Applying MIMO Techniques to Minimize Energy Consumption for Long Distances Communications in Wireless Sensor Networks

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Abstract. This paper explores the usage of cooperative multiple input multiple output (MIMO) technique to minimize energy consumption used to establish communications among distant nodes in a wireless sensor network (WSN). As energy depletion is an outstanding problem in WSN research field, a number of techniques aim to preserve such resource, especially by means of savings during communication among sensor nodes. One such wide used technique is multi-hop communication to diminish the energy required by a single node to transmit a given message, providing a homogeneous consumption of the energy resources among the nodes in the network. However, it is not the case that multi-hop is always more efficient than single-hop, even that it may represent a great depletion of a single node's energy. In this paper a cooperative MIMO transmission technique for WSN is presented, which is compared to single-hop and multi-hop transmission ones, highlighting its advantages in relation to both. Simulation results support the statement about the utility in applying the proposed technique for energy saving purposes.

Keywords: Wireless Sensor Networks; Cooperative Multiple Input Multiple Output; Energy Efficiency.

1 Introduction

Wireless sensor networks (WSN) are been used in a number of emerging applications representing an important technology for the future [1]. However, a paramount concern in relation to the usage of WSN is the energy consumption. Wireless sensor nodes are usually resource constrained platforms, driven by batteries, which limits their energy budget. Additionally, these sensor nodes are usually deployed in areas that are difficult to be accessed, thus making impracticable the replacement of such energy resources. As a result, to overcome such problem, a smart energy resource management is a must.

Considering that the most energy consuming task in the sensor nodes is communication [2], efficient communication mechanisms are highly desirable to reduce the energy depletion in wireless sensor networks. A number of proposals address this problem, such as alternative routing protocols [3], energy aware broadcast [4], among others. A common aspect of these approaches is the exploration of multi-hop communication to spread the energy depletion among the nodes in the network, so that no single node suffers a great decrease in its energy budget due to expensive long distance single-hop transmissions. However, multi-hop does not represent a "silver bullet" to solve the problem, as there are cases in which even a single-hop transmission can perform better than a multi-hop one.

To address the problem of long distance communications in WSN, this paper presents a cooperative multiple input multiple output (MIMO) strategy, in which a number of nodes cooperate to send/receive data aiming at an efficient usage of their energy resources. Theoretical and simulation comparisons are performed providing evidences of the value in applying the proposed techniques to address the energy consumption problem for long distance communications in WSN.

The remaining text is structured as follows: Section 2 presents background context and motivations. In Section 3 a theoretical analysis of energy consumption for single-ho and multi-hop transmissions is presented. Section 4 describes the proposed cooperative MIMO strategy is described, while Section 5 is dedicated to the presentation of simulation results and comparisons with single-hop and multi-hop alternatives. Related works are discussed in Section 6, and concluding, Section 7 summarizes the paper and provides directions for future works.

2 Motivation and Background

2.1 WSN Communications

Energy consumption is the paramount problem that still hinders a larger usage of WSN nowadays [2]. Due to the constrained energy budget that the sensor nodes count with, a careful usage of this resource in each individual node has to be taken into account in order to enlarge the lifespan of the entire network. As all distributed systems, WSNs have their basic functionalities highly dependent on the communication among their nodes. However, as wireless communications are very costly in terms of energy consumption, it leads to an impasse about the usage of the communications. The solution of this impasse has to consider an efficient usage of the communication in order to minimize the waste of energy.

Wireless sensor networks usually present a planar or a hierarchical architecture [5]. In the first one, sink nodes disseminate information in the network, which are transmitted from node to node according to the type of the information being disseminated, such as queries to specific locations for instance, and receive the replies by similar multi-hop communications from the nodes that provide the required information. Hierarchical-based WSNs restrict the more expensive communications to special nodes that exchange messages among them and are responsible for a number of other nodes, as representatives. Examples of such WSNs are clustered-based WSNs, in which those special sensor nodes are called cluster-heads, and they can be more powerful nodes that are in charge for long range communications with other cluster-heads and sink nodes, representing a group of sensor nodes under their responsibility (cluster members). Other configurations of clustered WSNs are possible, in which the cluster-heads and the cluster members are equally powerful, but differences such as remaining available resources, geographical positioning among other criteria can be used to select a given sensor node as the cluster-head [6]. Figure 1 presents an example of these two network architectures.

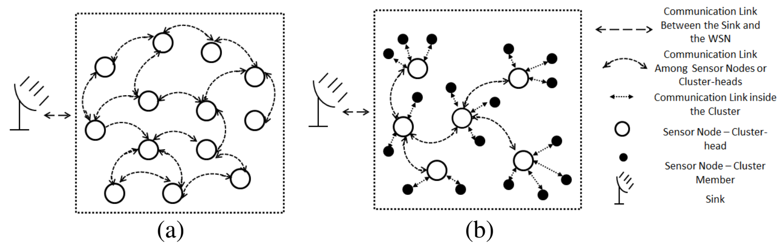


Fig.1. WSN architectures: (a) Planar; (b) Hierarchical.

Regardless of the WSN architecture, the sensor nodes need to communicate with each other, and their corresponding nodes can be close or far from them. In case of short range communication with close neighbour nodes, the problem related to energy consumption is not so significant, but the impact of long range communication for the energy resources consumption have to be considered. Usually, in order to avoid the energy depletion of a single node in an expensive single-hop transmission to another node far from the sender node, multi-hop communication is used, so that the sensor nodes do only perform short range transmissions. This is the case, for example, when a sensor node, or a group of them represented by a cluster-head, has to send replies from a query to the sink, as presented in Figure 2.

Although multi-hoping is considered an efficient communication solution for WSN, there are cases in which single hop represents a better alternative in terms of energy consumption [7]. Such cases are shown in Section 3.1. On the other hand, in several scenarios, the usage of single hop for long distance communication may compromise the entire network lifetime. This is the case, for instance, when the single hop communication results in an unpaired depletion of the energy resources of individual nodes, which is highly undesired.

Despite the specific problem of the energy consumption itself, the above described single hop and multi-hop schemes with fixed data rate may incur in several errors during communication, which require retransmissions, then increasing even more the energy cost associated to communication.

Observing the basic characteristics of a WSN, in which several nodes in a neighbourhood provide similar data, alternative solutions can be created. One of them explores the concept of hierarchical WSN presented above, in which different types of sensor aggregation or sensor fusion techniques are used [8]. In spite of the benefits of such techniques, they may require several communications among the cluster members, depending on the agreement protocol that is used, thus increasing the energy consumption due to communication.

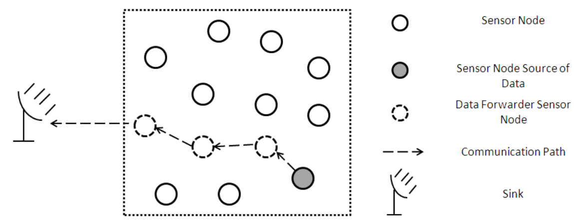


Fig.2. Multi-hop data communication from a data source sensor node towards the sink.

Besides single and multi-hop communication in WSN, cooperative multiple input multiple output (MIMO) schemes are also important alternative solutions that can be considered. As neighbouring sensors need to send the same or even not the same, but data at the same time, cooperative MIMO can be used, as briefly described in the next subsection, and further explored in next sections of this paper.

2.2 Cooperative MIMO

The cooperative MIMO communication considered in this work is based on two steps. The first step estimates the cooperative MIMO channel by using pilot signals. Once the channel is estimated, the new information can be transmitted. In Section 4 this cooperative MIMO approach for communication in WSN is detailed, while the results obtained with this alternative solution are compared with those obtained with single and multi-hop in Section 5.

3 Single-hop and Multi-hop Transmissions in WSN

From energy efficiency point of view, multi-hop are preferable in relation to single-hop transmissions in WSN. This is due to the minimization of the energy consumed by a single node and due to the more evenly depletion of the energy resources among the sensor nodes along the communication path. However, besides the aspect related to the uniform energy consumption among the sensor nodes, if only the total amount of energy spent in a given communication is considered, the advantage in using multi-hop instead of single-hop is not true for all cases, and depends on the distances between the source and destination nodes, and among the nodes between themselves, as presented and discussed in [7].

According to [7], the energy spent on a communication between two nodes, say *i* and *j*, can be divided in two terms, one for the transmission and another for the reception, respectively, according to (1) and (2):

$$E_t(i,j) = \alpha \cdot f_{i,j}, \quad (1)$$

$$E_r(j,i) = \beta \cdot f_{i,j}, \quad (2)$$

where $f_{i,j}$ stands for the bit rate, β is a constant and α is a parameter that depends on the distance between the nodes as follows:

$$\alpha = \begin{cases} a + b \cdot d_{i,j}^{\gamma}, if\ d_{min} \le d_{i,j} \le d_{max} \\ a + b\,, \quad\quad if\ 0 \le d_{i,j} \le d_{min} \end{cases}, \tag{3}$$

where *a* and *b* are constants corresponding to the energy consumption per transmitted bit, $d_{i,j}$ is the distance between nodes *i* and *j*, γ is a decay factor according to the propagation model, d_{min} and d_{max} are respectively the minimum and the maximum distances for the communication range.

To study the difference between the single and multi-hop transmission, assume an integer k so that $d_{max} = k \cdot d_{min}$, and consider two nodes, *i* and *j*, in a WSN that are d_{max} apart from each other. Node *i* can transmit to node *j* either via a single hop transmission, as its range reaches the destination node, or via multi-hop, using the sensor nodes between them, which by their turn are separated from each other by a d_{min} distance. Figure 3 illustrates this scenario.

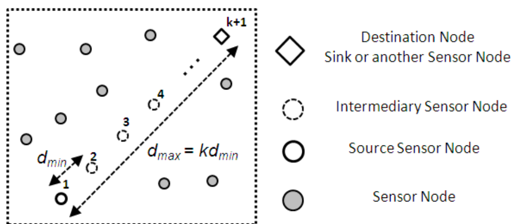


Fig.3. Distances between communicating nodes and intermediary nodes.

The cost in terms of the energy consumed by the single hop transmission of one bit can be expressed by the sum of the energy consumed in the transmission and the reception, and by using (1) – (3), it possible to come to the following expression:

$$E_t(1, k+1) + E_t(k+1, 1) = 2a + b \cdot d_{max}^2 = 2a + b(k \cdot d_{min})^2. \tag{4}$$

On the other hand, for the multi-hop alternative, the total energy consumed for the same one bit communication is:

$$\sum_{i=1}^{k} E_t(i, i+1) + \sum_{j=2}^{k+1} E_r(j, j-1) = k(a + b \cdot d_{min}^2) + k \cdot a = 2ka + bkd_{min}^2. \tag{5}$$

From [7], the condition that makes the single-hop alternative outperforms the multi-hop one is given by:

$$k \le \frac{2a}{b \cdot d_{min}^2}. \tag{6}$$

Assuming a pair of nodes apart from each other by a distance *D*, from [8] it is known that a condition to achieve the minimum energy consumption in a multi-hop communication between these two nodes is that the distances between the intermediary nodes be identical (*d*). Assuming *n* between them, $d = \frac{D}{n}$. Moreover, the optimum number of hops between a sender and receiver node is given by:

$$n_{opt} = \sqrt{\frac{b}{2a}} \cdot D. \tag{7}$$

The term $\sqrt{\frac{b}{2a}}$ in (7) derives $\sqrt{\frac{2a}{b}}$, which is called characteristic distance (d_{char}), and condition for the optimum number of hop n_{opt}, results in minimal consumed energy is $d = d_{char}$.

From the analysis of these results, the study in [7] concludes that the single-hop communication is more efficient that the multi-hop one when the distance between the communicating nodes is less than d_{char}. Observing the situation illustrated in Figure 3, this means that if $d_{max} < d_{char}$ the single-hop communication is more energy efficient than the multi-hop one.

4 Energy Efficient Transmissions in WSN based on Cooperative MIMO

Taking advantage of the cooperative nature of the sensor networks operation, cooperative MIMO can be introduced in these systems to provide a reliable communication, by diminishing the bit error rate (BER), possibly requiring less energy resources. Instead of a conventional arrangement of multiple antennas in a single sensor as in the traditional MIMO, in cooperative MIMO system, multiple sensors cooperate to transmit and receive data. Figure 4 presents an example in which two clusters of sensors establish a communication as a MIMO system. In the figure it is also possible to observe another possible situation in which a cluster of sensors establish communication with a single sensor similar to a single input multiple output/ multiple input single output (SIMO/MISO) system. Notice that the term "cluster" used to describe the situation in Figure 4 has not the same meaning that it has in the part of the paper that is used to explain the hierarchical WSN above (Section 2). In Figure 4 there is no difference among the sensor nodes, and the term "cluster" is used to identify a group of cooperating sensor nodes.

Using this approach, if two sensors near to each other cooperate to transmit information, and two sensors on a far cluster cooperate to receive data, the efficiency is effectively doubled, as two symbols can be transmitted over the same time slot.

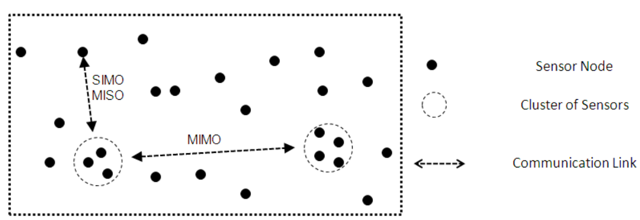
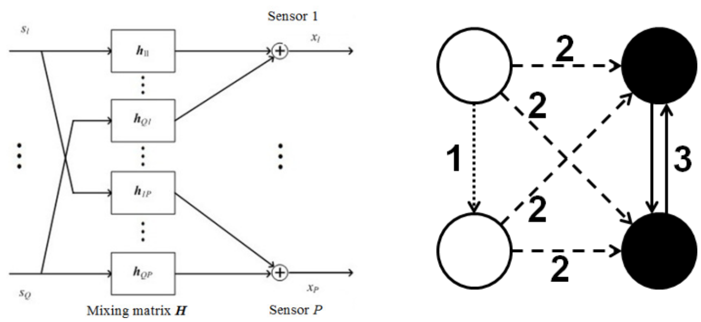


Fig. 4. Cooperative MIMO communication between clusters of sensors and SIMO/MISO communication between a cluster an individual sensor.

Figure 5a presents an example of a MIMO systems composed of Q transmitter sensors and P receiver sensors. The communication channel between the i-th transmitter sensor to the j-th receiver sensor is given by $h_{i,j}$.



(a) (b)

Fig. 5. Examples of: (a) cooperative *Q* by *P* MIMO system; (b) 2 by 2 MIMO system.

Considering the MIMO system in Figure 5, the output of the *j*-th sensor $x_j(n)$ is given by:

$$x_j(n) = \sum_{i=1}^{Q} h_{i,j} s_i(n), \tag{10}$$

where $s_i(n)$ is the transmitted symbol at the *n*-th time instant by the *i*-th source transmits.

Considering the *Q* input signals, the *P* output signals, and the mixing or channel matrix H, we can rewrite (10) in the matrix form as follows:

$$\boldsymbol{X} = \boldsymbol{HS}. \tag{11}$$

As mentioned in Subsection 2.1, the Bit Error Rate is going to be computed in two steps.

In the first step given $\boldsymbol{X}$ and $\boldsymbol{S}$, we can solve (11) and find $\widehat{\boldsymbol{H}}$, which is an estimate of $\boldsymbol{H}$. The symbol matrix $\boldsymbol{S}$ contains the pilot signals. For low Signal-to-Noise Ratio (SNR), the estimation of $\boldsymbol{H}$ can be severely degraded.

After the channel estimation step, the *Q* transmitter sensors send unknown symbols, which are estimated by using $\widehat{\boldsymbol{H}}$ and (11). Then, from this step, $\widehat{\boldsymbol{S}}$ is obtained, which are used to compute the Bit Error Rate (BER).

Figure 5b presents an example of 2 by 2 MIMO system in which the numbers represent the steps that are described as follows: (1) The transmitting sensors exchange the information that needs to be transmitted; (2) Both sensors transmit different symbols at the same time slot; (3) The receiving sensors exchange the received information so that the original symbol sequence can be obtained.

The next section presents the performance evaluation of the aforementioned cooperative MIMO scheme in a WSN in comparison to single-hop and multi-hop.

5 Experimental Results

5.1 Simulation Setup

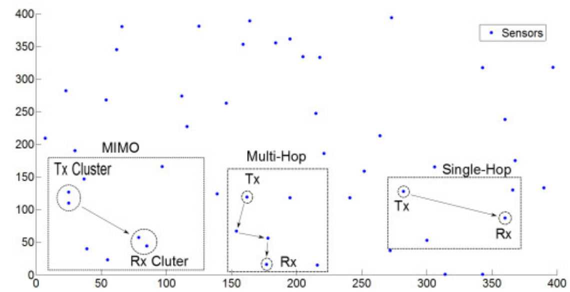
The cooperative MIMO channels are generated by using the IlmProp [13], which is a flexible geometry-based multi-user MIMO channel modeling tool. The evaluation of the efficiency of the cooperative MIMO communications for the WSN is done by measuring the Bit Error Rate (BER). Simulations are made to determine the BER for the cooperative MIMO, the single-hop and the multi-hop techniques. A random pair of sensors that are about 100 m apart from each other is selected presenting the possibility for multi-hop communication via other nodes that are 30 m apart from each other, i.e. 30 m distance for each hop. The single-hop approach involves only the sensor that has the data that needs to be transmitted and the sensor that will receive this data. Both sensors are 100 m away as mentioned above, so communication requires a very high power at the output of the antenna, since the free space attenuation is very high. 30 pilot symbols are transmitted to estimate channel gain and the rotation it causes on the symbol constellation. After 1000 data symbols are transmitted, the BER is estimated comparing the transmitted symbols with the received ones.

For the multi-hop approach the process is very similar, but the distance the data needs to travel is split in three, with sensors cooperating along the way to transmit the data over smaller distances, thus requiring less power. 30 pilot symbols are transmitted between each pair of sensors so the channel gain can be estimated, after that 1000 data symbols are transmitted similarly as in the single hop approach. It is worth to highlight that for a sensor start transmitting the data to the next sensor it first needs to receive the entire data string and decode it, which may imply in a significant delay. The BER is estimated comparing the transmitted symbols with the symbols received at the last sensor, i.e. last hop.

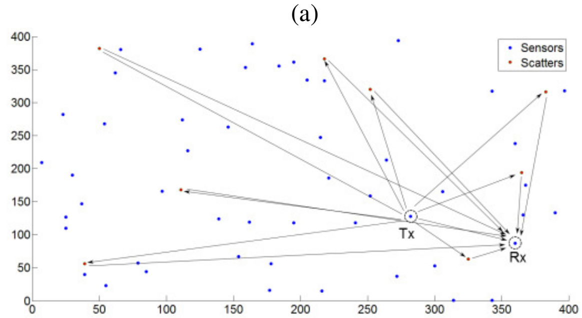
Direct communication between the two nodes is used, then a scenario with 3 hops is simulated, and then the MIMO scenario using a 2×2 configuration. The sensors are distributed according a random pattern following Poisson distribution in two dimensions, for all simulation runs. Following this distribution, 50 sensors are displaced in an area of 400×400 m^2. Figure 6a presents the simulated scenario without multipath components and also exemplifies each solution. Note that the selected sensors are varying during the simulations.

The first simulation considers only the line of sight (LOS); the second simulation considers 10 obstacles that provide 10 different multi-path components, in which each obstacle represents a reflection of the signal that presents different amplitude and phase from the LOS signal, resulting in heavy interference. The simulation conditions are the same for all experiments, the sensors' position are preserved, only the multipath components changed from one simulation to the other. For the cooperative MIMO case, the symbols to be transmitted are first transmitted to the cooperating sensors of the transmit cluster. Perfect synchronization among sensors is assumed.

The channel coefficients are estimated by means of a set of 30 pilot symbols, followed by the transmission of 1000 data symbols. The carrier frequency is 2.4GHz and flat fading over the transmission bandwidth is assumed. The simulation ranges from -10 to 10 dB SNR and 1000 independent Monte Carlo runs are assumed for each SNR. The results for the energy cost are based on the characteristics of the Berkeley Mica2 Mote [9].



(a)

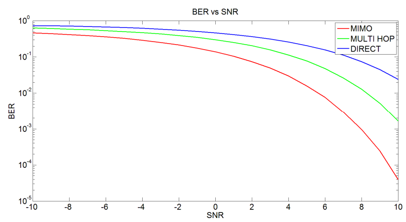


(b)

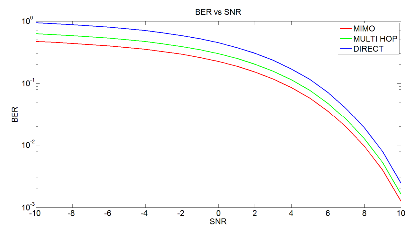
Fig. 6. Simulated scenario: a) LOS only exemplifying the Cooperative MIMO, Multi-hop and Single-hop solution; b) LOS and NLOS with 10 multipath exemplifying only the Single-hop solution.

5.2 Results and Discussion

Figure 7 presents the average BER as function of the SNR. Direct single-hop communication requires a high output power at the transmitter for the signal to be properly decoded. Multi hop communication requires much less transmitting power across the transmitters, but grows increasingly costly as the number of hops increases, due to the fact that receiving can cost up to twice as much power as transmitting a low power signal. In the MIMO case, the same signal can be transmitted by two or more sensors, and decoded by one or more sensors, signals can be transmitted at a lower power, thus requiring less energy. This further improves energy efficiency over the network when long distance transmissions need to be made and direct transmission is not possible. This impossibility can be either due to a high number of multi path components or due to the fact that there are no intermediary nodes available to relay the packages across the network.



(a)



(b)

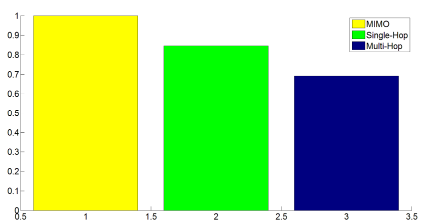
Fig. 7. BER vs. SNR results: a) LOS only; b) LOS and NLOS with 10 multipaths.

Comparing the energy spent by the 3 different configurations (single-hop, multi-ho and MIMO) to achieve the same BER, the following results are acquired. Considering the LOS case only, for a BER of 10^{-6} a SNR of 12.5 dB is necessary for the direct case, 10 dB for the multi-hop case and 7 dB for the MIMO case. Table 1 presents the amount of transmissions and receptions of data packages of the same size that are needed to perform the communication 100 m across the network. Figure 8a presents the relative energy consumption.

Table 1. Number of transmissions and receptions for each type of the performed simulations.

Case	Transmissions	Receptions
MIMO (2 × 2)	6	6
Multi-Hop	3	3
Single-Hop	1 (Very High Power)	1

Considering free space path loss, for the signal of 2.4 GHz used in the simulations, the results provide approximately 80 dB loss over 100m and 69.6 dB loss over 30 m, a loss approximately 11 times higher for a distance only 3.3 times longer.



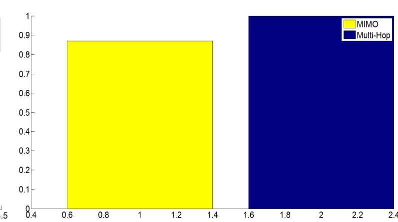


Fig. 8. Relative Energy Consumption: a) First comparison among MIMO, single-hop and multi-hop; b) Second comparison between MIMO and Multi-hop.

At first impression (Figure 8a) the 2 × 2 MIMO case seems to have the highest cost, but if two sensors in the transmit cluster and two at the receive cluster are allowed to cooperate, the proposed cooperative MIMO approach presented in Section 4.2 can be used. Now, with two symbols being transmitted over the same time slot, the energy cost per symbol is decreased by 50%. This configuration can achieve ranges much longer than the direct communication (single-hop), with a lower BER. As the distance increases, the amount of multi-hops necessary to get the data package to its destiny becomes increasingly costly, and if the data that needs to be transmitted is sensitive to delay, it might not be possible to use to multi-hop approach. Comparing the costs for the multi-hop and MIMO alternative to get a message across a distance in which 5 multi-hops are needed, the results show that MIMO is more energy efficient than multi-hop, as can be observed in Figure 8b.

In this case the energy efficiency of the MIMO case surpasses the efficiency of the multi-hop approach, which becomes increasingly costly especially due to the number of receptions that need to be performed. Receptions can cost twice as much energy in transmissions of a low power signal than in transmissions of high power.

Transmitting data over the direct approach is the best option only if the distance is smaller than d_{char} (see Section 3), or the multi-hop approach is not an option and the number of multi-paths of the signal is minimum.

The multi-hop approach is the best option if the data is not sensitive to delay and if the number of multi-hops necessary does not make the transmission cost bigger than the MIMO approach. It is also the case to use it if the MIMO approach is not available due to the absence of other sensors in the neighborhood to cooperate with in the reception.

A SIMO approach, a special case of MIMO (i.e. 1×2), is an option in case the multi-hop approach is not available, the number of multi-paths of the signal is too much for the single-hop and there is no sensor available to cooperate at the reception.

6 Related Work

The use of MIMO presents enhancement in the energy efficiency of WSN [10][11]. However, MIMO is also used for spatial diversity and multiplex gain. In [12] techniques for energy efficient communication aiming at to diminish the total energy transmission and the energy consumed in the processing performed by the circuit for MIMO and SISO systems were proposed. In [10] the increase in the overhead involved in the training of the MIMO systems is studied. In [11] the efficiency in the cooperative transmission of space-time block codes, STBC, is analysed. Besides the innovative usage of cooperative MIMO proposed in our paper, we presented a comparative study considering single and multi-hop alternatives, which was not performed so far to the best of authors' knowledge.

7 Conclusions and Future Work

This paper presents a study comparing single-hop, multi-hop and cooperative MIMO-based transmissions over WSNs. Simulation results were presented, discussed and compared to theoretical ones. As observed by the analysis of the obtained results, the cooperative MIMO approach becomes the best option as the number of multi-hops increase too much, (using the MICA2 power model assumed on this paper, when 4 hops are necessary, the MIMO approach costs 8.7% more power, for number of hops higher than that, the cooperative MIMO approach starts to be more power efficient than the multi-hop approach) or if the data is sensitive to delay. Our results corroborate that cooperative MIMO is a powerful option for data transmission over long distances across the WSNs.

Directions of future work are the investigation of possible enhancements in the proposed cooperative MIMO technique, in particular by considering sensor nodes' mobility, which was not addressed in the present paper.

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