a codeword  $\mathbf{x}$ , we shall assume that it includes a CRC check. Due to the broadcast nature of the wireless channel both the destination and the partner node  $s_2$  receive a noisy observation of  $\mathbf{x}_{1L}$ , denoted by  $\mathbf{y}_{1L}^d$  and  $\mathbf{y}_{1L}^{s_2}$ , respectively. If decoding is successful at node  $s_2$  (i.e.  $s_2$  is able to regenerate  $\mathbf{u}_{1L}$ ), it switches to the relaying mode; at the second phase, referred to as the *cooperation* phase,  $\mathbf{u}_{1L}$  is then interleaved through an interleaver  $\pi$  into  $\mathbf{u}_{2R} = \pi(\mathbf{u}_{1L})$ , encoded by  $\mathcal{C}_b$  into  $\mathbf{x}_{2R}$  and forwarded to the destination. The received observation of  $\mathbf{x}_{2R}$  is denoted by  $\mathbf{y}_{2R}^d$ . On the other hand, if decoding is not successful,  $s_2$  operates in the transmission mode (non-cooperative); at the second phase  $\mathbf{u}_{2L}$  is then interleaved by  $\pi$  into  $\tilde{\mathbf{u}}_{2L}$ , encoded by encoder  $\mathcal{C}_b$  into  $\tilde{\mathbf{x}}_{2L}$  and forwarded to the destination. The received vector is denoted by  $\tilde{\mathbf{y}}_{2L}^d$ . A similar operation is performed at node  $s_1$  during the second phase. Correspondingly, we define the vectors  $\mathbf{x}_{1R}$ ,  $\mathbf{y}_{1R}^d$ ,  $\tilde{\mathbf{x}}_{1L}$  and  $\tilde{\mathbf{y}}_{1L}^d$ .

(Remark: Notice that with some abuse of language we call the second phase the *cooperation* phase. However, in this phase source  $s_i$  may work either in the transmission mode or in the relaying mode, depending on the CRC check).

With reference to source  $s_1$  four cases are possible at the destination:

- 1) decoding at nodes  $s_1$  and  $s_2$  is successful: the destination receives two noisy observations of  $\mathbf{x}_{1L}$ ,  $\mathbf{y}_{1L}^d$  and  $\mathbf{y}_{2R}^d$ , from  $s_1$  and  $s_2$ , respectively. Notice that  $\mathbf{x}_{1L}$  and  $\mathbf{x}_{2R}$  form a codeword of a (distributed) turbo code, where the first component codeword is generated at  $s_1$  and the second component codeword is generated at  $s_2$ . Therefore, the relay network of Fig. 1 behaves as a distributed (over space) turbo code, and the destination can estimate  $\mathbf{u}_{1L}$  by exploiting jointly  $\mathbf{y}_{1L}$  and  $\mathbf{y}_{2R}$  in an iterative fashion.
- 2) decoding at node  $s_1$  is successful, decoding at node  $s_2$  fails: the destination attempts to estimate  $\mathbf{u}_{1L}$  by decoding  $\mathbf{y}_{1L}^d$ .
- 3) decoding at node  $s_1$  fails, decoding at node  $s_2$  is successful: the destination receives three noisy observations of  $\mathbf{x}_{1L}$ ,  $\mathbf{y}_{1L}^d$ ,  $\tilde{\mathbf{y}}_{1L}^d$  and  $\mathbf{y}_{2R}^d$ , which are decoded in a turbo fashion.
- 4) decoding at nodes  $s_1$  and  $s_2$  fails: the destination receives two noisy observations of  $\mathbf{x}_{1L}$ ,  $\mathbf{y}_{1L}^d$  and  $\tilde{\mathbf{y}}_{1L}^d$ . Therefore, a distributed (over time) turbo code is obtained and the destination can estimate  $\mathbf{u}_{1L}$  in an iterative fashion.

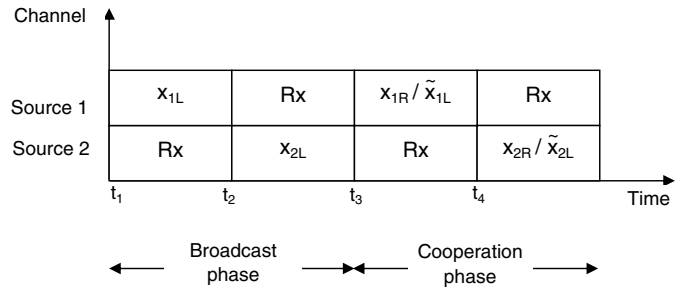


Fig. 2. Coded cooperation. Transmission of user data  $\mathbf{u}_{1L}$  and  $\mathbf{u}_{2L}$  is performed over two phases.

tive fashion.

The four cases are summarized in Fig. 2.

### A. Channel Model

We denote by  $\gamma_{s_i d}$  and  $\gamma_{s_i s_j}$  the signal-to-noise ratio  $E_s/N_0$  of the source  $i$ -to-destination channel and of the source  $i$ -to-source  $j$  channel, respectively, where  $E_s$  is the received signal energy and  $N_0$  is the single-sided noise power density. All channels are modeled as quasi-static Rayleigh fading channels, and BPSK modulation is assumed. Also, we assume that  $\gamma_{s_1 d} = \gamma_{s_2 d} = \gamma_{sd}$  and  $\gamma_{s_1 s_2} = \gamma_{s_2 s_1} = \gamma_{ss}$ . At the destination, the received symbol  $y_{1L}^d$  from source  $s_1$  is given by:

$$y_{1L}^d = h_{s_1 d} \bar{x}_{1L} + n \quad (1)$$

where  $\bar{x}_{1L} \in \{\pm 1\}$  denotes the BPSK modulated symbol of bit  $x_{1L}$ ,  $n$  is the AWGN noise and  $h_{s_1 d}$  is the channel gain, assumed to be Rayleigh-distributed with zero-mean and variance  $\sigma_{1d}^2 = E[h_{s_1 d}]$ . The coefficients  $h_{s_1 d}$  are assumed to be constant over the transmission of a packet  $\mathbf{u}_{1L}$ , i.e., over the two phases. Similar expressions are obtained for the symbols received from  $s_2$  and for the inter-user channels. On the other hand, we assume that the feedback channels are error free.

## III. PROPOSED ARQ PROTOCOLS

The goal of ARQ protocols in the two-user relay network of Fig. 1 must be twofold: first to increase throughput, by avoiding transmissions when unnecessary; second to improve error rate performance. With this aim, we propose three basic hybrid ARQ protocols, called relay-level ARQ, destination-level ARQ, and two-level ARQ, respectively. They are addressed in the following.

### A. Destination-Level ARQ Protocol

Compared to the non-cooperative scheme, coded cooperation may suffer from a throughput degradation, since two phases are always occupied for a single packet. The second phase brings degradation in throughput if the packets from both users are correctly decoded in the first phase. In this case, the additional phase is not required. To avoid this drawback ARQ can be performed at the destination: the destination estimates the transmitted data upon reception of  $\mathbf{y}_{1L}^d$  and  $\mathbf{y}_{2L}^d$  in the first phase. If decoding is successful (according to the

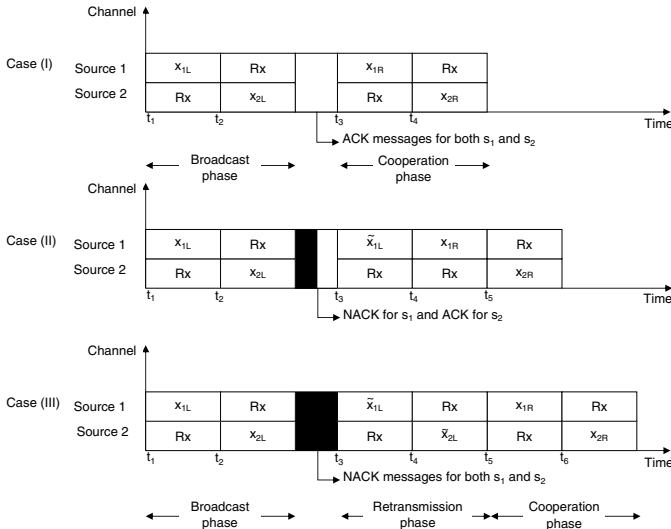


Fig. 3. Relay-level ARQ Protocol

CRC check) the second phase is not necessary, therefore an ACK is fed back to  $s_1$  and  $s_2$ . In this case transmission of  $u_{1L}$  and  $u_{2L}$  is limited to the first phase. Otherwise, if decoding of either  $u_{1L}$  or  $u_{2L}$  fails the destination feeds back a NACK and the cooperation phase is performed (see previous section).

### B. Relay-Level ARQ Protocol

It has been proved that diversity gain in coded cooperation systems is conditioned by the quality of the inter-user channels [5]. Indeed, diversity gain cannot be obtained unless successful decoding is accomplished at the partner node. An immediate suggestion from ARQ protocols to be designed for this system model is then to strengthen the inter-user link. Another problem of coded cooperation is that, depending on channel conditions, the resulting coding scheme is asymmetric, i.e., it favors one user over the other. Consider for instance the case where  $s_1$  decodes successfully and  $s_2$  does not. In that case, the destination will receive  $y_{1L}^d$  for  $u_{1L}$  and  $y_{2L}^d, \tilde{y}_{2L}^d$  and  $y_{1R}^d$  for  $u_{2L}$ . Therefore, a distributed turbo code is obtained for user  $s_2$  while the estimate of  $u_{1L}$  is based only on  $y_{1L}^d$ . As a result user 1 will suffer from a higher error probability. Relay-level ARQ can be used to avoid this drawback by allowing for more symmetry between users.

Here, we consider that source  $s_1$  ( $s_2$ ) implements an ARQ protocol upon reception of  $y_{2L}^{s_1}$  ( $y_{1L}^{s_2}$ ) in the first phase: CRC checking results at each source are fed back and exchanged between the two users. Three cases are possible:

- 1) decoding at nodes  $s_1$  and  $s_2$  is successful: both  $s_1$  and  $s_2$  transmit ACK messages which inform users that their packets were correctly received, and that relaying can be performed at both nodes. In the cooperation phase,  $s_1$  and  $s_2$  switch to the relaying mode to transmit  $x_{1R}$  and  $x_{2R}$ , respectively. Iterative decoding is possible for both sources at the destination. The protocol is depicted in Fig. 3.

- 2) decoding at node  $s_1$  is successful, decoding at node  $s_2$  fails:  $s_2$  stores the corrupted packet in a temporary buffer and feeds back a NACK, while  $s_1$  feeds back an ACK. A retransmission phase is then allocated for  $s_1$ , which transmits  $\tilde{x}_{1L}$ . Therefore,  $s_2$  can attempt to estimate  $u_{1L}$  from  $y_{1L}^{s_2}$  and  $\tilde{y}_{1L}^{s_2}$  applying turbo decoding. Then, the cooperation phase is performed as described in the previous Section. Note that if correct decoding is accomplished at  $s_2$ , the destination will receive three coded versions of  $u_{1L}$  ( $x_{1L}$ ,  $\tilde{x}_{1L}$  and  $x_{2R}$ ) while only two coded versions of  $u_{2L}$  ( $x_{2L}$  and  $x_{1R}$ ) are received. However, in all 4 possible cases turbo decoding at the destination is guaranteed thanks to the retransmission phase. In Fig. 3 depicts the case where  $s_2$  decodes correctly  $u_{1L}$  after the retransmission phase. The symmetric case is obtained if decoding at node  $s_2$  is successful and decoding at node  $s_1$  fails.

- 3) decoding at nodes  $s_1$  and  $s_2$  fails: each user stores the erroneous packet in a temporary buffer and sends a NACK message to request retransmission. A retransmission phase is then allocated for  $s_1$  and  $s_2$ , which transmit  $\tilde{x}_{1L}$  and  $\tilde{x}_{2L}$ , respectively. At partner node, iterative decoding using the two complementary transmission attempts is performed. The cooperation phase is then performed.

Note that due to the retransmission phase, the proposed ARQ protocol guarantees that iterative decoding for both users at destination is always possible even if only one source transmits in the relaying mode during the cooperation phase. Therefore, performance improvement is expected.

### C. Two-level ARQ protocol

Both destination-level and relay-level protocols can be combined to increase the throughput of the system and to improve error rate performance. We call this cooperation protocol *two-level ARQ*, since the protocol works at two levels: first, the destination feeds back ACK or NACK to the sources to determine whether the cooperation phase is required or not. The first ARQ level avoids degrading system throughput when packets are correctly decoded. Second, if a NACK was received, both sources feed back information on their own decoding to request retransmission from the partner node, if required. The goal of the second ARQ is to improve the inter-user channels, therefore allowing a higher degree of cooperation between users and a high symmetry, which will result in better performance. To illustrate the proposed protocol, we detail several possible cases:

- 1) decoding of both  $u_{1L}$  and  $u_{2L}$  is successful at the destination: the destination feeds back an ACK message to both users, informing that the cooperation phase is not required, and that transmission of the next information packet can be performed.
- 2)  $u_{1L}$  is corrupted at both destination and  $s_2$ : both the destination and  $s_2$  feed back a NACK message regarding  $u_{1L}$ . A retransmission phase is then allocated for  $s_1$ , which transmits  $\tilde{x}_{1L}$ .  $s_2$  attempts to decode  $u_{1L}$

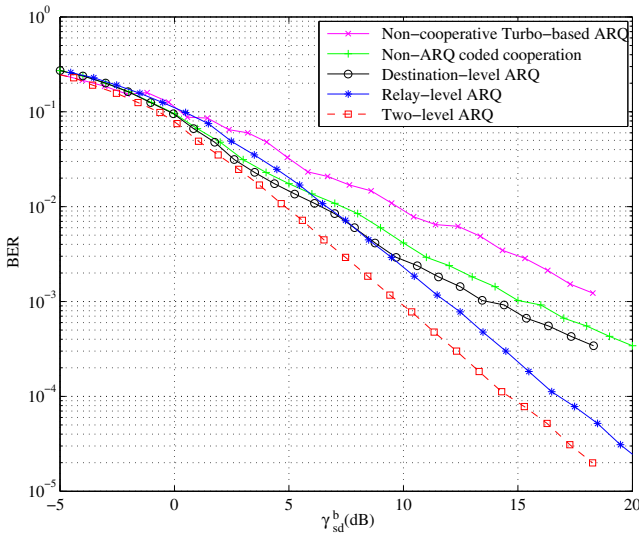


Fig. 4. Bit error rate curves of ARQ turbo coded cooperation for  $\gamma_{ss} = 6$  dB.

from  $\mathbf{x}_{1L}$  (from the broadcast phase) and  $\tilde{\mathbf{x}}_{1L}$  (from the retransmission phase) using iterative decoding. The cooperation phase is then performed as described in the previous Section.

- 3)  $\mathbf{u}_{1L}$  is corrupted at the destination but decoded correctly at  $s_2$ : the destination feedbacks a NACK regarding  $\mathbf{u}_{1L}$ ,  $s_2$  feedbacks an ACK. Since partner node feedback is positive, no retransmission phase is required for  $s_1$  and the cooperation phase is then performed.

#### IV. PERFORMANCE EVALUATION

In this Section, we give bit error rate (BER) results and throughput performance of the proposed ARQ protocols and compare them with the non-ARQ coded cooperation scheme and with the non-cooperative Turbo-ARQ of [10]. For the examples here we considered the rate-1/2 convolutional encoder with generator polynomials (1, 15/13) in octal form for  $C_a$  and the rate-1 convolutional encoder with generator polynomial (17/13) in octal form for  $C_b$ . The information block length is  $K = 128$  bits, a random interleaver is used for  $\pi$ , and at most one retransmission attempt is allowed.

In Fig. 4 BER curves are given for  $\gamma_{ss}^b = 6$  dB as a function of  $\gamma_{sd}^b$ , where  $\gamma^b = \gamma/R$ , being  $R$  the rate of the system. Note that the rate of the system depends on the code rate and the number of retransmission attempts. Adding cooperation to the non-cooperative Turbo-ARQ scheme yields 3.0 dB gain at  $\text{BER}=10^{-3}$ . This gain is exclusively due to cooperative diversity. The cooperative retransmission protocols improve BER performance compared to the original non-ARQ turbo coded cooperation system. The destination-level ARQ yields 1.5 dB gain at  $\text{BER}=10^{-3}$  with respect to the non-ARQ system, thanks to a better system rate (less retransmission attempts). Notice that in this case the slope of the curve does not change, since the level of cooperation does not improve with destination-level ARQ. On the other hand a

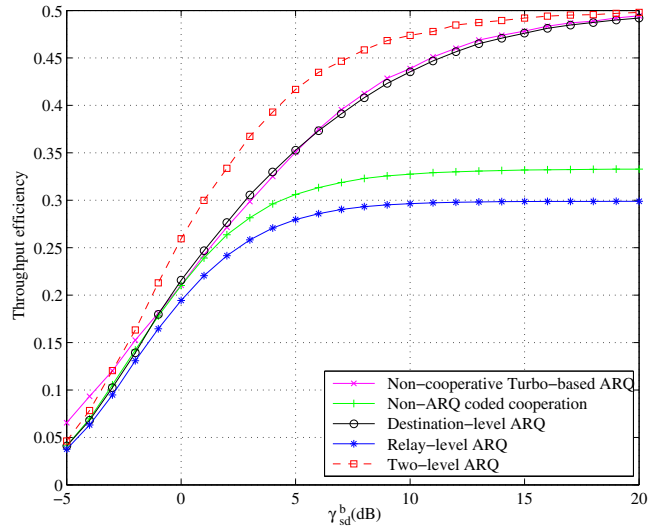


Fig. 5. Throughput efficiency of ARQ turbo coded cooperation as a function of  $\gamma_{sd}^b$ .  $\gamma_{ss} = 6$  dB.

higher diversity is obtained if relay-level ARQ is used (the quality of the inter-user channel is improved), thus improving BER for high  $\gamma_{sd}^b$ . The two-level ARQ protocol gives the best results: it achieves the diversity-gain of the relay-level protocol but it provides some extra coding gain, about 2 dB.

Throughput performance is reported in Fig. 5. In particular, we plot the *throughput efficiency* ( $\eta$ ), defined as [12]

$$\eta = \rho T \quad (2)$$

where  $\rho$  is the *reliability*, defined as the ratio between the number of correct bits and the number of received bits, and  $T$  is the *throughput* of the system, defined as the ratio between the average number of received bits and the total number of bits sent over the channel per unit time. Therefore, the throughput efficiency is defined as the ratio between the number of information bits correctly transmitted per user and time that channel is allocated to that user. The *throughput efficiency* of the coded cooperation system without ARQ is limited to  $\eta \leq 1/3$ , since two phases are always allocated for the transmission of a packet, hence  $R = 1/3$ . A throughput efficiency degradation is observed for the relay-level ARQ with respect to the non-cooperative scheme, since retransmissions can occur even if the packet is correctly decoded at destination in the broadcast phase. Notice that in this case the reliability  $\rho$  is improved (see Fig. 4), but not enough to compensate the degradation in throughput  $T$ . This phenomenon is more visible when inter-user channel is of bad quality. On the other hand, destination-level protocol avoids throughput degradation by allowing the cooperation phase only when it is necessary. In this case  $\eta$  tends to 1/2 since for high  $\gamma_{sd}^b$  only the broadcast phase is required, hence  $R = 1/2$ . However, as shown in Fig. 4 the error rate is higher than the one of the relay-level ARQ. The best results are achieved by the two-level ARQ protocol, since it combines the benefits of the destination-level protocol (i.e. increased throughput with respect to the non-



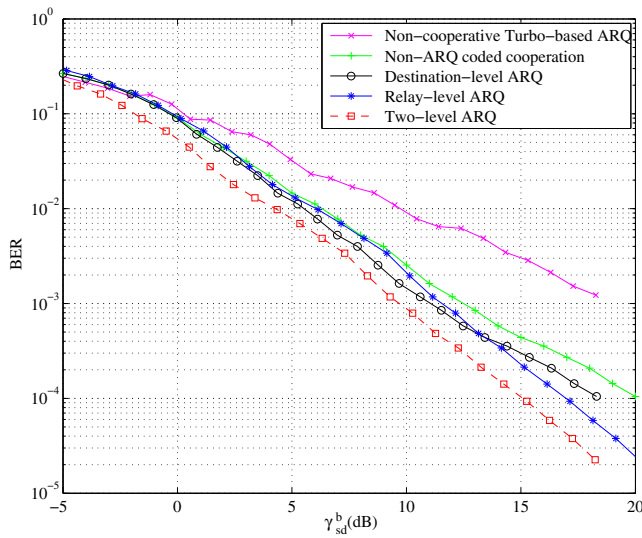


Fig. 6. Bit error rate curves of ARQ turbo coded cooperation for  $\gamma_{ss} = 12$  dB.

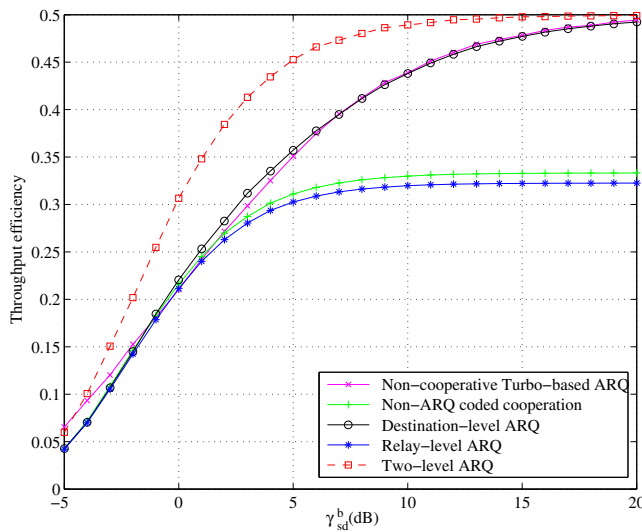


Fig. 7. Throughput efficiency of ARQ turbo coded cooperation as a function of  $\gamma_{sd}^b$ .  $\gamma_{ss} = 12$  dB.

ARQ cooperative scheme) and of the relay-level ARQ (higher reliability).

In Figs. 6 and 7 we plot BER curves and throughput efficiency performance, respectively, for  $\gamma_{ss}^b = 12$  dB. In terms of BER the destination-level ARQ curve improves with respect to Fig. 4, thanks to a better inter-channel user, while the performance of relay-level ARQ and two-level ARQ, are

similar. On the other hand, compared to the other presented protocols, the gain in throughput efficiency for the two-level ARQ protocol improves with  $\gamma_{ss}^b$ .

## V. CONCLUSIONS

In this work, three ARQ protocols applied to a two-user turbo coded cooperation scheme were presented. A first ARQ protocol, called destination-level ARQ, was considered to avoid throughput degradation due to the cooperation phase, when unnecessary. A second ARQ protocol, called relay-level ARQ, was then considered to improve inter-user channel quality, thus increasing the diversity of the system. However, relay-level ARQ brings a significant degradation in throughput. Finally, a third protocol, called two-level ARQ, combining the benefits of destination-level ARQ (higher throughput) and relay-level ARQ (higher reliability) is proposed. The two-level ARQ protocol achieves the best performance both in terms of error rate and throughput efficiency. Significant improvements were observed with respect to the non-ARQ scheme and the destination-level and relay-level ARQ protocols.

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