Energy Efficiency in Cooperative Wireless Sensor Networks

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1. Introduction

Wireless Sensor Networks (WSNs) are composed by a large number of sensor nodes, which are usually small in size and are deployed inside or close to some phenomenon of interest. Moreover, since usually there is no need for regular or predefined deployment, the sensors can be placed over irregular or inaccessible areas. Therefore, according to [2], it is expected that the sensors possess self-organizing capabilities. Such attributes provide to the WSNs a large number of applications such as medical, military, and commercial. For instance, in medical applications wireless sensor networks can be used in patient monitoring systems. In the military, the fast set-up and self-organizing characteristics of the sensors make WSNs interesting for communication applications, security, monitoring, and terrain recognition. Commercial applications can include inventory management, product quality control and monitoring disaster areas.

The nodes in a WSN are typically equipped with limited power sources such as batteries, whose recharge or replacement may not always be possible or of economical interest. Moreover, batteries capacity presented a modest increase in the last decades when compared to the gains obtained in computational capacity and wireless throughput, which motivates the study of the energy efficiency of these devices. The wireless throughput has grown by roughly one million times and the 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, as shown in [11, 24]. Thus, according to [9], due to these power source limitations, the overall energy consumption and energy efficiency have great importance and are major concerns in the design and analysis of wireless sensor networks.

Another challenge faced by WSNs is the wireless environment itself. The wireless channel is a difficult and unpredictable communication medium. A signal transmitted through wireless is subjected to many factors, such as noise, random fluctuations in time (usually referred to as fading), attenuation due to moving objects, etc. Therefore, a reliable system design comes at the expense of a significant amount of power, required to transmit a block of data from the sensors to the sink. According to [14], one of the most promising techniques to overcome such limitations of the wireless medium is to exploit diversity techniques. Time diversity, frequency diversity and spatial diversity are among the most common strategies used in wireless transmissions. For instance, the use of error correction codes is an example of time diversity, introducing a level of correlation among the symbols to be transmitted. Orthogonal Frequency-Division Multiplexing (OFDM) and spread spectrum techniques are examples of frequency diversity. Recently, spatial diversity, through the use of multiple antennas, has been on the focus of many works, as for instance in [3, 12, 30].

However, for the spatial diversity gains to be obtained in practice it is necessary that the antennas are sufficiently spaced at the transmitter and receiver. Small-sized devices such as sensor nodes do not dispose of sufficient area to place multiple antennas appropriately spaced. Another practical way to obtain spatial diversity is through the use of cooperative communications. Cooperative communications are based on the channel model introduced by [31], which was originally composed by three nodes: one source of information, the destination of the communication, and a relay node. The relay node is responsible for helping the communication between the source and the destination, so that it may be possible to establish a more reliable communication, or to reduce the transmission power. Thus, exploiting the broadcast nature of the wireless channel, the relay may be able to overhear the transmission from the source in a first time instant, and then retransmit this information to the destination in a second time instant.

At the time that it was proposed by Van der Meulen in 1971, the relay channel was of more theoretical interest. However, due to technological advances of wireless communications in the last decades, a renewed interest in cooperative communications appeared motivated by the recent works of [20, 26], showing that cooperation is a strong practical candidate to improve robustness and help in reducing the energy consumption of wireless networks.

Motivated by these recent advances in the cooperative communications field, and by the importance of reducing the energy consumption of wireless devices, the energy efficiency of some transmission schemes for wireless sensor networks is analyzed in this chapter. The goal is to outline the best strategy in terms of energy efficiency given the characteristics of a network. Such characteristics can include, for instance, the amount of error allowed at the receiver, or the maximum delay in the communication between two nodes. Moreover, in order to approximate the theoretical results to a practical sensors network scenario, the following analysis seeks to model the network in a realistic way. As the nodes in a WSN are often at close distances to each other, the severity of the wireless fading must be taken into account, since when nodes are closer, a better wireless channel is expected. Moreover, another factor that cannot be ignored in the energy efficiency analysis of WSNs is the consumption of the internal circuitry of the devices. As shown in [10, 25, 28], in networks where the nodes are distant, the transmit power dominates over the consumption of the RF circuits. However, when the nodes are closer, the circuitry consumption becomes relevant.

In the following, Section 2 reviews some important concepts of cooperative communications. This section starts by showing the gains that can be obtained with spatial diversity, followed by the introduction of the relay channel as a practical way to obtain spatial diversity. Moreover, some cooperative protocols are presented at the end of the section. In the sequence, Section 3 shows some applications of such concepts to wireless sensor networks. Various WSN scenarios are analyzed in terms of the energy consumption of the devices. The section starts with simple examples considering only three nodes, as in the case of the classical relay channel in [31], and is further generalized to multiple nodes randomly distributed over a field. Then, Section 4 presents the final comments of this chapter.

2. Cooperative communications

The modern cooperative communications concept is based on the classical relay channel model in [31], which allows different nodes to share resources in order to achieve a more reliable transmission. Relay channel is usually referred to systems where the relay is a dedicated device, without information of its own to transmit. On the other hand, the term cooperative communication is used when the relay is another user or node in the same network, which also has information to transmit. The main objective of this approach is to achieve spatial diversity gains, which usually are obtained by adding more antennas to the nodes. However, in cooperative communications spatial diversity is obtained through the shared use of the source and the relay antennas. Thus, even if each device has only one antenna, spatial diversity can be obtained, what in this case is usually referred to as cooperative diversity.

2.1. Spatial diversity

The spatial diversity exploits the use of multiple antennas at the transmitter and/or receiver in order to create independent paths for transmitting the same information, allowing the system to:

- increase the transmission rate without increasing the bandwidth, as in [12, 33];
- improve the link quality, and therefore decrease the transmission error probability as in [3, 30];
- combine the two previous alternatives in a hybrid option, as in [13, 39].

When only the receiver is equipped with multiple antennas, as illustrated in Figure 1(a), diversity combining techniques such as Maximal Ratio Combining (MRC) can be applied. The case that only the transmitter has multiple antennas is illustrated in Figure 1(b). In this scenario, one of the most effective techniques is the Alamouti scheme, which establishes a space-time coding for the symbols to be transmitted. And when there is a combination of multiple antennas at both the transmitter and the receiver the system is known as MIMO (Multiple-Input Multiple-Output), as shown in Figure 1(c).

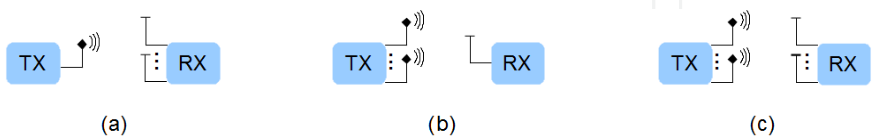


Figure 1. Spatial diversity through the use of multiple antennas: (a) at the receiver; (b) at the transmitter; (c) at both (MIMO system).

A comparison of different spatial diversity techniques is shown in Figure 2. The figure compares the bit error rate (BER) as a function of the signal-to-noise ratio (SNR), which is defined as E_b/N_0, where E_b is the energy per information bit, and N_0 is the power spectral density of the noise. In this particular example, the wireless channels are independent and modeled by a Rayleigh distribution, and the system operates with a Binary Phase Shift Keying (BPSK) modulation. It can be noted from the figure that all strategies using multiple antennas outperform the case when the transmitter and the receiver have only one antenna each (1TX and 1RX). The main conclusion that can be obtained from this figure is that the spatial diversity significantly increases the system performance. Moreover, the gain increases with the number of available antennas. It is important to note that the diversity gain can be observed by the change in the slope of the curves in relation to the case where there is only one transmitting antenna and one receiving antenna.

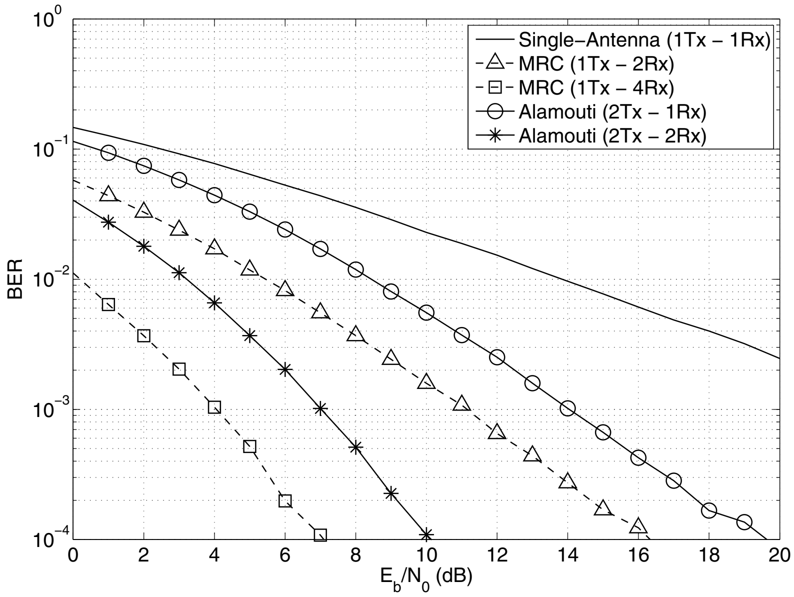


Figure 2. Bit error rate performance of different spatial diversity techniques.

However, it is necessary that the antennas are sufficiently spaced at the transmitter and at the receiver to obtain spatial diversity gain in practical applications. But small size devices, such as mobile phones or nodes in a WSN, may not dispose of enough area for the placement of multiple antennas properly spaced. Moreover, it is not expected from the user to accept a considerable increase in his device size to obtain a better performance. It is from this scenario that the cooperative communication emerged, aiming to obtain spatial diversity gains through sharing the resources of different devices that use the same wireless channel, as shown in [20, 26].

2.2. Relay channel

The relay channel, as proposed by [31], consists of three nodes: the source (S), the relay (R), and the destination (D), as shown in Figure 3. The function of the relay is to assist the source, forwarding the information to the destination using a different path, thus proving spatial diversity. The relay can either employ the same codebook as the source, acting as a repeater, or use a different codebook, also providing code diversity in this case. Moreover, this assisting node can either be a dedicated relay that has no specific information to transmit, or a system user. The term cooperative communication is usually employed when the relay is a user of the system, which also has information to transmit to the destination. Thus, the source and the relay act as partners to transmit the information from both, so the nodes act both as source, or as relay.

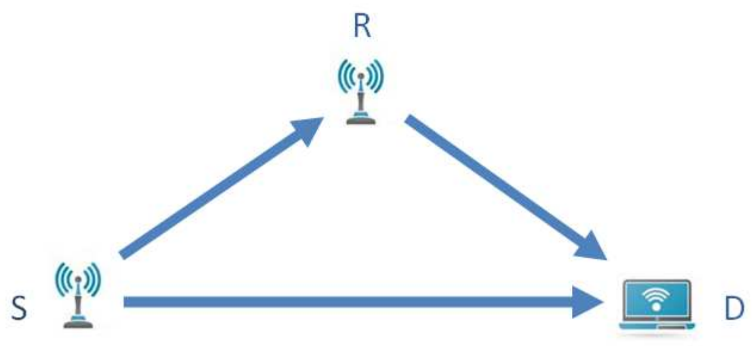


Figure 3. Source (*S*), relay (*R*) and destination (*D*) in a cooperative scenario.

The relay channel can be classified according to some of its characteristics, as the way that the bidirectional communication is performed, the multiple access method employed, the availability or not of a feedback channel, and the deployment scheme, as follows:

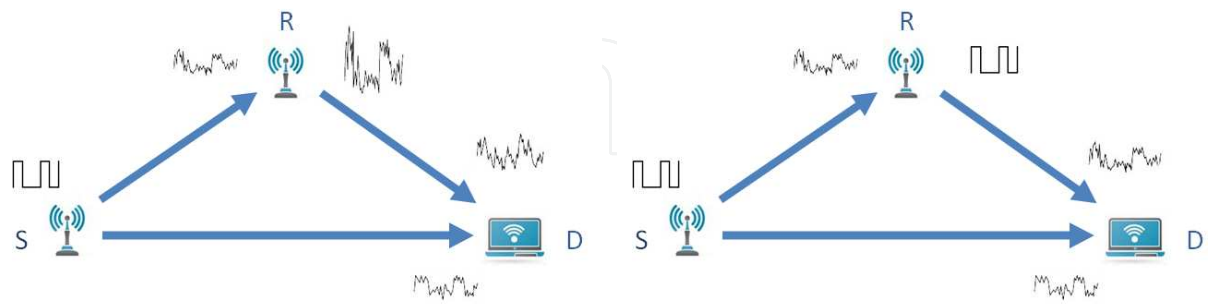
1. Based on the way that the bidirectional communication is made, it can be classified as:
   - *Full-Duplex*:
     The nodes are able to transmit and receive simultaneously. From a theoretical point of view, it is the model that provides the greatest channel capacity. However, there may be a large power difference between the transmitted signal and the received signal, up to a hundred dBs, making the isolation of these signals on the transceiver a very difficult task. Thus, its practical implementation is still considered a great challenge.
   - *Half-Duplex*:
     The transmission and the reception by each node are multiplexed in time, i.e., the nodes are not able to send and receive simultaneously. Although this model offers a smaller capacity if compared to full-duplex systems, it has a good trade-off between performance and complexity, being widely used in wireless scenarios.
2. Based on the multiple access method employed:
   - *Superposition*:
     The source and the relay broadcast their information at the same time and at the same frequency, i.e., in a superposed way. Thus, a larger complexity is required by the destination, since it must be able to decode the information from each user. The main advantage of this model is that there is no spectral efficiency loss if compared to the direct (non-cooperative) transmission.
   - *Orthogonal*:
     The source and the relay transmissions are multiplexed in time, in frequency, or in code (TDMA, FDMA, or CDMA). Taking the TDMA system as an example, the communication in the relay channel is performed in two different time slots. In the first time slot, the source broadcasts its information, and in the second time slot the relay forwards the information from the source to the destination. Thus, if compared to the direct transmission, there is loss of spectral efficiency due to this two steps communication process.
3. Based on the availability of a feedback channel:

- *No Feedback Channel*:
  The communication is only performed in the source-destination and relay-destination directions. The system provides no feedback from the destination.
- *With a Feedback Channel*:
  If there is a communication channel in both directions, the destination can exchange information with the source and the relay nodes to optimize the communication. The relay channel model that makes use of a return channel is able to apply classical retransmission techniques, and is denoted in [38] as a generalization of Automatic Repeat reQuest (ARQ) protocols.

4. Based on the deployment scheme and the mobility:
   - *Ad-Hoc Relays*:
     In general, the ad-hoc relays consist of other users that have information to send, share the same wireless environment, and are willing to cooperate. These relays usually face similar channel conditions to those faced by the source in relation to the destination.
   - *Infra-Structured Relays*:
     They are relays that operate in a dedicated manner, i.e., devices that are fixed and do not have information of their own to transmit. Furthermore, it can be assumed that the relay will be under better channel conditions in relation to the destination, since these devices are installed by the service provider with the appropriate positioning and antennas height as to optimize the communication.

2.3. Cooperative communication protocols

Some of the most known cooperative protocols for the wireless channel were presented in [20], as the Amplify-and-Forward (AF) and Decode-and-Forward (DF) protocols, while some other options can be found in [19, 21, 23]. The main idea of the AF protocol is that the relay only amplifies the received signal from the source, in order to compensate for the effects of the source-relay channel, and then the information is forwarded to the destination, as illustrated by Figure 4(a). In the DF protocol, illustrated by Figure 4(b), the relay tries to retrieve the information sent by the source, converts it to information bits, re-encodes them, modulates, and then forwards the message to the destination.



(a) Amplify-and-Forward. (b) Decode-and-Forward.

Figure 4. Cooperative protocols.

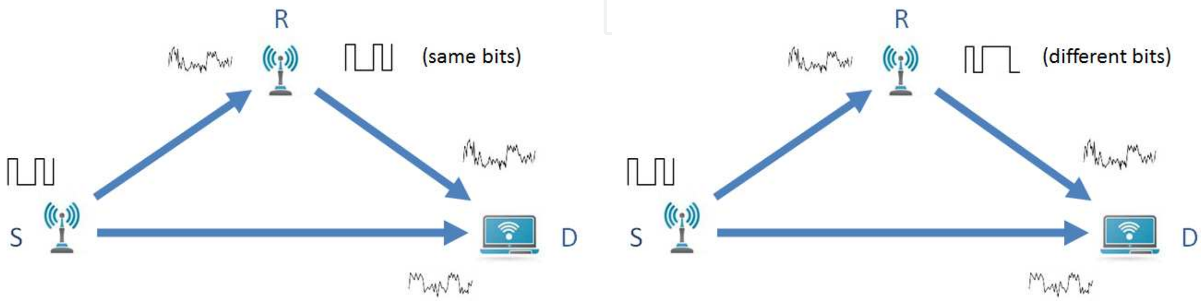
The DF protocol has at least three major variants: Fixed DF (FDF), Selective DF (SDF), and Incremental DF (IDF). In the FDF protocol the relay always acts in the communication, i.e., the message sent by the source is always forwarded to the destination, regardless the fact that the decoding at the relay was successfully performed or not. The disadvantage of this protocol is that the error propagation can be very large, reducing the system performance. The SDF protocol, on the other hand, establishes a condition for the relay to act. The objective is to allow the relay to detect whether the estimated message corresponds to the original message from the source or not. Thus, the information is only forwarded to the destination by the relay if the estimation is error free. Finally, the IDF protocol exploits the feedback channel from the the destination, so that the relay acts only if requested.

Another cooperative protocol that is less employed, but not less relevant, is the Compress-and-Forward (CF). In the CF protocol, the relay quantizes and compresses the message from the source, and then forwards it to the destination. Although [19] shows that the CF protocol can have better performance than the AF and DF protocols in some situations, CF is less employed due to the difficulty of implementation in practical systems.

2.4. Coded cooperation

With the use of error-correcting codes by the source, the information symbols vector, which represents a non-deterministic and uncorrelated sequence, is converted into a codeword vector, which adds redundancy to the symbols of the original word, introducing a correlation degree in the symbols to be sent. Thus, the decoding process in the receiver may be able to recover symbols that were incorrectly received due to the channel attenuation effect and noise at the receiver. Different error correction methods have been proposed over the years, among which the block codes, the convolutional codes, the turbo codes, and the Low-Density Parity-Check (LDPC) codes can be cited. Among these codes, the turbo and the LDPC codes are the ones that have the performance closer to the theoretical limit predicted by [27], and greatly outperform the convolutional and the block codes, although the former require in general more complex decoding algorithms.

The coded cooperation can be classified into two main types: Repetition Coding (RC) and Parallel Coding (PC). In repetition coding the same encoder is used in both the source and the relay, sending the same information and parity symbols, as shown in Figure 5(a). This technique has the advantage of simplicity in decoding, since the receiver uses the same circuit to decode the received words from the source and from the relay. In the parallel coding, the source and the relay encoders are specially designed to send different parities, increasing the coding robustness and, therefore, the complexity of the encoding and the decoding designs. Figure 5(b) illustrates this strategy.



(a) Repetition Coding. (b) Parallel Coding.

Figure 5. Coded cooperation.

Several schemes using repetition coding can be found in the literature, as in [29, 36]. Parallel coding had as pioneers the authors of [37], followed by [15, 36]. The results from these works show that the parallel coding outperforms the repetition coding in terms of error probability, specially when irregular LDPC or turbo codes are used. However, these codes need to be specially designed for the relay channel, substantially increasing the complexity. Another important factor is that the decoding process at the destination also becomes more complex.

3. Application of cooperative protocols to wireless sensor networks

This section focuses on the application of some cooperative communication concepts to WSNs and its impact on the energy efficiency of the system. Therefore, some non-cooperative and cooperative transmission schemes are analyzed in terms of their total energy consumption. Moreover, aiming at practical telecommunication scenarios, several characteristics of a real wireless network are taken into account for a more accurate performance measure.

In the sequence, some important concepts are presented in Section 3.1, and the transmission techniques are discussed in Sections 3.2 and 3.3. Three relevant nodes in a WSN are considered: one source node S, one destination node D, and one relay node R, where the source tries to communicate with the destination, and the relay is at an intermediate position. Some numerical examples are given in Section 3.4. Moreover, since practical scenarios may be composed of many sensors, the extension of this simple analysis to multiple nodes is discussed in Section 3.5 and further generalized in Section 3.6. Finally, a comparison among different cooperative protocols is given in Section 3.7.

3.1. Concepts

Typically, the data collected by each sensor in a WSN is transmitted to a fusion center (FC), where estimates are formed based on the aggregated data from the ensemble of the sensors, and where the end user can access such data. Depending on the application of the WSN, the data transmission from the sensor to the FC can be made by radio, infrared, optical, etc. In the case of a wireless communication using radio frequency (RF) circuits, according to [14], a transmission from a node i to a node j can be written as:

$$\mathbf{y}_j = \sqrt{P_i\,\gamma_{ij}}\,h_{ij}\,\mathbf{x} + \mathbf{n}_{ij}, \tag{1}$$

where $\mathbf{y}_j$ represents the signal received at the node j, while $\mathbf{x}$ is the original message transmitted by node i. From this equation it is possible to notice that the signal received at j depends on the power used by node i to transmit, denoted by P_i, the path-loss γ_{ij} between i and j, which will be detailed in the sequence, and on the characteristics of the wireless medium h_{ij}. In addition, the received signal is corrupted by the communication noise $\mathbf{n}_{ij}$, which is typically modeled as additive white Gaussian noise (AWGN), 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 a factor that expresses the attenuation of the signal propagating through the wireless channel. The path-loss depends on the distance between the transmitter and the receiver and is given by:

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

where G includes the gain of the antennas of the transmitter and receiver, λ corresponds to the wavelength of the signal being transmitted, M_l represents the link margin, and N_f is the noise figure at the receiver. Note that all these terms are constant, and the unique term that varies is d_{ij}, which is the distance between the nodes i and j. Finally, α represents the path-loss exponent, which usually assumes values between 2 and 4 depending on the type of the environment. For instance, $\alpha = 4$ is usually assumed for very dense urban areas. For a more detailed explanation on this subject, the work of [14] is suggested as reference.

To describe the behavior of the wireless medium, several probabilistic models can be used depending on the characteristics of this environment. One of the most adopted models is the Rayleigh distribution, which is mostly suitable for non line-of-sight (NLOS) communications, meaning that the transmitter and the receiver have no direct link to each other, and communication is achieved through signals reflected in different directions. Nevertheless, WSNs often experience at least a portion of LOS between the nodes, specially in dense networks. With the nodes closer to each other, there exists a higher probability of an available direct communication path between two nodes. Another statistical model that can be used in such conditions is the Nakagami-m distribution. In such distribution the severity of the fading can be adjusted by the parameter m. Lower values of m represent a channel with little or no LOS, while higher values of m are representative of some relevant LOS. Experimental results in [34] show that $m = 1$ suits NLOS scenarios (where Nakagami-m is equal to the Rayleigh distribution in this case) and $m = 2$ models a scenario with some LOS.

Then, an important concept in the transmission between i and j is the Signal-to-Noise Ratio (SNR) in the i-j link, defined as:

$$SNR_{ij} = |h_{ij}|^2 \cdot \frac{\gamma_{ij} P_i}{N}, \tag{3}$$

where $N = N_0 \cdot B$ is the noise power spectral density, with B being the system bandwidth.

Finally, another important concept in the wireless transmission is the outage probability. An outage event between i and j occurs when the SNR at the node j falls below a threshold β which allows error-free decoding. The term β can be calculated based on the capacity of the channel given in [14] resulting in $\beta = 2^\Delta - 1$, where Δ is the system spectral efficiency. Then, the outage probability depends on the probabilistic model used for the wireless channel, so that in the case of Nakagami-m fading is given by:

$$\mathcal{O}_{ij} = \frac{\Psi\left(m, \frac{mN(2^\Delta - 1)}{\gamma_{ij} P_i}\right)}{\Gamma\left(m\right)}, \tag{4}$$

where $\Psi(.,.)$ is the incomplete gamma function and $\Gamma(.)$ is the complete gamma function. At high SNR, according to [32], the outage probability in (4) can be approximated as:

$$\mathcal{O}_{ij} \simeq \frac{1}{\Gamma(m+1)} \left[\frac{mN(2^\Delta - 1)}{\gamma_{ij} P_i}\right]^m. \tag{5}$$

The energy efficiency is analyzed in terms of the total energy consumption per bit of the wireless transmission. In the case of WSNs, the following aspects must be taken into account to compute the energy consumption:

- the power P_i required by node i to transmit the data, which depends on the distance between i and j;
- the additional power wasted by the power amplifier, which is proportional to P_i;
- the power consumed by the RF circuitry of the transmitter and of the receiver;
- the bit rate of the communication.

It is noteworthy that, since the focus is on WSNs, where the nodes are typically equipped with narrow-band single-carrier transceivers, the power consumed by internal signal processing is very small when compared to the circuitry power consumption, and therefore can be neglected in this energy consumption analysis. If broadband multi-carrier transceivers were considered, as for instance in [5], then the power consumption of the baseband processing should also be taken into account. Moreover, in a more general wireless network concept, some control messages may be exchanged by the nodes in order to acknowledge if the packets have been correctly received or not. However, as shown in [8], the impact of these control messages in the overall energy consumption is also negligible since these messages are usually much smaller than the message of interest **x**.

Then, the total energy consumption per bit in a transmission from i to j can be expressed as:

$$E_{ij} = \frac{P_{PA,ij} + P_{TX} + P_{RX}}{R_b}, \tag{6}$$

where $P_{PA,ij} = \frac{\xi}{\eta} P_i$ is the power consumed by the power amplifier, which depends on the peak-to-average ratio ξ of the employed modulation scheme and on the drain efficiency η of the power amplifier, P_{TX} and P_{RX} are the RF circuitry power consumption for transmitting and receiving, respectively, and $R_b = \Delta \cdot B$ corresponds to the bit rate in bits/s. A representative model for the RF circuitry is given in [10], illustrated by Figure 6, which represents the state of the art for current hardware for sensor technologies, as also depicted in [9]. From the figure, the following components can be identified for the transmit circuit: digital-to-analog converter, mixer, transmission filter and frequency synthesizer, with the respective power consumptions given by P_{DAC}, P_{mix}, $P_{fil_{tx}}$ and P_{syn}, totalizing:

$$P_{TX} = P_{DAC} + P_{mix} + P_{fil_{tx}} + P_{syn}. \tag{7}$$

At the receiver side, the following components can be identified: frequency synthesizer, low noise amplifier, mixer, intermediate frequency amplifier, and analog-to-digital converter, with the respective power consumptions of P_{syn}, P_{LNA}, P_{mix}, P_{IFA}, $P_{fil_{rx}}$, and P_{ADC}, totalizing:

$$P_{RX} = P_{syn} + P_{LNA} + P_{mix} + P_{IFA} + P_{fil_{rx}} + P_{ADC}. \tag{8}$$

In the sequence, some wireless transmission schemes are presented. Specifically, a simple single-hop scheme is analyzed in Section 3.2, while cooperative amplify-and-forward is analyzed in Section 3.3.

3.2. Traditional non-cooperative transmission

Single-hop (SH) is the simplest communication scheme involving only two nodes, with a direct transmission from S to D, as illustrated by Figure 7. The total energy consumed per bit of SH can be simply obtained by replacing i and j by S and D in (6):

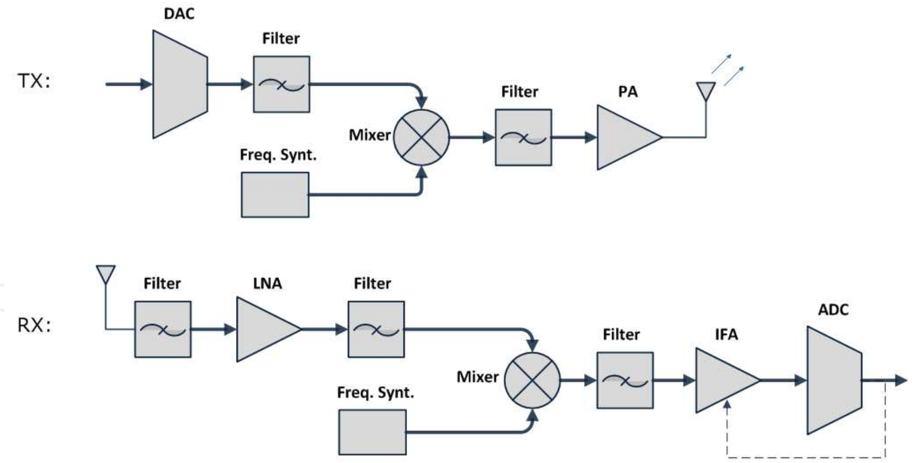


Figure 6. Block diagram for the TX and RX circuits.

$$E_{SH} = \frac{P_{PA,SD} + P_{TX} + P_{RX}}{R_b}. \tag{9}$$

Note that to minimize the energy consumption $P_{PA,SD}$ must be minimized, since P_{TX} and P_{RX}

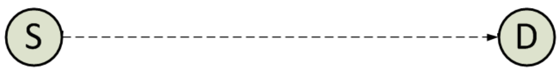


Figure 7. Single-hop transmission scheme.

are fixed and depend on the current technology. In order to do so, the following methodology can be applied:

1. a target outage probability $\mathcal{O}^{\star}$ is established at the destination. In other words, $\mathcal{O}^{\star}$ represents the maximum amount of frame error rate that the system may accept.
2. based on the outage probability of the scheme, which for the case of SH is given by (5) while replacing *i* and *j* by *S* and *D*, the optimal transmit power can be found as the minimal power that still reaches the outage threshold $\mathcal{O}^{\star}$.

Such strategy has been widely exploited in the literature, and for some more detailed examples the works of [7, 8, 17, 25] are given as references.

3.3. Cooperative amplify-and-forward transmission

Many cooperative protocols can be applied to WSNs in order to improve the throughput performance, or to reduce the energy consumption of the network. For instance, Selective and Incremental Decode-and-Forward have been analyzed in [7, 8, 17, 25, 28]. Nevertheless, motivated by the simplicity of analog schemes and since no decoding is required at the relay node in this case, Amplify-and-Forward is considered in this section.

In the cooperative transmission, two time slots are reserved for the communications process. In the first time slot the source broadcasts its message, which is received by the destination and also overheard by the relay. Then, in the second time slot, the relay amplifies the received message and forwards it to the destination. At the receiver, a combination between the two received signals is made, which increases the performance. However, note that the cooperative transmission presents an inherent spectral efficiency loss when compared to SH, since the end-to-end throughput is reduced to half due to the communication in two time slots. Such spectral efficiency loss can compromise the performance of some systems. In order to avoid this, the nodes in the AF scheme must transmit with a higher spectral efficiency. Thus, the nodes are assumed to operate with a spectral efficiency two times higher than that in SH. The main concern here is to obtain the same end-to-end throughput in both transmission schemes.

Therefore, since the spectral efficiency is multiplied by two, an outage event occurs when the received SNR falls below a threshold of $\beta' = 2^{2\Delta} - 1$. Then, the outage probability of each *i*-*j* link becomes:

$$\mathcal{O}_{ij} \simeq \frac{1}{\Gamma(m+1)} \left[\frac{mN(2^{2\Delta}-1)}{\gamma_{ij} P_i} \right]^m . \tag{10}$$

In addition, another important aspect in analyzing the energy consumption of AF is the exploitation of a feedback channel. The energy consumption of AF differs if a feedback channel is present or not. For instance, when a feedback is not available, the relay will always retransmit the message from the source in the second time slot, independently on the result of the first transmission. In such case, the total energy consumption of AF can be expressed by:

$$E_{AF} = \frac{P_{PA,S} + P_{TX} + 2P_{RX}}{2R_b} + \frac{P_{PA,RD} + P_{TX} + P_{RX}}{2R_b}, \tag{11}$$

where the first term corresponds to the transmission from S to R and D, and the second term corresponds to the transmission from R to D. Moreover, note that all terms are divided by two, since with a spectral efficiency multiplied by two, each individual transmission is two times faster. It is also noteworthy that, since both the relay and the destination listen to the source transmission in the first time slot, additional energy is consumed by the receive hardware (represented by $2P_{RX}$). In (11), $P_{PA,S}$ and $P_{PA,RD}$ represent the power consumed by the source and by the relay, respectively, and can be obtained based on the outage probability of the cooperative scheme.

On the other hand, Incremental AF (IAF) exploits a feedback channel from the destination so that the relay retransmits only if the destination could not decode the message from the source in the first time slot. This clearly leads to an energy improvement when compared to AF without feedback, since the transmission from the relay may not be always necessary. The energy consumption of IAF can be expressed as:

$$E_{IAF} = \frac{P_{PA,S} + P_{TX} + 2P_{RX}}{2R_b} + p_{SD} \cdot \frac{P_{PA,RD} + P_{TX} + P_{RX}}{2R_b}, \tag{12}$$

where the term p_{SD} represents the probability of incorrect decoding at the destination of the message from the source after the first time slot.

3.4. Numerical examples

In this section we discuss the energy efficiency of a WSN with three nodes and using the AF protocol. First, consider the required transmission power for single-hop and amplify-and-forward schemes, $P^{\star}_{SH}$ and $P^{\star}_{AF}$. The rest of the system parameters are given by

Table 1 and the relay is assumed to be at the intermediate position between the source and the destination. Figure 8 shows the required transmit power for each of the transmission schemes for both NLOS and LOS scenarios, where many important conclusions can be obtained. For instance, a significant difference in the required transmit power is observed for NLOS and LOS scenarios. The power consumed by SH is around 22 times smaller in LOS than in NLOS, and 5 times smaller for AF. In addition, the gains of the cooperative transmission becomes evident in Figure 8, where AF consumes up to 11 times less transmit power than the non-cooperative scheme.

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	$\alpha = 2.5$
Spectral Efficiency	$\Delta = 2$ b/s/Hz
Target Outage Probability	$\mathcal{O}^{\star} = 10^{-3}$

Table 1. System Parameters.

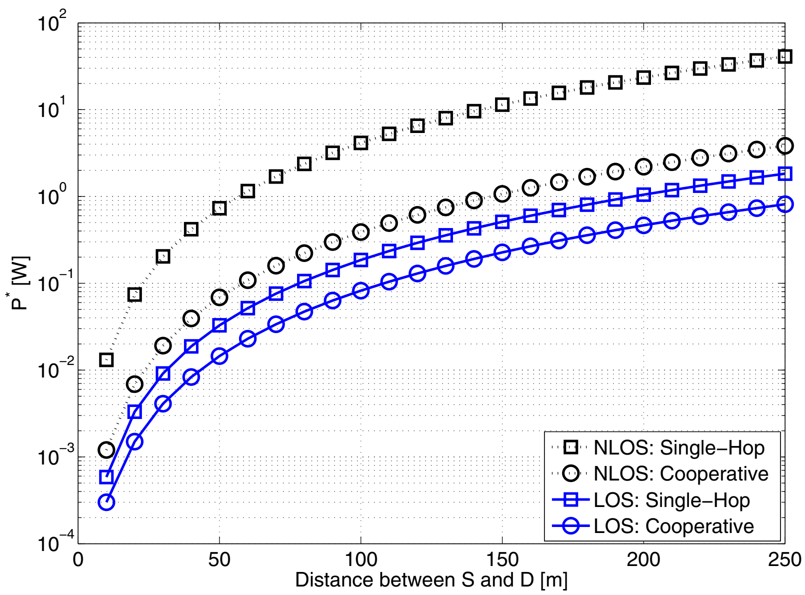
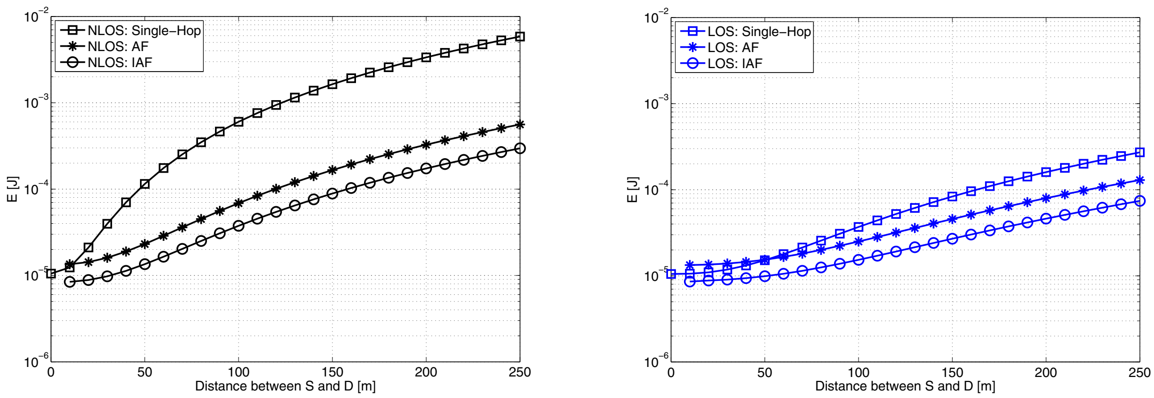


Figure 8. Transmit power for SH and AF schemes in Nakagami-m fading.

A more insightful comparison is given by the total consumed energy per bit for each scheme, E_{SH}, E_{AF} and E_{IAF}. In order to model the circuitry energy consumption, the same parameters as in [10] are used and are listed in Table 2. Figure 9 shows the obtained results where it is interesting to notice that SH is more energy efficient than AF at short transmission ranges. When the distance between the nodes increases, SH is outperformed. This fact is explained by the energy consumption of the circuitry of the additional node involved in AF. When the distance between the nodes is small, the circuitry consumption dominates in the total energy consumption, and therefore SH presents the best performance. On the other hand, while the distance increases, transmit power becomes more relevant and the cooperation outperforms the other schemes. Considering the NLOS scenario of Figure 9(a), AF is more energy efficient than SH when the *S*-*D* distance is longer than 12 m. On the other hand, observing the LOS scenario of Figure 9(b), it is possible to notice that these values increase considerably, with AF being more energy efficient for distances grater than 52 m, which is four times greater than the distances for the NLOS scenario. Finally, the most interesting conclusion is that IAF outperforms all the other schemes at any transmission range, which shows that a significant performance gain can be obtained with cooperation when a feedback channel is available.

Mixer	$P_{mix} = 30$ mW
TX/RX Filters	$P_{fil_{tx}} = P_{fil_{rx}} = 2.5$ mW
Frequency Synthesizer	$P_{syn} = 50$ mW
Low Noise Amplifier	$P_{LNA} = 20$ mW
Intermediate Frequency Amplifier	$P_{IFA} = 3$ mW
Analog-to-Digital Converter	$P_{ADC} = 6.7$ mW
Digital-to-Analog Converter	$P_{DAC} = 15.4$ mW
Drain Efficiency of the Amplifier	$\eta = 0.35$

Table 2. RF Circuitry Power Consumption.



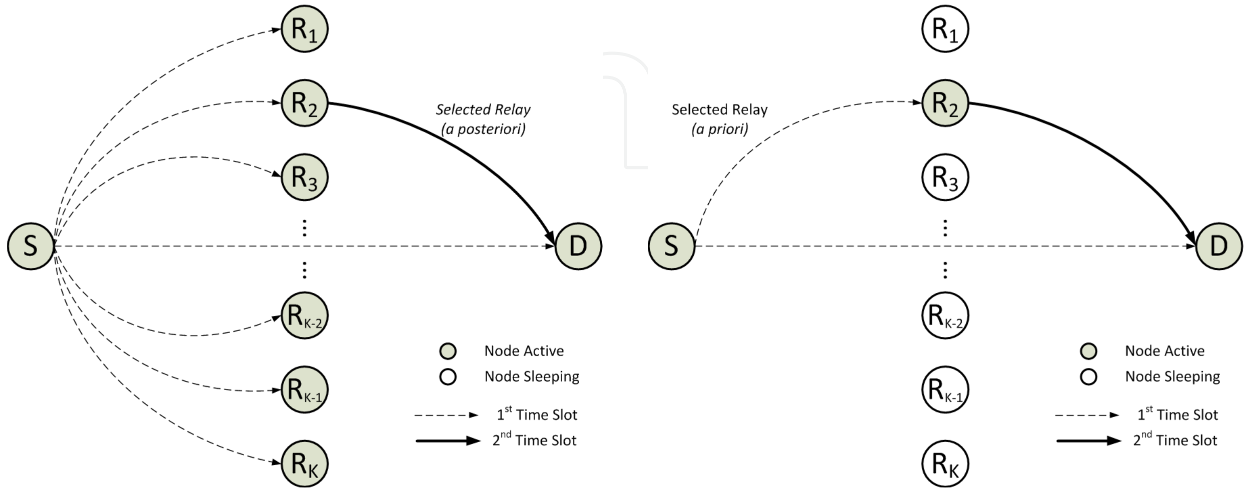
(a) NLOS ($m = 1$). (b) LOS ($m = 2$).

Figure 9. Total energy consumed per bit for SH, AF without feedback and IAF in Nakagami-m fading.

3.5. Multiple relays

As it is usual in WSNs, multiple nodes can be available in the network and the cooperative concept can be extended so that there is not only one, but multiple relays. The performance of the cooperative schemes increases with multiple relays since a larger number of independent paths will be available and, consequently, the probability that one of these relays is in good conditions increases. On the other hand, the complexity of the cooperative protocols increases since some criterion for choosing which relay will cooperate must be defined.

Two different approaches for relay selection are discussed in [4]. These two algorithms are named *reactive* and *proactive* relay selection, illustrated by Figure 10. In the reactive algorithm of Figure 10(a) the relay is chosen after the source transmission, and all relays have to listen to the source, what may increase the network energy consumption. On the other hand, the proactive algorithm of Figure 10(b) selects the relay before the source transmission, such that only the *a priori* selected relay has to listen to the source. In practice, the reactive algorithm is easier to implement, since it is distributed and no global information about the channel quality of the other nodes is required. Specific details about the implementation of each algorithm will not be discussed in this chapter, and the works of [1, 6, 22] are suggested to the interested reader.



(a) Reactive relay selection. (b) Proactive relay selection.

Figure 10. Relay selection algorithms.

As an example, consider a network composed by one source S, one destination D, and K relay nodes denoted by R_k, $1 \leq k \leq K$, where all relays lie at the intermediate position between S and D. This simplification is only to allow the mathematical tractability of the problem, which may bring important insights into the energy consumption of relay selection algorithms. The relays operate under the IAF protocol, exploiting the presence of the feedback channel from the destination.

In terms of energy consumption, the total consumption depends on the employed relay selection algorithm. In the case of the proactive algorithm, only the *a priori* selected relay and the destination overhear the transmission from the source in the first time slot. Thus:

$$E_{IAF}^{(pro)} = \frac{P_{PA,S} + P_{TX} + 2P_{RX}}{2R_b} + p_{SD} \cdot \frac{P_{PA,R_kD} + P_{TX} + P_{RX}}{2R_b}. \tag{13}$$

Note that this equation is very similar to (12) in terms of energy consumption, however, the power required to transmit the data decreases with a higher number of relays, since the outage probability decreases with K.

On the other hand, in the reactive algorithm, besides the source, the destination and the selected relay, all other $K-1$ relays overhear the transmission from the source in the first time slot. Therefore:

$$E_{IAF}^{(re)} = \frac{P_{PA,S} + P_{TX} + (K+1)P_{RX}}{2R_b} + p_{SD} \cdot \frac{P_{PA,R_kD} + P_{TX} + P_{RX}}{2R_b}, \tag{14}$$

which clearly indicates a higher energy consumption with respect to the proactive algorithm.

The optimal transmit power $P^{\star}_{PA}$ for $K \in \{0, 1, 2, 4, 8\}$ is shown in Figure 11 for a NLOS scenario. From the figure it can be observed that IAF requires less transmit power than SH and that the transmit power decreases with K. As the transmit power depends only on the outage probability, reactive and proactive algorithms lead to the same results. In the LOS scenario, similar conclusions are obtained.

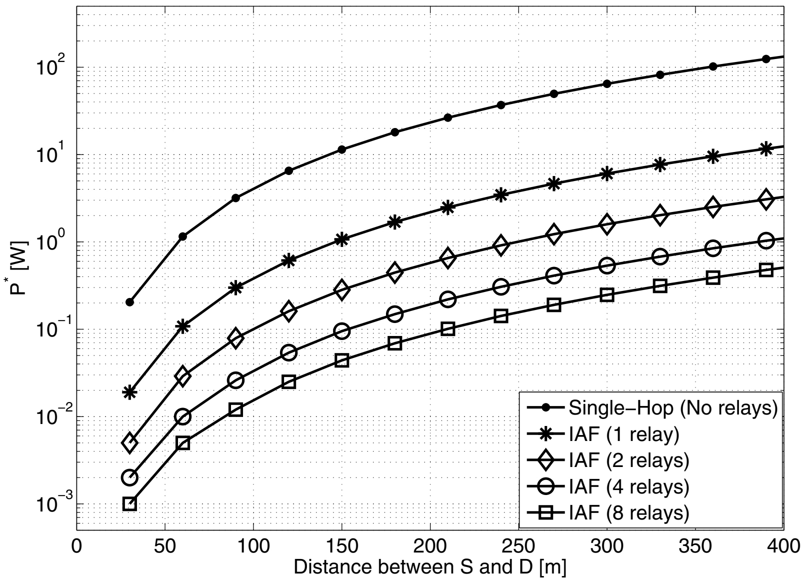
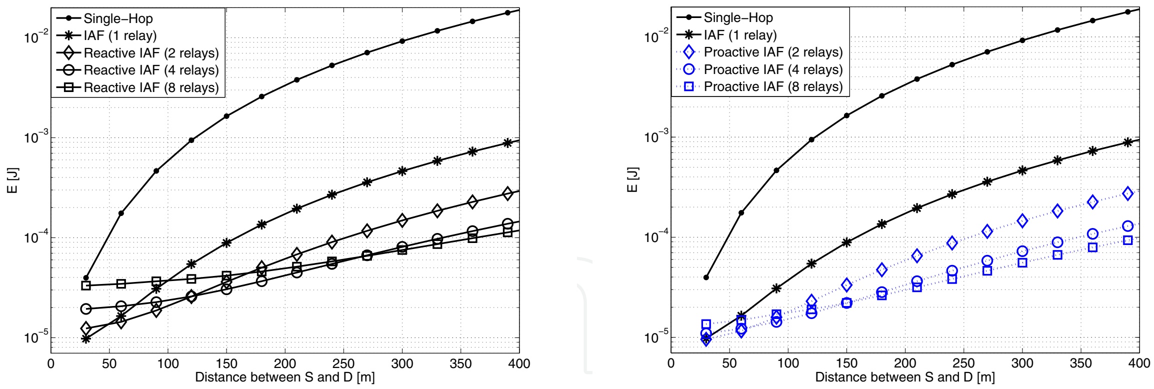


Figure 11. Optimal transmit power required in NLOS for multi-relays WSNs.

The total energy consumption is presented in Figure 12, also for NLOS. Regarding the reactive algorithm, it can be observed from Figure 12(a) that IAF with $K = 2$ relays is more energy efficient than with $K = 1$ when $d_{SD} \geq 49$ m, IAF with $K = 4$ outperforms $K = 1$ when $d_{SD} \geq 72$ m, and IAF with $K = 8$ outperforms $K = 1$ when $d_{SD} \geq 100$ m. It can also be observed that the energy savings in long transmission ranges do not increase linearly with K. For instance, reactive IAF with $K = 8$ is more energy efficient than reactive IAF with $K = 4$ only when $d_{SD} \geq 264$ m, and by a very small margin. In the LOS scenario, the energy savings are even less significant.

It can be also seen from Figure 12(b) that the proactive algorithm takes a better advantage from a larger number of relays. In this case, IAF with $K = 2$ relays is always more energy efficient than with $K = 1$, $K = 4$ outperforms $K = 1$ when $d_{SD} \geq 38$ m, and $K = 8$ outperforms $K = 1$ when $d_{SD} \geq 53$ m. Moreover, reactive IAF with $K = 8$ is more energy efficient than reactive IAF with $K = 4$ already with $d_{SD} \geq 150$ m, which is a considerable decrease in the energy consumption when compared to the reactive algorithm. This is due to the *a priori* relay selection, since all other relays remain in sleep mode during the source transmission. However, this algorithm depends on a fixed (or reduced mobility) topology, where the channel is constant for a long period, allowing for a pre-selection strategy. In addition, while the transmission range increases, the energy consumption of reactive IAF approaches that of proactive IAF, since the transmit power dominates over the RF circuitry energy consumption.

A more detailed comparison, which also considers the impact of a nonlinear discharge model that the batteries of the sensors may have, is also given in [6].



(a) Reactive algorithm. (b) Proactive algorithm.

Figure 12. Total consumed energy per bit for multi-relays WSNs in NLOS.

3.6. Generalized wireless sensor networks

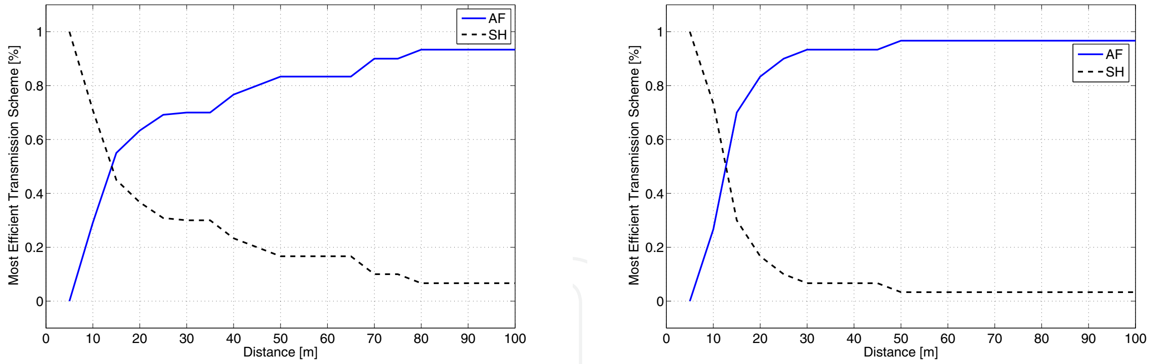
Simpler scenarios composed by three or more nodes distributed over a line segment are very useful due to the mathematical tractability of the problem. Nevertheless, the sensors in a WSN are usually distributed over a certain region in order to monitor some phenomenon of interest, which characterizes a two-dimensional topology with a random deployment of the sensors. Therefore, one should question if the results obtained over a line segment are still valid for a more general and realistic network scenario.

To investigate a larger scenario, consider that a number of sensors are randomly distributed over a certain area of interest. All the sensor nodes can act as source by gathering information from the environment and sending it to the destination node, which is positioned at the center[1]. Moreover, any sensor node can be selected to operate as relay. Since multiple nodes are available, relay selection is employed. Here, two strategies are compared: proactive relay selection, and random relay selection. Random relay selection is the simplest selection algorithm, as analyzed in [35], and the choice for the proactive algorithm is due to its good performance in terms of energy efficiency, as shown in Section 3.5.

A total of 121 sensor nodes are randomly deployed over a square area and the energy efficiency of SH and AF are analyzed for different distances between the nodes. Figure 13 plots the most energy efficient scheme as a function of the distance between the nodes in the square area. For instance, a result of 0.8 means that such a scheme is more energy efficient for 80% of the nodes in that scenario. Random relay selection is presented in Figure 13(a), and proactive relay selection in Figure 13(b). Moreover, a LOS scenario is considered. Note that at shorter distances, due to the circuitry consumption provided by the additional transmission of AF, SH is the most energy efficient transmission scheme. However, as transmit power increases with distance, AF presents better efficiency and outperforms SH when the distance between the nodes increases.

When random relay selection of Figure 13(a) is compared to proactive relay selection of Figure 13(b), it is possible to notice that the advantage of AF increases when the best relay is able to be selected, as the percentage of nodes operating with AF is higher when proactive relays

[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, by dividing the area it into quadrants.



(a) Random relay selection.

(b) Proactive relay selection.

Figure 13. The most efficient transmission scheme, considering SH and AF, for different distances between nodes in LOS.

selection is employed. In addition, if a return channel is available, IAF is the most energy efficient method for all distances. Under NLOS, AF is the most energy efficient scheme for all cases, regardless of the availability of a return channel or not. The energy consumption in LOS is 3.5 times lower than in NLOS, and the availability of a feedback channel also presents a significant impact on the energy consumption, as IAF consumes up to six times less than AF without feedback. This results corroborate with the findings of Section 3.4, showing that the mathematical predictions obtained for simpler scenarios of a few nodes are representative of more general cases of wireless sensor networks.

3.7. Other cooperative protocols

The energy efficiency analysis carried out so far assumes that the cooperation may occur using the Amplify-and-Forward protocol, whose use is motivated by its low complexity. Nevertheless, other cooperative protocols exist and could be also applied to WSNs, as described in Section 2.3. For instance, the Decode-and-Forward protocol is also of practical interest. In DF, the relay no longer operates in the analog mode, but the message received from the source is decoded by the relay, re-encoded, and then forwarded to the destination.

From a practical point of view, AF is very interesting due to its simplicity and DF may be more robust to transmission errors. Moreover, one important characteristic of DF is that different channel codes can be used at the source and relay, which is known as parallel coding (PC), in opposition to repetition coding (RC) when source and relay use the same channel code. The difference among these protocols in terms of energy consumption comes from the difference in the outage probability of each scheme. For the the derivation of the outage probability of these three schemes, the work of [16, 18] are recommended references.

The goal of the following analysis is to compare the energy efficiency of each one of these cooperative techniques: AF and DF. Since in WSNs the nodes are usually assumed to have the same hardware configurations, only DF with repetition coding is considered[2].

[2] DF with parallel coding requires different encoders at source and relay, such that the relay forwards the message from the source with a different codebook, increasing the error correction capability of the network. However, the hardware complexity increases with this protocol. Nevertheless, for a more detailed comparison including DF with PC, the work of [16] is suggested for the interested reader.

As the outage probability of these schemes behaves differently according to the relative position of the relay with respect to the source, the energy consumption of each scheme is analyzed with respect to the relative position of the relay, which is defined as $d_r = d_{SR}/d_{SD}$. Figure 14 illustrates the energy efficiency of these schemes when d_r is between 0.1 and 0.9, with the distance between the source and the destination being of $d_{SD} = 50$ m. Note that when the relay is close to the source (when d_r is small) both AF and DF present similar performance in terms of energy consumption. On the other hand, when R is not so close to the source (when $d_r > 0.4$ according to Figure 14), the AF method outperforms DF. The SH consumed energy is also shown as comparison, but note that it is constant since the SH performance is not a function of d_r. These results show that AF can be a very good option for WSNs.

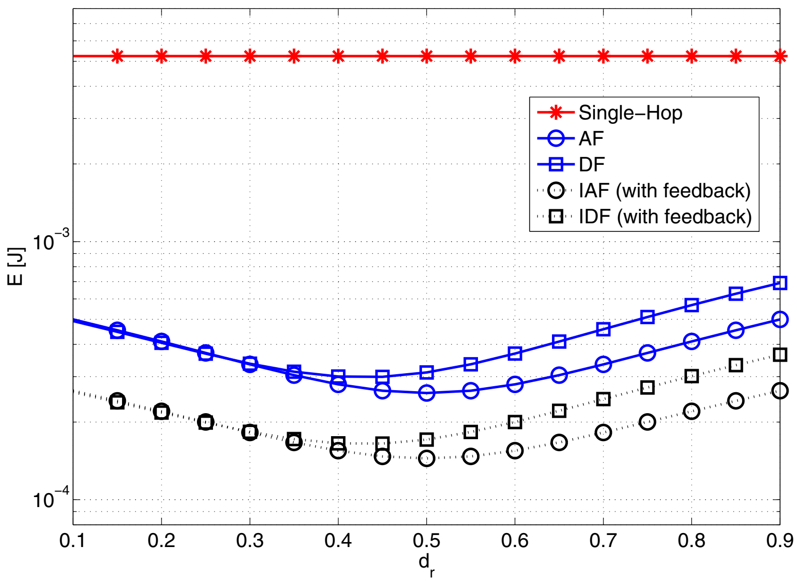


Figure 14. Total consumed energy per bit of AF and DF with RC for $d_{SD} = 50$ m.

4. Final comments

Although sensor nodes have existed for decades, the modern development of tiny sensor nodes is due to recent advances in hardware miniaturization, making possible to produce silicon footprints with more complex and lower powered microcontrollers. As a consequence, a large number of modern applications makes use of such devices. However, many challenges are still to be faced in the development of these systems. Nowadays, one major concern in the sensors industry is to develop low cost sensors with low energy consumption.

Coupled with the hardware development for WSNs, many advances have been reached in the telecommunications industry in the last years. Since WSNs are composed by many nodes, usually close to each other, the broadcast nature of the wireless medium can be exploited by the use of cooperative techniques. As shown in Section 2.1, spatial diversity is a promising technique to improve system performance, and cooperative communications, discussed in Section 2.2, is a practical way to achieve spatial diversity with small-sized devices, where the use of multiple antennas may not be possible. The use of cooperative protocols, as those presented in Section 2.3, proved to be effective in terms of reducing the power required by each node.

When the energy efficiency of WSNs is analyzed, some important characteristics of the network must be taken into account in order to obtain a fair comparison. For instance, as shown in Section 3, the maximum amount of error tolerated by the receiver and the characteristics of the wireless environment can have significant impact on the conclusions, and therefore must be carefully taken into account. Moreover, since WSNs usually deal with short range communications, the energy consumption of the transmit and receive circuits must also be taken into account. As shown in the examples of Section 3.4, in networks where there is no feedback from the destination, simpler transmission schemes such as single-hop are more energy efficient at short transmission ranges, since less nodes are involved in the communication (as well as less circuitry energy is being consumed). On the other hand, cooperation is able to save an important amount of energy when the transmission range increases. Nevertheless, if a feedback channel is available, the advantage of using cooperative schemes becomes evident at any transmission range.

The basic idea of energy efficiency in cooperative WSNs is presented in Section 3.3, while Section 3.5 extends such concept to a more interesting scenario. When multiple nodes are available, multiple sensors are potential candidates to act as a relay, and therefore some relay selection criterion can be established. However, from an energy efficiency point of view, to select one relay may be a challenging task. An important amount of energy is spent when multiple nodes are involved in a relay selection process, since these nodes consume energy if they must overhear the source transmission. Two relay selection algorithms are discussed in Section 3.5, however, energy efficient relay selection schemes are still a quite open research area.

Finally, in order to validate the results of Sections 3.4 and 3.5, the study is further generalized in Section 3.6. In this section, a WSN composed of multiple nodes is considered, with the nodes randomly distributed over a finite area. The results match with the predictions obtained over simplified networks, confirming the relevance of the analysis. In addition, Section 3.7 compares the performance of cooperation with analog relaying, by employing the amplify-and-forward protocol, to that of digital relaying, by employing the decode-and-forward protocol with repetition coding. The comparison shows a similar performance of both protocols when the relay is very close to the source, with a performance advantage of AF when the relay moves towards the destination.

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