Semi-Orthogonal MARC with half duplex relaying: A Backward Compatible Cooperative Network with Interference Channels

Mohieddine El Soussi†, Thang X Vu*, Hong N Nguyen*, Pierre Duhamel*, Florence Alberge* and Luc Vandendorpe†

* Laboratoire des Signaux et Systèmes (L2S, UMR CNRS 8506)
Univ. Paris-Sud - CNRS - CentraleSupélec - Université Paris-Saclay - 3, rue Joliot-Curie, 91192 Gif-sur-Yvette
Tel: +33 1 69851757; fax: +33 1 69851765 e-mail:{firstname.name@l2s.centralesupelec.fr}
†ICTEAM, Université catholique de Louvain, Belgium
e-mail:{firstname.name@uclouvain.be}

***Abstract*—This paper proposes a full-rate cooperative scheme adapted to the slow fading semi-orthogonal multiple access relay channel (MARC). It is assumed that the sources transmit on orthogonal channels and the relay is half duplex transmitting on the same channels as the one of the sources. The sources employ LDPC to encode their messages before transmitting them, while the relay uses a simple demodulate-and-forward strategy to transmit the combination of the received codewords. The presence of the relay does not affect the time-scheduling of the sources. Therefore, this scheme is backward compatible to existing non-cooperative systems. In order to cancel the interference at the destination, we propose a joint network-channel decoder that uses maximum a posteriori (MAP) detection and channel decoding. Through numerical results, we show the benefits of joint network-channel decoder. We also show that the proposed scheme significantly outperforms, in terms of BER, the non-cooperative system as well as the classical relay-assisted orthogonal channel network and that it achieves the maximum code diversity.**

I. Introduction

The multiple access relay channel (MARC) is a network in which several sources communicate with a destination with the help of a relay [1]. The MARC has received a lot of attention in the recent years under various relaying modes. The most studied ones are Amplify-and-Forward (AF) [1], [2], Decode-and-Forward (DF) [3], [4], [5], Demodulate-and-Forward (DMF) [6], and Compute-and-Forward (CoF) [7], [8].

Resource allocation plays a major role in the performance of the MARC. In this context, the orthogonal transmission (the situation where each transmission occupies different resources either in time or frequency) is clearly the most studied case [4], [9]. This methodology ensures that the process does not introduce any additional interference, at the cost of the use of additional resources. Conversely, in a non-orthogonal transmission, the sources and the relay transmit simultaneously on all channels. The benefit is a more efficient usage of the resources, at the cost of additional interference [8], [10]. In order to achieve diversity gain in wireless networks and to reduce the number of transmissions by the relay, network coding has been introduced [9], [11], [12]. Network coding [13], refers to intermediate node (in this case the relay) sending out a linear combination of messages instead of the messages themselves.

Most of the works dealing with MARC based on network coding did not consider channel coding. The joint network-channel coding for MARC was initially proposed in [14]. In [15], the authors propose a joint full-diversity network-channel LDPC code for the MARC network. In [16] joint network-channel coding based on turbo codes was applied for MARC. All the above works consider that both the sources and relay transmit in orthogonal fashion. In [17], the authors propose an intermediate situation between fully orthogonal channels and fully overlapping channels denoted as semi-orthogonal channels, which is defined as follows. In the first transmission phase, only the sources transmit simultaneously while in the second transmission phase only the relay is allowed to transmit. They study the joint network-channel coding scheme for the semi-orthogonal MARC and compare it with the orthogonal MARC.

In this work, we consider a specific semi-orthogonal MARC motivated by the following scenario. Consider an uplink situation in a classical wireless communication system where each user has its own resources, which are orthogonal. Assume that the operator is willing to help these users by allowing some idle node (a relay) to forward their signals without impairing the available resources, i.e., without allocating a new channel to the relay. If the initial users do not change their way of transmitting, they do not need to be aware of this relaying, only the base station will have to adapt its reception algorithm to the new situation. This is the reason why this situation can be considered as being *backwards compatible* since users operating in a classical mode will not have to change the algorithms used for transmitting. Obviously, if one relay is available per initial user, classical relaying with overlapping channel can solve the problem. However, we are interested in reducing the number of relays that are involved in this process, i.e., in our setting, a relay helps several users. This can be obtained by allowing the relay to perform network coding. Furthermore, we protect the messages against transmission errors and interference by using forward error corrections codes. We focus on the block fading channel model where channel links are independent and subject to slow Rayleigh fading and additive white Gaussian noise. In such setting, coded information is transmitted over a finite number of independent fading blocks to provide diversity. The diversity order defines the slope of word error rate of the decoder. Full diversity codes are codes that have a diversity equal to the number of fading blocks in a codeword. Root LDPC codes [18] are able to achieve the maximum diversity of a block fading channel. Here, the relay performs DMF. This is in contrast with [17] that assumes a selective DF at the relay meaning that only correctly decoded messages are transmitted, which is at the expense of a loss of spectral efficiency due to the addition of Cyclic Redundancy Check into each message. We compare the proposed transmission scheme with the non-cooperative system as well as the classical relay-assisted orthogonal channel network, and show that the proposed scheme achieves full diversity and yields a lower bit error rate (BER).

II. System model

We consider a cooperative system consisting of two sources S_1, S_2, a relay R and a destination D. The sources would like to communicate with the destination with the help of a half duplex relay. The relay uses demodulate-and-forward strategy, i.e., it only estimates the sources symbols. The corresponding demodulation errors will be taken into account at the receiver. The transmission time is divided into six periods with equal duration. The sources transmit their messages alternately using their dedicated channels. However, the relay does not have any allocated channel and thus transmits its messages on the same channels that are being used by the sources.

During the first two transmission periods, sources S_1 and S_2 transmit in distinct time slots their modulated symbols $\mathbf{x}_1$ and $\mathbf{x}_2$ over the channel, respectively. During these periods the measured outputs at the relay and the destination are given by

$$\mathbf{y}_{1R} = \sqrt{P_{S_1} d_{S_1R}^{-\alpha}} h_{S_1R,1}\mathbf{x}_1 + \mathbf{z}_{1R}, \tag{1}$$

$$\mathbf{y}_{2R} = \sqrt{P_{S_2} d_{S_2R}^{-\alpha}} h_{S_2R,2}\mathbf{x}_2 + \mathbf{z}_{2R}, \tag{2}$$

$$\mathbf{y}_{1} = \sqrt{P_{S_1} d_{S_1D}^{-\alpha}} h_{S_1D,1}\mathbf{x}_1 + \mathbf{z}_{1}, \tag{3}$$

$$\mathbf{y}_{2} = \sqrt{P_{S_2} d_{S_2D}^{-\alpha}} h_{S_2D,2}\mathbf{x}_2 + \mathbf{z}_{2}, \tag{4}$$

where P_{S_1} and P_{S_2} are the allocated power to the symbols $\mathbf{x}_1$ and $\mathbf{x}_2$, respectively; $h_{S_iD,f}$ is the channel gain from source S_i, $i = 1, 2$, to the destination at frame f, $f = 1, 2$; $h_{S_iR,f}$ is the channel gain from source S_i to the relay at frame f; d_{S_iR} and d_{S_iD} are the distance between source S_i and the relay and between source S_i and the destination, respectively; α is an attenuation exponent; $\mathbf{z}_{fR}$ and $\mathbf{z}_f$, $f = 1, 2$ are the additive noise at the relay and the destination, respectively. After estimating the symbols sent by the sources, the relay transmits symbol $\mathbf{x}_{R1}$ to the destination during the third time slot. During this time slot, source S_1 also transmits its symbol $\mathbf{x}_3$ to the destination. Hence, the output at the destination during this time slot is given by

$$\mathbf{y}_3 = \sqrt{P_{S_1} d_{S_1D}^{-\alpha}} h_{S_1D,3}\mathbf{x}_3 + \sqrt{P_R d_{RD}^{-\alpha}} h_{RD,3}\mathbf{x}_{R1} + \mathbf{z}_3, \tag{5}$$

where P_R is the allocated power to the symbol $\mathbf{x}_{R1}$; $h_{S_1D,3}$ is the channel gain on the link from source S_1 to the destination at frame 3; $h_{RD,3}$ is the channel gain from the relay to the destination at frame 3; d_{RD} is the distance between the relay and the destination and $\mathbf{z}_3$ is the additive noise. Similarly, sources S_1 and S_2 transmit their symbols $\mathbf{x}_4$, $\mathbf{x}_5$, $\mathbf{x}_6$ during the three remaining time slots, while the relay only transmits the symbol $\mathbf{x}_{R2}$ during the last time slot.

Throughout the paper, we assume that the states of the channel are known perfectly at the relay and the destination and that the channel coefficients are modeled as Gaussian with unit variance. The noises at the relay and the destination are independent among each others, and i.i.d. with components drawn according to a circular complex Gaussian distribution with zero mean and variance σ^2.

III. Transmission strategy

This section first describes the encoding and transmission of the messages at the sources and the relay. Then, we present the decoding process of the desired messages at the destination. Recall that the transmission time is divided into six transmission periods with equal duration. Each slot has a length equal to $2N/3$ where N is the length of a codeword.

A. Encoding at the sources

For the considered model, we assume that each source wants to transmit two information messages to the destination. Let $\mathbf{u}_i(l)$ of length K, be the l-th information message, $l = 1, 2$, available at source S_i, $i = 1, 2$. The information bits are protected against transmission errors with channel encoders. In the considered setting, each source, S_i, encodes the information message $\mathbf{u}_i(l)$ to a codeword $\mathbf{c}_i(l) = [\mathbf{m}_{i1}(l),\ \mathbf{m}_{i2}(l),\ \mathbf{m}_{i3}(l)] \in \mathcal{C}_i$ of length N using root LDPC codes with rate $R = 1/3$ [18], where $\mathcal{C}_i$ is the codebook. Following the partition of the codewords proposed in [18], each $\mathbf{m}$ is divided into two parts: the first part contains $N/9$ information bits and the second part contains $2N/9$ parity bits. Then, source S_i transmits its codewords using three time slots or frames. More specifically, source S_1 maps its frames $\mathbf{C}_1 = [\mathbf{m}_{11}(1), \mathbf{m}_{12}(1)]$, $\mathbf{C}_3 = [\mathbf{m}_{13}(1), \mathbf{m}_{13}(2)]$ and $\mathbf{C}_5 = [\mathbf{m}_{11}(2), \mathbf{m}_{12}(2)]$ into symbols $\mathbf{x}_1$, $\mathbf{x}_3$ and $\mathbf{x}_5$, respectively, using BPSK modulation before transmitting it over the channel. Note that each codeword $\mathbf{c}_i(l)$ is transmitted using three different fading blocks: two are from the source and the third is from the relay. Similarly, source S_2 transmits its codewords using three frames as shown in Figure 1.

B. Encoding at the Relay

After the first two transmission periods, the relay first demodulates the received signals $\mathbf{y}_{1R}$ and $\mathbf{y}_{2R}$ (given in (1)-(2)) using ML (Maximum Likelihood) method as follows

$$\hat{x}_{f,m} = \underset{x_{f,m} \in \{-1,1\}}{\arg\min} |y_{fR,m} - \sqrt{P_{S_i}} h_{S_iR,f} x_{f,m}|^2,$$

with $m = 1, .., 2N/3$, $i = 1, 2$, $f = 1, 2$ and $x_{f,m}$ denotes the m-th component of symbol $\mathbf{x}_f$. Second, it estimates $\widehat{\mathbf{C}}_1$ and $\widehat{\mathbf{C}}_2$ from $\hat{\mathbf{x}}_1$ and $\hat{\mathbf{x}}_2$, respectively. Third, it performs network encoding by calculating $\mathbf{C}_{R1} = \pi\left(\widehat{\mathbf{C}}_1\right) \oplus \pi\left(\widehat{\mathbf{C}}_2\right)$,

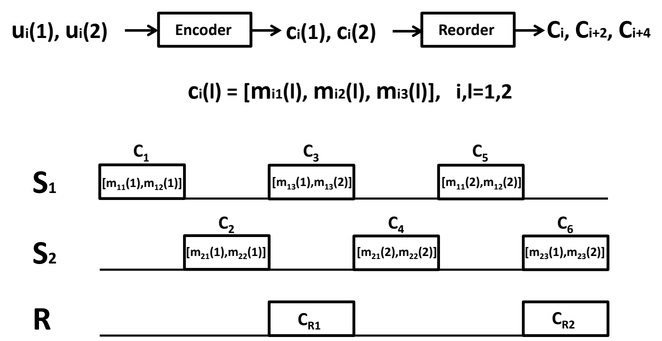

Fig. 1. The transmission of the six frames for the proposed cooperation scheme.

where $\pi()$ denotes a random interleaving function and $\oplus$ is modulo 2 addition. Finally, it maps $\mathbf{C}_{R1}$ into symbol $\mathbf{x}_{R1}$ using BPSK modulation and transmits it during the third time slot. Similarly, the relay transmits symbol $\mathbf{x}_{R2}$ during the sixth transmission period after obtaining $\mathbf{C}_{R2} = \pi\left(\widehat{\mathbf{C}}_4\right) \oplus \pi\left(\widehat{\mathbf{C}}_5\right)$.

C. Decoding at Destination

The destination starts decoding after receiving the six frames. The probabilities of decoding error at the relay, $\mathrm{Pe}_{R1} \triangleq \Pr\{C_{R1,k} \neq C_{1,k} \oplus C_{2,k}\}$ and $\mathrm{Pe}_{R2} \triangleq \Pr\{C_{R2,k} \neq C_{4,k} \oplus C_{5,k}\}$, are assumed to be available at the destination. Let $\mathbf{U}$, $\mathbf{C}$ and $\mathbf{Y}$ be defined as $\mathbf{U} \triangleq \{\mathbf{u}_1(1), \mathbf{u}_1(2), \mathbf{u}_2(1), \mathbf{u}_2(2)\}$, $\mathbf{C} \triangleq \{\mathbf{c}_1(1), \mathbf{c}_1(2), \mathbf{c}_2(1), \mathbf{c}_2(2)\}$ and $\mathbf{Y} \triangleq \{\mathbf{y}_1, ..., \mathbf{y}_6\}$. The MAP decoding rule reads:

$$\begin{aligned}[\widehat{\mathbf{U}}] &= \arg\max_{\mathbf{U}} \Pr\{\mathbf{U}|\mathbf{Y}\} \\ &= \arg\max_{\mathbf{U}} \sum_{\mathbf{C}} \Pr\{\mathbf{U}|\mathbf{C}\} \times \Pr\{\mathbf{C}|\mathbf{Y}\}. \qquad (6)\end{aligned}$$

Since the data messages are independent, we have:

$$\Pr\{\mathbf{U}|\mathbf{C}\} = \prod_{i=1,2} \prod_{l=1,2} \Pr\{\mathbf{u}_i(l)|\mathbf{c}_i(l)\},$$

which stands for the channel decoding. The second factor in (6) corresponds to the network coding on the coded bits. Let $C_{f,k}$ denote the k-th element of $\mathbf{C}_f$ then

$$\Pr[C_{f,k}|\mathbf{Y}] = \begin{cases} \Pr[C_{f,k}|\mathbf{y}_1, \mathbf{y}_2, \mathbf{y}_3], & f = 1,2,3 \\ \Pr[C_{f,k}|\mathbf{y}_4, \mathbf{y}_5, \mathbf{y}_6], & f = 4,5,6 \end{cases}. \qquad (7)$$

The problem in (6) can be solved iteratively first by using network decoder followed by four channel decoders as shown in Figure 2. The iterative decoding algorithm stops either if two successive estimated codewords are kept constant or if the maximum number of iterations is reached. At the end of the joint decoding process, a hard decoding is applied on the extrinsic information of the data bits.

IV. Joint Network-Channel Decoder

A. Network Decoder

For the coded bits in the first three frames, we have:

$$\Pr[C_{f,k}|\mathbf{y}_1, \mathbf{y}_2, \mathbf{y}_3] = \sum_{\substack{C_{i,k}, C_{j,k} \\ i \neq j \neq f \in \{1,2,3\}}} \Pr[C_{f,k}, C_{i,k}, C_{j,k}|y_{1,k}, y_{2,k}, y_{3,k}].$$

The joint probability can be expressed as follows:

$$\begin{aligned}&\Pr[C_{1,k}, C_{2,k}, C_{3,k}|y_{1,k}, y_{2,k}, y_{3,k}] \\ &\quad \propto \Pr[y_{1,k}|C_{1,k}] \Pr[y_{2,k}|C_{2,k}] \\ &\quad \times \Pr[y_{3,k}|C_{1,k}, C_{2,k}, C_{3k}] \Pr[C_{1,k}, C_{2,k}, C_{3,k}]. \qquad (8)\end{aligned}$$

The last term in (8) stands for the prior information of coded bit $C_{j,k}$, which is fed back from the channel decoders. The first two factors in (8) can be directly computed from the channel model in (3-4). The third term in (8) is computed as

$$\sum_{C_{R1,k}} \Pr[y_{3,k}|C_{R1,k}, C_{3,k}] \Pr[C_{R1,k}|C_{1,k}, C_{2,k}], \qquad (9)$$

where $C_{R1,k} = \widehat{C}_{1,k} \oplus \widehat{C}_{2,k}$ is an estimate of a network-coded bit. Note that $\widehat{C}_{1,k}, \widehat{C}_{2,k}$ are estimated at the relay and that they may differ from $C_{1,k}, C_{2,k}$. The first term $\Pr[y_{3,k}|C_{R1,k}, C_{3,k}]$ is obtained thanks to the channel model in (5) whereas the last term accounts for the possible decoding error at the relay of the network-coded bits in the first three frames, denoted by $\mathrm{Pe}_{R1} = \Pr[C_{R1,k} \neq C_{1,k} \oplus C_{2,k}]$ (see [19] for the computation of Pe_{R1} at the destination), which is computed as follows:

$$\Pr[C_{R1,k}|C_{1,k}, C_{2,k}] = \begin{cases} \mathrm{Pe}_{R1} & \text{if } C_{R1,k} \neq C_{1,k} \oplus C_{2,k} \\ 1 - \mathrm{Pe}_{R1} & \text{if } C_{R1,k} = C_{1,k} \oplus C_{2,k} \end{cases}.$$

The network decoding process for the frames $f = 4, 5, 6$ is performed in a similar way. After the network decoding process, the network decoder computes the extrinsic information $\mathbf{LCE}_f$, $f = 1, \ldots, 6$, of frame $\mathbf{C}_f$, $LCE_{f,k} = LC_{f,k} - LCA_{f,k}$, where $LC_{f,k}$ is the log likelihood ratio (LLR) value of the coded bit $C_{f,k}$, and $LCA_{f,k}$ is the LLR value of coded bit $C_{f,k}$ from the previous iteration. Then, the extrinsic information $\mathbf{LCE}_f$ are re-ordered to provide the extrinsic information $\mathbf{Lc}_i(l)$, $i, l = 1, 2$, to the channel decoder as shown in Figure 2. We denote by $\mathbf{Lc}_i(l)$ the LLR value that corresponds to the codeword $\mathbf{c}_i(l)$.

B. Channel decoding

The four transmitted codewords, $\mathbf{c}_i(l)$, $i, l = 1, 2$, are decoded using root LDPC decoder that has the Tanner graph depicted in Figure 3 [18]. We can observe that the information bits are divided into three classes of length $N/9$ denoted as $1i$, $2i$ and $3i$. These classes are transmitted on different channels. The parity bits are also partitioned into three sets $1p$, $2p$ and $3p$. All information bits are connected to the rootchecks [18] (special type of check nodes) with degree one to ensure full diversity.

The output of the LDPC decoders which are denoted by $\mathbf{Lc}_i^{\mathrm{dec}}(l)$, $i, l = 1, 2$, are reordered and fed back to the network decoder as prior information for the next iteration.

V. Simulations

The performance of the proposed system is evaluated and compared with a system that does not consider a relay, i.e., a non-cooperative system, and with a system that considers an orthogonal (classical) relay channel (ORC), i.e., a cooperative system with orthogonal transmissions. Note that the transmissions for the non-cooperative system and the ORC system are done in the same way as described in Figure 1. However, for the first one, the transmission is conducted without considering the relay's transmissions, i.e., without $\mathbf{C}_{R1}$ and $\mathbf{C}_{R2}$, and for the second one, the transmission is conducted without the sources' transmissions during the third and sixth transmission periods, i.e., without $\mathbf{C}_3$ and $\mathbf{C}_6$, this means that the sources need to puncture the information before transmitting.

Hereafter, we assume that the channels are subject to block Rayleigh fading and that the channel gains are known at the receivers. The transmitted power at the sources and the relay are equal and the total power consumption in the three systems is the same. A root-LDPC code (3006,2004) with a rate of 1/3 is used. Each data message consists of 1002 bits. The maximum number of iterations for the LDPC decoders is set to 10 iterations and the maximum number of iterations of the iterative decoder is set to 5 iterations.

Figures 4 and 5 depict the BER obtained using the proposed scheme, i.e., "Cooperative mode", the BER obtained using the non-cooperative scheme, i.e., "Non-Cooperative mode" and the BER obtained using the ORC scheme, i.e., "ORC mode". The BERs are taken as functions of E_b/N_0 (in decibels). For the example shown in Figure 4, the two sources are equidistant from the relay and the destination, and the relay is located in the middle between the sources and the destination, such that $d_{S_1R} = d_{S_2R} = d_{RD} \approx 0.5$ and $d_{S_1D} = d_{S_2D} \approx 1$. The attenuation factor α is assumed to be equal to 2. We observe that the proposed scheme significantly outperforms both the non-cooperative and the ORC schemes in the SNRs of interest. Note that, in this example, the non-cooperative and the ORC schemes have similar performance, since in the ORC scheme the data are punctured before being transmitted. Hence, the relay, using the ORC scheme, does not help to decrease the BER for the given scenario. Moreover, we observe that the proposed scheme achieves the maximum diversity, which is equal to three, whereas the non-cooperative and the ORC schemes have a diversity equal to 1.85 and 2, respectively.

For the example shown in Figure 5, we study the case where the relay is located between one of the sources and the destination such that $d_{S_1R} \approx 0.5$, $d_{S_1D} \approx 1.5$ and $d_{RD} \approx 1$ and the other source is located between the relay and the destination such that $d_{S_2R} = d_{S_2D} \approx 0.5$. The attenuation factor α is assumed to be equal to 3. We observe that the proposed scheme outperforms both schemes and that the ORC scheme outperforms the non-cooperative scheme in the SNRs of interest. Also, by comparing Figures 4 and 5, we can observe that the curve of the ORC scheme is closer to the proposed scheme since the source S_1 to destination link is worse than both the source S_1 to relay link and the relay to destination link.

In terms of complexity, we can observe in Figure 6 that the average total number of iterations per LDPC decoder, i.e., the number of iterations of a LDPC decoder considering all network decoding iterations, is equal to 16 at low SNR and 2 at high SNR. Also, we observe that the complexity of "Cooperative mode" significantly decreases at high SNR and approaches the one of "Non-Cooperative mode". Comparing the proposed scheme with the ORC scheme, we can notice that, for a given energy, the proposed scheme has lower BER, lower complexity and higher diversity. Moreover, the relay does not need any additional resource and the sources do not need to adapt their transmissions.

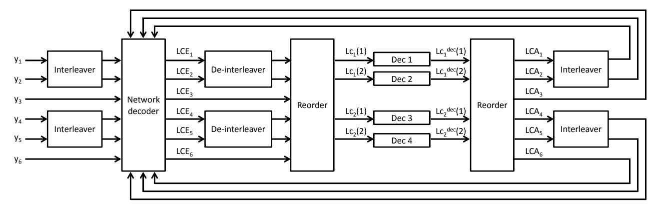

Fig. 2. Structure of the joint network-channel decoder at the destination.

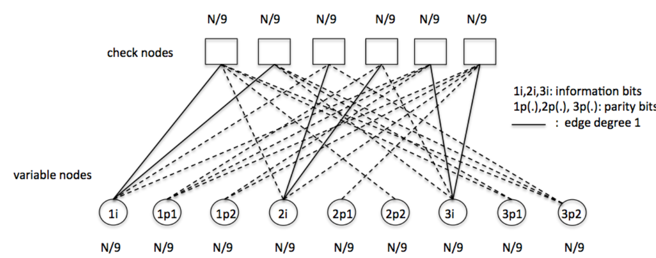

Fig. 3. Tanner graph of a root LDPC decoder with $R = 1/3$.

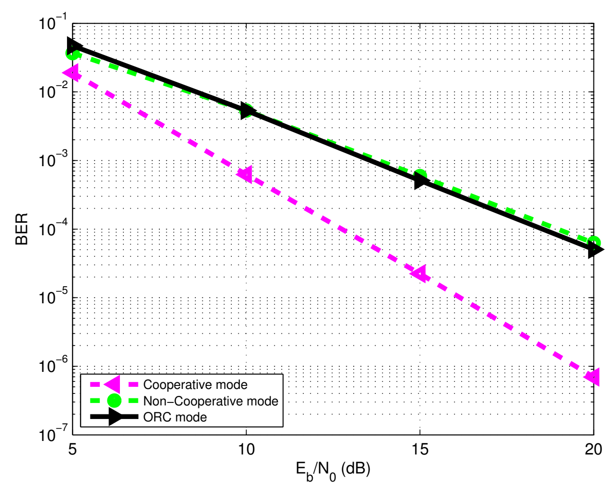

Fig. 4. BER comparison. The two sources are equidistant from the relay and the destination with $d_{S_1R} = d_{S_2R} = d_{RD} \approx 0.5$, $d_{S_1D} = d_{S_2D} \approx 1$ and $\alpha = 2$.

VI. Conclusion

In this paper, we propose a "backwards compatible" transmission scheme for the MARC network. In this scheme, the

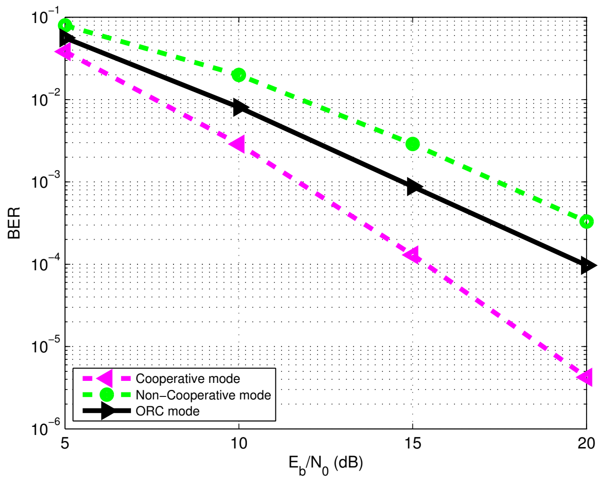

Fig. 5. BER comparison. The relay is located between one of the sources and the destination and the other source is located between the relay and the destination with $d_{S_1R} \approx 0.5$, $d_{S_1D} \approx 1.5$, $d_{RD} \approx 1$, $d_{S_2R} = d_{S_2D} \approx 0.5$ and $\alpha = 3$.

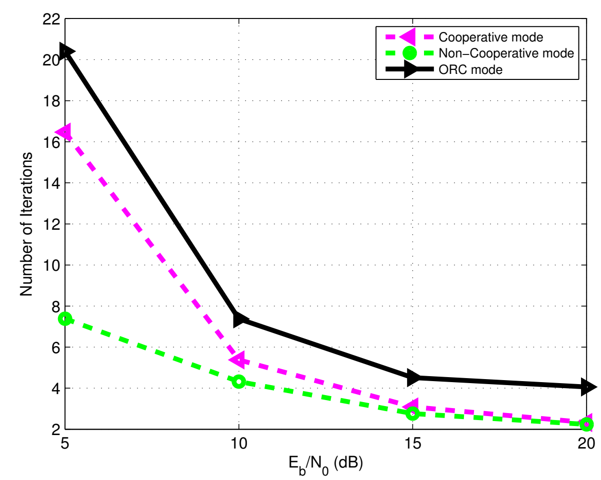

Fig. 6. Complexity analysis. The two sources are equidistant from the relay and the destination with $d_{S_1R} = d_{S_2R} = d_{RD} \approx 0.5$, $d_{S_1D} = d_{S_2D} \approx 1$ and $\alpha = 2$.

sources transmit alternately in an orthogonal fashion and the relay, which is half duplex, assists both sources with no additional resources (time or frequency). The relay implements network coding in order to help both sources and to reduce the number of transmissions. A joint network-channel decoder is implemented at the destination to cancel the interference and to increase the diversity of the system. The performance of the decoder and the transmission scheme in terms of BER is demonstrated to be largely improved at no additional cost in terms of power or resource usage.

Acknowledgment

The authors would like to thank the IAP BESTCOM project funded by BELSPO, and the NEWCOM# Network of Excellence.

References

[1] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *Inform. Theory, IEEE Trans. on*, vol. 51, no. 9, pp. 3037–3063, Sept 2005.

[2] L. Sankaranarayanan, G. Kramer, and N. B. Mandayam, "Hierarchical sensor networks: capacity bounds and cooperative strategies using the multiple-access relay channel model," in *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*, Oct 2004, pp. 191–199.

[3] L. Sankar, H. Liang, and N. Mandayam, "Opportunistic communications in an orthogonal multiaccess relay channel," in *Inform. Theory, 2007. ISIT 2007. IEEE International Symposium on*, June 2007, pp. 1261–1265.

[4] W. Mesbah and T. Davidson, "Power and resource allocation for orthogonal multiple access relay systems," in *Inform. Theory, 2008. ISIT 2008. IEEE International Symposium on*, July 2008, pp. 2272–2276.

[5] M. El Soussi, A. Zaidi, and L. Vandendorpe, "Df-based sum-rate optimization for multicarrier multiple access relay channel," *EURASIP Journal on Wireless Commun. and Networking*, vol. 2015, no. 1, p. 133, 2015. [Online]. Available: http://jwcn.eurasipjournals.com/content/2015/1/133

[6] T. Cover and A. Gamal, "Capacity theorems for the relay channel," *Inform. Theory, IEEE Trans. on*, vol. 25, no. 5, pp. 572–584, Sep 1979.

[7] B. Nazer and M. Gastpar, "Compute-and-forward: Harnessing interference through structured codes," *Information Theory, IEEE Trans. on*, vol. 57, no. 10, pp. 6463–6486, Oct 2011.

[8] M. El Soussi, A. Zaidi, and L. Vandendorpe, "Compute-and-forward on a multiaccess relay channel: Coding and symmetric-rate optimization," *Wireless Communications, IEEE Trans. on*, vol. 13, no. 4, pp. 1932–1947, April 2014.

[9] D. Woldegebreal and H. Karl, "Multiple-access relay channel with network coding and non-ideal source-relay channels," in *Wireless Communication Systems, 2007. ISWCS 2007. 4th International Symposium on*, Oct 2007, pp. 732–736.

[10] O. Sahin and E. Erkip, "Achievable rates for the gaussian interference relay channel," in *Global Telecommunications Conference, 2007. GLOBECOM '07. IEEE*, Nov 2007, pp. 1627–1631.

[11] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, "Xors in the air: Practical wireless network coding," *Networking, IEEE/ACM Transactions on*, vol. 16, no. 3, pp. 497–510, June 2008.

[12] R. Koetter and M. Medard, "An algebraic approach to network coding," *Networking, IEEE/ACM Transactions on*, vol. 11, no. 5, pp. 782–795, Oct 2003.

[13] R. Ahlswede, N. Cai, S.-Y. Li, and R. Yeung, "Network information flow," *Inform. Theory, IEEE Trans.on*, vol. 46, no. 4, pp. 1204–1216, Jul 2000.

[14] C. Hausl, F. Schreckenbach, I. Oikonomidis, and G. Bauch, "Iterative network and channel decoding on a tanner graph," in *Communication, Control, and Computing, 2006. Proceedings of 43rd Allerton Conference on*, Sept. 2005.

[15] D. Duyck, D. Capirone, M. Moeneclaey, and J. Boutros, "A full-diversity joint network-channel code construction for cooperative communications," in *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on*, Sept 2009, pp. 1282–1286.

[16] C. Hausl and P. Dupraz, "Joint network-channel coding for the multiple-access relay channels," in *in Proc. Intern. Workshop on Wireless Ad-hoc and Sensor Networks (IWWAN)*, 2006.

[17] A. Hatefi, R. Visoz, and A. Berthet, "Joint channel-network coding for the semi-orthogonal multiple access relay channel," in *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, Sept 2010, pp. 1–5.

[18] J. Boutros, A. Guillen i Fabregas, E. Biglieri, and G. Zemor, "Low-density parity-check codes for nonergodic block-fading channels," *Inform. Theory, IEEE Trans. on*, vol. 56, no. 9, pp. 4286–4300, Sept 2010.

[19] X.-T. Vu, "Joint network/channel decoding over noisy wireless networks," Ph.D. dissertation, Univ. Paris-Sud, Orsay, france, 2014.