Energy Efficiency Evaluation of Alternative MIMO – based Sensor Networks

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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. Based on that idea several alternatives have been examined, mainly focusing on 2x2 MIMO systems. In this paper, we summarize two MIMO schemes and compare their performance in terms of energy efficiency. Moreover, we investigate more complex MIMO systems, emphasizing on 4x4 structures, and prove that depending on the scenario, such systems may offer remarkable energy gains.

Index Terms – Energy efficiency, Multiple-Input-Multiple-Output systems, 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. 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 ([1]).

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 is assigned the role of a transmitting or receiving antenna of the MIMO structure. This structure may offer enhanced energy gains for a WSN, depending on the distance between the Tx and the Rx side of the system. It has been proved ([3]) that specific distance thresholds can be estimated, above which the MIMO approach is more energy efficient than the simple SISO approach.

In ([2]) it was demonstrated 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.

A very interesting extension of the work on MIMO - based WSNs is an architecture called MIMO-Sensor Networks with Mobile Agents (M-SEMNA) ([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. A thorough comparison of the energy consumed by MIMO and SISO based WSNs is made in [7]. Finally, in [8] a combined multihop–MIMO approach is presented, and was proven to offer enhanced energy gains.

In this paper we summarize the structure and the energy consumption of two MIMO schemes applied in a WSN, the simple MIMO scheme and the combined MIMO – multihop approach. We compare their performance in terms of energy efficiency, and implement them using both 2x2 and 4x4 MIMO systems. The effect of the increment in the number of nodes forming the virtual arrays is investigated. Furthermore, we analyze the energy efficiency of all examined schemes for different operating scenarios, regarding mainly the channel state and the network density.

The remainder of this paper is organized as follows. In Section II a brief description of the models used regarding the simple MIMO and the combined MIMO – multihop schemes used. A presentation of the examined 2x2 and 4x4 alternative scenarios is given in Section III. Section IV analytically presents the performance of the investigated schemes, mainly in terms of energy efficiency, for different applications. Finally, Section V summarizes and proposes open topics for future work.
II. THE MIMO STRUCTURES

A. Simple MIMO Structure

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 quantizing it into \( n_r \) bits per transmitted symbol. The MIMO approach is explained in more details in ([3]) and is summarized in Fig. 1.

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

where \( E_{b,i}^r \) and \( E_{b,j}^r \) are the energy consumptions for transmitting and receiving one bit of data in the transmitter side, and for the long-haul transmission respectively, and \( L_{MIMO} = \frac{L}{M_t} \). The estimation of \( E_b \) for all cases is based on the analysis provided in [12] and [7], using basic knowledge from [10], [11].

In general, \( E_b \) is a function of the path loss factor, \( n \), and the average desired range of the nodes \( d \). In the case of local transmissions, the range depends on the distance between two neighboring nodes, \( d_k \). On the other hand, when we refer to long – haul transmissions, \( d \) is actually the average distance between source and destination node, denoted with \( D \). That is, \( E_b^r = E_b^r(d_k,n) \) and \( E_b^i = E_b^i(D,n) \). We assume that the channel’s conditions are approximately the same in both the receiver and the transmitter’s side, so the value of the path loss factor \( n \) is the same for all cases. Finally, \( \frac{L_{MIMO} \times M_t}{b} \) expresses the total number of symbols transmitted from the transmitter’s side, assuming that \( b \) is the constellation size used by the Alamouti code. More details regarding the modeling of the distances may be found in [8], [13], [14].

B. Combined MIMO – multihop Structure

This communication model is a combination of MIMO – based and multihop transmission. Let us examine the scenario of \( M \) nodes being deployed in an area of range \( R \). The nodes form clusters just like the LEACH protocol. These clusters, operate as MIMO transmitters and receivers, hence we call them MIMO – clusters. The architecture is depicted in Fig. 2, where we assume that it takes \( H \) MIMO hops for the data to reach the destination node. That is, there are \((H-1)\) MIMO clusters formed in total.

\[
E_{MIMO_{multihop}} = E_{MIMO}(D_t) \times H
\]

(2)

\[
H = \frac{D}{D_t}
\]

(3)

The main parameter that affects the energy consumption described in the above set of equations is the parameter \( D_t \). Moreover, the path loss factor \( n \) as well as the network’s density expressed via the distance of neighboring nodes in local transmissions \( d_k \) highly affect this scheme’s performance. The distance \( D_t \) may be determined by higher layers’ protocols, and an optimization problem that estimates \( D_t \) by minimizing the total energy consumption has been solved in [8]. From now on it is assumed that the optimum value of \( D_t \) is used in all examined alternatives.

III. EXAMINED SCENARIO

We examine the cases where an event is sensed by more than two nodes, and has to be forwarded towards a destination node. The forwarding may be accomplished either by the simple MIMO structure, or based on the combined multihop – MIMO scheme already described. The main question to be answered is whether using a combination of 2x2 MIMO systems is the optimum way to deliver the data. The main concern in sensor networks is energy efficiency. Thus, we point out the impact of the size of the virtual array on the energy consumption of the network, and we examine the formation of MIMO schemes consisting of more than 2 nodes.
In particular, let us assume that four nodes sense an event and have data to send. Then, two different scenarios may be utilized. According to the first one, the four nodes form two groups of two nodes each, as shown in Fig. 3. Then the data is forwarded using a 2x2 MIMO based structure. The second scenario is depicted in Fig. 4, and includes the formation of a 4x4 system in order to deliver the data to the destination node. Both figures refer to the case of combined multihop – MIMO structure. In both cases, the virtual MIMO clusters are formed based only on distances between nodes. Hence, when a node has to transmit or receive data, it chooses the closest node (or the three closest nodes, respectively) to cooperate with. Alternatively, a cooperation node selection algorithm may be applied to control the way the clusters are formed. In this paper though, we restrict our scenarios using the simple case where cooperation nodes are chosen based on distances.

In the first case, the total energy consumption will be given by

\[ E_i = 2 \times E_i, \quad i = \text{MIMO, MIMO}_\text{multihop} \]  

where \( E_i \) is given by equations (1) and (2), with \( M_t = M_r = 2 \). Alternatively, when a 4x4 MIMO system is formed, the total energy consumption is estimated using equation (5), where \( M_t = M_r = 4 \):

\[ E_i = E_i, \quad i = \text{MIMO, MIMO}_\text{multihop} \]

We should mention that regarding the evaluation of \( E_i \) in our scenarios, the destination node is not part of the array formed at the receiver’s side. Hence, there is an additional link to be added in the calculations, regarding the gathering of the data in the destination node. The two proposed scenarios may be used in combination with both the simple MIMO and the multihop – MIMO structures.

Using a 4x4 MIMO system is expected to lead in reduced energy consumption regarding the long – haul transmission, due to additional diversity and coding gain, by a factor \( E_{\text{gains long}} \). This is observed from Fig. 5, where the performance in BER vs. SNR is depicted for a 2x2 and a 4x4 system. On the other hand, the implementation of a 4x4 structure demands more communication overhead between the nodes that form the virtual arrays, increasing the energy consumed in local transmissions by \( E_{\text{losses local}} \). Therefore, the gain inserted by the 4x4 MIMO system is expected to be less than the one shown in Fig. 5, as described by:

\[ E_{\text{gains}} = E_{\text{gains long}} - E_{\text{losses local}} \]

The additional energy consumed by a 4x4 system is mainly due to the fact that when 4 nodes have to communicate with each other, the distances are greater and thus \( E_i \) increase. From now on, we assume the worst case scenario regarding the distances between the 4 nodes forming the virtual array. That is having the four nodes forming a straight line, as shown in Fig. 4. Hence, two of the nodes have to adjust their transmission range \( d \) to \( 3d_k \), while the other two require \( d = 2d_k \). For all examined cases, we assume static environment and channel including large scale fading effects, with variance \( \sigma^2 \). Regarding the modulation scheme, BPSK is used in all transmissions.

Moreover, sensor nodes able for transmission power adjustment and channel state estimation are considered. Such considerations have been proven to be easily implemented in nodes in the literature.
are feasible. Negligible variances are expected though due to different network sizes.

When the combined multihop – MIMO structure is applied, the gains are less evident, as shown in Fig. 7. In particular, and according to the network’s density, the implementation of the 4x4 MIMO scheme could lead in increased energy consumption. The behavior though is similar, and gains are apparent for high network densities and worse channel states. Another interesting conclusion that can be extracted is the important decrease in energy consumption when the combined MIMO – multihop structure is used. That is apparent when comparing these results with the energy consumed as shown in Fig. 6.

**TABLE 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits to be transmitted (L)</td>
<td>10000</td>
</tr>
<tr>
<td>Frequency (f)</td>
<td>2500 MHz</td>
</tr>
<tr>
<td>(n)</td>
<td>10</td>
</tr>
<tr>
<td>(M_t)</td>
<td>2 / 4</td>
</tr>
<tr>
<td>(M_r)</td>
<td>2 / 4</td>
</tr>
<tr>
<td>Target BER (Bit Error Rate)</td>
<td>10^-4</td>
</tr>
<tr>
<td>(\sigma^2)</td>
<td>5 dB</td>
</tr>
<tr>
<td>Area Range (R)</td>
<td>50 meters</td>
</tr>
</tbody>
</table>

The energy gains inserted by the implementation of the 4x4 system are obvious in Fig. 8, for the case of simple MIMO structure and a network consisting of 100 nodes. The total gains are not as many as the diversity and coding gains inserted in the long-haul transmissions. The losses due to increased local communications lead to total energy losses, when the channel is good. On the other hand, as the channel gets worse, the energy savings become remarkable.

The following two figures summarize the performance analysis in terms of energy consumption versus the network’s density, expressed via the number of nodes \(M\). The consumed energy in the simple MIMO structure is depicted in Fig. 9, for three different channel states. The gains are significantly greater when \(n = 3\). Meanwhile, as the network density increases the energy consumption decreases for both schemes until the number of nodes is about 100. Adding more nodes to the network does not seem to affect the performance of the examined schemes.

Similar are the deductions from Fig. 10, where the case of the combined MIMO – multihop scheme is examined. Once again, the energy consumption now is smaller than in the simple MIMO case. Moreover, it is obvious from this figure that the gains inserted by the 4x4 MIMO system are restricted with comparison to the simple MIMO structure.
the 4x4 MIMO system is greater when the simple MIMO structure is used. Furthermore, the gains are negligible for path loss factor values less than 2.4.

Similar results may be concluded from Fig. 12, where the energy gains are depicted versus the path loss factor. When using a 2x2 MIMO system, energy gains appear for \( n > 2.4 \), while the threshold increases to 2.6 when a 4x4 system is investigated.

Fig. 10: Energy Consumption comparison Vs. M using MIMO - multihop structure

Fig. 11: Energy Gains Vs. M with respect to simple MIMO structure

Fig. 12: Energy Gains Vs. n with respect to simple MIMO structure

In this paper a detailed analysis of MIMO – based WSNs is presented. Two different transmission models are briefly discussed, one based on a simple MIMO structure and a combined MIMO – multihop scheme. In the following, these two alternatives are combined with two different cases regarding the size of the virtual antennas that form the MIMO systems. We examined the performance of these schemes, and reached the conclusion that using a 4x4 MIMO structure may yield reduced energy consumption of the sensor network. The results were proven to depend on the channel conditions and the network’s density. In particular, worse channel conditions resulted in the increase of energy gains inserted by the implementation of the 4x4 MIMO system. Moreover, the gains inserted by the usage of the MIMO – multihop scheme depend on the MIMO system applied. When using a 4x4 MIMO system, the gains due to the combined MIMO – multihop scheme are less than the ones inserted when a 2x2 MIMO system is preferred.

V. CONCLUSIONS

In this paper a detailed analysis of MIMO – based WSNs is presented. Two different transmission models are

REFERENCES


