Adaptive Communication and Cooperative MIMO Cluster Formation for Improved Lifetime in Wireless Sensor Networks

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***Abstract*—One of the main limitations that still keeps Wireless Sensor Networks (WSNs) from being adopted in a large scale is the limited energy supply, i.e. the lifetime of the nodes that constitute the network. The wireless communication between nodes is responsible for most of the energy consumed in WSNs. A promising method to improve the energy efficiency is the usage of a Cooperative Multiple Input Multiple Output (CO-MIMO) scheme, where nodes form clusters to transmit and receive signals using a virtual antenna array. This work presents a study on the energy consumption of multi-hop and single-hop transmission compared to CO-MIMO and how to select the most efficient method. It also proposes a method for adaptively choosing the number of nodes that form a CO-MIMO cluster in order to maximize the lifetime of the network and to avoid disconnections. The proposed method takes into account not only the total energy consumption but also the distribution of energy within the network, aiming to keep the energy distribution across the network as uniform as possible. The effects of the proposed methods in the total available energy of the network and in the distribution of the energy is presented by means of numerical simulations.**

***Index Terms*—Wireless Sensor Networks, Multiple Input Multiple Output, Synchronization, Routing, Energy Efficient Communications**

I. Introduction

Wireless Sensor Networks (WSNs) have recently been applied to tackle a large number of problems, ranging from health care to military applications [1]. While the usage of WSNs has become popular it still is hindered by the limited energy supply present in the nodes. Maximizing the energy efficiency of WSNs has been a topic of interest, with a large number of proposals being presented in the recent years [2].

Research dealing with energy efficiency in WSNs have been proposed through different layers, with energy efficiency being analyzed for all tasks involved in WSNs. Observing that communication is the most energy consuming task [3], efforts in diminishing the need for communication and its efficiency are promising directions to achieve WSNs with longer lifetime [4]. Focusing on enhancing communication efficiency, energy efficient protocols for medium access control have been proposed in [5] and for network layer in [6].

A promising approach to achieving higher energy efficiency is the usage of Multiple-Input Multiple-Output (MIMO) communications [7]. MIMO takes advantage of spacial diversity to provided multiple benefits such as a larger spectral efficiency and reduced bit error ratio (BER). Despite its benefits, MIMO requires more complex communication systems to be employed since it relies on multiple synchronized transmissions and receptions from different antennas in order to operate. However, most WSNs are based on very simple nodes, with limited hardware capabilities. Constructing sensor nodes with multiple antennas may be unfeasible due to size or complexity limitations. In order to avoid the hardware complexity increase, WSNs can employ MIMO cooperatively. In this case, the multiple antennas used for MIMO communication are not contained within a single node. In cooperative Multiple-Input Multiple-Output (CO-MIMO), multiple nodes form transmit and receive clusters, synchronizing and exchanging data so that the clusters can employ standard MIMO communication schemes.

II. Related Works

The formation of CO-MIMO clusters has been proposed in [8]. Also in [8], the energy consumption is studied, with Single-Input Multiple-Output (SIMO) and Multiple-Input Single-Output (MISO) alternatives also analyzed, coming to the conclusion that CO-MIMO can be more efficient than SIMO and Single-Input Single-Output (SISO). The same work also highlights benefits with respect to communication delay when CO-MIMO is employed. A similar conclusion with respect to energy efficiency is drawn in [9]. In [10] an energy

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analysis considering single-hop, multi-hop and CO-MIMO is shown, where CO-MIMO is shown to outperform single and multi-hop when the receiving and transmitting nodes are far apart. The work presented in [11] proposes a multi-hop CO-MIMO system, optimizing the number of MIMO hops based on network parameters with a fixed MIMO configuration. Furthermore, [12] describes methods for selecting the best MIMO configuration for CO-MIMO with respect to energy consumption.

However, none of these works consider the implementation of CO-MIMO alongside multi-hop communications in networks. In the work at hand, a method for selecting between multi-hop and CO-MIMO is proposed. The proposed method also decides on the best CO-MIMO configuration to be employed for a certain transmission. This automatic selection allows the network to be more energy efficient and to have a better distribution of its energy reserves by taking advantage of the multiple available transmission techniques and possible cluster sizes for CO-MIMO transmissions.

In [13] a routing algorithm for CO-MIMO networks was proposed, however, this algorithm separates the nodes into three distinct kinds, namely, head nodes, coordination antenna nodes and ordinary nodes. In the work at hand, no such assumptions are made and all nodes are treated equally and a full peer-to-peer concept is adopted. Another routing algorithm for WSNs was previously proposed in [14], however, this work only considers routing between multiple CO-MIMO clusters. Such approach differs from the algorithm proposed in this work where the problem of optimal dynamic cluster formation for MIMO communications is addressed. In [15] a detailed assessment of energy consumption for a specific scenario is shown, however, the problem of selecting the number of nodes involved in a transmission is not addressed.

In this work the method for cluster size selection is integrated with the routing algorithm used by the network. A step is performed during the construction of the graph used for routing which allows the routing algorithm to select the best cluster size based on metrics such as energy efficiency and energy distribution. Furthermore, the proposed method allows the graph to be dynamically updated making the network more robust to failures or changes in topology.

III. Cooperative MIMO

When employing CO-MIMO the transmitted data can come from a single node or various nodes of the transmitting cluster. Figure 1 presents the necessary steps in a CO-MIMO communication. The first step represented by ① consists of synchronization and exchanging data that needs to be transmit among the transmitting nodes.

The synchronization accuracy depends heavily on the symbol period used for data transmission. That is, faster symbol rates require more precise synchronization. For instance, networks operating at 256 ksps rate, the resulting symbol duration is approximately 4 μs. In this case, a synchronization error of 1 μs represents 25 % of symbol duration and will lead to a high BER. For networks relying on GPS synchronization, it has been shown that very precise synchronization is possible by keeping the variations as small as 200 ns [16]. However, not all WSNs are constituted by nodes that are equipped with GPS receivers. An alternative for such cases arebroadcast synchronization schemes, such schemes are capable of achieving 1 μs of accuracy have been proposed in [17].

In step ② both sensors transmit different symbols at the same time slot using a MIMO scheme. This work considers the use of a Vertical-Bell Laboratories Layered Space-Time (V-BLAST) transmission as described in [18] for MIMO communications in order to exploit spatial diversity. In a normal transmission a single symbol would be transmitted over the channel at each time slot. In case of V-BLAST, the symbols are grouped into frames the size of the receiving antenna array.

Finally in step ③ the receive nodes exchange the received information in order to decode the received symbol. The binary output of the analog-to-digital converter at the receiver node is sent to the node or nodes responsible for equalizing and decoding the received signal.

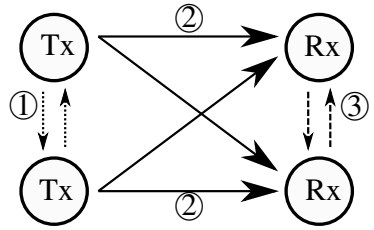

Fig. 1: CO-MIMO communication steps

IV. Adaptive Communication Method Selection and CO-MIMO Cluster Formation

In WSNs where nodes have limited energy supply it is possible that nodes fail unevenly. Figure 2 presents an example of a WSN with areas highlighted based on their expected communication energy consumption considering only multi-hop or single-hop communication. In this example, the center area, shown with a checkered background, is expected to expend more energy than the rest of the network due to communication. The nodes that are located in the center are responsible for forwarding a large number of packets from nodes that are located closer to the edges of the network. Therefore, the nodes located in this area reach the end of their energy reserves faster than the rest of the network. On the other hand, nodes that are located on the stripped area have longer lifetimes as these nodes are rarely responsible for routing information for other nodes.

With CO-MIMO, it is possible to improve the energy distribution in the network by transmitting over larger distances. This reduces the energetic demand over nodes that are located near the center of the network. The benefits of CO-MIMO over multi-hop and single-hop are relative to the distance between the transmitting node and the final destination node. Using CO-MIMO to transmit to nodes located close to the transmitting node is inefficient, as the energy necessary to

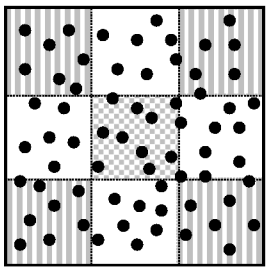

Fig. 2: Example of WSN areas with different energetic demands

spread the information and synchronize the nodes at the receive and transmit clusters would outweigh any gain achieved on the MIMO step. Therefore, the network must be capable of autonomously selecting whether or not to use CO-MIMO and select what is most appropriate size for the cluster and what nodes should be used to form such cluster.

Based on the steps illustrated in Figure 1 it is possible to derive an analytical expression for the energy consumption of CO-MIMO. Defining E_{intra} as the energy necessary to transmit an entire data packet to another sensor located within the CO-MIMO cluster frontier, represented as ① and ③ in Figure 1, the energy spent on spreading the packet for transmission and for consolidating it for equalization and decoding is given by

$$E_{\text{tx}_{\text{intra}_{\text{tx}}}} = \frac{M_t - 1}{M_t} E_{\text{intra}} \in \mathbb{R}, \quad (1)$$

$$E_{\text{tx}_{\text{intra}_{\text{rx}}}} = \frac{M_r - 1}{M_r} E_{\text{intra}} \in \mathbb{R}, \quad (2)$$

respectively. For a $M_t \times M_r$ CO-MIMO transmission, a central node that spreads its packet to neighbor nodes needs to perform $M_t - 1$ transmissions with a cost of $\frac{E_{\text{intra}}}{M_t}$, as the packet is split into M_t smaller packets for the CO-MIMO transmission. The same applies for consolidating the packet on the receiving CO-MIMO cluster, where $M_r - 1$ transmissions with a cost of $\frac{E_{\text{intra}}}{M_r}$ are made to a central node for equalization and decoding.

The packet's dissemination and consolidation on the CO-MIMO clusters also consumes significant energy on the radios listening to the transmissions. Therefore, $M_t - 1$ receptions with a cost of $\frac{E_{\text{rx}}}{M_t}$, where E_{rx} is the energy cost for receiving an entire data packet, are necessary at the transmitting cluster. At the receiving cluster, $M_r - 1$ receptions with a cost of $\frac{E_{\text{rx}}}{M_r}$ are necessary when the received symbols are transmitted to the central node for decoding. Thus, the energy spent with receptions at the transmit and receiver clusters is given by

$$E_{\text{rx}_{\text{intra}_{\text{tx}}}} = \frac{(M_t - 1)}{M_t} E_{\text{rx}} \in \mathbb{R}, \quad (3)$$

$$E_{\text{rx}_{\text{intra}_{\text{rx}}}} = \frac{(M_r - 1)}{M_r} E_{\text{rx}} \in \mathbb{R}, \quad (4)$$

respectively. Additionally, as the packet is transmitting over long distances using CO-MIMO, the M_r receiving nodes must listen. Therefore, another M_r receptions with $\frac{E_{\text{rx}}}{M_r}$ cost are necessary.

Finally, $E_{\text{tx}_{\text{inter}}}$ is the energy spent to transmit a data packet using a higher power for the long distance transmission step ②. M_t nodes transmit $\frac{1}{M_t}$ of the data packet.

Hence, the total cost for transmitting a packet using CO-MIMO is given by

$$\begin{aligned} E_{\text{C-MIMO}} &= E_{\text{tx}_{\text{inter}}} + E_{\text{tx}_{\text{intra}_{\text{tx}}}} + E_{\text{tx}_{\text{intra}_{\text{rx}}}} \\ &\quad + E_{\text{rx}_{\text{intra}_{\text{tx}}}} + E_{\text{rx}_{\text{intra}_{\text{rx}}}} + E_{\text{rx}} \in \mathbb{R}. \end{aligned} \quad (5)$$

CO-MIMO is capable of reaching large distances without demanding too much power of a single node, since the cost shown in (5) is spread among the various nodes in the receive and transmit clusters. In addition, due to multiple copies of the same signal being received, the BER is considerably smaller at the same signal to noise ratio (SNR), this makes the CO-MIMO capable of reaching large distances using much less power than SISO configurations. CO-MIMO configurations can lead to even lower BER ratios, and this allows even less power to be used at long range transmissions.

Next assuming a multi-hop communication where the nodes involved are uniformly spaced and the energy necessary to transmit a data packet to the next node is equivalent to the energy necessary to transmit inside a CO-MIMO cluster, E_{intra}, the energy used for a multi-hop transmission is given by

$$E_{\text{mhop}} = k\left(E_{\text{intra}} + E_{\text{rx}}\right) \in \mathbb{R}, \quad (6)$$

where k is the number of hops necessary to reach the destination node. From (5) and (6), it can be shown that CO-MIMO is more efficient than multi-hop, i.e. $E_{\text{C-MIMO}} < E_{\text{mhop}}$, iff

$$\begin{aligned} E_{\text{tx}_{\text{inter}}} &< \left(k - \left(\frac{M_t - 1}{M_t} + \frac{M_r - 1}{M_r}\right)\right) E_{\text{intra}} \\ &\quad + \left(k - \left(\frac{M_t - 1}{M_t} + \frac{M_r - 1}{M_r} + 1\right)\right) E_{\text{rx}}. \end{aligned} \quad (7)$$

From (7) it is clear that CO-MIMO is more efficient than multi-hop only when the nodes are separated by a large number of hops. With these expressions it is possible for the nodes to choose the communication method that is more energy efficient, using CO-MIMO only for larger distances.

Choosing between CO-MIMO, multi-hop, and single-hop is not enough. Since CO-MIMO can be used with different cluster sizes, it is important to choose the best possible cluster size for reaching a given node in the network, representing it on the routing graph as a vertex with the lowest possible cost. However, minimizing energy consumption is, by itself, not enough to maximize the lifetime of a WSN. If energy consumption is low but the energy distribution is uneven, some nodes will fail before others. This distribution can be area dependent, for instance, regions with a high traffic of information will tend to be depleted ahead of the rest of the network. Node failures in such area might lead to a disconnected network, reducing the effective lifetime of the network. Generally, it is desirable that the nodes in a WSN have their energy reserves evenly depleted, so that the network can stay fully connected as long as it is operational. Therefore,

by being aware of the energy reserves of its neighbors, a node can, when using CO-MIMO, choose the configuration and neighbors that minimize the difference between the energy reserves of its neighbors.

This work proposes calculating the cost of a transmission as a function of transmission power, cluster size and effects on the energy reserves of neighbors. The metric shown in (8) is used to define the cost of a transmission between a pair of nodes indexed by $n = 1, \ldots, L$ and $m = 1, \ldots, L$. In this expression L is the number of nodes that compose the network, $w = 1, \ldots, W$ indexes the possible sizes for the CO-MIMO clusters up to the limit W, $E_{\mathrm{C-MIMO}}(w)$ is the energy cost for a CO-MIMO transmission using clusters composed of w elements, $\sigma_0(n, m, w)$ and $\sigma_1(n, m, w)$ are the standard deviations of the energy available in the node's neighbors before and after the possible CO-MIMO transmission. $\mathcal{N}_{n,w}$ is the set of nodes that can be reached by node n with a CO-MIMO cluster size w. For a fixed cluster size, the nodes n and m always choose the neighbors with the highest amount of energy in order to maximize the network lifetime. However, it is possible that some formations, even if the total energy cost is lower, cause the variance of the energy available on the neighbors to increase too much. This means that the distribution of the available energy between the nodes is less uniform leading to some nodes running out of energy before others, and resulting in a disconnected network. Finally, α is a weighting factor that dictates the importance of keeping a uniform energy reserve versus the importance of minimizing overall communication energy consumption. If the transmit node n has knowledge about the state of the energy reserves of the receive cluster it may also take into account its changes on the calculation of the cost.

Each node n stores the cost relative to reaching a given neighbor in a cost matrix

$$[\mathbf{R}_n]_{m,w} = J(n, m, w) \in \mathbb{R}. \tag{9}$$

A graph used for routing can be set up by grouping all of the cost matrices from the nodes that form the network into a tensor structure

$$\mathcal{R} = [\mathbf{R}_1 | \mathbf{R}_2 | \ldots | \mathbf{R}_L] \in \mathbb{R}^{L \times L \times W}, \tag{10}$$

where $|$ denotes a stacking operation onto the first dimension. However, constructing a graph based on this structure will result in vertices that are connected by multiple edges, since nodes can communicate using different CO-MIMO cluster sizes. To avoid this problem, some edges must be filtered from the graph. This decision is simple, and can be based solely on the cost of the edges, leaving only the edges with the smallest cost between two vertices. Therefore, the decision on what cluster size $s_{n,m}$ to use to communicate between a pair of nodes is given by

$$s_{n,m} = \underset{w}{\operatorname{argmin}} [\mathcal{R}]_{n,m,w} \in \mathbb{N}^+. \tag{11}$$

V. Numerical Simulations

For the numerical simulations, this work assumes that the sensors follow the communication characteristics of the Harvard Mica2 platform [19]. An area of 100 m $\times$ 100 m is filled with 300 nodes randomly placed with coordinates following independent uniform distribution. The noise power density at the radios during reception is considered to be -174 dBm/Hz and the radios are assumed to have a 5 dB noise figure. The communication is assumed to take place using a 2.4 GHz center frequency and a 20 MHz channel, filtered using a 22 MHz filter. Transmissions are assumed to follow the free-space path loss model and the antennas are assumed to have no gain (isotropic antennas). Note that from Figures 3 to 6 the graphs for the cases where no CO-MIMO is used are shorter due to the fact that the network becomes too disconnected for the simulation to proceed after a certain point. For the simulations it is assumed that the nodes have knowledge of the energy level of their neighbors and the results presented are the average of 1000 Monte Carlos runs.

Figures 3 and 4 highlight the effects of the proposed CO-MIMO cluster formation on the available energy reserve of nodes located at the center and near the edges of the network. The results shown in Figures 3 are expected, since the nodes that are located in the center have to perform less re-transmissions of data from other nodes on the network. Since CO-MIMO can reach longer distances the nodes that generate the data can communicate with more distant nodes without requiring a large number of intermediary hops. On the other hand, while the results in Figure 4 show a decrease in the mean available energy for nodes located near the edges of the network. This, however, is desirable. The decrease in available energy indicates that the nodes located on the edges that, without CO-MIMO, would generate packets and hand them over for other nodes to transmit across the network are now able to transmit over larger distances and spend their own energy reserves. This alleviates the energetic strain on sensors located at the center of the network. The results also show that, if a fixed CO-MIMO cluster size is used the center nodes have their energy reserves depleted faster since fixing the cluster size prevents minimizing the energy consumption with respect to the distance between nodes.

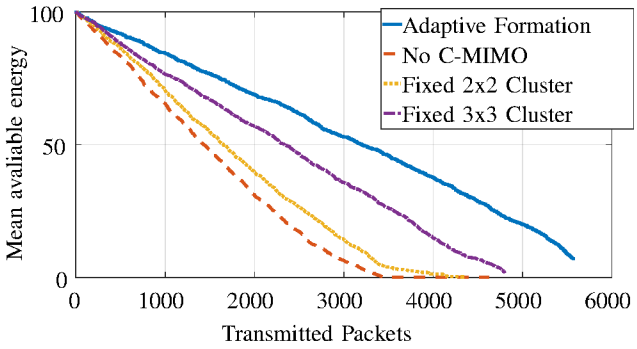

Fig. 3: Mean available energy at the center region of the network

$$J(n,m,w) = \begin{cases} \alpha(\sigma_0(n,w) - \sigma_1(n,w)) + E_{\text{C-MIMO}}(w), & \text{if } n \neq m \text{ and } w \neq 1 \text{ and } m \in \mathcal{N}_{n,w} \\ E_{\text{intra}} + E_{\text{rx}}, & \text{if } n \neq m \text{ and } w = 1 \text{ and } m \in \mathcal{N}_{n,1} \\ 0, & \text{if } n = m \\ \infty, & \text{if } n \neq m \text{ and } m \notin \mathcal{N}_{n,w} \end{cases} \tag{8}$$

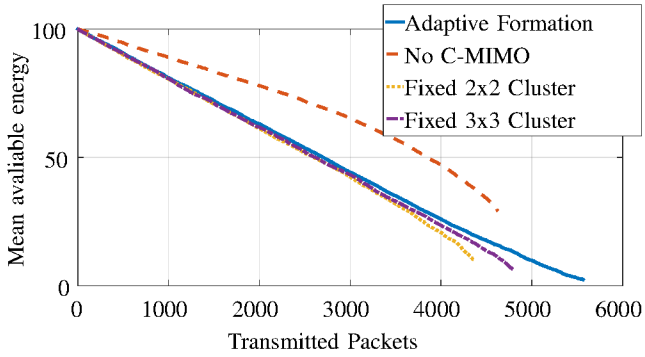

Fig. 4: Mean available energy at the edges of the network

Figures 5 and 6 present the effects of the proposed CO-MIMO cluster formation on the distribution of energy on the network. Figure 5 shows that when no CO-MIMO is used the energy on the center is poorly distributed, illustrated by the large standard deviation σ between the energy reserves of the nodes. Although the distribution seems to improve after a certain instant, this is only true due to the fact that the nodes on the center are running out of energy, resulting in a smaller σ as the number of nodes with very small energy reserves grows. Figure 6 shows that also for the edges of the network the energy distribution is more uniform when the proposed algorithm is used.

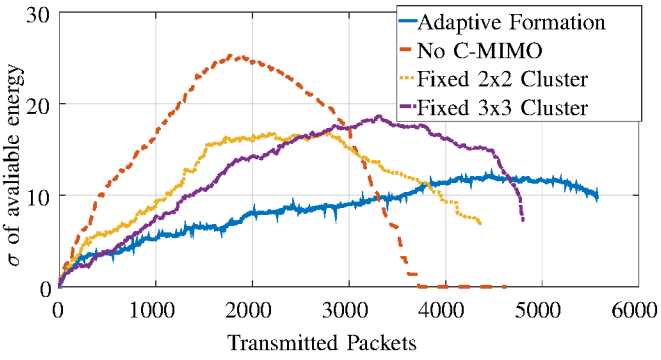

Fig. 5: Standard deviation of available energy at the center region of the network

VI. Conclusion

In this work a method to adaptively select the communication mechanism and the CO-MIMO cluster sizes for WSNs is proposed. The proposed method takes into account not only the energy spent but also the impact that the communication will have on the distribution of energy among neighbor nodes. The proposed method results in networks that have a longer lifetime. Less power is spent while correctly choosing between

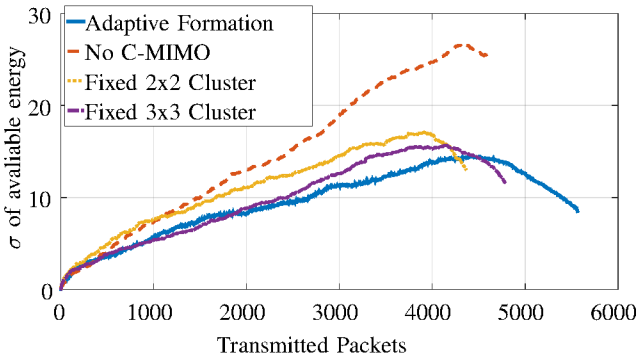

Fig. 6: Standard deviation of available energy at the edges of the network

CO-MIMO and standard communication techniques. The improved distribution of energy results in a network with a longer lifetime since nodes have more uniform lifetimes, resulting in a network that remains fully connected for longer.

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