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Superposed CDMA relay cooperation in wireless sensor networks

Yizhi Yin, Karine Amis and Ramesh Pyndiah

Institut Telecom / Telecom Bretagne, Lab-STICC UMR CNRS 6285

Université Européenne de Bretagne, France

Email: {yizhi.yin, karine.amis, ramesh.pyndiah}@telecom-bretagne.eu

Abstract—This paper addresses the problem of cooperation application in an existing non-cooperative wireless sensor network. Sensors are low-energy and low-data rate devices. They transmit small independent individually-encoded information packets to the same destination. The cooperation scheme is based on a product code distributed among sources and relays and turbode-coded at the destination. We propose a system where a relay code division multiple access-based transmission is superposed with the sources time division multiple access-scheduled transmissions. A relay interference cancellation algorithm is defined and the whole system is simulated considering source-destination and relay-destination AWGN channels. The source-relay channel is assumed error-free. An optimized energy allocation between the sources and the relay is extracted from simulations.

I. INTRODUCTION

We consider an already deployed high-density wireless sensor network (WSN). Sensors have limited energy and low complexity capabilities. They transmit independent and individually-encoded packets of small size to the same destination using an orthogonal multiple access technique. The goal is to enhance the overall network transmission quality or to increase the service coverage with the help of a relay, without modifying the network architecture nor adding resources (time/frequency).

Usual WSN have a hierarchical structure where some less-constrained nodes serve as relays to improve the transmission quality. The relay can eavesdrop on the source transmissions and help to forward the information to the destination after processing [1]. Different kinds of relay cooperation have been developed to promote the data transmission [2]. In this paper we are interested in cooperation based on distributed network coding [5]. We consider the scheme proposed in [3] which applies a distributed product code [4]. Similar schemes have also been studied in [6], [7] and [8]. In above works, all transmissions are scheduled in the full time-division multiple-access (TDMA) mode, such that the sources and the relay transmit separately in different time slots. This resource allocation between sources and relays cannot be applied in our context, as we consider an existing non-cooperative WSN with orthogonal multiple access to the resources. Instead, we propose to superpose the relay transmission to the sources transmissions.

All sources use the same short-length systematic block code and broadcast the codewords to the destination in a full-TDMA mode. The relay is full-duplex. We assume error-free source-relay channel and perfect self-interference cancellation

at the relay. The difficulties raised by the necessity of a full-duplex relay is out of scope of our study. The relay overhears the source transmissions, detects the source codewords and applies a product code. The resulting additional redundancy is CDMA-formatted and transmitted. At the destination, sources and relay transmissions are superposed. An interference canceller is applied to mitigate the interference coming from the relay. Source information is recovered using a turbo decoding of the product code [4]. This scheme benefits from the equivalent capacity-achieving long-length code.

This paper is organized as follows. In Section II, we present the network setup. In Section III, we introduce the relay-destination (R-D) CDMA transmission. We analyze the interference on each link and present a turbo decoding procedure including the interference cancellation in Sections IV and V. We introduce the energy scenarios in Section VI and evaluate the network error performance according to different energy allocation through simulations in Section VII. At last, we conclude this paper and point out future research directions.

II. NETWORK SETUP

Suppose a WSN has already been deployed with K sensors transmitting to a same destination. All sensors use the same systematic linear block code (n_S, k_S) and each one broadcasts a codeword to the destination in the TDMA mode. In order to enhance the transmission quality or to increase the network coverage, we setup a relay *without modifying the sensors nor the existing network structure*.

The relay applies the Network Coding on its detected source codewords as proposed in [3] such that: at the relay, the K detected source codewords are stored in the first K rows of a matrix. Then the relay encodes the matrix columns using a second systematic linear block code $(n_R, k_R = K)$ and forwards only the column redundancy to the destination. We denote the relay code redundancy length $r_R = n_R - k_R$. The destination observes K source codewords from the S-D channel and the relay-generated redundancy from the R-D channel. The whole observation corresponds to a product codeword and we apply the turbo decoding [4] to recover the source information. In this paper, the relay uses a CDMA transmission. The source and relay signals are superposed and interfere with each other at the destination. The corresponding network is shown in Fig. 1.

The source-relay channel is supposed error-free to simplify the problem. For the source transmissions, there are $K \times n_S$ coded symbols. The source coded symbol duration is denoted $T_s^{(S)}$. We use the BPSK modulation, so $T_s^{(S)}$ is also the source codeword bit duration. The relay uses the single antenna

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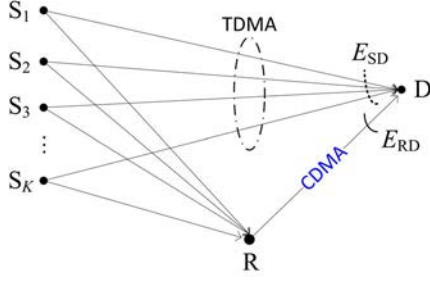


Fig. 1. Superposed CDMA relay cooperation

CDMA. The relation between the symbol duration $T_s^{(R)}$ of the relay-generated redundancy and the chip duration $T_{chip}^{(R)}$ is:

$$T_s^{(R)} = PG \cdot T_{chip}^{(R)}, \quad (1)$$

where the processing gain PG equals K in order that the relay CDMA signal occupies the same RF band as the source signals. Furthermore, to ensure that sources and relay transmit in the same time interval, we impose that:

$$K \cdot n_S T_s^{(S)} = PG \cdot n_S T_{chip}^{(R)}, \quad (2)$$

which leads to:

$$T_s^{(S)} = T_{chip}^{(R)} = T_s. \quad (3)$$

The hybrid TDMA-CDMA transmission scheme is illustrated in Fig. 2.

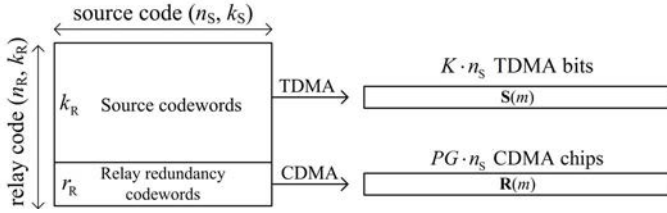


Fig. 2. Multiple access of the TDMA-CDMA scheme, $K = PG = k_R$.

Compared to the full TDMA relaying [3], which needs an additional bandwidth of $(n_R - k_R)/n_R$ for the relay transmission, the superposed CDMA-TDMA relaying occupies exactly the same RF band as the source transmissions.

III. RELAY-DESTINATION CDMA MODEL AND MAXIMUM-LIKELIHOOD MULTI-USER DETECTION (MUD)

In Fig. 3, we illustrate the relay-destination CDMA transmission model (without the source interference). The relay-generated codewords are stored in a matrix denoted \mathbf{D} whose q -th column is denoted $\vec{d}_q^{(R)} = (d_{0q}^{(R)}, d_{1q}^{(R)}, \dots, d_{r_R-1,q}^{(R)})^T$.

The relay has only one transmitter and uses a synchronous CDMA scheme [9] to transmit its codewords. During the q -th transmission interval, the relay simultaneously transmits the r_R binary components of $\vec{d}_q^{(R)}$ thanks to the spreading sequences of length PG . Defining $\mathbf{S} = (\vec{s}_0, \vec{s}_1, \dots, \vec{s}_{r_R-1})$ the $PG \times r_R$ spreading sequence matrix, the received vector (excluding the source interference) at the destination is given by:

$$\vec{r}_q = A_R \mathbf{S} \vec{d}_q^{(R)} + \vec{n}_q, \quad (4)$$

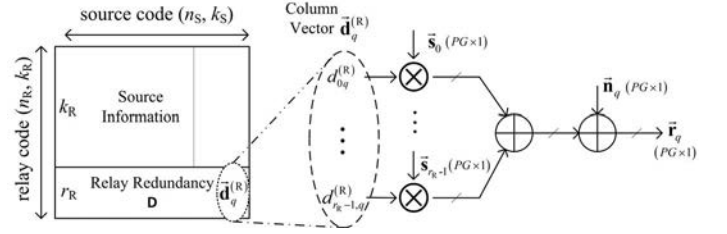


Fig. 3. CDMA-based relaying model.

where A_R is the received amplitude. \vec{n}_q is the average white Gaussian noise vector. In the following, we suppose BPSK modulation and $d_{iq}^{(R)} \in \{\pm 1\}$ for $i = 0, 1, \dots, r_R - 1$.

In our case, there are r_R virtual CDMA users corresponding to r_R relay redundancy rows. In general, r_R is a small integer because the relay code rate is close to 1. For example, if we use the BCH (32, 26) code at the relay, $r_R = 6$. For every transmitted vector $\vec{d}^{(R)}$, there are $2^{r_R} = 64$ possible vectors to be tested by using the maximum-likelihood (ML) detection.

At the destination, the received signal \vec{r} in Eq. 4 can be despread through a matched filter bank:

$$\begin{aligned} \vec{y}_{(r_R \times 1)} &= \mathbf{S}^T \vec{r}_{(PG \times 1)} = A_R \mathbf{S}^T \mathbf{S} \vec{d}^{(R)} + \mathbf{S}^T \vec{n} \\ &= A_R \mathbf{C} \vec{d}^{(R)} + \vec{n}_t, \end{aligned} \quad (5)$$

where \mathbf{C} is the cross-correlation matrix of the r_R spreading sequences.

We apply the ML rule based on the log-likelihood ratio (LLR) so that the soft detection result can be directly provided to the TPC decoder in a later step. We calculate the LLR of the k -th bit $d_k^{(R)}$ in the relay transmitted vector $\vec{d}^{(R)}$ as:

$$\begin{aligned} \Lambda(d_k^{(R)}) &= \ln \frac{\Pr(d_k^{(R)} = 1 | \vec{y})}{\Pr(d_k^{(R)} = -1 | \vec{y})} \\ &= \ln \frac{\sum_{\vec{d}^i \in \text{set}\{\vec{d}_{+1}\}} p(\vec{y} | \vec{d}^{(R)} = \vec{d}^i)}{\sum_{\vec{d}^i \in \text{set}\{\vec{d}_{-1}\}} p(\vec{y} | \vec{d}^{(R)} = \vec{d}^i)}, \end{aligned} \quad (6)$$

where the set \vec{d}_{+1} (resp. \vec{d}_{-1}) denotes the transmitted vector set satisfying that the k -th bit of the vector equals 1 (resp. -1).

Based on Eq. 5, we model $\vec{y} - A_R \mathbf{C} \vec{d}^{(R)} = \vec{n}_t$ as a 0-mean multivariate Gaussian variables whose covariance matrix is:

$$\text{COV} = \text{Cov}(\vec{n}_t) = E(\mathbf{S}^T \vec{n} \cdot \vec{n}^T \mathbf{S}) = \sigma_n^2 \mathbf{C}, \quad (7)$$

where σ_n^2 is the variance of the elements in \vec{n} . We derive that:

$$\begin{aligned} p(\vec{y} | \vec{d}^{(R)} = \vec{d}^i) &= \frac{1}{(2\pi)^{r_R/2} |\text{COV}|^{1/2}} \exp \left\{ -\frac{1}{2} (\vec{y} - A_R \mathbf{C} \vec{d}^{(R)})^T \right. \\ &\quad \left. \cdot (\text{COV})^{-1} (\vec{y} - A_R \mathbf{C} \vec{d}^{(R)}) \right\}. \end{aligned} \quad (8)$$

Canceling the common term in the numerator and denominator of Eq. 6, we get the following exponent part (metric) to be computed for each possible $\vec{d}^{(R)}$ in place of using Eq. 8:

$$\exp \frac{1}{2\sigma_n^2} \left(2A_R \vec{y}^T \vec{d}^{(R)} - A_R^2 \left(\vec{d}^{(R)} \right)^T \mathbf{C} \vec{d}^{(R)} \right). \quad (9)$$

IV. TIME-ALIGNED TRANSMISSION AND TURBO DECODING WITH INTERFERENCE CANCELATION

We carefully select the CDMA parameters including the processing gain, chip duration, carrier frequency, such that:

1. The relay CDMA signal occupies the same RF band as the source signals;
2. The duration of one relay CDMA transmission, i.e., the time used to forward the relay-generated redundancy part, equals the total time required by all sources to transmit their data. We denote this duration T_{Block} .

The K sources broadcast their data using one time block T_{Block} . The relay encodes the detected source codewords and forwards the relay-generated redundancy in the following time block, which is also used by the sources for the next-round of source transmission. In this way, the relay CDMA transmission associated with the current data block is superposed with the source transmission of the next data block.

We denote the source data part including K source codewords as $\mathbf{S}(m)$ where m is the data block index. The relay redundancy part of $\mathbf{S}(m)$ is denoted $\mathbf{R}(m)$. The time-aligned transmission is illustrated in Fig. 4. The circled couple $[\mathbf{S}(m), \mathbf{R}(m)]$ corresponds to the same product codeword.

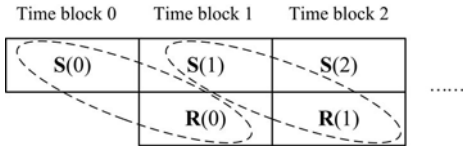


Fig. 4. Time-aligned data blocks at the destination.

As shown in Fig. 4, the source and relay signals are superposed at the receiver causing mutual interference. We thus propose a turbo decoding procedure including an interference cancellation.

There is an initialization step in time block 0 where the relay is silent and the destination observes only the noisy source codewords $\mathbf{S}(0)$ and stores them. In time block 1, the destination observes the source part $\mathbf{S}(1)$ of the second product codeword superposed with the CDMA relay redundancy part $\mathbf{R}(0)$ of the previous product codeword. Using the ML MUD, the destination detects $\mathbf{R}(0)$ in the presence of $\mathbf{S}(1)$. The destination thus observes the first product codeword by combining the observed interference-free $\mathbf{S}(0)$ and the detected LLR of $\mathbf{R}(0)$. After turbo decoding [4], we get the decoded $\hat{\mathbf{S}}(0)$, which contains less errors than the direct soft decoding of $\mathbf{S}(0)$ at the initialization step.

Based on the decoded $\hat{\mathbf{S}}(0)$, we can regenerate the relay redundancy part $\hat{\mathbf{R}}(0)$ at the destination through product encoding. $\hat{\mathbf{R}}(0)$ will usually be more reliable than the ML-detected $\mathbf{R}(0)$ because of the turbo decoding gain. Once we

get $\hat{\mathbf{R}}(0)$, we can regenerate the relay CDMA signal and cancel its interference on the source-destination transmission to get a 'cleaned' version of $\mathbf{S}(1)$.

The above procedure is then repeated. After each turbo decoding, we recover the source information of the previous data block. The main steps of the procedure are given below:

- *Time block 0: Initialization.*

Destination (D) stores the noisy $\mathbf{S}(0)$ as $\tilde{\mathbf{S}}(0)$.

- *Time block 1: D receives $\mathbf{S}(1) + [\text{CDMA } \mathbf{R}(0)] + \text{noise}$.*
 - (a) *D applies ML multi-user detection to detect $\mathbf{R}(0)$ in the presence of $\mathbf{S}(1)$.*
 - (b) *D turbo decodes the product codeword $[\mathbf{R}(0)^T, \tilde{\mathbf{S}}(0)^T]^T$ to decide $\hat{\mathbf{S}}(0)$.*
 - (c) *D recalculates the column redundancy $\hat{\mathbf{R}}(0)$ from $\hat{\mathbf{S}}(0)$.*
 - (d) *D cancels the interference coming from the relay:*

$$\tilde{\mathbf{S}}(1) = \mathbf{S}(1) + [\text{CDMA } \mathbf{R}(0)] + \text{noise} - [\text{CDMA } \hat{\mathbf{R}}(0)]$$

- *Repeat the above procedure with incremental indices.*

V. RECEIVER STRUCTURE

The noise-free received signals at the destination on the S-D (resp. R-D) channel can be expressed by:

$$r_{\text{SD}}^{\text{TDM}}(t) = \sum_n A_S d_n^{\text{TDM}} h_{T_s} \left(t - nT_s^{(S)} \right) \cos 2\pi f_0 t. \quad (10)$$

$$r_{\text{RD}}^{(R)}(t) = \sum_{i=0}^{r_R-1} A_R \sum_n d_{i,n}^{(R)} \sum_m s_{i,m} \cdot h_{T_s} \left(t - PG \cdot nT_s^{(S)} - mT_s^{(S)} \right) \cos 2\pi f_0 t. \quad (11)$$

Here $h_{T_s}(t)$ is the root-raised-cosine pulse shaping function. $d_n^{\text{TDM}} \in \{\pm 1\}$ is the source codeword bit in the TDMA data stream. $d_{i,n}^{(R)} \in \{\pm 1\}$ is the relay codeword bit of the i -th CDMA user. $s_{i,m}$ is the m -th element of the spreading sequence \tilde{s}_i . f_0 is the carrier frequency. The superposed noisy signal received at the destination is thus given by:

$$r(t) = r_{\text{RD}}^{(R)}(t) + r_{\text{SD}}^{\text{TDM}}(t) + n(t). \quad (12)$$

After coherent detection, we express the received signal as:

$$\vec{r}_{(PG \times 1)} = A_R \mathbf{S} \vec{d}_{(r_R \times 1)}^{(R)} + A_S \vec{d}_{(PG \times 1)}^{\text{TDM}} + \vec{n}_{(PG \times 1)}, \quad (13)$$

where \vec{d}^{TDM} corresponds to the TDMA source codeword bit sequence whose variance $\sigma_1^2 = 1$.

(1) For the relay CDMA part, the ML MUD with source TDMA interference has the same structure as described in Section III. The difference is that the output of the matched filter bank (Eq. 5) becomes:

$$\vec{y}_{(r_R \times 1)} = \mathbf{S}^T \vec{r}_{(PG \times 1)} = A_R \mathbf{C} \vec{d}^{(R)} + A_S \vec{d}_t^{\text{TDM}} + \vec{n}_t. \quad (14)$$

We model $\vec{y} - A_R \mathbf{C} \vec{d}^{(R)} = A_S \vec{d}_t^{\text{TDM}} + \vec{n}_t$ as a multi-variate Gaussian variable. Its covariance matrix $\mathbf{COV} = (A_S^2 \sigma_1^2 + \sigma_n^2) \mathbf{C}$ and the exponent metric (Eq. 9) becomes:

$$\exp \frac{1}{2(A_S^2 \sigma_1^2 + \sigma_n^2)} \left(2A_R \vec{y}^T \vec{d}^{(R)} - A_R^2 \left(\vec{d}^{(R)} \right)^T \mathbf{C} \vec{d}^{(R)} \right) \} \quad (15)$$

Substituting Eq. 15 into Eq. 6, we obtain the LLR of $\mathbf{R}(m)$.

(2) For the source part detection, once we have recalculated the relay redundancy $\hat{\mathbf{R}}(m)$ from $\hat{\mathbf{S}}(m)$ (step c. of the pseudo-code in Section IV), we cancel its interference and obtain $\tilde{\mathbf{S}}(m)$ as shown in Fig. 5, where $\hat{d}_m^{(R)}$ is the elements of $\hat{\mathbf{R}}(m)$.

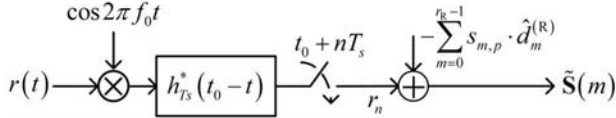


Fig. 5. Coherent detection and relay-interference cancellation for source part

VI. ENERGY SCENARIOS

The destination receives the superposed signal $r(t)$ given in Eq. 12. After the matched filtering and perfect sampling, we can verify that the average received energy on the S-D (resp. R-D) link in a given duration of $T_s^{(S)} = T_{chip}^{(R)}$ is:

$$E_{SD} = (A_S)^2 \varphi_{T_s}(t_0) / 2. \quad (16)$$

$$E_{RD} = \frac{(A_R)^2}{2} \varphi_{T_s}(t_0) \cdot \frac{r_R}{PG}. \quad (17)$$

Here $\varphi_{T_s}(t_0) = \int |h_{T_s}(t)|^2 dt$ is a constant.

The corresponding noise variable has a variance of $\sigma_n^2 = (N_0/4) \cdot \varphi_{T_s}(t_0)$. Thus we have the following energy ratio:

$$x = \frac{E_{RD}}{E_{SD}} = \frac{r_R}{PG} \cdot \left(\frac{A_R}{A_S} \right)^2. \quad (18)$$

We want to optimize x through simulations according to the network error performance as a function of E_b/N_0 , where E_b denotes the average received energy per source information bit at the destination. We consider two different energy scenarios:

Case A: The energy consumed by the relay is considered such that E_b is a function of both E_{SD} and E_{RD} . Based on the product code scheme, we have the following relation:

$$(k_S \times k_R) E_b = (K \times n_S) E_{SD} + (PG \times n_S) E_{RD}, \quad (19)$$

Substituting Eq. 16-18 into Eq. 19, we have:

$$\sigma_n^2 = \frac{(A_S)^2}{8 \frac{R_S}{1+x} \cdot \frac{E_b}{N_0}}, \quad (20)$$

where $R_S = k_S/n_S$ corresponds to the source code rate.

Case B: The relay is autonomous in energy so that E_b depends only on E_{SD} . We investigate this case because it corresponds to a ‘self-powered’ relay scenario in a WSN. A self-powered relay usually has abundant low-cost energy,

e.g., the relay is equipped with a solar panel. The relay energy consumption is subordinate to that of the sensors. The network energy consumption is then dominated by the source transmission energy. So we have the following relation:

$$(k_S \times k_R) E_b = (K \times n_S) E_{SD}. \quad (21)$$

Similarly, we derive the corresponding noise variance:

$$\sigma_n^2 = \frac{(A_S)^2}{8 R_S \cdot \frac{E_b}{N_0}}. \quad (22)$$

VII. SIMULATION RESULTS

We consider the same TPC scheme as in [3] such that the source code is BCH(64, 51) and the relay code is BCH(32, 26). We need $r_R = 6$ spreading sequences with $PG = 26$. Since there is no conventional spreading sequences satisfying $PG = 26$, we randomly generate the spreading sequences set. We have made an exhaustive search with stopping criterion and found a set of 6 optimized sequences. In its corresponding normalized cross-correlation matrix \mathbf{C} (diagonal values normalized to 1), the biggest off-peak value is 0.2308. In the simulation, we use BPSK modulation and all channels are modeled as AWGN channels.

In Fig. 6, we plot the network bit error rate (BER) performance versus E_b/N_0 where E_b includes the energy received from R-D channel (Case A). We have considered different energy allocations between sources and relay.

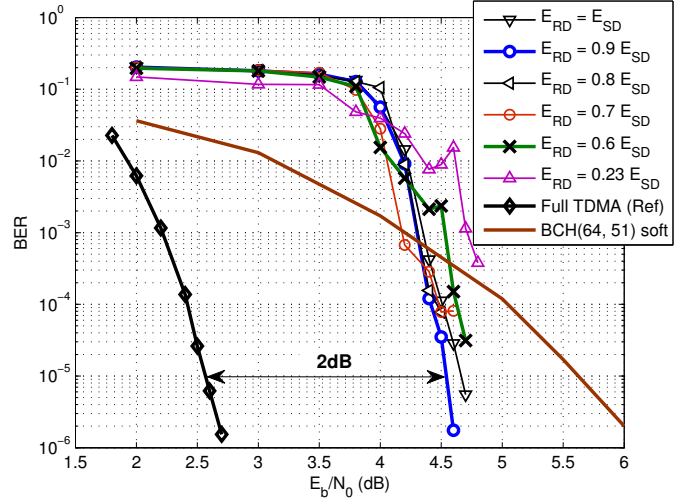


Fig. 6. BER versus E_b/N_0 of the CDMA-TDMA cooperation, BPSK, AWGN channel, E_b includes the energy from relay-destination channel.

The curve labeled ‘Full TDMA (Ref)’ corresponds to the BER of the error-free relay cooperation using TDMA to schedule both the sources and the relay transmissions, which is the cooperation scheme studied in [3]. This curve serves as a reference here although it needs a little larger bandwidth than the proposed CDMA relay cooperation. Another reference curve labeled ‘BCH (64, 51) soft’ corresponds to the soft decoding BER performance of the direct S-D transmission without relay cooperation. Different BER performance curves associated with different source-relay energy ratios are given in the figure. The corresponding relay-source energy relation is

denoted as ' $E_{RD} = xE_{SD}$ ' in the legend. We can observe that $E_{RD} = 0.9E_{SD}$ ($A_R \approx 1.97A_S$) is the optimal configuration in the case where the relay energy consumption is taken into account. Compared to the reference TDMA relay cooperation curve, the penalty to maintain the same RF bandwidth is about 2dB at a $BER = 10^{-5}$. Compared with the case of no relay cooperation, the coding gain offered by the CDMA relay cooperation is about 1.2dB at a $BER = 10^{-5}$.

In Fig. 6, some configurations exhibit an unstable BER performance even with increased trial numbers, especially when $E_{RD} < 0.8E_{SD}$. It is caused by the high error probability ($> 1 \times 10^{-1}$) at the input of the turbo decoder in the detection of either the source TDMA data (26 source BCH codewords) or the relay CDMA data (6 relay codewords), which harms the iterative interference cancellation proposed in Section IV.

In Fig. 7, we show the network BER measured considering only the energy used by the sources (Case B). We observe that $E_{RD} = 1.5E_{SD}$ ($A_R \approx 2.55A_S$) is the best configuration if the relay energy consumption is neglected. This curve has a gain of about 4.1dB at $BER = 10^{-5}$ compared to the case of no relay cooperation. This gain is close to the gain offered by the referenced full TDMA relay cooperation. As a conclusion, adding a relay in an existing WSN without modifying its structure is possible by adopting the proposed scheme, which enables to enhance the transmission quality and coverage.

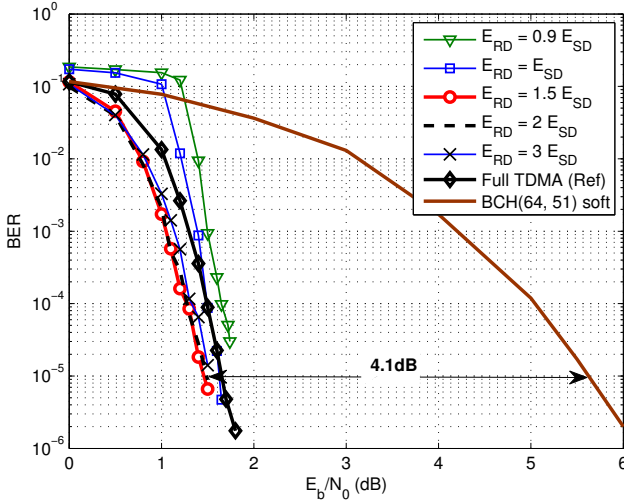


Fig. 7. BER versus E_b/N_0 of the CDMA-TDMA cooperation, BPSK, AWGN channel, E_b excludes the energy from relay-destination channel.

VIII. CONCLUSION AND PERSPECTIVES

This paper has addressed the problem of enhancing the transmission quality and service coverage in an already deployed WSN, without modifying its structure nor the resources, with the help of full-duplex relays. The studied cooperation scheme is based on the distributed product code described in [3]. We have proposed to superpose a relay CDMA-formatted transmission with the source TDMA-scheduled transmissions. We have defined an interference canceller to mitigate the interference coming from the relay at the destination. We have designed an iterative receiver including an interference

canceller and a turbo decoder. The existence of an optimal energy allocation ratio between the sources and the relay has been shown through simulations. Further works will consider the theoretical analysis of the optimal energy allocation both for AWGN and Rayleigh channels. Besides that, we can also investigate the multi-antenna transmission/reception to benefit from the spatial diversity.

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