Energy Efficiency Analysis of a Two Dimensional Cooperative Wireless Sensor Network with Relay Selection

Marcos KAKITANI, Glauber BRANTE, Richard SOUZA

CPGEI, Federal University of Technology - Paraná (UTFPR), Av. Sete de Setembro 3165, 80230-901 Curitiba, PR, Brazil

mtkakitani@ieee.org, gbrante@ieee.org, richard@utfpr.edu.br

Abstract. *The energy efficiency of non-cooperative and cooperative transmissions are investigated in a two-dimensional wireless sensor network, considering a target outage probability and the same end-to-end throughput for all transmission schemes. The impact of the relay selection method in the cooperative schemes is also analyzed. We show that under non line-of-sight conditions the relay selection method has a greater impact in the energy efficiency than the availability of a return channel. By its turn, under line-of-sight conditions a return channel is more valuable to the energy efficiency of cooperative transmission than the specific relay selection method. Finally, we demonstrate that the energy efficiency advantage of the cooperative over the non-cooperative transmission increases with the distance among nodes and with the nodes density.*

Keywords

Energy efficiency, wireless sensor networks, cooperative communications, relay selection.

1. Introduction

The nodes of a wireless sensor network (WSN) are usually small in size and are deployed inside or close to a phenomenon of interest. The sensor nodes are not required to be positioned in engineered or predetermined positions and are also prone to failures. As the ad hoc networks, the WSNs are not dependent of a previous infrastructure, however the number of nodes in a WSN can be several orders of magnitude higher. The power units of the sensor nodes are composed of limited power sources, whose replenishment or replacement might be impossible [1]. In addition, batteries capacity present a modest increase if compared to the computational capacity and wireless throughput gains obtained in the last decades. The wireless throughput has grown by roughly one million times and computational capacity has had an increase of 40 million times since 1957, while the average nominal battery capacity has increased only 3.5 percent per year over the last two decades [2], [3]. Thus, due to the power source limitations, the overall energy consumption and energy efficiency have great importance and are major concerns in the design and analysis of a WSN [4], [5].

One way to reduce the required transmit power, and therefore possibly reduce the energy consumption, is to consider cooperative transmission (CT) schemes [6], [7], [8], [9]. Differently from the multi-hop (MH) transmission, where the message from the source is passed from node to node up to the destination, cooperative transmission schemes take advantage from the broadcast nature of the wireless transmission. Thus, in a transmission from a source to a destination, a partner relay can overhear the source message and then forward it to the destination node. At the destination, both messages are combined in the decoding process. Moreover, the relay node can have different behaviors after receiving a source transmission. One possibility is that the relay node just amplifies the received signal and afterward retransmits it to the destination, which is defined as amplify-and-forward (AF) cooperative protocol. However, the AF protocol can be outperformed by the selective decode-and-forward protocol (SDF) in some scenarios. In the SDF protocol the overheard message is only forwarded to the destination in the case of successful decoding at the relay. In scenarios where a return channel is available, the incremental decode-and-forward (IDF) protocol can be employed. In these scenarios, the destination node is able to inform other nodes if a relay transmission is required or not. Therefore, a retransmission from a relay node only occurs if required by the destination node, which increases the maximum achievable throughput. Note that the only difference between SDF and IDF is the return channel, which is present in IDF, but not in SDF.

The use of CT schemes can contribute to the energy efficiency by reducing the required transmit power, however additional relay nodes and additional RF circuitry are also involved. Although the transmit power is more relevant at longer distances, the transmitter and receiver circuitry power consumptions are significant at short distances [10]. The power consumed by the RF circuitry can be properly represented by the model in [11], which is composed of several building blocks of typical transmitter and receiver circuitry. Another factor that should not be ignored when different transmission schemes are compared is the end-to-end throughput. For example, the CT schemes require more time slots than single-hop (SH) to perform a transmission. In SH, only two sensor nodes are involved and a relay is not required. The CT schemes composed of half-duplex nodes require two time slots, while only one time slot is needed for SH. Thus, for a fair comparison, each transmission of a CT scheme should use not less than twice the spectral efficiency of SH.

In [12], non-cooperative SH and MH are compared to the SDF cooperative scheme in terms of their bit error rate (BER). It is concluded that the best results are obtained by the SDF scheme. However, the analysis does not consider energy efficiency nor end-to-end throughput restrictions. A cellular network considering the MH and CT schemes is analyzed in [13]. Although higher achievable rates are obtained by SDF if compared to MH, the energy efficiency and the end-to-end throughput are also not included in the analysis. The IDF protocol is studied in [14]. The energy efficiency analysis showed that although IDF is more efficient at most of the scenarios, SH outperforms IDF when the source and destination nodes are at short distances. However, no end-to-end throughput restrictions are imposed to the transmission schemes. For instance, we show in [15] and [16] the importance of the circuitry consumption and end-to-end throughput requirements when the energy efficiency of different transmission schemes are compared. The network topology is composed of three nodes in [15] and some nodes in [16], where the sensor nodes are distributed over a line. The results show that CT presents the best performance, being the most energy efficient scheme even for small transmission distances, specially if a return channel is available.

In the case of WSNs distributed over a two-dimensional topology, many nodes can operate as relays, which may increase the performance of the cooperative protocols. In such case, some relay selection algorithm must be defined. Relay selection algorithms have been the focus of many works, as for instance in [17], [18], [19], [20], [21], [22], [23]. In [17], two types of selection algorithms are discussed: reactive and proactive. In the reactive algorithm, the relay is chosen after the source transmission, while in the proactive algorithm, the relay is selected before the source transmission. A survey of distributed relay selection schemes can be found in [18], where the authors compare such algorithms in terms of energy efficiency, complexity and performance. A general framework for energy efficient relay selection has been considered in [19], where the number of relays that participate in the cooperation is optimized. Relay selection schemes for 802.11-like networks have been considered in [20], [21]. The best relay is selected in [20] in a way to keep the residual energy of each node comparatively the same, while in [21] a joint MAC design and physical layer power control is used. Another selection strategy is presented in [22], where the nodes are modeled as energy sellers. The relay is selected in a way to minimize the total transmission cost. The simplest selection algorithm is the random relay selection [23]. In such algorithm, the relay is randomly chosen among the available nodes in the network.

In this paper, we analyze the energy efficiency performance of SH and CT (SDF and IDF) transmission schemes by considering a two-dimensional network topology. For the sake of fairness, we assume in our analysis that the system is under a target outage probability and also under the same end-to-end throughput requirement for all transmission schemes. Differently than [15] and [16], we investigate the impact of the relay selection on the energy efficiency of the cooperative techniques. Our results show that under some line-of-sight (LOS) conditions, the best relay selection has just a small advantage over the random relay selection (which is less complex than the best relay selection), while in the case of non line-of-sight (NLOS) the best relay selection is of paramount importance for maximizing the energy efficiency. Therefore, as our main contribution, we conclude that in some scenarios the relay selection method can be more critical than the availability of a return channel in terms of the energy consumption, so that SDF with best relay selection can outperform IDF with random relay selection in terms of energy efficiency. We also show that, in case of NLOS, CT is in general more energy efficient than SH, while SH can be more energy efficient in case of some LOS or very high attempted information rates. Moreover, the energy efficiency advantage of CT over SH increases both with the distance among nodes and with the nodes density. To the best of our knowledge, there are no similar works in the literature that perform an analysis in terms of the energy efficiency comparing the impact of the relay selection method with the availability of a return channel.

The rest of this paper is organized as follows. Section 2 presents the system model. In Section 3 the outage probability and the energy consumption of the SH and CT schemes are presented. Section 4 presents numerical results, including the impact of the outage probability, end-to-end throughput requirements and different network topologies. Finally, Section 5 concludes the paper.

2. System Model

The nodes are disposed in either a random or uniform grid topology. In the random topology the sensor nodes are randomly distributed in an area, while in the grid topology the nodes are placed in a structured grid, with the same distance between each line and each column. All the sensor nodes can act as source (S) by gathering information from the environment and sending it to the destination node (D), which is positioned at the center. Moreover, any sensor node can be selected to operate as relay (R). We also consider that all the sensor nodes are half-duplex and all transmissions are orthogonal in time.

The Nakagami-m distribution [24] is employed to model the multipath fading. As the Nakagami-m distribution allows the severity of the fading to be adjusted by the parameter m, it can be adapted to represent a wide variety of conditions. We consider in our analysis, based on the experimental results in [25], $m = 1$ for NLOS and $m = 2$ for the case of some LOS. Note that for the particular case of $m = 1$, the Nakagami-m distribution is the same as Rayleigh [27]. In addition, we consider that the channel is in long-term quasi-static fading.

The energy efficiency of SH and CT is analyzed in terms of the total energy consumption per bit. The transmitting and receiving power consumed by the internal RF circuitry, besides the distance dependent transmit power, are also included in our analysis. Thus, the total consumed energy per bit in a transmission from node i to node j is

$$E_{bt,ij} = \frac{P_{PA,ij} + P_{TX} + P_{RX}}{R_b} \tag{1}$$

where $P_{PA,ij}$ represents the power consumed by the power amplifier, P_{TX} and P_{RX} are respectively the energy consumed by the transmitting and the receiving circuitry, and R_b corresponds to the bit rate in bits/s. Moreover, $R_b = \Delta \cdot B$, where Δ is the spectral efficiency and B is the system bandwidth, in hertz. The transmitting and receiving RF circuitry follows the block diagrams introduced in [11]. For the transmitting circuitry, the total consumed power is

$$P_{TX} = P_{DAC} + P_{mix} + P_{fil\_tx} + P_{syn} \tag{2}$$

where P_{DAC} represents the power consumed by the digital-to-analog converter, P_{mix} is the power consumed by the mixer, P_{fil_tx} corresponds to the power consumed by the transmit filters and P_{syn} is the power consumed by the frequency synthesizer. For the receiving circuitry, the following component blocks are considered: frequency synthesizer, low-noise amplifier, mixer, intermediate frequency amplifier, receive filters and analog-to-digital converter, with the respective power consumptions: P_{syn}, P_{LNA}, P_{mix}, P_{IFA}, P_{fil_tx}, P_{ADC}. The total power consumption for the receiving circuitry is:

$$P_{RX} = P_{syn} + P_{LNA} + P_{mix} + P_{IFA} + P_{fil\_rx} + P_{ADC}. \tag{3}$$

The power amplifier consumption is modeled as [11]

$$P_{PA,ij} = \frac{\xi}{\eta} P_i \tag{4}$$

where $\xi = 3\left(\frac{\sqrt{M}-1}{\sqrt{M}+1}\right)$ is the peak-to-average ratio for an M-QAM modulation, η is the amplifier drain efficiency and P_i is the transmit power of node i.

Most of our analysis is based on the network total energy consumption. We calculate the total consumed energy (including source, relay and destination) when each node acts as source and then perform the sum of these values in order to obtain the energy consumption of the entire network for different transmission schemes. The energy efficiency analysis is performed under the constraint of an outage probability, which predicts well the frame error rate of good practical codes [26]. In the transmission of a frame from node i to node j, an outage occurs when the SNR (Signal-to-Noise-Ratio) at node j falls below a threshold $\beta = 2^{\Delta} - 1$ [27]. Thus, the received frame at node j is given by

$$\mathbf{y}_{ij} = \sqrt{P_i\,\gamma_{ij}}\, h_{ij}\, \mathbf{x} + \mathbf{n}_{ij} \tag{5}$$

where γ_{ij} represents the path loss in the $i-j$ link, h_{ij} is a scalar that represents the unity variance Nakagami-m quasi-static fading, $\mathbf{x}$ corresponds to the transmitted frame and $\mathbf{n}_{ij}$ represents the AWGN vector, with variance $N_0/2$ per dimension, where N_0 is the thermal noise power spectral density per hertz. The path loss between i and j is given by [27]

$$\gamma_{ij} = \frac{G\lambda^2}{(4\pi)^2 d_{ij}^{\alpha} M_l N_f} \tag{6}$$

where G represents the total gain of the transmit and receive antennas, $\lambda = 3 \cdot 10^8/f_c$ is the wavelength, where f_c is the carrier frequency, d_{ij} corresponds to the distance in meters between nodes i and j, and α represents the path loss exponent. Moreover, note that we also include the link margin (M_l) and the noise figure at the receiver (N_f) in the path loss. The instantaneous SNR in the $i-j$ link is

$$SNR_{ij} = |h_{ij}|^2 \cdot \overline{SNR_{ij}} \tag{7}$$

where $\overline{SNR_{ij}} = \frac{\gamma_{ij}P_i}{N}$ and $N = N_0 \cdot B$ is the noise power spectral density. The outage probability of the $i-j$ link is [28]

$$O_{ij} = \frac{\Psi\left(m, \frac{mN\beta}{\gamma_{ij}P_i}\right)}{\Gamma(m)} \tag{8}$$

where $\Psi(a,b) = \int_0^b y^{a-1}\exp(-y)dy$ is the incomplete gamma function and $\Gamma(a) = \int_0^\infty y^{a-1}\exp(-y)dy$ is the complete gamma function. At high SNR (low outage region), the incomplete gamma function can be approximated by $\Psi(a,b) \simeq (1/a) \cdot b^a$ [28]. Thus:

$$O_{ij} \simeq \frac{1}{\Gamma(m+1)} \left(\frac{mN\beta}{\gamma_{ij}P_i}\right)^m. \tag{9}$$

3. Transmission Schemes

In this section we analyze the outage probability, the optimal transmit power, and the consumed energy per bit of SH and CT schemes.

3.1 Single-hop Transmission (SH)

The SH scheme consists of a direct transmission from S to D, thus a relay node is not required. The consumed energy per bit of the SH scheme can be obtained by replacing i and j by S and D in (1):

$$E_{bt,SH} = E_{bt,SD} = \frac{P_{PA,SD} + P_{TX} + P_{RX}}{R_b}. \tag{10}$$

Note that as P_{TX} and P_{RX} are dependent of the specific technology, the minimum consumed energy per bit in (10) is obtained by minimizing $P_{PA,SD}$, or equivalently P_{SH}. Using

(9), and for a target end-to-end outage probability O^*, we obtain the minimum transmit power of the SH scheme as

$$P_{SH}^* = \frac{mN\beta}{\gamma_{SD}\left[\Gamma(m+1)\,O^*\right]^{1/m}}. \tag{11}$$

3.2 Cooperative Transmission (CT)

In the CT scheme, a selected relay node (R) cooperates in the transmission process. In the CT model, two time slots are required to perform the communication: an initial transmission from S, followed by a retransmission from R in the second time slot. Thus, in order to obtain the same end-to-end throughput, each transmission requires twice the spectral efficiency of SH. Consequently, an outage occurs when the received SNR is below a threshold $\beta' = 2^{2\Delta} - 1$. Thus, the outage probability for each $i-j$ link is

$$p_{ij} \simeq \frac{1}{\Gamma(m+1)}\left(\frac{mN\beta'}{\gamma_{ij}P_i}\right)^m. \tag{12}$$

Considering selection combining [27] at D, the end-to-end outage probability for the CT model, which includes the outage probabilities of each of the links that are involved in the transmission ($S-D$, $S-R$ and $R-D$), is given by

$$O_{CT} = p_{SD}\cdot\left[p_{SR} + (1-p_{SR})\cdot p_{RD}\right], \tag{13}$$

which can be rewritten as

$$O_{CT} = \frac{f_{SD}}{(P_{CT})^m}\cdot\left[\frac{f_{SR}}{(P_{CT})^m} + \left(1 - \frac{f_{SR}}{(P_{CT})^m}\right)\cdot\frac{f_{RD}}{(P_{CT})^m}\right] \tag{14}$$

where $f_{SD} = \frac{1}{\Gamma(m+1)}\left(\frac{mN\beta'}{\gamma_{SD}}\right)^m$, $f_{SR} = \frac{1}{\Gamma(m+1)}\left(\frac{mN\beta'}{\gamma_{SR}}\right)^m$ and $f_{RD} = \frac{1}{\Gamma(m+1)}\left(\frac{mN\beta'}{\gamma_{RD}}\right)^m$. The optimal transmit power P_{CT}^* can be obtained by replacing O_{CT} by O^* in (14), and finding the smallest real and positive root of

$$O^*(P_{CT})^{3m} - (f_{SR}f_{SD} + f_{RD}f_{SD})(P_{CT})^m + (f_{SR}f_{RD}f_{SD}) = 0. \tag{15}$$

In the following we consider the cases where a return channel from the destination node may be available or not by analyzing two CT protocols: SDF and IDF.

SDF: in the CT scheme using the SDF protocol, node R cooperates if it successfully decodes the message from S. The total consumed energy per bit is then

$$\begin{aligned} E_{bt,SDF} &= p_{SR}\times\frac{P_{PA,CT}+P_{TX}+2P_{RX}}{2R_b} \\ &+ (1-p_{SR})\times\frac{2P_{PA,CT}+2P_{TX}+3P_{RX}}{2R_b}. \end{aligned} \tag{16}$$

The first term in (16) represents the consumed energy if the message from S can not be decoded by R. The second term represents the case where R is successful in decoding the message, which is retransmitted to D.

Note that, since the energy spent with baseband processing is considered to be very small when compared to the consumption of the RF circuitry [11], the power consumption for decoding at the relay and at the destination have been ignored in this paper.

IDF: the IDF cooperative protocol makes use of a return channel, which here is considered to be error free. Through this channel, node D is able to request a retransmission from R if the previous transmission from S was not successful. Thus, R only retransmits if required by D. The total consumed energy per bit is:

$$\begin{aligned} E_{bt,IDF} &= (1-p_{SD})\times\frac{P_{PA,CT}+P_{TX}+2P_{RX}}{2R_b} \\ &+ p_{SD}\cdot p_{SR}\times\frac{P_{PA,CT}+P_{TX}+2P_{RX}}{2R_b} \\ &+ p_{SD}\cdot(1-p_{SR})\times\frac{2P_{PA,CT}+2P_{TX}+3P_{RX}}{2R_b}. \end{aligned} \tag{17}$$

The first term in (17) represents a successful transmission from S to D. A failure is represented in the second term, where neither D nor R can decode the message. In the third term, although the transmission from S to D is not successful, R is able to decode it, resulting in the cooperation with an additional transmission from R to D. Moreover, since the feedback message from D has usually much less bits than a frame from S, the energy consumption of the ACK/NACK messages have not been taken into account [15].

In addition, we consider that node R is selected by a proactive selection algorithm, which allows all the other sensor nodes that are not involved in the communication process to be in idle mode during the transmission [17]. We consider that the relay nodes can be selected by two different methods: best relay selection and random relay selection. The first selects the best relay in terms of the energy efficiency, thus the relay that provides the lowest energy consumption is selected. The other is the least sophisticate algorithm, in which a relay is randomly selected among all the available sensor nodes according to a uniform distribution. Therefore, the best relay selection always provides the most energy efficient transmission for each scheme, while in the random selection, although the energy efficiency and throughput are not maximized, the implementation complexity is rather low.

4. Results and Analysis

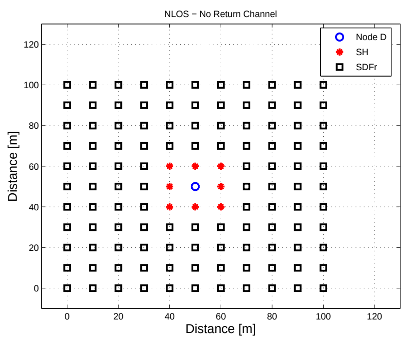
In this section the energy efficiency of SH and CT are numerically evaluated and compared under LOS and NLOS conditions, considering that a return channel may be available or not. The system parameters are listed in Tab. 1 and the circuitry consumption parameters follow the values presented in [11], with $P_{TX} = 97.9$ mW and $P_{RX} = 112.2$ mW.

We start considering that the nodes are uniformly distributed in an 11×11 grid with a distance of 10 meters between each line and each column. Node D is positioned at the center of the grid[1]. Initially we assume a maximum outage of $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz.

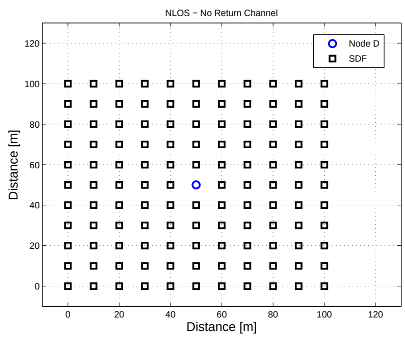
Link Margin	$M_l = 40$ dB
Noise Figure	$N_f = 10$ dB
Antenna Gain	$G = 5$ dBi
Carrier Frequency	$f_c = 2.5$ GHz
Noise Power Spectral Density	$N_0 = -174$ dBm
Bandwidth	$B = 10$ kHz
Path Loss Exponent (LOS)	$\alpha = 2.5$
Path Loss Exponent (NLOS)	$\alpha = 3.5$

Tab. 1. System parameters.

Figure 1(a) illustrates the most energy efficient transmission schemes for each node in NLOS condition with the random relay selection and without a return channel. SH is more energy efficient than SDF for short $S-D$ distances. However, if the best relay is selected, the SDF transmission scheme is the most energy efficient for all node positions, as shown in Fig. 1(b).



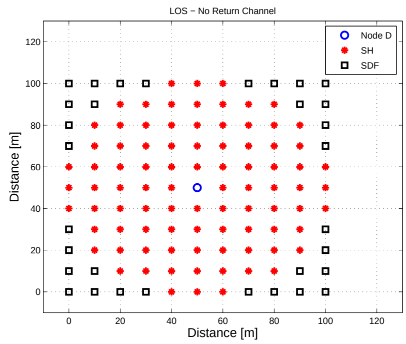
(a) Random relay selection.



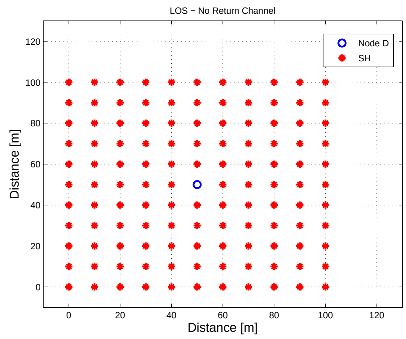
(b) Best relay selection.

Fig. 1. The most energy efficient transmission schemes for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz without a return channel in NLOS.

However, in LOS condition (which can be common in some WSNs [28]), cooperation has a decreased advantage over SH. Fig. 2(a) shows that under some LOS even with the selection of the best relay for each source, SDF is only advantageous at longer distances. With random relay selection, SH is the most energy efficient scheme for all nodes in the grid, as can be observed in Fig. 2(b). Thus, in case of some LOS, the relay selection is of paramount importance for the energy efficiency of cooperative communication. In the availability of a return channel IDF is more energy efficient than SH for all positions in the grid either with the best or random relay selection in LOS. However, under NLOS conditions, SH is more energy efficient than IDF with random relay selection for some node positions, while IDF with best relay selection is the most energy efficient scheme for all positions in the grid, as shown in Fig. 3.



(a) Best relay selection.



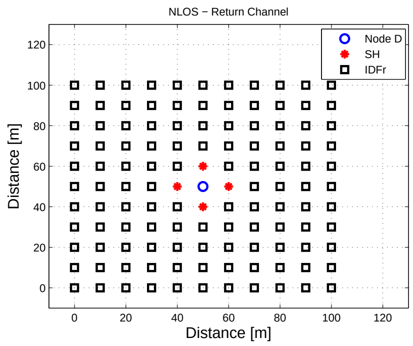
(b) Random relay selection.

Fig. 2. The most efficient transmission schemes for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz without a return channel in LOS.

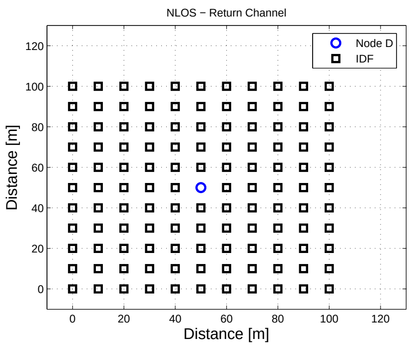
Table 2 lists the network total energy consumption for the SH and CT transmission schemes in the same 11×11 grid scenario for many conditions. From this table we can conclude that: i) while in LOS condition the best relay selection has just a small advantage over the random relay selection, under NLOS, where cooperation is more energy efficient, the advantage is much more relevant; ii) under NLOS, SDF with the selection of the best relay ($E_{bt} = 3.3 \cdot 10^{-4}$ J) is more energy efficient than IDF with random relay selection ($E_{bt} = 6.7 \cdot 10^{-4}$ J). Thus, the relay selection method can prevail over the availability of a return channel in terms of the energy efficiency in NLOS. Under this condition, it can be more energy efficient to employ the best relay selection method than having a return channel; iii) in LOS

[1] Note that assuming D at the center is a general case. For instance, considering D at a corner can be seen as a particular case of the grid, by dividing it into quadrants.

we can observe an opposite situation, where the availability of a return channel prevails over the relay selection method and IDF with random relay selection ($E_{bt} = 0.11 \cdot 10^{-4}$ J) has some advantage over SDF with best relay selection ($E_{bt} = 0.15 \cdot 10^{-4}$ J); iv) besides being a simpler transmission scheme, SH is more energy efficient than SDF in LOS condition either with the best or random relay selection; v) in NLOS, CT even with random relay selection outperforms SH.



(a) Random relay selection.



(b) Best relay selection.

Fig. 3. The most efficient transmission schemes for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz with a return channel in NLOS.

4.1 Spectral Efficiency and Outage Probability

In this section the impact of different spectral efficiencies and outage probabilities in the network total energy consumption are analyzed. Table 3 shows that for $\Delta = 4$ b/s/Hz, the relay selection method is more impacting in the energy efficiency than for $\Delta = 2$ b/s/Hz. For instance, now CT with random relay selection is always outperformed by SH, unless in the case of a return channel being available (IDF) and NLOS. Thus, it is clear that the choice of the attempted rate changes the relative performance between the different schemes. In this regard, the total energy consumption of SH and CT with the best relay selection, under NLOS and some LOS, for $1 \leq \Delta \leq 10$ b/s/Hz, are compared in Fig. 4. Note that under NLOS SDF and IDF are outperformed by SH for $\Delta > 6$ b/s/Hz and $\Delta > 7$ b/s/Hz, respectively. In some LOS, SH outperforms SDF for $\Delta > 3$ b/s/Hz, while IDF is outperformed for $\Delta > 5$ b/s/Hz. The outage probability requirement also impacts the energy efficiency of the transmission schemes. Table 4 shows that, for $O^* = 10^{-2}$, CT does have an advantage over SH under NLOS, however smaller than in the case of $O^* = 10^{-3}$, and it has a similar performance as SH in case of some LOS. If $O^* = 10^{-4}$ is considered, which results we do not show here for the sake of brevity, then CT has a greater advantage over SH, specially under NLOS.

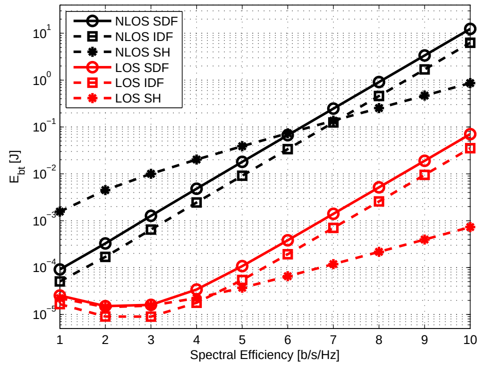


Fig. 4. Total consumed energy per bit of the Single-hop and Cooperative transmission schemes under NLOS and LOS conditions for $O^* = 10^{-3}$.

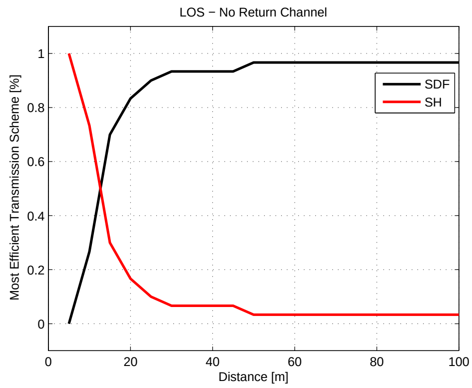


Fig. 5. The most efficient transmission schemes (considering SH and SDF with the best relay selection) for different distances between nodes in LOS condition for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz, without a return channel.

4.2 Nodes Density and Number of Nodes

We analyze in this section the total energy consumption for different nodes densities and number of nodes in the grid topology for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz. First we consider an 11×11 grid with uniform variation of the distance (ranging from 5 meters to 100 meters) between each line and each column. Figure 5 shows the most energy efficient schemes considering SH and SDF with the best relay selection under LOS. For instance, a result of 80 % means that such a scheme is more energy efficient for 80 % of the nodes in the grid. Note that at short distances, due to the circuitry consumption provided by the additional transmission of SDF, SH is the most energy efficient transmission scheme. However, as transmit power increases with distance, then SDF presents better efficiency and outperforms SH for most of the grid positions. If a return channel is available, IDF is the most energy efficient method for all distances. Under NLOS, CT

	SH	SDF Best Relay	SDF Random Relay	IDF Best Relay	IDF Random Relay
NLOS	$45 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$	$13 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$6.7 \cdot 10^{-4}$
LOS	$0.14 \cdot 10^{-4}$	$0.15 \cdot 10^{-4}$	$0.18 \cdot 10^{-4}$	$0.09 \cdot 10^{-4}$	$0.11 \cdot 10^{-4}$

Tab. 2. Total network energy consumption per bit in joules [J] for each transmission scheme for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz.

	SH	SDF Best Relay	SDF Random Relay	IDF Best Relay	IDF Best Relay
NLOS	$200 \cdot 10^{-4}$	$48 \cdot 10^{-4}$	$200 \cdot 10^{-4}$	$24 \cdot 10^{-4}$	$100 \cdot 10^{-4}$
LOS	$0.22 \cdot 10^{-4}$	$0.34 \cdot 10^{-4}$	$0.85 \cdot 10^{-4}$	$0.18 \cdot 10^{-4}$	$0.43 \cdot 10^{-4}$

Tab. 3. Total network energy consumption per bit in joules [J] for each transmission scheme for $O^* = 10^{-3}$ and $\Delta = 4$ b/s/Hz.

is the most energy efficient scheme for all cases, regardless of the availability of a return channel.

Moreover, we also analyze the impact of the number of nodes in the grid. We consider grid scenarios composed of different number of nodes: from 9 nodes (3×3 topology) to 841 nodes (29×29 topology) with a constant distance of 5 meters between each line and each column. Figure 6 shows that under LOS condition SH outperforms SDF most of the time. Note, however, that for a large number of nodes SDF starts becoming more energy efficient than SH. Under NLOS, SH and SDF have similar energy efficiency only for the smallest 3×3 topology, and as the number of nodes increases, SDF outperforms SH most of the time. If a return channel is available, then SH is always outperformed by IDF.

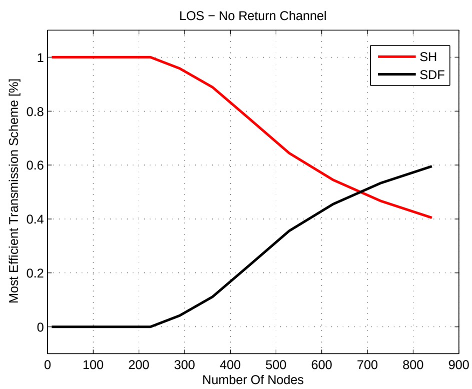
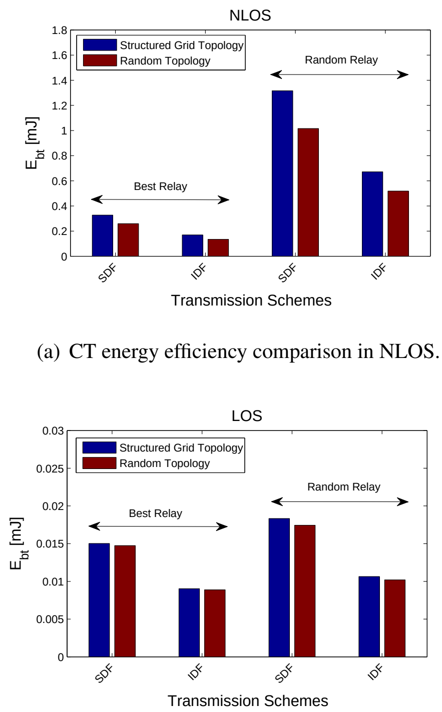


Fig. 6. The most efficient transmission schemes (considering SH and SDF with the best relay selection) for different number of nodes in LOS condition for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz, without a return channel.

4.3 Random Topologies

In this section we consider that the nodes are randomly positioned. The objective is to show that the previous analysis, based on a structured grid, is relevant. Here we assume a network composed of 121 nodes in which 120 of the sensor nodes take random positions in a 100 meters by 100 meters area. Moreover, the D node is still positioned at the center of this area. We considered 50 random topologies and evaluated the mean network energy consumption for each transmission scheme. Figure 7 compares the network energy consumption of the random topologies and the 11×11 structured grid topology for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz. Note that either if the best or the random relay selection is employed, the results obtained for the random topologies have similar values and, more importantly, lead to the same conclusions as for the grid topology. Thus, in NLOS the relay selection method is more relevant than the availability of a return channel, as SDF with best relay selection is more energy efficient than IDF with random relay selection.



(a) CT energy efficiency comparison in NLOS.

(b) CT energy efficiency comparison in LOS.

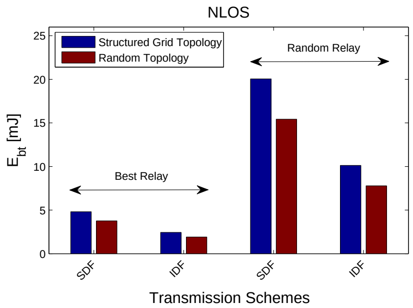
Fig. 7. Network energy consumption comparison considering a structured grid topology and random topology under LOS and NLOS for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz.

Even for higher spectral efficiency values, as shown in Figure 8 ($\Delta = 4$ b/s/Hz), the same conclusions can be obtained for the grid and random topologies. Several other O^* and Δ combinations were also analyzed, without relevant changes in the conclusions. Moreover, as in the structured grid topology many sensors are positioned in further $S-D$ distances, a lower mean network energy consumption is obtained for the random topology, as in the random topology nodes are more likely found close to D. In addition, note that as in LOS the nodes position and the $S-D$ distance

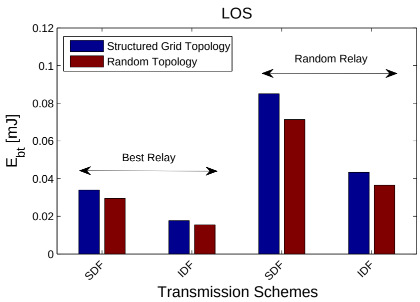
	SH	SDF Best Relay	SDF Random Relay	IDF Best Relay	IDF Random Relay
NLOS	$46 \cdot 10^{-5}$	$11 \cdot 10^{-5}$	$41 \cdot 10^{-5}$	$6.2 \cdot 10^{-5}$	$22 \cdot 10^{-5}$
LOS	$1.2 \cdot 10^{-5}$	$1.4 \cdot 10^{-5}$	$1.6 \cdot 10^{-5}$	$0.88 \cdot 10^{-5}$	$0.95 \cdot 10^{-5}$

Tab. 4. Total network energy consumption per bit in joules [J] for each transmission scheme for $O^* = 10^{-2}$ and $\Delta = 2$ b/s/Hz.

have a lower impact in the required transmit power, the network energy consumption of the random topology is closer to the grid topology than in the case of NLOS.



(a) CT energy efficiency comparison in NLOS.



(b) CT energy efficiency comparison in LOS.

Fig. 8. Network energy consumption comparison considering a structured grid topology and random topology under LOS and NLOS for $O^* = 10^{-3}$ and $\Delta = 4$ b/s/Hz.

Table 5 details the mean network energy consumption of the random topologies with their respective standard deviation values. Note that these mean values are close to the values in Tab. 2, thus the conclusions are the same as those from the previous analysis. Therefore, the structured grid topology, where the sensor nodes are uniformly positioned, can be considered as a good reference to analyze the energy consumption for different transmission schemes.

5. Conclusion

We compare the energy efficiency of SH and CT schemes in two-dimensional WSNs. The impact of the availability of a return channel and of the relay selection method are taken into account in the performance of the CT schemes. Moreover, the constraint of a target outage probability and end-to-end throughput under LOS and NLOS conditions are also considered. Results show that the relay selection method can have great impact on the energy efficiency of the CT schemes. The SDF scheme employing best relay selection presents better performance than IDF with random relay selection under NLOS. Thus, under NLOS condition the relay selection method can be a more relevant factor than the availability of a return channel for the energy efficiency of a cooperative WSN. However, under some LOS the presence of a return channel prevails over the relay selection method in terms of the energy efficiency. Therefore our main contribution is to show that in NLOS scenarios, it can be more relevant to employ the best relay selection algorithm than having a return channel. Additionally, we show that, under NLOS, CT schemes are in general more energy efficient than SH, while in LOS condition SH outperforms SDF in many situations. Finally, we also demonstrate that the energy efficiency advantage of the CT schemes over SH increases with the distance among nodes as well as with the nodes density.

Acknowledgements

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References

[1] AKYILDIZ, I., SU, W., SANKARASUBRAMANIAM, Y., CAYIRCI, E. A survey on sensor networks. *IEEE Communications Magazine*, 2002, vol. 40, no. 8, p. 102 - 114.

[2] PENTIKOUSIS, K. In search of energy-efficient mobile networking. *IEEE Communications Magazine*, 2010, vol. 48, no. 1, p. 95 - 103.

[3] DOHLER, M., HEATH, R., LOZANO, A., PAPADIAS, C., VALENZUELA, R. Is the phy layer dead? *IEEE Communications Magazine*, 2011, vol. 49, no. 4, p. 159 - 165.

[4] CHEN, G., HANSON, S., BLAAUW, D., SYLVESTER, D. Circuit design advances for wireless sensing applications. *Proceedings of the IEEE*, 2010, vol. 98, no. 11, p. 1808 - 1827.

[5] ISLAM, M. R., An issue of boundary value for velocity and training overhead using cooperative MIMO technique in wireless sensor network. *Radioengineering*, 2011, vol. 20, no. 2, p. 505 - 511.

[6] SENDONARIS, A., ERKIP, E., AAZHANG, B. User cooperation diversity – part I: System description. *IEEE Transactions on Communications*, 2003, vol. 51, no. 11, p. 1927 - 1938.

[7] LANEMAN, J., TSE, D., WORNELL, G. Cooperative diversity in wireless networks: Efficient protocols and outage behavior *IEEE Transactions on Information Theory*, 2004, vol. 50, no. 12, p. 3062 - 3080.

	SH	SDF Best Relay	SDF Random Relay	IDF Best Relay	IDF Random Relay
NLOS	$35 \cdot 10^{-4} \pm 9.1\%$	$2.6 \cdot 10^{-4} \pm 9.2\%$	$10 \cdot 10^{-4} \pm 10\%$	$1.3 \cdot 10^{-4} \pm 9.2\%$	$5.2 \cdot 10^{-4} \pm 9.8\%$
LOS	$0.14 \cdot 10^{-4} \pm 1.6\%$	$0.15 \cdot 10^{-4} \pm 0.8\%$	$0.17 \cdot 10^{-4} \pm 1.9\%$	$0.09 \cdot 10^{-4} \pm 0.6\%$	$0.1 \cdot 10^{-4} \pm 1.6\%$

Tab. 5. Mean and standard deviation network energy consumption per bit in joules [J] for random topologies for $O^* = 10^{-3}$ and $\Delta = 2$ b/s/Hz.

[8] WANG, S., NIE, J. Energy efficiency optimization of cooperative communication in wireless sensor networks. *EURASIP Journal on Wireless Communications and Networking*, 2010, p. 3:1 - 3:8.

[9] CHANDRA, A., BOSE, C., BOSE, M. Wireless relays for next generation broadband networks. *IEEE Potentials*, 2011, vol. 30, no. 2, p. 39 - 43.

[10] CUI, S., GOLDSMITH, A., BAHAI, A. Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks. *IEEE Journal on Selected Areas in Communications*, 2004, vol. 22, no. 6, p. 1089 - 1098.

[11] CUI, S., GOLDSMITH, A. J., BAHAI, A. Energy-constrained modulation optimization. *IEEE Transactions on Wireless Communications*, 2005, vol. 4, no. 5, p. 2349 - 2360.

[12] ONG, L., MOTANI, M. Optimal routing for decode-forward in cooperative wireless networks. *IEEE Transactions on Communications*, 2010, vol. 58, no. 8, p. 2345 - 2355.

[13] JACOBSON, K., KRZYMIEN, W. Cooperative vs multihop relaying in cellular systems. In *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. Tokyo (Japan), 2009, p. 1853 - 1857.

[14] SADEK, A. K., YU, W., LIU, K. J. R. On the energy efficiency of cooperative communications in wireless sensor networks. *ACM Transactions on Sensor Networks*, 2009, vol. 6, no. 1, p. 1 - 21.

[15] BRANTE, G., KAKITANI, M., SOUZA, R. Energy efficiency analysis of some cooperative and non-cooperative transmission schemes in wireless sensor networks. *IEEE Transactions on Communications*, 2011, vol. 59, no. 10, p. 2671 - 2677.

[16] KAKITANI, M., BRANTE, G., SOUZA, R., MUNARETTO, A. Comparing the energy efficiency of single-hop, multi-hop and incremental decode-and-forward in multi-relay wireless sensor networks. In *IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. Toronto (Canada), 2011, p. 970 - 974.

[17] BLETSAS, A., SHIN, H., WIN, M. Cooperative communications with outage-optimal opportunistic relaying. *IEEE Transactions on Wireless Communications*, 2007, vol. 6, no. 9, p. 3450 - 3460.

[18] ABDULHADI, S., JASEEMUDDIN, M., ANPALAGAN, A. A survey of distributed relay selection schemes in cooperative wireless ad hoc networks. *Wireless Personal Communications*, 2012, vol. 63, no. 4, p. 917 - 935.

[19] MADAN, R., MEHTA, N., MOLISCH, A., ZHANG, J. Energy-efficient cooperative relaying over fading channels with simple relay selection. *IEEE Transactions on Wireless Communications*, 2008, vol. 7, no. 8, p. 3013 - 3025.

[20] CHEN, Y., YU, G., QIU, P., ZHANG, Z. Power-aware cooperative relay selection strategies in wireless ad hoc networks. In *IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. Helsinki (Finland), 2006, p. 1 - 5.

[21] ZHOU, Z., ZHOU, S., CUI, S., CUI, J. H. Energy-efficient cooperative communication in a clustered wireless sensor network. *IEEE Transactions on Vehicular Technology*, 2008, vol. 57, no. 6, p. 3618 - 3628.

[22] KE, F., FENG, S., ZHUANG, H. Relay selection and power allocation for cooperative network based on energy pricing. *IEEE Communications Letters*, 2010, vol. 14, no. 5, p. 396 - 398.

[23] ZARIFI, K., ABUTHINIEN, M., GHRAYEB, A., AFFES, S. Relay selection schemes for uniformly distributed wireless sensor networks. In *IEEE Wireless Communications and Networking Conference (WCNC)*. Budapest (Hungary), 2009, p. 1 - 6.

[24] SIMON, M. K., ALOUINI, M. S. *Digital Communication over Fading Channels*. 2nd ed. Wiley Interscience, 2004.

[25] YACOUB, M. The $\kappa-\mu$ distribution and the $\eta-\mu$ distribution. *IEEE Antennas and Propagation Magazine*, 2007, vol. 49, no. 1, p. 68 - 81.

[26] KNOPP, R., HUMBLET, P. A. On coding for block fading channels. *IEEE Transactions on Information Theory*, 2000, vol. 46, no. 1, p. 189 - 205.

[27] GOLDSMITH, A. *Wireless Communications*. New York (NY, USA): Cambridge University Press, 2005.

[28] SAVAZZI, S., SPAGNOLINI, U. Cooperative space-time coded transmissions in Nakagami-m fading channels. In *IEEE Global Telecommunications Conference (GLOBECOM)*. Washington (USA), 2007, p. 4334 - 4338.

About Authors ...

Marcos KAKITANI was born in Maringá, Brazil, in 1983. He received the B.Sc. degree in Electrical Engineering in 2006 from the Federal University of Paraná (UFPR), Curitiba, Brazil. He received the M.Sc. degree in Electrical Engineering in 2010 from the Federal University of Technology - Paraná (UTFPR), Curitiba, Brazil. He is currently pursuing the D.Sc. in Electrical Engineering at the UTFPR. His research interests include wireless systems, energy efficiency, and cooperative communications.

Glauber BRANTE was born in Arapongas, Brazil, in 1983. He received the B. Sc. degree in Electrical Engineering in 2007 and the M. Sc. in Electrical Engineering in 2010, both from the Federal University of Technology - Paraná (UTFPR), Curitiba, Brazil. He is currently pursuing the D.Sc. degree in Electrical Engineering at the same University. His research interests include wireless systems, cooperative communications, HARQ and digital systems.

Richard Demo SOUZA was born in Florianópolis, Brazil, in 1978. He received the B.Sc. and the D.Sc. degrees in Electrical Engineering from the Federal University of Santa Catarina (UFSC), Florianópolis, Brazil, in 1999 and 2003, respectively. From March 2003 to November 2003 he was a visiting researcher in the Department of Electrical and Computer Engineering at the University of Delaware, USA. Since April 2004 he has been with the Federal University of Technology - Paraná (UTFPR), Curitiba, Brazil, where he is now an associate professor. His research interests are in the area of error control coding and wireless communications.