Energy efficiency of MIMO-based Sensor Networks with a Cooperative Node Selection Algorithm

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Abstract — Low-cost and low-power sensor nodes forming Wireless Sensor Networks (WSNs) have become suitable for a wide range of applications during recent years. These networks, due to their special functional characteristics, demand the implementation of energy-aware techniques in all layers. Recently a MIMO -- based structure has been proposed to offer enhanced energy savings in WSNs under certain circumstances. In this paper, we present a detailed analysis of the dissipated power during a sensor node’s operation, to prove that as micro-electronics develop the MIMO -- based architecture will outperform the equivalent SISO structure for almost any case, in terms of energy efficiency. Moreover, we introduce a simple Cooperative Node (CN) Selection algorithm to achieve additional energy gains in the MIMO approach along with enhanced network lifetime. We examine the scalability of the algorithm on different channel conditions and varying network density, and investigate the effect of the power dissipation analysis on its efficiency.

Index Terms — Cooperative techniques, Energy efficiency, Multiple-Input-Multiple-Output systems, Node – selection algorithms, Wireless Sensor Networks

I. INTRODUCTION

Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate untethered mainly in short distances. These nodes, which consist of sensing, data processing and communicating components, leverage the potential of sensor networks. A Wireless Sensor Network (WSN) is composed of a large number of sensor nodes that are densely deployed either inside the phenomenon or very close to it. It may operate in places difficult to reach and in hostile environments, where the nodes may move or be static and gather various information, e.g. temperature, humidity, movement etc., and transmit it mainly using low data rates (~10 to 200 Kbps). These features ensure a wide range of applications for sensor networks ([1]); some of them are in the areas of health, military, agriculture, home etc.

One of the most important characteristics of a WSN is that the sensor nodes in most cases operate on small batteries, which are difficult to replace, and thus have restricted sources of energy. Consequently, the design of such networks should focus primarily on improving the performance in terms of energy efficiency.

A technique that has been recently introduced in WSNs focusing on energy efficiency is Cooperative networking. A sensor network may be seen as a multi-input-multi-output (MIMO) system, where a sensor node may be assigned the role of a transmitting or receiving antenna of the MIMO structure. In [2] it was proved that a MIMO system may support higher data rates without increasing transmission power, which is equivalent to the conclusion that MIMO systems demand less transmission energy than SISO systems for the same throughput requirements. This view was used in [3], where the authors proved that under certain conditions a sensor network may operate based on a MIMO structure. According to that proposal, two or more nodes on the transmitter side cooperate and encode their transmission sequence based on Alamouti diversity codes. On the receiver side, a number of nodes join the cooperative reception. This MIMO based transmission requires additional energy for local communication between the nodes at the transmitter side and those at the receiver side, but simultaneously introduce important gains for the long-haul communication. It has been shown that according to the MIMO scheme used, there is a critical distance between transmitter and receiver above which MIMO transmission is more energy efficient than SISO. This topic was furtherly discussed in [4], where more enhanced study towards the energy efficiency of MIMO based schemes was carried out. The authors of [4] also take into account the effect of increasing training overhead required in MIMO systems in order to estimate the extra channel coefficient values.

A very interesting extension of the work on MIMO based WSNs is an architecture called MIMO-Sensor Networks with Mobile Agents (M-SEMNA), and has been proposed in [5]. According to M-SEMNA, several neighbouring nodes are
selected to transmit information cooperatively. The scheme is based on the assumption that the receiver is a sink node called mobile agent that is equipped with multiple receiver antennas. Such receiver though does not suffer from energy limitations; thus the results obtained, however promising they are, they are not applicable for several WSN applications.

One of the most recent progresses of research towards this direction may be found in [6]. The proposed protocol is based on the traditional low-energy adaptive clustering hierarchy protocol (LEACH) and its extension by incorporating the cooperative MIMO communication. A very interesting algorithm for cooperative nodes (CN) selection is used, based on channel characteristics of the links to every possible CN and on the energy remains of these nodes.

In this paper, we extend the work done in [3] as follows. First, we examine the effect of the power consumed in all electronics and circuitry of a node apart from transmission power on the energy efficiency of the MIMO-based structure. As electronics science develops, the construction of more energy efficient circuitry becomes more feasible. On the other hand, the distance thresholds evaluated in [3], [4] are highly dependent on the power dissipation of these parts of the node. Therefore, these thresholds may become looser and the MIMO-based structure on WSNs outperforms SISO schemes for a greater range of distances offering increased energy gains. Moreover, we implement a simple node selection algorithm. According to that scheme, each node that is ready to transmit a piece of data is able to choose cooperative nodes among its neighbours that result in maximum energy savings and increased network lifetime. Finally, we investigate the effect of the electronics power consumption on the algorithm’s performance, and examine the algorithm’s scalability on different channel conditions and for various values of nodes’ density.

The remainder of this paper is organized as follows. In Section II a brief description of the MIMO – based approach on WSNs is given, followed by the analysis of the effect of the power consumed on various electronics apart from transmitting and receiving data on the MIMO-based and the SISO-based schemes, in Section III. The cooperative node selection scheme is presented and examined as far as its performance is concerned in Section IV. Finally, a summary and future plan description is carried out in Section V.

II. THE MIMO APPROACH

The basic idea in the MIMO – based structure for WSNs is that there are \( M_t \) neighbor nodes with data to be transmitted to a destination node. Each node broadcasts its information to all the other nodes using different time slots (local transmissions), and in the following the transmission sequence is encoded according e.g. to the Alamouti diversity codes ([2]). The \( i-th \) node then transmits the sequence that the \( i-th \) antenna should transmit in an Alamouti MIMO system (long – haul transmission).

On the receiver side, the \( M_r \) nodes (including destination node) receive the encoded data, and the \( M_r -1 \) nodes forward the data to the destination node after decoding it into \( n_r \) bits. The MIMO approach is explained in more details in [3] and [4], and is summarized in Fig. 1.

The energy needed in order to complete a transmission of \( L \) bits based on the above MIMO structure is given by (1):

\[
E_{MIMO} = L \sum_{i=1}^{M_t} E_{b,i}^t + LE_b^r M_r + \left( \frac{L \times M_t}{b} \right) \sum_{j=1}^{M_r-1} E_{b,j}^r n_r \quad (1)
\]

where \( E_{b,i}^t \), \( E_b^r \), \( E_b^t \) are the energy consumptions for transmitting and receiving one bit of data in the transmitter side, the receiver side and for the long-haul transmission respectively. The estimation of \( E_b \) for all cases is analyzed in Section III. \( \frac{(L \times M_t)}{b} \) expresses the total number of symbols transmitted from the transmitter’s side, assuming that \( b \) is the constellation size used by the Alamouti code.

III. POWER DISSIPATION ANALYSIS

During the operation of a WSN, each sensor node dissipates energy that depends not only on the transmission power but also on the electronics used in the analog and digital parts of the node. According to [7], the total energy consumption for transmitting and receiving one bit of data may be expressed by (2):

\[
E_b = E_{ana} + E_{dig} \quad (2)
\]

where \( E_{ana}, E_{dig} \) is the energy consumed by the analog and the digital parts of the node. Here, we focus on distinguishing the energy consumed by the circuitry of the node, denoted with \( E_{circ} \), from the energy that depends on the transmission power, \( E_{trans} \). It is shown in the Appendix that using the
above notation, the energy consumption may also be given by (3):

\[ E_b = E_{\text{trans}} + E_{\text{circ}}, \]
\[ E_{\text{trans}} = (a + 1)P T_{\text{on}} / L \]
\[ E_{\text{circ}} = ((P_{\text{ana}} + P_{\text{detector}} + P_{\text{dig}})T_{\text{on}} + 2P_{\text{syn}}T_e) / L \]

where \( P_{\text{ana}} \), \( P_{\text{detector}} \), \( P_{\text{dig}} \) and \( P_{\text{syn}} \) are the power dissipations on the analog circuitry, the detector, the digital circuitry and the frequency synthesizer respectively, and are furtherly analyzed in the Appendix. \( T_{\text{on}} \) is the time needed for the transmission of \( L \) bits and \( T_e \) is the time needed for a node to change from the “sleep” mode to the “awake” mode. The importance of the power dissipated on the circuitry on the total performance of the MIMO architecture is obvious from Fig. 2, which depicts the total energy consumption for MIMO 2x2 and SISO architectures versus the distance of the long-haul transmission, based on the parameters shown in Table 1 and explained in detail in [7]. Distance in local transmissions is assumed to be fixed and equal to 1m, while the constellation sizes used derive from the rate-optimization algorithms presented in [3]. According to that figure, a 2x2 MIMO structure is more energy efficient than a SISO-based WSN when the distance between the receiver and the transmitter side is greater than 20m. We may observe though that the term that actually increases the energy consumption in the MIMO approach is \( E_{\text{circ}} \), which includes the energy consumed by all electronics that do not have to do with transmission power, such as filters, mixers etc. If we consider the rapid deployment in micro-electronics during the last years, it is highly expected that more energy efficient circuitry will be available soon. Therefore, MIMO structure is expected to become more energy efficient. This is not the case with the SISO approach though, where \( E_{\text{trans}} \) inserts the greater parts of energy consumption. Less energy consumed in the circuitry results in lower distance thresholds and thus makes the MIMO structure more energy efficient for almost any case.

In order to examine the effect of \( E_{\text{circ}} \) on the distance thresholds above which the MIMO structure is more energy efficient than SISO, we use four different scenarios for the value of \( E_{\text{circ}} \) as shown in Table 2. Scenario 3 is more optimistic than the one evaluated using the parameters of Table 1, while Scenario 4 is based on the parameters used by the authors of [3]. The results summarized in Fig. 3 show that if, for example, the value of \( E_{\text{circ}} \) drops to 0.1 mJ due to the development of more efficient micro-electronic devices, then a MIMO – based structure in WSNs would be more energy efficient than the traditional SISO structure for a distance greater than a couple of meters.

### IV. CN Selection

Implementing a MIMO approach in a WSN as described above, introduces several research topics that mainly have to do with cooperative techniques. One of the most important issues on cooperative networks that remain open until now is the node selection problem. In [11] a new MAC protocol based on cooperation is proposed. No specific relay algorithm is defined though. An interesting scheme is proposed in [12], including two different policies in order to choose the best relay node, based mainly on channel estimates. This algorithm seems to be applicable also for WSNs, as it requires only local channel measurements, and it is based on a distributed protocol without demanding any kind of topology knowledge. Finally, an algorithm that considers also the remaining energy of the neighbour nodes before choosing the cooperation node may be found in [13]. Here, we focus on implementing a simple Cooperative Node Selection algorithm, based on estimations of the channel conditions in the links between neighbouring nodes. This algorithm applies to MIMO structures described in previous sections. We introduce a novel metric \( TEL \) (Total Energy – Lifetime), that is defined in following paragraph.

![Fig. 2: Energy Consumption for SISO and MIMO architectures Vs distance](image)

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### Table 1: Power Dissipation Parameters

<table>
<thead>
<tr>
<th>Bits per Packet (L)</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (f)</td>
<td>2500 MHz</td>
</tr>
<tr>
<td>( P_{\text{filters}} )</td>
<td>7 mW</td>
</tr>
<tr>
<td>( P_{\text{syn}} )</td>
<td>25 mW</td>
</tr>
<tr>
<td>( P_{\text{ADC}} )</td>
<td>7 mW</td>
</tr>
<tr>
<td>( P_{\text{mix}} )</td>
<td>4.7 mW</td>
</tr>
<tr>
<td>( P_{\text{LNA}} )</td>
<td>7.2 mW</td>
</tr>
<tr>
<td>( P_{\text{IFA}} )</td>
<td>3 mW</td>
</tr>
<tr>
<td>( T_{\text{r}} )</td>
<td>5 ( \mu )s</td>
</tr>
<tr>
<td>( P_{\text{detector}} )</td>
<td>5 mW</td>
</tr>
<tr>
<td>( n )</td>
<td>2</td>
</tr>
<tr>
<td>( P_{\text{dig}} )</td>
<td>1 mW</td>
</tr>
</tbody>
</table>
Let us assume that the channel both in local and long-haul transmissions suffers from log-normal shadowing, and that each node has to choose from $N$ neighbor nodes to cooperate. That is, the received power at each node $j$ $(j = 1, 2, \ldots N)$ after a source node transmits a packet of data may be estimated by (4).

$$P_r^j = P_t - PL(d_j) + G_t + G_r$$

where $G_t$, $G_r$ are the gains of the transmitter and the receiver antenna, respectively. We assume here that the gains are equal to 0 dBi. Shadowing is expressed by the normally distributed variable $\chi$, with zero mean and variance equal to 5 dB. If we assume that at the beginning of the network’s operation each node sends a pilot symbol and waits for acknowledgments to specify its neighbours, then the knowledge of the transmission power level combined with the knowledge of the acknowledgement’s power level allows the node to be aware of the path loss given by equation (4). As the path losses between the used links are one of the main factors that affect total energy consumption in the network, $TEL$ is a function of $PL(d_j): TEL_j = f(PL(d_j))$.

Apart from the total energy consumed in the network, another important metric to measure energy efficiency is lifetime. A spatially uniform energy consumption network assures increased lifetime. Therefore, $TEL$ also includes information about the energy left at each node $j$, denoted with $E_{left}^j: TEL_j = f(E_{left}^j)$. The Cooperation Node (CN) selection is made according to (5):

$$TEL_j = \frac{PL(d_j)}{E_{left}^j}$$

$$CN = \arg\min\{TEL_j\}$$

For the scenario described by Table 1, the gains of the implementation of CN selection algorithm are depicted in Fig. 4. The 2x2 MIMO curves derive from an averaging of 1000 random choices of the cooperation node, and we present the total energy consumption with and without the proposed algorithm as well as the case when the worst cooperation node is selected. As we can deduce from the figure, gains are obvious only for distances greater than 40 meters. Moreover, in the case of worst node selection, the energy cost is very important.

Let us now examine the effect of the proposed CN selection algorithm with another scenario regarding the value of $E_{circ}$, e.g. scenario 3. This case is depicted in Fig. 5, and it refers to a 2x2 MIMO system. It is obvious that now the importance of a CN selection algorithm becomes greater. The gains inserted are clear for any value of the distance. Meanwhile, there is a drop of the distance threshold from 15 to about 8 meters, with energy gains of 20%.

In the following, we investigate the impact of the channel conditions and the network’s node density on the performance of CN selection. First, we implement the specific scheme in networks that operate on areas with increased path loss factors, e.g. for values of $n = 2.5$ and $n = 3$. As we observe from Fig. 6, the gains inserted due to CN selection become remarkably greater as the channel conditions get worse. For the case of $n = 2.5$, energy gains are close to 100% for a distance equal to 25 meters. The SISO case is not depicted in the figure, as the MIMO 2x2 system for these values of $n$ outperforms the traditional SISO structure for almost every value of the distance.
In Fig. 7 on the other hand, we are able to investigate cases with different values of nodes’ density. We assume that the density of the network is expressed by the variable $d_m$, which denotes the average distance between nodes in the local transmissions. In the figure we examine the cases for larger values of $d_m$ (that is lower network density), since for values of $d_m$ less than 1m the effect on the total energy consumption is negligible. As $d_m$ increases, the total energy consumption increases due to the demand for more transmission power to establish connection. The implementation of the CN selection algorithm though is not affected, offering remarkable gains in terms of energy efficiency.

Finally, Fig. 8 depicts the effect of the proposed scheme on the network’s lifetime. Here, lifetime is defined as the number of packets delivered until the first node runs out of energy. We examine three different cases regarding the number of possible neighbours from which the source node has to choose the CN. We may observe that even when the choice is made out of two nodes, gains are inserted in terms of lifetime. As the number of neighbour nodes increases, the gains become greater. The decreased lifetime observed when fewer nodes are used in the transmitter’s side is due to the fact that fewer nodes are used to transmit the same amount of data and hence they remain out of energy faster.

V. CONCLUSIONS – FUTURE WORK

This paper focuses on the MIMO – based architecture applied on WSNs, where sensor nodes cooperate and form virtual multiple transmitting and receiving antennas in order to achieve greater performance than traditional SISO approaches in terms of energy efficiency. Making a detailed analysis on the power dissipation of a sensor node, we deduced that the effect of the power consumed in the electronics that do not have to do with transmission power is great and seriously affects the performance of the MIMO – based scheme. The fact though that micro-electronics technology is evolving rapidly during the last years ensures us
that within the short future the MIMO structure will significantly outperform traditional SISO schemes. Moreover, we implemented a simple Cooperative node selection algorithm so that the neighbour node chosen to form the multiple-input antenna requires the least possible energy consumption. The proposed scheme requires few hardware or software implementations, and it provides additional energy gains. The worse the channel the network operates with, the more significant the gains inserted by the CN selection algorithm.

Regarding current and future work, we intend to implement more sophisticated CN selection algorithms in order to improve not only energy consumption within one node but also increase the network’s lifetime however that may be defined. Additionally, the cooperation of the MIMO approach with already proposed routing protocols, especially built for WSNs is of major concern.

APPENDIX

The energy consumed by the analog parts of the transceiver is given by:

\[
E_{\text{ana}} = ((a + 1) P_t + P_{\text{ana}} T_{\text{on}} + 2 P_{\text{syn}} T_{\text{on}}) / L
\]

\[
E_{\text{dig}} = P_{\text{dig}} T_{\text{on}}
\]

where \( P_t \) is the transmission power which depends on the required BER, the modulation scheme, the channel, the communication distance, the frequency of the carrier and the antenna gains; \( a \), expresses the energy consumption in the power amplifier (PA) and depends on the modulation scheme (e.g. \( a = 0.33 \) for MFSK). The term \( P_{\text{ana}} \) is a factor that includes the power consumption of all the circuitry including mixers, LNA, IF amplifier (IFA), ADC and filters, and \( P_{\text{syn}} \) is the power needed by each frequency synthesizer:

\[
P_{\text{ana}} = 2 P_{\text{syn}} + P_{\text{mix}} + P_{\text{LNA}} + P_{\text{filters}} + P_{\text{IFA}} + P_{\text{ADC}}
\]

The transmission power is calculated by the link budget equation ([8]):

\[
P_t = \frac{P L(dB) + E_{\text{b}} / N_0(dB) + R_0(dB Hz) - 204(dBW / Hz) + S(dB)}{10}
\]

where \( P L \) is the average Path Loss with a path loss factor equal to \( n \), \( S \) is the Safety Margin (typical value: \( S = 10 \) dB), -204 dBW/Hz is the value of \( N_0 \) for the typical value of temperature \( T = 27 \) °C and \( d_0 \) is the reference distance. \( E_{\text{b}} / N_0 \) depends on the channel, on the modulation used and on the target BER and may be evaluated by equations found in [9].

On the other hand, we assume that the power dissipated by the digital parts of a transceiver, \( P_{\text{dig}} \) is divided in two categories. The power dissipated by parts needed for the detection of the data (e.g. FSK detector) and the power by the circuitry before the Local Oscillator (LO) as expressed in (9):

\[
P_{\text{dig}} = P_{\text{detector}} + P_{\text{c-dig}}
\]

An example of a non-coherent binary FSK detector is described in more details in [10]. The power dissipation of such a detector mainly depends on the constellation size \( M \).

The power needed for the rest digital circuitry is assumed to be the same for every value of the constellation size \( M \) and equal to \( P_{\text{c-dig}} \).

REFERENCES