Throughput-efficient Relay assisted Hybrid ARQ

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***Abstract*—Reliable data transmission within wireless communication systems can be obtained via various means, including (i) Hybrid Automatic Repeat reQuest (HARQ) mechanisms which allow retransmission of incorrectly decoded packets; (ii) Additional nodes, called relays, which may also help the transmission by retransmitting these packets. An efficient combination of both techniques is therefore of great interest. This paper investigates a relay assisted HARQ protocol aiming at maximizing the system throughput. The protocol allows the source to transmit a new message during the same time-slot in which the relay is retransmitting a previous message. By using an efficient interference canceler at the destination, the numerical results show significant throughput gain compared to standard approaches.**

I. Introduction

We consider a wireless communication where a message is sent from one source to one destination. When the decoding fails at the destination side, a common approach is to re-encode the message into other packets retransmitted by the source (known as Hybrid Automatic ReQuest –HARQ– [1]). Another way to improve the communication is to add one relay along the route between the source and the destination. Assuming the destination does not decode correctly the message but the relay does, the relay retransmits a packet related to this message and mimics either a multi-hop routing or an ARQ retransmission mechanism. In this paper, the main objective is to combine these complementary approaches into HARQ protocols taking into account the presence of relays.

As HARQ mechanisms (without the presence of relays), one can mention Chase Combining (CC) [2] where an identical packet associated to the message is retransmitted, all received packets corresponding to the same message being combined at the receiver. Another technique is Incremental Redundancy (IR) [3] where the packet related to the message contains other redundancy bits which are decoded jointly with the previous ones. The performance of HARQ is evaluated via the following metrics: Throughput and Message Error Rate (MER) [1], [4]. In addition, the HARQ protocol can be modeled as a Markov Chain whose transition probabilities enable us to evaluate the previously-mentioned metrics [5], [6].

Many relaying protocols have been proposed regardless of the presence of a HARQ mechanism [7]–[12]. One can mention i) the orthogonal approach (where the source remains silent when the relay is active) with the strategy Amplify and Forward (AF), Decode-and-Forward (DF), etc., and more interestingly ii) the non-orthogonal approach (where the source is still transmitting its packet when the relay is active) with the Slotted Amplify and Forward (SAF) [10] or the Non-orthogonal Decode-and-Forward (NDF) [11]. Note that, in NDF, even if the relay has correctly decoded the packet, it does not completely take over the message transmission since the source continues to broadcast the same message through other packets.

In contrast, only few works have considered jointly relay assisted transmission and HARQ. They assume half-duplex (HD) relays using a decode-and-forward strategy. In [13], a distributed Alamouti relaying scheme is investigated. Network coding approach for relay assisted HARQ has been developed in multi-user context as in [14] where a linear combination of bits is sent by the relay when it has decoded and stored more than one incorrectly received packet at the destination. In [15], [16], a superimposed modulation (linear combination of symbols) is proposed in multi-user context where a node transmits simultaneously its own data packet and the packet of another transmitter for which it acts as a relay. In [17], [18], a protocol in single-user context combining HARQ and DF relay is introduced. The idea is to let the source send a new message while the relay is retransmitting a previous one. In both papers, this idea is only considered for a CC-HARQ with one retransmission credit. In addition, only a Minimum Mean Square Error (MMSE) receiver is employed for handling the interference between both simultaneously received messages at the destination. More precisely, in [17], the authors considered a dynamic protocol where the source sends a new message rather than a space-time coded version of the previous message as soon as the received Signal-Interference-to-Noise Ratio (SINR) is higher than a pre-defined threshold. This implies i) that the source only seldom uses the ability to send a new message, and ii) that the source has the channel state information of the future channels. In [18], the authors considered only BPSK-modulated signals. In both papers, the gain in throughput is marginal probably due to the choice of the sub-optimal MMSE receivers. Note that the idea of sending more than one message simultaneously is close to the Multi-Packet reception in random access protocol as explained in [19].

The main contribution of this paper is to analyze the real impact of the protocol of [17], [18] (the source sends a new message while the relay retransmits another one) in a more

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realistic setting: IR-HARQ, no channel state information at the transmitter, and better decoders. Indeed, we will show the gain in throughput of this protocol when the receiver is either optimally designed through information-theoretic tools (e.g., Multiple Access Channel –MAC– capacity region) or sub-optimally chosen by using the Successive Interference Canceler (SIC).

The remainder of the paper is organized as follows: In Section II, the system model along with existing relay assisted HARQ schemes is presented. The protocol, the considered decoder as well as its Markov chain model are drawn in Section III. Numerical results and comparison with other protocols are provided in Section IV. Finally, Section V is devoted to concluding remarks.

II. System Model

Consider a three nodes system with one source, one relay, and one destination. Each link (source-relay, source-destination, relay-destination) is modeled as a Rayleigh flat fading channel independent of the other ones. The coherence time of each link is equal to the time-slot duration containing N time-instants. Let $h_{sr}(t)$, $h_{sd}(t)$, and $h_{rd}(t)$ be the fading components for the source-relay, source-destination, and relay-destination links at the t-th time-slot respectively. The associated gains are $g_{sr}(t) = |h_{sr}(t)|^2$, $g_{sd}(t) = |h_{sd}(t)|^2$, and $g_{rd}(t) = |h_{rd}(t)|^2$ with variance $\sigma^2_{sr} = \mathbb{E}[g_{sr}(t)]$, $\sigma^2_{sd} = \mathbb{E}[g_{sd}(t)]$, $\sigma^2_{rd} = \mathbb{E}[g_{rd}(t)]$.

The relay is assumed to work in a half-duplex, decode-and-forward mode. After each time-slot, the relay and the destination broadcast an instantaneous error-free Acknowledgment (ACK) if they succeeded to decode their message or a Negative Acknowledgment (NACK) otherwise. Moreover perfect Channel State Information (CSI) at each receiver (relay or destination) is assumed available.

The sequence of messages to be transmitted by the source is denoted as $\mathbf{m}_\ell$ with $\ell \in \mathbb{N}^+$. Each message contains NR information bits. In CC-HARQ, each message $\mathbf{m}_\ell$ is channel encoded with a rate R and modulated into a packet $\mathbf{x}_\ell$ of length N (equal to the time-slot duration). The packet is sent through a propagation channel at most $C_{\max}$ times, using the HARQ mechanism. In IR-HARQ, each message $\mathbf{m}_\ell$ is encoded via a mother code of rate R_0 and then punctured into C_{max} codeword chunks denoted by $\mathbf{d}_\ell^{(c)}$ with $c \in \{1, 2, \ldots, C_{\max}\}$. The c-th codeword chunk is modulated into a packet of length N denoted as $\mathbf{x}_\ell^{(c)}$.

In presence of a relay, the performance depends on the forwarded packet. An efficient method [13] relies on the Alamouti space-time coding [20]. If the destination fails to decode the message ℓ after the c-th chunk and the relay succeeds to decode, the relay sends, at the next time-slot, the Alamouti-conjugate chunk $\tilde{\mathbf{x}}_\ell^{(c+1)} = [-\overline{x}_{\ell,2}^{(c+1)}, \overline{x}_{\ell,1}^{(c+1)}, -\overline{x}_{\ell,3}^{(c+1)}, \cdots, \overline{x}_{\ell,N-1}^{(c+1)}]$ assuming even N, while the source sends the chunk $\mathbf{x}_\ell^{(c+1)}$ if $c+1 \le C_{\max}$.

III. Protocol analysis

A. Protocol description

In the investigated protocol, once the relay has decoded the message $\mathbf{m}_\ell$, it is able to help the source by transmitting the appropriate chunks related to the message $\mathbf{m}_\ell$ to the destination. Hence, the source trusts the relay in managing the message $\mathbf{m}_\ell$ and it decides to send a new message $\mathbf{m}_{\ell'}$ in parallel. This protocol is expected to provide a higher throughput since two messages are sent simultaneously. However, the message error rate (MER) is also likely to be higher since, at the destination, interference (one message is coming from the relay and another one from the source) occurs and degrades the detection. As a result, more transmissions are likely to occur, and one can hope that MER increase is small enough.

More precisely, assuming that we are starting a protocol session, the source transmits and the relay overhears a sequence of chunks $\mathbf{x}_1^{(c)}, (c = 1, \ldots, r)$, where r is the HARQ round from which the relay successfully decodes the message 1. At round $r+1$, the relay transmits the sequence $\mathbf{x}_1^{(r+1)}$, to the destination while the source transmits the first chunk of the next message, i.e., $\mathbf{x}_2^{(1)}$. The destination tries to decode both messages 1 and 2 simultaneously. A pair of ACK/NACK is sent to the relay and the source according to the success of decoding of each message. Let (N)ACK$_\ell$ be the (non)acknowledgment message associated with the message $\mathbf{m}_\ell$.

- If ACK$_1$/ACK$_2$: the source sends $\mathbf{x}_3^{(1)}$, the relay overhears,
- if ACK$_1$/NACK$_2$: the source sends $\mathbf{x}_2^{(2)}$, the relay overhears,
- if NACK$_1$/ACK$_2$: the source sends $\mathbf{x}_3^{(1)}$ and the relay transmits $\mathbf{x}_1^{(r+2)}$ (if $r+2 \le C_{\max}$, else the relay overhears),
- if NACK$_1$/NACK$_2$: the source sends $\mathbf{x}_2^{(2)}$ and the relay transmits $\mathbf{x}_1^{(r+2)}$ (if $r+2 \le C_{\max}$, else the relay overhears),

and so on.

B. Decoder description

Assuming that the destination is receiving during the t-th time-slot, the decoder relies on the set of observations $\mathcal{O}_t$ given by the $B_{\max}$ last time-slots, i.e., from $t - B_{\max} + 1$ to t. The contributions of the decoded messages in previous time-slots are removed from the observations. Let the set $\mathcal{M}_t$ correspond to all the undecoded messages having at least one transmit packet within the observations set $\mathcal{O}_t$. Within $\mathcal{M}_t$, we select the subset of messages $\mathcal{D}_t$ whose first transmission is less old than $D_{\max}$ time-slots. For instance, if a message has been sent at least once before the $(t - D_{\max} + 1)$-th time-slot, the message is considered to be delayed and we stop trying to decode it. Consequently, based on the observations $\mathcal{O}_t$, we have a Multiple Access Channel (MAC) where the messages to decode are $\mathcal{D}_t$ and the other messages $\mathcal{M}_t/\mathcal{D}_t$ are not to decode but are seen as a structured interference and not as a Gaussian noise. Thus, the probability of successfully decoding messages in $\mathcal{D}_t$ is the probability that the rates belong to a MAC capacity region since we assume capacity-achieving codes.

C. Theoretical analysis

We would like to exhibit the performance metrics (such as throughput and MER). We will see that the described protocol can be modeled as a Markov chain, then the performance metrics can be expressed using the related transition probabilities [5], [6].

Hereafter we will i) describe the corresponding Markov chain, ii) characterize the transition probabilities (assuming decoders described in Section III-B), and iii) derive the throughput and MER based on these transition probabilities. Except otherwise stated, we assume $C_{\max} = 2$, $B_{\max} = 2$, and $D_{\max} = 2$ due to space limitation. In Figs. 1-4, we provide the 8 states of the Markov chain needed for describing the protocol. Notice that even if only one time-slot t is required for completely characterizing the states, they also provide information on the previous time-slot $t-1$ and the future one $t+1$. For instance, in $\mathbf{S}_1$ and $\mathbf{S}_3$, $\mathbf{x}_{\ell+1}^{(1)}$ is necessarily sent at time-slot $t+1$. In $\mathbf{S}_2$ and $\mathbf{S}_4$, $\mathbf{x}_{\ell+2}^{(1)}$ is necessarily sent at time-slot $t+1$. In $\mathbf{S}_5$, $\mathbf{x}_{\ell}^{(2)}$ is necessarily sent at time-slot $t+1$. In $\mathbf{S}_7$, the relay and the source send $\mathbf{x}_{\ell}^{(2)}$ and $\mathbf{x}_{\ell+1}^{(1)}$ respectively at time-slot $t+1$. In $\mathbf{S}_6$ and $\mathbf{S}_8$, the source sends $\mathbf{x}_{\ell+1}^{(2)}$ at time-slot $t+1$. Moreover, in $\mathbf{S}_2$, $\mathbf{S}_4$, $\mathbf{S}_6$, and $\mathbf{S}_8$, the system was in $\mathbf{S}_7$ at time-slot $t-1$.

Fig. 1: States $\mathbf{S}_1$ (left) and $\mathbf{S}_2$ (right)

Fig. 2: States $\mathbf{S}_3$ (left) and $\mathbf{S}_4$ (right)

Fig. 3: States $\mathbf{S}_5$ (left) and $\mathbf{S}_6$ (right)

Fig. 4: States $\mathbf{S}_7$ (left) and $\mathbf{S}_8$ (right)

Extension to any value $C_{\max}$ can be done at the expense of the number of states. For instance, we succeeded to exhibit the states for $C_{\max} = 3$ and $C_{\max} = 4$ where their numbers are 19 and 49 respectively. Due to lack of space, we do not describe them here.

The transition matrix of the previous Markov chain is denoted by $\mathbf{T} = (t_{i,j})_{(i,j)\in\{1,\cdots,8\}^2}$ where $t_{i,j}$ is the transition probability from $\mathbf{S}_j$ to $\mathbf{S}_i$. We have $\sum_{i=1}^{8} t_{i,j} = 1$. Except otherwise stated, $t_{i,j} = 0$ for any i, j. Let $\mathbb{P}(\Omega)$ be the probability of the event Ω. Consequently, we have

$$t_{i,j} = \mathbb{P}(\mathbf{S}_i|\mathbf{S}_j).$$

According to Bayes' rule, we get

$$t_{i,j} = \frac{q_{i,j}}{p_j}$$

with

$$p_j = \mathbb{P}(\mathbf{S}_j) \text{ and } q_{i,j} = \mathbb{P}(\mathbf{S}_i, \mathbf{S}_j).$$

When $j = 1, \cdots, 4$, we get that

$$t_{1,j} = \mathbb{P}\left(R < \log_2(1 + g_{sd}(1))\right),$$

$$t_{5,j} = \mathbb{P}(R > \log_2(1 + g_{sd}(1)), R > \log_2(1 + g_{sr}(1))),$$

and $t_{7,j} = 1 - t_{5,j} - t_{1,j}$.

When $j = 5$, we get that $t_{1,5} = q_{1,5}/p_5$ with

$$p_5 = \mathbb{P}(R > \log_2(1 + g_{sd}(1)), R > \log_2(1 + g_{sr}(1)))$$

and

$$\begin{aligned} q_{1,5} \;&=\; \mathbb{P}(R < \log_2(1 + g_{sd}(1)) + \log_2(1 + g_{sd}(2)), \\ &\quad\; R > \log_2(1 + g_{sd}(1)), R > \log_2(1 + g_{sr}(1))). \end{aligned}$$

Finally, $t_{3,5} = 1 - t_{1,5}$.

When $j = 6$, we obtain $t_{1,6} = q_{1,6}/p_6$ with

$$\begin{aligned} p_6 \;&=\; \mathbb{P}(R > \log_2(1 + g_{sd}(0)), R < \log_2(1 + g_{sr}(0)), \\ &\quad\; R < \log_2(1 + g_{sd}(0)) + \log_2\left(1 + \frac{g_{rd}(1)}{1 + g_{sd}(1)}\right), \\ &\quad\; R > \log_2(1 + g_{sd}(1)) \end{aligned}$$

and

$$\begin{aligned} q_{1,6} \;&=\; \mathbb{P}(R < \log_2(1 + g_{sd}(1)) + \log_2(1 + g_{sd}(2)), \\ &\quad\; R > \log_2(1 + g_{sd}(0)), R < \log_2(1 + g_{sr}(0)), \\ &\quad\; R < \log_2(1 + g_{sd}(0)) + \log_2\left(1 + \frac{g_{rd}(1)}{1 + g_{sd}(1)}\right), \\ &\quad\; R > \log_2(1 + g_{sd}(1))). \end{aligned}$$

Finally, $t_{3,6} = 1 - t_{1,6}$.

When $j = 7$, we have $t_{2,7} = q_{2,7}/p_7$ with

$$p_7 = \mathbb{P}(R > \log_2(1 + g_{sd}(1)), R < \log_2(1 + g_{sr}(1)))$$

and

$$\begin{aligned} q_{2,7} \;&=\; \mathbb{P}(R < \log_2(1 + g_{sd}(2)), \\ &\quad\; R < \log_2(1 + g_{sd}(1)) + \log_2(1 + g_{rd}(2)), \\ &\quad\; 2R < \log_2(1 + g_{sd}(1)) + \log_2(1 + g_{rd}(2) + g_{sd}(2)), \\ &\quad\; R > \log_2(1 + g_{sd}(1)), R < \log_2(1 + g_{sr}(1))). \end{aligned}$$

In order to obtain $q_{2,7}$, we noticed that the state $\mathbf{S}_2$ deals with MIMO-Multiple Access Channel (MAC) whose capacity region is provided in [21]. We also have $t_{4,7} = q_{4,7}/p_7$ with

$$\begin{aligned} q_{4,7} &= \mathbb{P}(R > \log_2(1+g_{sd}(1)) + \log_2\left(1+g_{rd}(2)\right), \\ &\quad R < \log_2\left(1+\frac{g_{sd}(2)}{1+g_{rd}(2)}\right), \\ &\quad R > \log_2(1+g_{sd}(1)), R < \log_2(1+g_{sr}(1))). \end{aligned}$$

The term $q_{4,7}$ is obtained by remarking once again that we have a MIMO-MAC but the message coming from the relay is incorrectly decoded while the message coming from the source is. Therefore the message coming from the source requires a rate smaller than the SIC corner point of the capacity region which justifies the ratio $g_{sd}(2)/(1+g_{rd}(2))$ [22]. In a similar way, we have $t_{6,7} = q_{6,7}/p_7$ with

$$\begin{aligned} q_{6,7} &= \mathbb{P}(R < \log_2(1+g_{sd}(1)) + \log_2\left(1+\frac{g_{rd}(2)}{1+g_{sd}(2)}\right), \\ &\quad R > \log_2(1+g_{sd}(2)), \\ &\quad R > \log_2(1+g_{sd}(1)), R < \log_2(1+g_{sr}(1))). \end{aligned}$$

Finally, $t_{8,7} = 1 - t_{2,7} - t_{4,7} - t_{6,7}$.

When $j = 8$, we get $t_{1,8} = q_{1,8}/p_8$ with

$$\begin{aligned} p_8 &= \mathbb{P}(R > \log_2(1+g_{sd}(0)), R < \log_2(1+g_{sr}(0)), \\ &\quad R > \log_2(1+g_{sd}(0)) + \log_2\left(1+\frac{g_{rd}(1)}{1+g_{sd}(1)}\right), \\ &\quad 2R > \log_2(1+g_{sd}(0)) + \log_2(1+g_{rd}(1)+g_{sd}(1)), \\ &\quad R > \log_2\left(1+\frac{g_{sd}(1)}{1+g_{rd}(1)}\right)). \end{aligned}$$

Moreover $q_{1,8} = q'_{1,8} + q''_{1,8}$ with

$$\begin{aligned} q'_{1,8} &= \mathbb{P}(\mathbf{S}_8, R < \log_2(1+g_{rd}(1)), \\ &\quad R < \log_2(1+g_{sd}(1)) + \log_2(1+g_{sd}(2)), \\ &\quad 2R < \log_2(1+g_{rd}(1)+g_{sd}(1)) + \log_2(1+g_{sd}(2))), \end{aligned}$$

and

$$\begin{aligned} q''_{1,8} &= \mathbb{P}(\mathbf{S}_8, R > \log_2(1+g_{rd}(1)), \\ &\quad R < \log_2\left(1+\frac{g_{sd}(1)}{1+g_{rd}(1)}\right) + \log_2(1+g_{sd}(2))) \end{aligned}$$

where $\mathbf{S}_8$ is the event described in p_8. Finally, $t_{3,8} = 1 - t_{1,8}$.

We remind that the throughput is the average number of information bits correctly received at the destination per time-instant. The MER is the average ratio of the number of dropped messages over the number of sent messages. We have

$$\begin{aligned} \text{Throughput} &= R\left(\pi_1 + 2\pi_2 + \pi_4 + \pi_6\right), & (1) \\ \text{MER} &= \frac{\pi_3 + \pi_4 + \pi_8}{\pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_6 + \pi_8}. & (2) \end{aligned}$$

where $\boldsymbol{\pi} = [\pi_1, \cdots, \pi_8]$ denotes the steady state vector of the Markov chain related to the investigated protocol. This vector is computed by solving $\mathbf{T}\boldsymbol{\pi} = \boldsymbol{\pi}$ and forcing $\sum_{k=1}^{8} \pi_k = 1$. In (1), π_2 is multiplied by 2 since $\mathbf{S}_2$ leads to acknowledge two messages simultaneously.

IV. Numerical Results

We briefly illustrate numerically the interest of the investigated protocol. To do that, we consider

- either capacity-achieving coding: the metrics (throughput and MER) are obtained according to (1)-(2) where $\boldsymbol{\pi}$ is replaced with $\hat{\boldsymbol{\pi}}$ computed by estimating the matrix $\mathbf{T}$. In addition, we also simulate the HARQ mechanism according to the Markov chain's rule and count the number of correctly received packets to estimate the throughput and the MER.
- or practical coding: IR-HARQ is implemented using Rate-Compatible Punctured Convolutional Codes (RCPC) of memory 4 and period 8 as defined in [24], and modulated by BPSK. The receiver yields Log Likelihood Ratio (LLR) for each message to each channel decoding. These LLR have been calculated assuming interference as a noise. Once the hard decision is made on the LLR, a SIC is applied in an iterative manner.

E_b is the average energy consumed for sending one information bit, i.e., the energy consumed by the retransmission due to HARQ and relaying is taken into account. The relay is located halfway between the source and the destination.

In Fig. 5 we plot the throughput of no relay, Alamouti-based [13], and investigated protocols versus E_b/N_0 for capacity-achieving codes with $C_{\max} = 2$ and $R = 0.8$. The investigated protocol offers much higher throughput than existing ones, especially for any SNR. This gain is explained by the fact that the source transmits a new message while the relay still retransmits the previous one and that the interference is well managed through capacity-achieving codes. Notice that the gain is much higher than those seen in [17], [18] due to the considered decoder. As a consequence, the protocol is powerful and so of great interest. In Fig. 6, we display MER

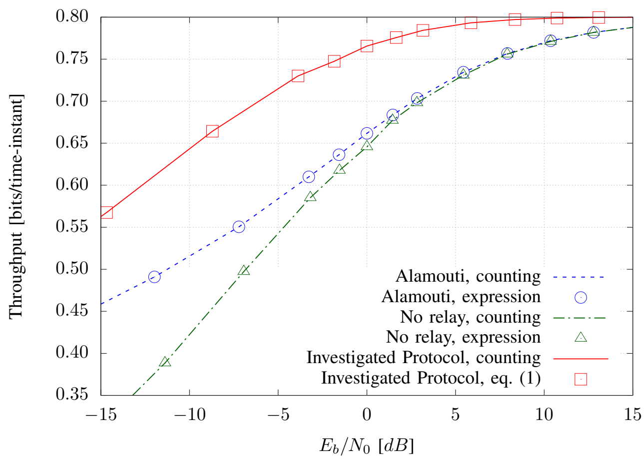

Fig. 5: Throughput for capacity-achieving codes.

of no relay, Alamouti-based [13], and investigated protocols versus E_b/N_0 for capacity-achieving codes with $C_{\max} = 2$ and $R = 0.8$. The investigated protocol has higher MER than the Alamouti-based protocol due to the interference at the destination between messages coming from the source and the relay. Nevertheless, this loss in MER does not damage the throughput as seen in Fig. 5. In Fig. 7, we plot the

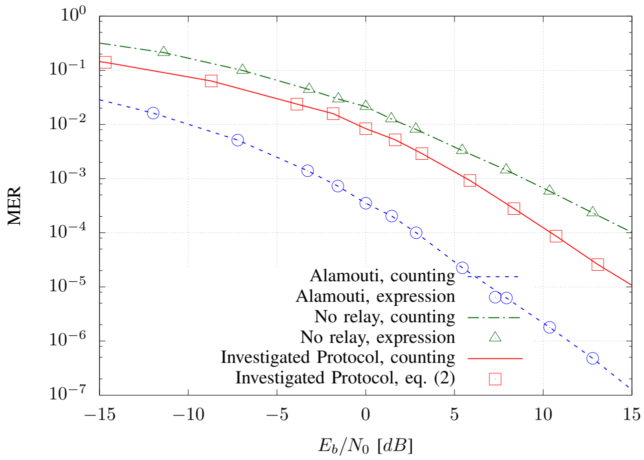

Fig. 6: MER for capacity-achieving codes.

throughput of no relay, Alamouti-based [13], and investigated protocols versus E_b/N_0 for practical codes with $C_{\max} = 2$ and $C_{\max} = 3$. Once again, the investigated protocol outperforms the existing ones in terms of throughput. The gain is significant and higher as in the literature for medium and high SNR. Thus the SIC decoder instead of the MMSE one is crucial for such a protocol.

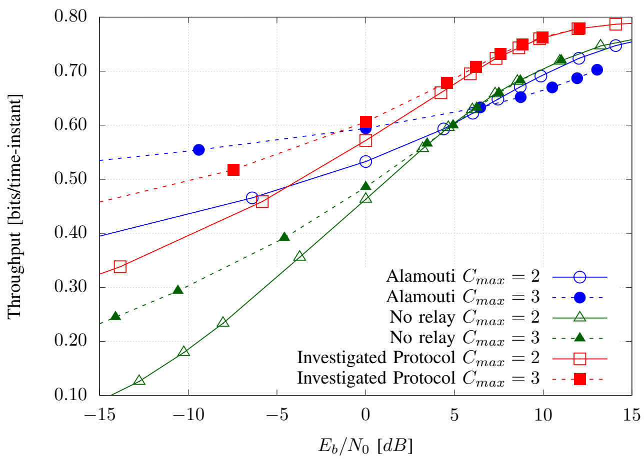

Fig. 7: Throughput for practical codes.

V. Conclusion

The protocol, enabling the source to transmit a new message while the relay retransmits the previous one, offered significant gain in throughput. Future work may focus on the power allocation between the source and the relay.

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