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High throughput and low power consumption on a wireless sensor network ☆

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ABSTRACT

Wireless communications are subject to fading and interferences that affect their performance. However, the broadcast nature of wireless transmissions is an advantage that has been exploited in the past to improve performance. Nodes belonging to a sensor network could listen to messages sent from other nodes and participate in this communication for the benefit of the entire network. In this paper, we present a protocol following these lines. The novelty of our approach is to obtain high throughput with low complexity and low energy consumption.

1. Introduction

Sensor networks consist of many autonomous nodes performing a portion of a common task. In most scenarios, a sensor network is used after massive deployment of nodes in an area of study. Chances to recover all the sensors are little and the nodes' limited batteries impose the lifetime of the network. An important feature of these sensors is that they communicate through a wireless channel, and in most cases, by organizing ad hoc networks without infrastructure. The main challenge for many of these networks is to maximize the throughput with efficient energy consumption.

As it is well known, wireless communications suffer from signal fading. The combined effects of signal strength decay as we move away from the source, along with the presence of multiple paths and obstacles before we reach the destination, degrade the quality of the transmission. The error probability is increased by several orders of magnitude if we are immersed in a Rayleigh fading environment as shown in [1].

Spatial diversity has been recognized as a way to improve the error probability as a function of the signal to noise ratio (SNR). A multiple transmitter system increases the slope of the error probability curve on a log scale in as many orders as transmit antennas are used (see [1] or [2]). The increase factor is called diversity gain.

Cooperative MAC protocols have been proposed as a way to use spatial diversity on a sensor network (see [3] or [4]). The main idea is to generate a communication with multiple transmitters using distributed nodes over the network. Each node may be considered as a virtual antenna, effectively leading to different path gains from the message destination to the source. However, cooperation leads to a non co-located antenna array, and coordination among nodes is required. This coordination may be performed by either using a feedback channel from the destination to the source or using direct transmission among sensors [5].

Along these lines of thought, a protocol called *randomized cooperative MAC* (RCoopMAC) is proposed in [6]. This protocol considers two different forms of transmission, *direct* transmission, where a message is sent from source to destination without any intermediary, and *cooperative* transmission that uses numerous relays simultaneously. The main goal is to increase the effective rate at which data is sent, while keeping the average error rate bounded. This protocol uses the idea behind *space–time block codes* (STBC) [2] to achieve diversity in a cooperative transmission. However, to simplify the coordination process, the nodes that act as a distributed network of antennas, send a random combination of the chosen encoding matrix instead of the matrix itself.

For each particular scenario, this protocol determines whether to establish the communication in a cooperative or in a direct manner. The deciding factor is the total time spent on the transmission. It is shown in [6] that cooperation among several nodes increases the diversity gain of the overall transmission. However, the actual throughput of the network decreases considerably due to the code rates that are less than one. This observation is overlooked during the performance evaluation of the protocol RCoopMAC.

In this paper, we propose a cooperative framework which employs fewer participants, but yet, improves the effective transmission rate. This achievement is obtained with the use of the Alamouti code, the only orthogonal STBC with unitary code rate.

The rest of the paper is organized as follows. In Section 2, we present the model of the communication system and we analyze its components. In Section 3, we introduce the problem of cooperation and we specify a possible implementation of the protocol.

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In Section 4, we show the results of our simulations. Finally, in Section 5, we present our conclusions.

In this paper we use the following notation, boldface lower (upper) case letters, e.g. $\mathbf{a}$ ($\mathbf{A}$), represent a vector (matrix). $\mathbb{R}^m$ and $\mathbb{C}^m$ is a shorthand for $\mathbb{R}^{m\times 1}$ and $\mathbb{C}^{m\times 1}$. $\mathbf{0}_m \in \mathbb{R}^m$ is the null vector and $\mathbf{I}_m \in \mathbb{R}^{m\times m}$ is the identity matrix. $\{\mathbf{A}\}_{i,j}$ is the (i,j)th element of $\mathbf{A}$. And a circular symmetric Gaussian random vector $\mathbf{x} \in \mathbb{C}^n$ with mean $\boldsymbol{\mu} \in \mathbb{C}^n$ and covariance matrix $\boldsymbol{\Sigma} \in \mathbb{C}^{n\times n}$ is denoted as $\mathbf{x} \sim \mathcal{CN}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$.

2. System model

We will consider a model similar to the one used in [6]. There is a wireless sensor network with $N+2$ nodes $\mathcal{N}_i$, with $i \in \{1,\dots,N+2\}$, random and uniformly distributed in a region. Two of these nodes are the source (S) and destination (D) of a transmission, and the remaining N nodes may be used as relays, in order to cooperate with the link (S,D) and to increase the transmission data rate.

The frequency response of the proposed channel is flat for the entire bandwidth used and it is constant during the transmission of the message. Let $\eta_{i,j}$ be the distance between the node $\mathcal{N}_i$ and $\mathcal{N}_j$, and $g_{i,j}$ the channel transference for the link $(\mathcal{N}_i, \mathcal{N}_j)$ where $g_{i,j} \sim \mathcal{CN}(0, \eta_{i,j}^{-\alpha})$, where α is the *path-loss exponent*. We assume that the channels are symmetrical, i.e., $g_{i,j}$ and $g_{j,i}$ are equally distributed.

2.1. System and transmission modes

The Physical Layer (PHY) of our system must work with an average bit error probability (BEP) below a certain fixed level set in advance. This level will be called $ABEP_{target}$ and the chosen transfer data rate must comply with it. Therefore, the error probability of the link (S,D) has to be estimated in order to select the appropriate rate.

The transmission used will be single-carrier, with a symbol duration T_s constant for all possible transfer data rates. This restriction is convenient to simplify the transceiver implementation. Following [6], square QAM constellations will be used in this work to achieve different rates, but the results could be applied to other type of constellation. The PHY layer supports Q possible constellations, each one with M_q symbols, where $q \in \{0,1,\dots,Q-1\}$. Existing data rates are $R_q = b_q/T_s$, where $b_q = \log_2(M_q)$ is the number of bits sent in each symbol period. The average energy sent is constant for all nodes and all possible data rates.

Two transmission modes are possible. The first one is the *direct mode*, in which S sends a block of K i.i.d. symbols belonging to an M_q-QAM constellation. We will call this vector $\mathbf{a} \triangleq [a_1, a_2, \dots, a_K] \in \mathbb{C}^K$. This is the transmitting mode used to start transmission and to send data without cooperation. In contrast, in *cooperative mode*, S transmits the message $\mathbf{a}$ to the nearby nodes, and then, they all relay the information together using a code matrix $\mathcal{C}(\mathbf{a}) \in \mathbb{C}^{P\times L}$ associated with the original block of K M_q-QAM symbols. In this transmission, P is the new block length and L, the number of virtual antennas.

Let r_c be the transmission code rate used, B, the number of bits of information sent, and R' and R'', the rates used in both phases of the cooperative transmission. The total amount of time spent on a transmission is

$$T_{coop} = KT_s + PT_s = B\left(\frac{1}{R'} + \frac{1}{r_c R''}\right),$$

therefore, we will benefit from cooperative communication if

$$T_{coop} < T_{dm} \quad \Rightarrow \quad \frac{1}{R'} + \frac{1}{r_c R''} < \frac{1}{R_{dm}}, \tag{1}$$

where T_{dm} and R_{dm} are the total amount of time spent in direct mode and the data rate in that mode, respectively.

We see, that in our system, the error probability expected for a particular transmission imposes restrictions to the eligible transmission data rates. Next, we will analyze bounds on the error probability for both modes of transmission. These bounds will be used as a means of deciding whether a cooperative transmission is beneficial or not.

2.2. Direct mode: BEP analysis

As shown in [1] and [7], the average bit error probability for a Gray-coded QAM constellation is

$$P_{i,j}^{(q)}(e) \approx \frac{2}{b_q}\left(1 - \frac{1}{\sqrt{M_q}}\right)\left(1 - \sqrt{\frac{3\overline{\gamma}_{i,j}}{2(M_q-1)+3\overline{\gamma}_{i,j}}}\right) \tag{2}$$

where q is modulation index used, i and j are the node indices involved, and $\overline{\gamma}_{i,j} \triangleq \gamma/\eta_{i,j}^{\alpha}$ is the average signal to noise ratio (SNR) associated with the link $(\mathcal{N}_i, \mathcal{N}_j)$, where γ is the signal to noise ratio expected at the transmitter output $\gamma \triangleq E[|a_k|^2]/N_0$.

We say that the node $\mathcal{N}_i$ can reliably communicate with the node $\mathcal{N}_j$ in direct mode at the data rate R_q, if that rate satisfies $P_{i,j}^{(q)}(e) \leqslant ABEP_{target}$, which implies that the channel SNR fulfills the following inequality

$$\overline{\gamma}_{i,j} \geqslant \overline{\gamma}_{\min,q} \triangleq \frac{2(M_q-1)(1-\Omega)^2}{3[1-(1-\Omega)^2]}, \tag{3}$$

with $\Omega \triangleq b_q(ABEP_{target}/2)(1-1/\sqrt{M_q})^{-1}$. Note that this inequality depends only on transmission parameters.

2.3. Cooperative mode: RCoopMAC

In this transmission mode, coding is based on orthogonal space–time block codes (OSTBC) [2]. A generic OSTBC matrix is expressed as $\mathcal{C}(\mathbf{a}) \in \mathbb{C}^{P\times L}$, where, as we said before, P represents the new block length and L, $(P \geqslant L)$, the number of virtual antennas. This matrix satisfies that $\mathcal{C}^H(\mathbf{a})\mathcal{C}(\mathbf{a}) = \|\mathbf{a}\|^2\mathbf{I}_L$.

The work [6] proposes that once the N_h active relays receive and correctly decode the message $\mathbf{a}$, they re-encode it, along with node S itself, using an RSTBC rule [8] at the data rate $R'' = \log_2(M'')/T_s$. It is assumed in this work, that both the relays and S are time- and frequency-synchronized in a centralized or distributed fashion.

The advantage of implementing the code using RSTBC is that each node can encode the message to convey independently. Otherwise, we should have a rule for assigning codes to the relays, and invest time in communicating it to the participating nodes in the cooperative transmission. The RSTBC method for allocating codes is suitable if the number of active relays at any given time is unknown in advance.

3. Cooperative transmission with unitary r_c

Unfortunately, the use of many relays does not compensate the loss in throughput due to the coding rate (r_c) when using a suitable OSTBC. It is shown in [2] that large orthogonal codes cannot transmit complex symbols with unitary rate. Moreover, r_c cannot exceed 1/2 when $L \geqslant 8$. On the other hand, the Alamouti code has an effective transmission rate that equals unity, because it needs two symbol periods to send two symbols.

Now, if we use the Alamouti code to transmit data in a cooperative manner, two nodes only are involved in the transmission. Since S is a necessary player in this scheme, we need only a single

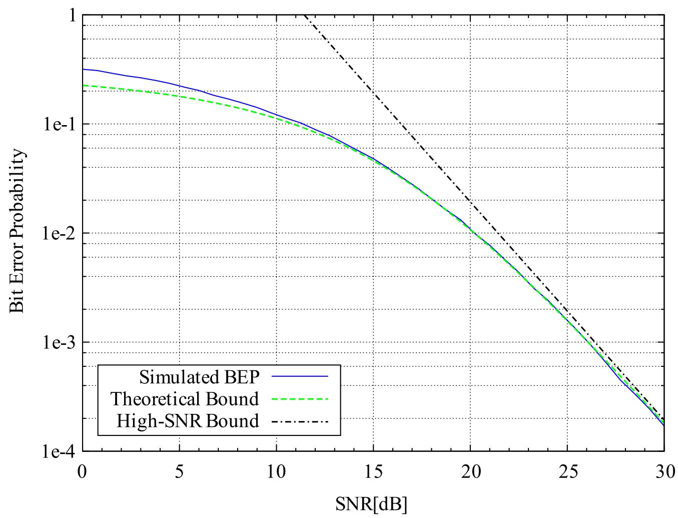

Fig. 1. Bit error probability of a 64-QAM with Alamouti code through a channel with Rayleigh fading ($\sigma^2_{s,d} = \sigma^2_{h,d} = 1$).

node as relay, and the use of RSTBC random codification is unnecessary. If S transmits by default one of the two columns of the Alamouti matrix $\mathcal{C}(a)$, the only active relay would send the other column of the matrix. The signal received by D, using this strategy will be

$$\mathbf{r}_d = \underbrace{\begin{bmatrix} s_1 & s_2 \\ s_2^* & -s_1^* \end{bmatrix}}_{\mathcal{C}(\mathbf{a})} \underbrace{\begin{bmatrix} g_{s,d} \\ g_{h,d} \end{bmatrix}}_{\mathbf{g}_d \in \mathbb{C}^2} + \mathbf{n}_d, \tag{4}$$

where $\mathbf{g}_d \sim \mathcal{CN}(\mathbf{0}_2, \boldsymbol{\Sigma}_{\mathbf{g}_d})$, with $\boldsymbol{\Sigma}_{\mathbf{g}_d} \triangleq \operatorname{diag}(\eta_{s,d}^{-\alpha}, \eta_{h,d}^{-\alpha}) \in \mathbb{R}^{2\times 2}$ and $\mathbf{n}_d \sim \mathcal{CN}(\mathbf{0}_2, N_0\mathbf{I}_2)$ is AWGN. Let us assume that the receiver perfectly estimates the channel coefficients, so it can decode $\mathbf{a}$ according to the ML decision rule $\hat{\mathbf{a}} = \arg\min_{\mathbf{a}} \|\mathbf{r}_d - \mathcal{C}(\mathbf{a})\mathbf{g}_d\|^2$. For Alamouti, the ML criterion is equivalent to 2 independently ML decision rules over 2 parallel and independent AWGN channels: $y_k = \|\mathbf{g}_d\| a_k + w_k$, for $k \in \{1, 2\}$, where $w_k \sim \mathcal{CN}(0, N_0)$ is the noise term, with $E[w_1 w_2^*] = E[w_2 w_1^*] = 0$ [2].

If we call $\mathcal{E}^c$ the event in which the only relay decodes $\mathbf{a}$ correctly, and $P_d(e \mid \mathcal{E}^c, \mathbf{g}_g)$ symbolizes the BEP at the output of the ML detector of D, conditioned to $\mathcal{E}^c$ and $\mathbf{g}_d$, we have

$$P_d\big(e \mid \mathcal{E}^c, \mathbf{g}_d\big) \simeq \frac{4}{b''}\left(1 - \frac{1}{\sqrt{M''}}\right) \mathrm{Q}\left(\sqrt{\frac{3\gamma \|\mathbf{g}_d\|^2}{M'' - 1}}\right), \tag{5}$$

where $\mathrm{Q}(x) \triangleq (1/\sqrt{2\pi}) \int_x^{+\infty} e^{-u^2/2}\, du$ is the probability of the tail of the normalized Gaussian distribution and $b'' = \log_2(M'')$, the number of bits per symbol.

If we average over all possible values of $\mathbf{g}_d$ (see Appendix A) we can establish the following bound over (5) at high SNR

$$P_d\big(e \mid \mathcal{E}^c\big) \leqslant \frac{2}{b''}\left(1 - \frac{1}{\sqrt{M''}}\right) \frac{(M'' - 1)^2}{6\,\overline{\gamma}_{s,d}\,\overline{\gamma}_{h,d}}. \tag{6}$$

The previous bound was verified by simulations for different sizes of M-QAM constellations when using the Alamouti code. It was obtained that (6) remained always above the actual error probability, and get close enough for SNRs greater than 30 dB as shown in Fig. 1. It is worth noting that at low SNR the hypothesis of one erroneous bit per symbol is not valid, and therefore, the theoretical bound (A.5) found in Appendix A cannot be used. However, we will employ the high SNR bound (6). Our estimates will always be pessimistic, and we will perform a worst-case scenario strategy.

3.1. Protocol implementation

Both RCoopMAC protocol and our approach are designed to be used in sensor networks without any kind of central coordination. Also, these protocols allow cooperative transmissions, which need the participation of one or more nodes. To achieve a successful transmission, a node must fulfill the role of coordinator in this transmission.

In particular, in our implementation node S has to search for a node that can help it, and if it finds one, then it starts a cooperative transmission. This transmission mode uses only one relay, so S needs to be sure that the selected node will be able to participate in the communication. To convey the message in a cooperative manner with no active relay, represents an unnecessary expenditure of time and energy to the network.

We will not cover in this work the sequence of coordination messages to be exchanged between S, D, and the relay in order to communicate in a cooperative way. We assume that the MAC layer of the protocol has a messaging system based on CSMA-CA (*Carrier Sense Multiple Access with Collision Avoidance*) with some modifications. Moreover, these messages are sent using a much slow rate with high reliability.

The selection of a relay is performed by the transmitter. For this, it needs to be aware of the channel state of all the possible links. The way in which S stores this information is through a channel state matrix $\mathbf{A}$ called *CoopMatrix*. The components $p_1, p_2 \in \{1, 2, \ldots, N+2\}$ of the matrix are equal to $\{\mathbf{A}\}_{p_1,p_2} = \overline{\gamma}_{p_1,p_2}$. The values $\overline{\gamma}_{p_1,p_2}$ can be estimated by each node using (3) by passively listening to the communications made by other nodes, or proactively exchanging information with neighboring nodes. The order of the matrix $\mathbf{A}$ increases with the number of nodes involved in the cluster. Note that since all channels are symmetric, the matrix is symmetric, i.e. $\{\mathbf{A}\}_{p_1,p_2} = \{\mathbf{A}\}_{p_2,p_1}$. From now on, we assume that all nodes always have the components of the *CoopMatrix* updated.

3.2. Decision algorithm

Knowing the possible cooperative transmission rates R'_{coop} and R''_{coop} and the direct transmission rate R_{dm}, the restriction in (1) determines which communication mode is more beneficial. Likewise, the chosen transmission should be below an average error probability bound, which was previously estimated for both types of communication.

The error probability, for a direct transmission between S and D at a rate R_{dm}, is determined by (2). Cooperative transmission is more complex. We will analyze this mode next.

Let $\mathcal{E}$ be the event that the relay H makes an error in the decodification of the symbol a_k belonging to the message $\mathbf{a}$. The event $\mathcal{E}^c$, previously used in this section, is the complement of $\mathcal{E}$. In this way, we can express the cooperative error probability $P_{coop}(e)$ as follows

$$P_{coop}(e) = P_{coop}(e \mid \mathcal{E}) P(\mathcal{E}) + P_{coop}\big(e \mid \mathcal{E}^c\big) P\big(\mathcal{E}^c\big), \tag{7}$$

where $P(\mathcal{E})$ and $P(\mathcal{E}^c)$ are the occurrence probabilities of the events $\mathcal{E}$ and $\mathcal{E}^c$ respectively. We will assume that if H commits an error in the decoding process, then D will also do, so that $P_{coop}(e \mid \mathcal{E}) = 1$. Furthermore, if $P(\mathcal{E}) \ll 1$ and $P_{coop}(e \mid \mathcal{E}^c) \ll 1$ we can reduce the expression to

$$P_{coop}(e) \approx P(\mathcal{E}) + P_{coop}\big(e \mid \mathcal{E}^c\big). \tag{8}$$

The probability $P(\mathcal{E})$ is determined by (2), while the conditional probability $P_{coop}(e \mid \mathcal{E}^c)$ is bounded by (6). Replacing these equations in (8) we obtain

$$P_{coop}(e) \approx \frac{2}{b'}\left(1-\frac{1}{\sqrt{M'}}\right)\left(1-\sqrt{\frac{3\overline{\gamma}_{s,h}}{2(M'-1)+3\overline{\gamma}_{s,h}}}\right) + \frac{2}{b''}\left(1-\frac{1}{\sqrt{M''}}\right)\frac{(M''-1)^2}{6\overline{\gamma}_{s,d}\overline{\gamma}_{h,d}}. \quad (9)$$

The error probability in a cooperative transmission is the sum of the error probabilities in both phases of the communication, as found in (8). When choosing the transmission rates, our algorithm will have to face a critical decision, as a very high R'_{coop} rate, yet complying with the error bound can be prohibitive for any R''_{coop}. Taking into account that $P_{coop}(e) \leqslant ABEP_{target}$, we will rewrite (9) to show that commitment as follows

$$\frac{2}{b''}\left(1-\frac{1}{\sqrt{M''}}\right)\frac{(M''-1)^2}{6\overline{\gamma}_{s,d}\overline{\gamma}_{h,d}} \leqslant \tau, \quad (10)$$

where

$$\tau \triangleq ABEP_{target} - \frac{2}{b'}\left(1-\frac{1}{\sqrt{M'}}\right)\left(1-\sqrt{\frac{3\overline{\gamma}_{s,h}}{2(M'-1)+3\overline{\gamma}_{s,h}}}\right). \quad (11)$$

Assuming that the link (S, D) allows a direct transmission at a rate R_{dm}, in cooperative mode we need the rate of the first phase to be $R'_{coop} > R_{dm}$ due to the restriction (1). If the transmission rate between S and the relay fulfills the error probability bound, then the parameter τ will be in the range $0 < \tau < ABEP_{target}$. Finally, the rate R''_{coop} is selected so that the error probability for the second phase is less than τ.

The achievable transmission rate in cooperative mode is limited by the minimum of the two rates R' and R'', according to (1). Because the first phase lacks diversity even though the nodes are close to each other, the rate used in this phase is the restrictive one and we have to prioritize this rate. If all potential relays are closer to D than S, the optimal relay node is always the closest to S. It is not advisable to choose relays farther from D than S since this would result on a greater error probability for the second phase. Recall that the values of the SNRs $\overline{\gamma}_{i,j}$ found in the denominator of (10) decreases with the distance between nodes $\mathcal{N}_i$ and $\mathcal{N}_j$.

Following the previous analysis, the involved steps performed to choose the transmission mode and rates are the following:

1. Using *CoopMatrix*, look for the node $\mathcal{N}_h$, with $h \in \{1, 2, \ldots, N+2\} - \{s, d\}$, which has the largest value for $\overline{\gamma}_{s,h}$.
2. If for that node $\overline{\gamma}_{h,d} < \overline{\gamma}_{s,d}$, then discard $\mathcal{N}_h$ as a potential relay and return to step 1. If only the nodes S and D are left, no cooperation is possible.
3. If the highest available rate (R') on the link (S, H) is equal to or less than the rate R_{dm} no cooperation is possible. Otherwise, estimate τ according to (11) for this particular R'.
4. Find the highest rate R'' which verifies (10) with the calculated τ. If such rate is not found, go back to step 3. Try with a lower rate R'.
5. Given rates R', R'' and R_{dm} verify the restriction (1), and if it is not fulfilled, a cooperative communication is not possible.

If the process is successfully completed, the rates R'_{coop} and R''_{coop} allowing a cooperative communication faster than a direct communication are found.

4. Results

Numerical experiments were conducted to compare direct mode, RCoopMAC and our approach with $r_c = 1$ that will be referred as UCRCoop for simplicity – this term stands for Unitary Coding Rate Cooperation. The results are summarized in this section.

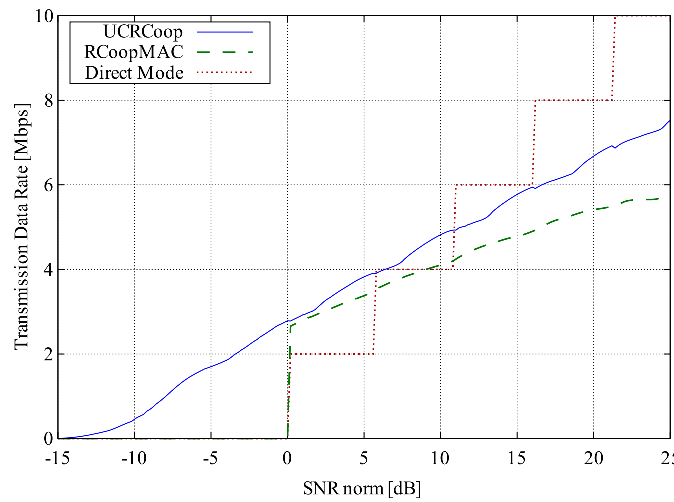

Fig. 2. Achievable data rates for different transmission modes: red-dotted for direct mode, green-dashed for RCoopMAC, and blue-solid for UCRCoop.

In particular, the implementation of the protocol RCoopMAC used in this paper differs from the original one proposed in [6] in two points. First, nodes that are farther apart from S than D are discarded as potential relays. As we explained previously, using relay channels with a smaller gain than the (S, D) channel only degrades the overall performance. Second, while computing the average rate achieved by RCoopMAC, we take into account the coding rate resulting from the utilization of an orthogonal code of the required size.

For all the simulations, we distributed $N = 25$ nodes uniformly in a circular area of radius $\eta_{network} = 10$ meters. In addition to these nodes, we placed the nodes S and D on opposite sides of the circle, so that $\eta_{s,d} = 20$ meters. The symbol period is $T_s = 10^{-6}$ seconds and $ABEP_{target} = 10^{-5}$. The PHY layer may use up to $Q = 15$ different constellations, each one with transfer rates of $R_q = 2(q+1)$ Mbps, with $q \in \{0, 1, \ldots, 14\}$. According to the structure of RCoopMAC, this protocol can only use the first 5 rates available for the direct mode, whereas our protocol does not have this restriction. The path loss exponent is assumed to be unitary. All results were obtained after averaging 10^4 independent simulations for each different SNR value.

The results are shown in Figs. 2 to 6. The plots are evaluated as a function of a normalized SNR, where 0 dB is the minimum SNR that guarantees reliable communication between S and D. The data rates achieved with each transmission mode are depicted in Fig. 2. The final transmission data rate will be the highest one between direct and cooperative mode. This figure shows that the proposed scheme achieves higher data rates than RCoopMAC employing fewer relays, as seen in Fig. 3, and at low SNR, even higher than direct mode. However, with increasing SNR values, direct mode outperforms both cooperative schemes. This behavior is a natural consequence of cooperation strategy established in (1).

Since UCRCoop employs a low-rate control channel, this protocol can establish a link for negative SNR. On the other hand, RCoopMAC transmits control messages on the data channel, therefore it cannot communicate when SNR is less than zero. However, we have noticed that without this restriction, both cooperative schemes would have similar performance in that region.

We have also considered the energy consumption per bit. Fig. 4 shows the average energy transmitted at the source as a function of the SNR, and Fig. 5 shows the average energy transmitted by the relays. The system model assumes that the energy per symbol is always equal to one. Then, when B bits are transmitted in a

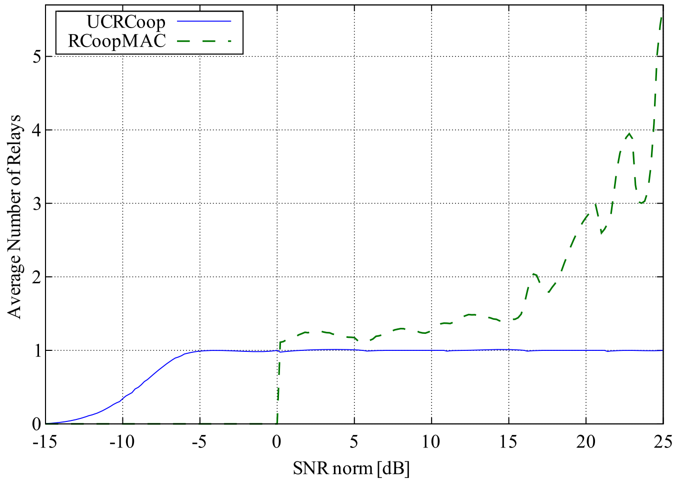

Fig. 3. Average number of active relays for both cooperative strategies: green-dashed for RCoopMAC, and blue-solid for UCRCoop.

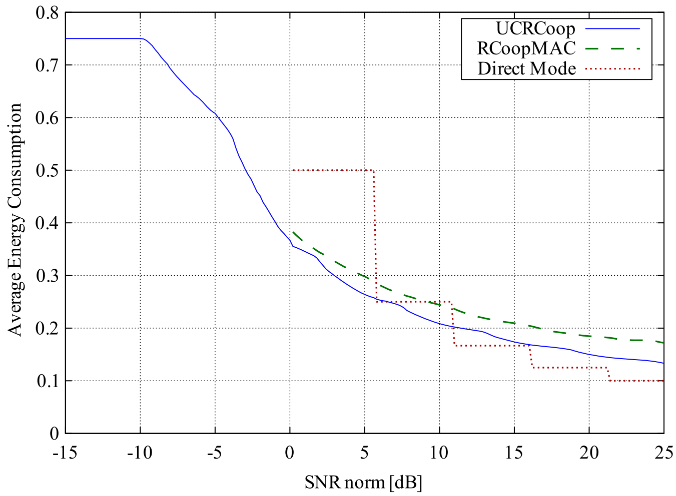

Fig. 4. Energy per bit E_b transmitted at the source node for each transmission mode: direct mode, RCoopMAC and UCRCoop.

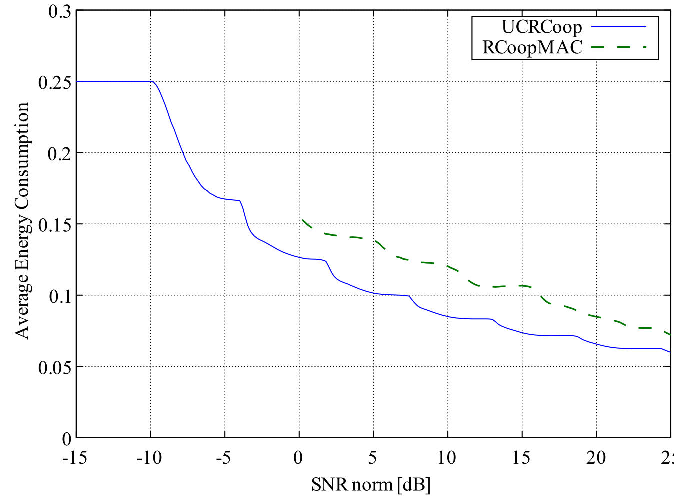

Fig. 5. Average energy per bit $\bar{E}_b$ transmitted at each relay node for both cooperative strategies: RCoopMAC and UCRCoop.

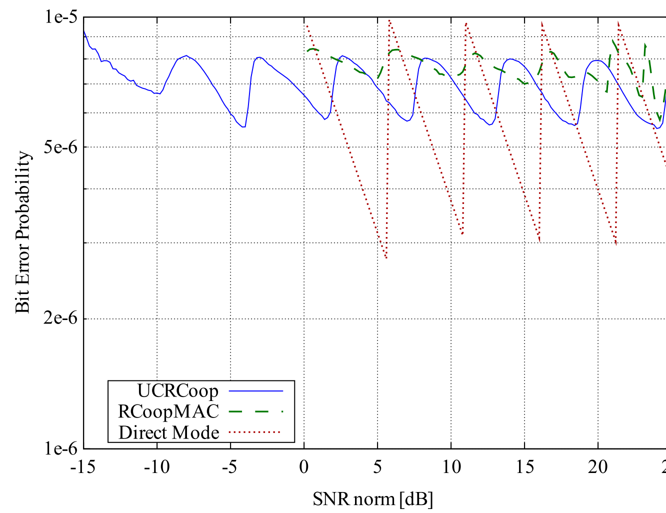

Fig. 6. ABEP for each transmission mode: red-dotted for direct mode, green-dashed for RCoopMAC, and blue-solid for UCRCoop.

symbol period, $1/B$ energy per bit is consumed. Observe that direct mode is less energy efficient for low SNR than UCRCoop. Also, UCRCoop has always a lower consumption than RCoopMAC. And as it shows Fig. 3, the average number of active relays in RCoopMAC is generally between one and two whereas our protocol cannot use more than one relay. Therefore, we say that UCRCoop achieves high rates in an energy efficient manner using minimum network resources.

Finally, in Fig. 6 we compare the bit error probability in the various transmission modes. According to (2), the direct mode BEP follows the form $\alpha(\mathrm{SNR})^{-1}$. The saw-like curve is the result of gradually increasing the transmission rate as it meets the error probability bound. In contrast, cooperative modes are governed by (8), and the BEP curve is a combination of the different phases.

5. Conclusions

In this paper, we have proposed a new cooperative protocol for a wireless sensor network. This protocol uses the Alamouti orthogonal code to achieve transmission diversity and to facilitate the decoding process at the recipient of the message.

Our approach has been compared to another cooperative protocol, called RCoopMAC, that uses random STBC. The new approach, which has been called UCRCoop, has shown an improvement in the average transmission data rate. Also, since UCRCoop uses less number of relays than RCoopMAC, the new protocol has an overall reduction of energy consumption for the entire network. When considering the energy per bit spent at the source and at each relaying node, we have also observed that UCRCoop incurs on a smaller energy consumption than RCoopMAC. Hence, by using the Alamouti code in a distributed fashion, we have been able to obtain a cooperative protocol that achieves high throughput at a reduced energy cost.

An improvement on this approach will be to consider a cluster of cooperative nodes. This will allow us to superimpose the first phase of a transmission with the second phase of another one, and thus to improve further on the overall throughput of the network.

Appendix A. BEP with Alamouti code

The bit error probability for a transmission of Gray-coded symbols belonging to a square QAM constellation in AWGN channel is bounded in [7]. This result can be extended in the case of an MISO transmission with the Alamouti scheme through a Rayleigh-faded channel by

$$P_d\big(e \mid \mathcal{E}^c, \mathbf{g}_d\big) \leqslant \frac{4}{b}\left(1 - \frac{1}{\sqrt{M}}\right)\mathrm{Q}\left(\sqrt{\frac{3\gamma \|\mathbf{g}_d\|^2}{M-1}}\right), \tag{A.1}$$

where $\mathbf{g}_g = [g_{s,d} \;\; g_{h,d}]^T$ [1]. In order to calculate the expected value of (A.1) we need the probability density function of $\|\mathbf{g}_d\| = \sqrt{|g_{s,d}|^2 + |g_{h,d}|^2}$.

Since $g_{i,j} \sim \mathcal{CN}(0, \eta_{i,j}^{-\alpha})$, each $|g_{i,j}|^2$ follows an exponential distribution with parameter $1/\eta_{i,j}^{-\alpha}$. If we define $X = \|\mathbf{g}_d\|^2$, X is the sum of two independent and exponentially distributed random variables, and its probability density function is the convolution of each one of its terms:

$$f_X(x) = \frac{1}{\eta_{s,d}^{-\alpha} - \eta_{h,d}^{-\alpha}}\left[\exp\left(-\frac{x}{\eta_{s,d}^{-\alpha}}\right) - \exp\left(-\frac{x}{\eta_{h,d}^{-\alpha}}\right)\right]. \tag{A.2}$$

The probability density function of the desired variable $Y = \|\mathbf{g}_d\|$ is:

$$f_Y(y) = \frac{2y}{\eta_{s,d}^{-\alpha} - \eta_{h,d}^{-\alpha}}\left[\exp\left(-\frac{y^2}{\eta_{s,d}^{-\alpha}}\right) - \exp\left(-\frac{y^2}{\eta_{h,d}^{-\alpha}}\right)\right]. \tag{A.3}$$

Next, we proceed to calculate the expectation of $\mathrm{Q}(\cdot)$:

$$E\left[\mathrm{Q}\left(\sqrt{\frac{3\gamma \|\mathbf{g}_d\|^2}{M-1}}\right)\right] = E\big[\mathrm{Q}(ay)\big] = \int_0^\infty \mathrm{Q}(ay) f_Y(y)\,dy, \tag{A.4}$$

where $a = \sqrt{\frac{3\gamma}{M-1}}$. If $u = \mathrm{Q}(ay)$ and $dv = f_Y(y)\,dy$, the result of integrating (A.4) by parts and replacing in (A.1) is:

$$\begin{aligned} P_d\big(e \mid \mathcal{E}^c\big) \leqslant{} & \frac{2}{b}\left(1 - \frac{1}{\sqrt{M}}\right) \\ & \times \left\{1 + \frac{1}{\eta_{s,d}^{-\alpha} - \eta_{h,d}^{-\alpha}}\left[\eta_{h,d}^{-\alpha}\sqrt{\frac{3\,\overline{\gamma}_{h,d}}{3\,\overline{\gamma}_{h,d} + 2(M-1)}} \right.\right. \\ & \left.\left. - \eta_{s,d}^{-\alpha}\sqrt{\frac{3\overline{\gamma}_{s,d}}{3\overline{\gamma}_{s,d} + 2(M-1)}}\right]\right\}. \end{aligned} \tag{A.5}$$

The Taylor series expansion at high SNR yields the approximation:

$$P_d\big(e \mid \mathcal{E}^c\big) \leqslant \frac{2}{b}\left(1 - \frac{1}{\sqrt{M}}\right)\frac{(M-1)^2}{6\overline{\gamma}_{s,d}\overline{\gamma}_{h,d}}. \tag{A.6}$$

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