Applying Cooperative MIMO Technique in an Adaptive Routing Mechanism for Wireless Sensor Networks

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***Abstract*—Energy consumption in Wireless Sensor Networks (WSNs) is a limiting factor that hinders the application of such networks into solving a broader set of problems. Various ways of saving energy have been proposed, from energy efficient processing to power aware cluster organization. With communication between nodes being responsible for a large part of the energetic demand, energy efficient methods of communication have been proposed, with multi-hop communication being a wide used technique, capable of minimizing energy consumption and spreading it amongst the network. However, multi-hop is not always more efficient and is prone to a high delay, due to the decode and forward mechanism usually employed. In this paper a cooperative MIMO technique is studied, its energy consumption analyzed, and a mechanism for integrating it in existing WSNs and allowing its coexistence with multi-hop communication is suggested. Energy efficiency, packet delivery delay and packet loss ratios are analyzed and the results compared to standard WSNs.**

***Index Terms*—multiple-in multiple-out systems, wireless sensor networks**

I. Introduction

Wireless sensor networks are being employed in a large number of emerging applications, from small scale networks, such as personal area networks (PANs), to cooperative cellular systems [1]. However the usage of WSNs is still limited by the strict energy constraints to with these networks are subjected to, and by the fact that, once the sensor nodes are deployed, replacing their energy source or replacing a single node can be prohibitively costly.

The problem of energy consumption has been approached trough different layers, with energy efficiency being analyzed for all tasks involved in WSNs. Energy efficient protocols for medium access control have been proposed on [2], while many proposals focus on enhancing energy efficiency in the network layer, by means of energy efficient routing protocols [3]. Other proposals consider energy aware processing approaches for communications among sensor nodes in WSN, as presented in [4], as well as alternatives solutions on the physical layer [5].

Special attention has been given to the study of energy efficient communication methods, with multi-hop communication being a widely used technique in order to obtain improved energy efficiency and maximize network life time by spreading energy consumption over different nodes [6]. Multi-hop takes advantage of the cooperative nature of WSNs in order to split the distance involved in communication by employing intermediary nodes to forward data packets. However care must be taken when applying multi-hop in order to avoid reduced energy efficiency, as presented in [6].

Techniques involving multiple sensors working together to form a virtual MIMO system have been studied. In this context, the work in [7] proposes a cooperative MIMO system used in the communication amongst the sensor nodes, however, the energy consumption involved in receiving data is not taken into account, also, no direct comparison between MIMO and multi-hop systems is presented. In [8] cooperative MIMO transmissions are studied, and SIMO and MISO cases are taken into account, however, only Alamouti coding is considered and it is assumed that intermediary hops are error free. In [9] a energy analysis considering single-hop, multi-hop and cooperative MIMO is presented. Results obtained in this work showed that cooperative MIMO is only advantageous when long distances are involved. Nevertheless, the advantages of cooperative MIMO are not restricted to energy efficiency, the faster data rates achievable with MIMO system allow the interaction between fast moving mobile as well as traditional static nodes [10][11], also, antenna array techniques such as beam forming or direction of arrival estimation can be employed.

In this paper, we analyze the behavior of an adaptive routing mechanism for WSNs employing cooperative MIMO. The routing algorithm is extended in order to consider MIMO hops when deciding on the shortest path and more energy efficient path. This algorithm is also responsible for choosing the optimal amount of nodes, in terms of energy consumption, present in cooperative MIMO cluster for communication. Temporary node outage is implemented in order to analyze the network behavior with the employment of cooperative MIMO. Energy consumption, packet delivery delay and packets dropped due to unreachable destination errors are used as metrics.

II. MIMO Communications

MIMO communications consist of the use of multiple antennas for data transmission and reception. This work focuses on MIMO techniques to achieve spatial multiplexing. Spatial multiplexing is used to transmit parallel bit streams simultaneously over the same frequency. MIMO also results in the array gain phenomenon, which is the increase of effective received power, due to multiple copies of the signal being received on different antennas.

Consider a sequence of symbols

$$\boldsymbol{s} = [s_1, s_2, ..., s_N], \tag{1}$$

that needs to be transmitted over a wireless channel. The channel is assumed to be flat fading, which means that channel impulse response is constant over the frequency domain, also equivalent to considering the transmitted signal to be narrowband. The impulse response between antennas is assumed to be uncorrelated and constant over a transmission period.

A technique called V-BLAST [12] which is employed for MIMO communications in this work, is of particular interest. In a normal transmission at each time slot a single symbol would be transmitted over the channel while, in the case of V-BLAST transmission, the symbols are grouped into multiple parallel streams. In the case shown in Figure 1, groups of size Q , and transmitted over the same time slot.

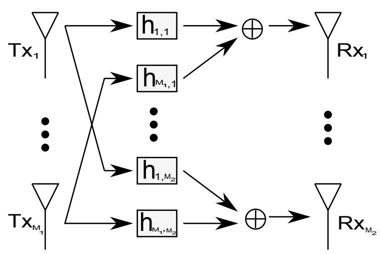

Figure 1: Example of a Q by Q MIMO system

The received signal at a given receiving antenna x_i at a given time slot can be modeled as

$$x_i = \sum_{k=1}^{Q} h_{k,i} \cdot s_k + n_i, \tag{2}$$

where $h_{k,i}$ represents the complex impulse response of channel between transmit antenna k and receive antenna i and s_k is the symbol transmitted by the k-th antenna. n_i is the noise present at the i-th receiving antenna during sampling. Equation 2 can be rewritten in matrix form as

$$\boldsymbol{x} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n}, \tag{3}$$

The first step necessary in order to estimate the transmitted symbols is to estimate the channel matrix $\boldsymbol{H}$. An estimate $\hat{\boldsymbol{H}}$ can be obtained by transmitting a set of pilot symbols vectors $\boldsymbol{P} = [\boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_U] \in \mathbb{C}^{Q\times U}$ where $\boldsymbol{p_i} \in \mathbb{C}^{Q\times 1}$ and $U > Q$

$$\hat{\boldsymbol{H}} = \boldsymbol{X}\boldsymbol{P}^{\dagger}, \tag{4}$$

here $\boldsymbol{P}^{\dagger} = \boldsymbol{P}^{\mathrm{H}}(\boldsymbol{P}\boldsymbol{P}^{\mathrm{H}})^{-1}$ is known as the right pseudo inverse of matrix $\boldsymbol{P}$ and the operator $^{\mathrm{H}}$ denotes the conjugate transposition. For a more detailed discussion on trade offs and optimal pilot symbol selection for MIMO channel estimation the reader may refer to [13], [14].

Once the channel matrix estimate $\hat{\boldsymbol{H}}$ has been obtained the receiver needs to equalize the received symbols in order to obtain an estimate of the transmitted symbols, various methods exist for performing this equalization, here the performance of the Zero Forcing, Minimum Mean Square Error (MMSE) and Maximum Likelihood (ML) methods is analyzed. Figure 2 shows a comparison between standard SISO systems and a 2×2 MIMO configuration using these equalization methods. The ML equalization method is clearly the most efficient in terms of minimizing the bit error rate (BER) of the received bit stream, thus it is the method of choice for the remainder of this work.

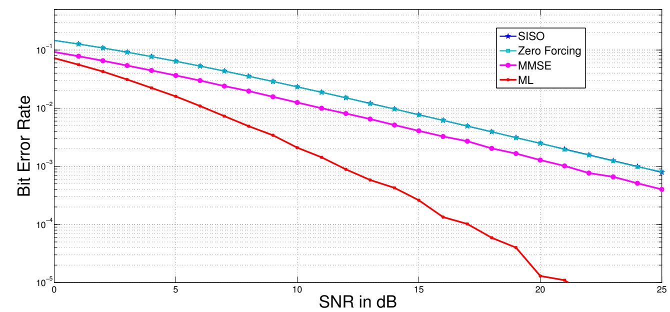

Figure 2: Performance comparison between standard SISO systems and 2×2 MIMO systems using Zero Forcing, MMSE and ML equalization

III. Conventional Communication Techniques

In standard WSNs communication is usually done using either single-hop transmissions or multi-hop transmissions. Single-hop transmissions consist of end to end communications without aid of intermediary nodes while multi-hop transmissions consist of using multiple intermediary nodes as routers in order to convey the necessary data to the destination node.

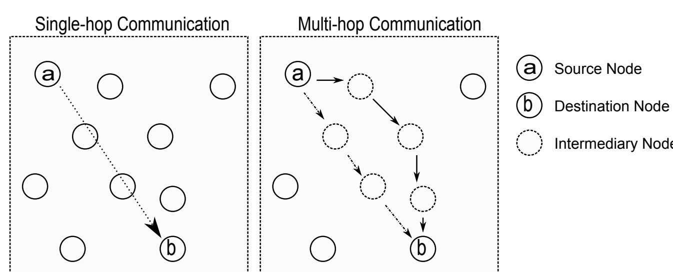

Figure 3: Examples of single-hop and multi-hop communication

Figure 3 shows an example of single and multi-hop configurations. Note that the multi-hop configuration presents multiple available paths for signal transmission, optimal path selection is problem related to the routing protocol, the reader may refer to [15], [16], [17].

The increased efficiency provided by multi-hop communication is due to the fact that the attenuation suffered by a wireless signal increases exponentially with the distance. However an analysis must be made in order to determine the point where multi-hop ceases to outperform single-hop. According to the energy consumption model proposed in [6]

$$E_t = \alpha, \tag{5}$$

$$E_r = \beta, \tag{6}$$

where E_t is the energy necessary for transmitting a single symbol over a certain distance and E_r is the energy necessary for receiving and decoding the given symbol. The parameter α is directly dependent on the distance between the transmitting and receiving nodes and can be written as

$$\alpha = \begin{cases} a + b \cdot d^{\gamma} & ; d_{max} \geq d > d_{min} \\ a + b \cdot d_{min}^{\gamma} & ; d \leqslant d_{min} \end{cases} \tag{7}$$

here d_{min} defines the maximum distance that can be reached by setting the transmit power of the transmitting node radio to its minimum configurable value, d_{max} is the maximum reachable distance by setting the transmit power to its highest configurable value, d is the distance between the transmitting and receiving nodes, γ is the path loss coefficient and a and b are fixed parameters that depend on the sensor radio hardware and can be empirically obtained. In order to evaluate the energy efficiency of both techniques we compare a transmission over d_{max} using both techniques. Let $d_{max} = k \cdot d_{min}$ and the path loss coefficient be equal to the free space loss coefficient $\gamma = 2$ and the power necessary for receiving a signal being equivalent to the power necessary for minimal transmission $\beta = a$.

The total energy consumed in a single-hop transmission can be described by using Equations 5 and 6 as

$$E_r + E_t(d_{max}) = 2a + b \cdot d_{max}^2 = 2a + b \cdot (k \cdot d_{min})^2, \tag{8}$$

equivalently, the energy consumed by the multi-hop transmission over k symmetric hops can be written as

$$k \cdot E_r + k \cdot E_t(d_{min}) = k \cdot a + k \cdot (a + b \cdot d_{min}^2) = 2 \cdot k \cdot a + b \cdot k \cdot d_{min}^2. \tag{9}$$

From Equations 8 and 9 we can derive the condition that makes single-hop more energy efficient than multi-hop

$$k \leq \frac{2a}{b \cdot d_{min}^2}. \tag{10}$$

According to [18][19], a condition necessary for minimizing energy consumption in multi-hop is that the hop distance is the same for all hops. For n intermediary nodes place between two nodes separated by a distance D we have the hop distance

$$d_{hop} = \frac{D}{n}, \tag{11}$$

replacing 11 at 9 and taking its derivative with respect to n, the number of hops that minimizes the energy consumption in multi-hop communications can be found

$$n_{opt} = \sqrt{\frac{b}{2a}} \cdot D. \tag{12}$$

By replacing 12 at 11 the optimum hop distance in terms of energy consumption can be written as

$$d_{char} = \sqrt{\frac{2a}{b}}, \tag{13}$$

where d_{char} is known as the characteristic distance. Note that d_{char} depends only upon the values of a and b, thus it is a parameter intrinsic to the sensor in question.

Care must be taken when employing the multi-hop approach to avoid reducing energy efficiency by using an unnecessary number of hops. When properly employed the multi-hop approach can lead to significant energy saving in WSNs. However, multi-hopping suffers from some serious disadvantages. Data forwarding is usually done on a best effort delivery way. That means that the transmitting node has no guarantee of the transmitted data reaching its destination, or that it will be delivered within a given time frame. Multi-hop networking can lead to data congestion on nodes that are located between node clusters that generate heavy traffic, this heavy traffic will also result in a high drain of energy resources the in the nodes responsible for forwarding the data. This will result in a high delivery delay and will eventually lead to depletion of energy in these midway nodes, resulting in a disconnected network. Data relaying is usually done in a decode and forward fashion, this can result in a high delay even when there is no network congestion present.

Single-hop transmissions are not affected by network congestion as they are end to end communications, but they require a very high signal power when employed over large distances. If a single sensor is responsible for producing a large amount of data that needs to be transmitted over a large distance, this will lead a very fast depletion of its energy resources. This uneven depletion is highly prejudicial to WSN operation, since replacing individual nodes might be as costly as replacing the entire network. Furthermore single-hop transmissions might be unattainable over large distances due to the limited power at which sensor radios usually operate.

IV. Cooperative MIMO

Wireless sensor networks are cooperative by nature, taking advantage of this behavior a cooperative MIMO approach can be implemented in order to minimize the energy spent with communication between nodes. As opposed to traditional MIMO systems, where a set of antenna is present at the transmitter and at the receiver, the cooperative MIMO utilizes a virtual MIMO approach, where the multiple antennas involved are present at different systems (different nodes). This avoids the increased hardware complexity involved, which is specially important in WSNs due to their limitations in term of size and hardware complexity. The additional complexity is transferred to the communication protocol. Figure 4 presents the steps involved in a cooperative MIMO communication.

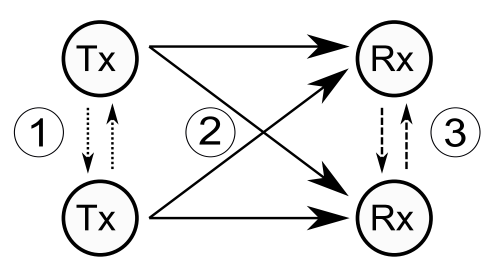

Figure 4: Steps involved in a cooperative MIMO transmission

The first step represented by ① consists of synchronization and exchanging data that needs to be transmitted, if both sensors need to transmit data this exchange is not necessary, as each sensor can transmit its own data. Note that since WSNs usually operate at low data rates the synchronization does not need to be extremely precise as the symbol duration is usually long enough so that small or even moderate offset in transmission instants does not result in errors. The same can be said for the synchronization in the reception. Small offsets in the sampling instant in the reception will not interfere with the overall system performance. On ② both sensors transmit different symbols at the same time slot. Finally on ③ the receiving sensors sample and quantify the received symbols and exchange the quantified data so that the originally transmitted symbols can be extracted. If the data is destined to only one sensor of the receiving cluster this exchange becomes uni directional. Another option is to exchange only a portion of the received information so that every sensor is responsible for part of the decoding, alleviating the computational burden of a single node.

V. Selection between cooperative MIMO and standard communications

On [9] it was demonstrated that due to the number of transmissions necessary to synchronized and spread data between the members of the cooperative MIMO clusters this communication scheme is only efficient when employed over large distances. A method for choosing between the available transmission methods must be implemented for the cooperative MIMO to be efficiently employed in WSNs. The layer responsible for choosing the optimal path to a certain destination in terms of any given metric is the network layer, more specifically the routing algorithms.

As WSNs can be deployed on harsh environments, the network must be capable of dealing with node outage (temporary or not), due to conditions such as extreme hear or cold, or temporary link outage due to eventual interferences in a given area or even energy depletion and nodes permanent failure. Routing algorithms developed for WSNs have to be capable of repairing a route if a given link fails along the way due to such situations,which is a characteristic that must be present in WSNs that implement cooperative MIMO. Depending on the frequency of such failures different routing algorithms can be employed. For networks with fairly stable links a routing table can be maintained at each node, with either the full path to a given destination or only the next hop, depending on the memory available for the nodes or on limitations in maximum packet overhead. If the communication links are not reliable maintaining a large routing table up to date every node of the network might be unattainable, for such cases routing algorithms such as Ad hoc On-Demand Distance Vector (AODV) in which paths are only discovered on demand, avoiding the need to maintain routing tables on the nodes, are generally used.

Algorithm 1 presents the proposed solution for choosing the optimal cluster formation for reaching a given node. A list of neighbors is present at each node and associated to this entry there is information about the number of nodes involved in the cooperative MIMO clusters for reaching such destination, and the involved cost. This cost can be calculated based on metrics such as: RSSI, LQI, RTT [20] or ETX [15]. For the sake of simplicity, in the simulations, the RSSI was adopted

Algorithm 1 Lower Cost Hop

```
1: load neighborList
2: if routePacketReceived then
3:     nodes ← routePacket.getOriginNodes()
4:     size ← routePacket.clusterSize()
5:     cost ← calculateCost(routePacket)
6:     for node : nodes do
7:         if neighborList.contains(node) then
8:             if node.cost() > cost then
9:                 neighborList.remove(node)
10:                neighborList.add(node, cost, size)
11:            end if
12:        else
13:            neighborList.add(node, cost, size)
14:        end if
15:    end for
16: end if
```

as the metric of choice. It may also take into account the number of nodes involved in this transmissions (cooperative MIMO cluster size), associating, for example, a higher cost to transmissions involving many nodes. Other metrics such as delay, packet loss or available bandwidth may also be used. If there is no entry on the list related to one of the nodes transmitting the packet, this entry is added on the neighbor list If an entry is exists, the cost of the associated to the received packet is compared to the cost present in the list (Lines 7 - 8 of Algorithm 1), if the cost of the received packet is lower than the cost present in the list, this list entry is replaced (Lines 9 – 10 of Algorithm 1). This optimal entry can be then sent to the transmitting node or cluster, assuming that all connections characteristics are reflective, or the transmitting node or cluster may use the response itself to calculate the cost associated to the reverse path. Using this algorithm, when a packet needs to be forwarded, a node will be able to decide the optimal number of nodes that need to be involved in a cooperative MIMO transmission to reach a certain neighbor on the list. The graph structure is not modified, so classic graph routing algorithms can still be employed.

Figure 5 presents a case in which the cost is not reflective, since the receiving node is not able to form a cooperative MIMO cluster, and thus, it must rely on the standard multi-hop transmission to reach the transmitting node. The figure also illustrates the fact that cooperative MIMO can also be more efficient when small distances are involved, depending on the configuration of the network.In this case, even though the transmitting node has the receiving node in its neighbor entry the inverse is not true.

The selection of the nearby nodes that will participate on the cooperative MIMO clusters uses a similar algorithm. The nodes that can be reached with only SISO transmissions and that presents the lowest costs are selected to participate in the cooperative MIMO cluster, as spreading the information among these nodes represents the lowest cost locally.

The proposed algorithm is capable of taking advantage of the cooperative MIMO technique and of traditional multi-hop technique to achieve the lowest possible energy consumption

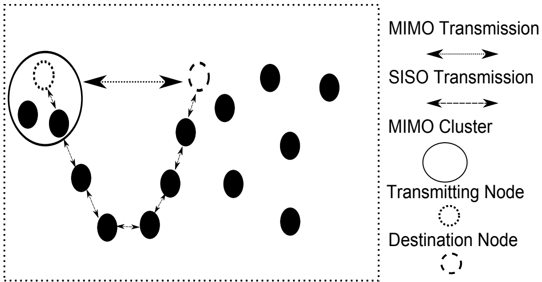

Figure 5: Different communication paths

in the network. The same algorithm is also used to select the optimal number of cluster members that must be present in a cooperative MIMO transmission. Thus, cooperative MIMO transmissions can be employed adaptively, with cluster configurations changing as the network topology changes and without disturbing the operation of standard transmission techniques already employed in WSNs.

It is important to highlight the difference between the method proposed here and other existing techniques. In [21] a routing algorithm for cooperative MIMO networks was proposed, however, this algorithm separates the nodes into three distinct kinds, head nodes, coordination antenna nodes and normal nodes. This distinction is not present in the algorithm proposed here, as all nodes are treated equally and a full peer-to-peer concept is adopted, where there is no such node as a cluster head. Another routing algorithm for WSNs was previously proposed in [22], however this work only considers routing between multiple cooperative MIMO clusters, this differs from the algorithm proposed in this work where the problem of optimal dynamic cluster formation for MIMO communications is addressed. In [23] a detailed assessment of energy consumption for a specific scenario is done, however the problem of selecting the number of nodes involved in a transmission and routing information across the network is not addressed.

VI. Experiments and Results

An area of 10 km $\times$ 10 km is filled with 5000 static nodes whose positions are randomly chosen according to a two dimension uniform distribution. The number of nodes deployed is selected so that when all nodes are operational there is a high probability of the network being fully connected. This probability can be calculate according to a two dimensional Poison distribution, where a certain probability of every node having at least another node on its vicinity (meaning a connection to the rest of the network) is given by:

$$P(c > 1) = (1 - e^{-d\pi r^2})^n, \tag{14}$$

where r is the communication radius of the nodes present in the WSN, d is the node density and n is the number of nodes deployed in the area.

Packets are generated randomly also following an exponential distribution and the source and destination are chosen randomly following a uniform distribution. In order to simulate temporary or permanent node outage a node rate probability is introduced according to an exponential distribution. Nodes that fail return to operation also following an exponential distribution.

The first analyzed metric is the energy consumption of the network. Figure 6 shows the normalized energy consumption comparison between the network employing the proposed adaptive routing mechanism using Cooperative MIMO and the network using multi-hop communication (non Cooperative MIMO) for the same number of non functional nodes. The energy spent with communications was reduced to roughly 60% of the total energy consumed for transmitting the same amount of data from the same source to the same destination. The energy efficiency of cooperative MIMO enabled networks in relation to standard multi-hop networks increases as the number of nodes out of operation increases, this is due to the increasing presence of situations as the one presented in Figure 5. Even for fully connected networks (no node failures) cooperative MIMO enabled networks are evidently more efficient than standard networks, this is due to the fact that packets that need to be forwarded across long distances employ a large number of hops in standard networks. In this cases multi-hop is less efficient than a single long haul cooperative MIMO transmission across the same distance as shown in [9].

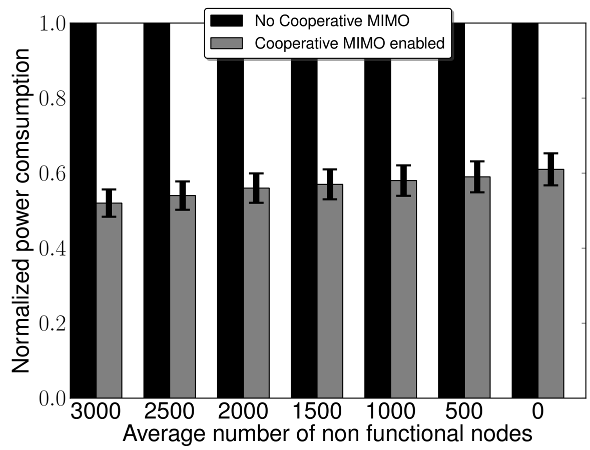

Figure 6: Energy consumption comparison between cooperative MIMO enabled networks and non cooperative MIMO networks

Another important factor to be analyzed is the packet delivery delay across the network. Figure 7 shows a comparison between packet delivery delay in cooperative MIMO and non cooperative MIMO networks. There is a drastic reduction in the average delay even for fully operational networks. The reason for this is also the fact that long transmission, which are the ones responsible for the larger portion of the delay, can be performed using the cooperative MIMO. Since multi-hop transmissions are usually made using the decode and forward approach, intermediary nodes need to decode the received packet and read its header before forwarding it over the network. This procedure induces a high delay compared to cooperative MIMO transmission that can be made directly cluster to cluster over large distances, and only the nodes with direct interest on the transmitted data need to decode the received data. Also, packets depend on a smaller number of nodes to be transmitted, hence the probability of a packet being forced to wait for a busy intermediary node is smaller. For this simulation the channel characteristics where assumed to me fixed, this can be true for static sensor networks place in stable environments. For highly dynamic environments or networks where moving nodes are present the delay can be made worse by the cooperative MIMO since more time is needed to perform channel estimations.

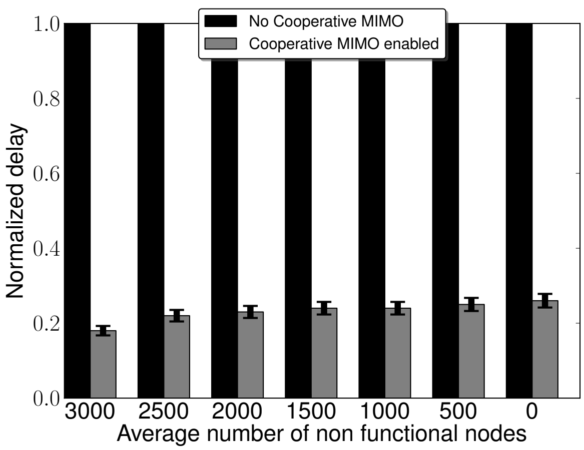

Figure 7: Normalized packet delivery delay comparison between cooperative MIMO networks and non cooperative MIMO networks

Next, the energy consumption when the number of members in MIMO clusters is kept fixed and when the proposed adaptive selection algorithm is used is compared for the case in which the network is fully operational, i.e. all nodes are working properly. When the number of members in a cluster is kept fixed, the benefits of cooperative MIMO can be reduced, since for a small number of nodes in a MIMO cluster the reachable distance is relatively small, thus resulting in lower efficiency for long range transmission. On the other hand, if a large number of members is fixed for cooperative MIMO clusters, intermediary range communications become less efficient with cooperative MIMO than with standard multi-hop communication. These results are presented in Figure 8.

The adaptive algorithm considers a maximum of 5 members in a MIMO cluster. As can be observed in the results presented in Figure 8, and highlighted above, an increase in the energy efficiency can be obtained even comparing the proposed solution to the configuration that keeps the number of 5 nodes as members in a MIMO cluster, which can be explained by the fact that a smaller number of members can be used to reach intermediary distances with increased energy efficiency when the proposed adaptive algorithm is used.

Figure 9 presents a similar comparison as the previous one, for the metric packet delivery delay. The results are similar to the ones shown in the the energy consumption comparison. Delay decreases as larger cluster configurations are used forthe cooperative MIMO, since long range transmissions can be used instead of a large number of multi-hop transmissions.

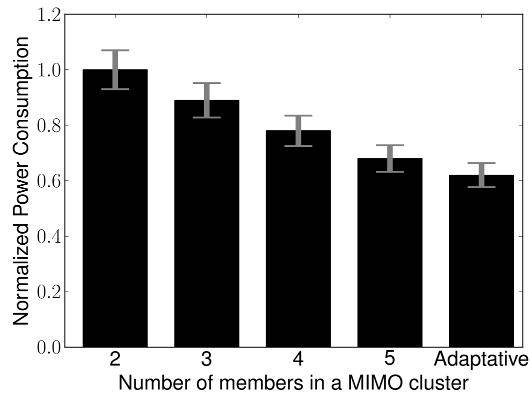

Figure 8: Energy consumption comparison between different cooperative MIMO configurations with fixed number of cluster members and the proposed adaptive algorithm.

When the adaptive algorithm is used, the delay is reduced when compared to fixing a large number of nodes for the MIMO since smaller configurations can be used to reach closer nodes without relying on multi-hop.

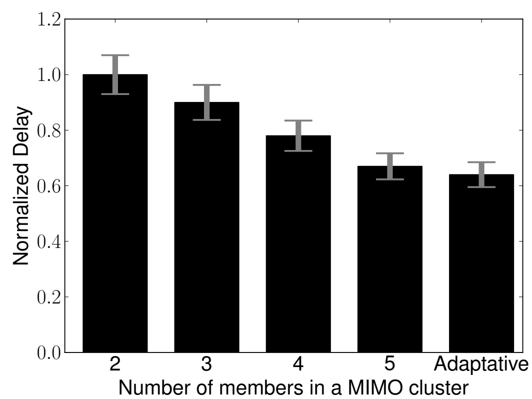

Figure 9: Delay comparison between different cooperative MIMO configurations with fixed number of cluster members and the proposed adaptive algorithm.

Finally, Figure 10 presents a comparison between the energy consumption of keeping a fixed number of nodes in a MIMO cluster and using the proposed adaptive algorithm for different amount of active nodes on the network. When the node density is low, i.e few nodes are available, fixing the number of nodes in a cluster to a large number had no effect, since it is impossible to form large clusters in sparse networks. In this case the adaptive algorithm has no effect when compared to fixing the number of nodes, since cooperative MIMO will only be available at small configurations. When the node density is higher, the proposed algorithm starts to positively impact the energy consumption since MIMO clusters with a large number of nodes become available, and selecting the number of nodes for optimum energy efficiency yields positive effects.

VII. Conclusion

This paper presents an approach to employ cooperative MIMO techniques to increase efficiency in WSNs commu-

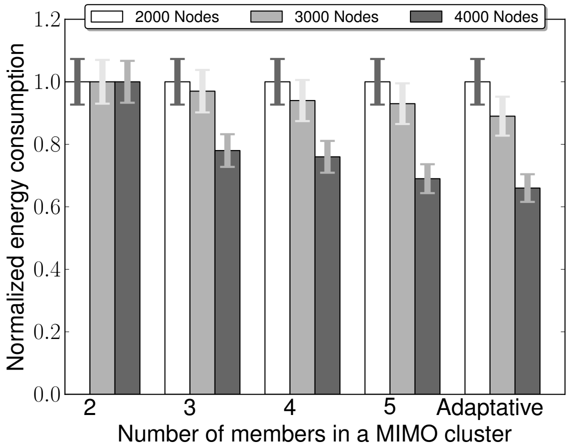

Figure 10: Energy consumption comparison between different MIMO cluster configurations and number of nodes active in the area.

nications. MIMO cluster size and optimal path selection are made automatically and adaptively with a modified routing algorithm. The results provide evidence of the benefits in applying the proposed algorithm in WSNs with energy efficiency being largely increased. Network connectivity is also greatly enhanced with the increased range provided by cooperative MIMO, allowing much sparser networks using cooperative MIMO to remain fully connected compared to standard networks. Packet delivery delay is also reduced with the application of cooperative MIMO in conjunction with the proposed adaptative selection algorithm. These results are especially remarkable in situations in which there are node failures. However, the adaptive behavior of the proposed solution shows enhancements even compared to the application of MIMO with fixed and static number of nodes in the cluster. These last enhancements are not as remarkable as those presented in the presence of node failures, but still represent advantage in relation to the fixed and static size of the cluster members. Future works are planned to study efficient medium access control for cooperative MIMO enable networks and efficient synchronization and data sharing algorithms for intra cooperative MIMO cluster communication.

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REFERENCES

[1] V. Potdar, A. Sharif, and E. Chang, "Wireless sensor networks: A survey," in *Advanced Information Networking and Applications Workshops, 2009. WAINA '09. International Conference on*, 2009.

[2] S. Cho and A. Chandrakasan, "Energy-efficient protocols for low duty cycle wireless microsensor," in *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, 2000.

[3] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, "Highly-resilient, energy-efficient multipath routing in wireless sensor networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 5, no. 4, p. 1125, 2001.

[4] M. Weiser, B. Welch, A. Demers, and S. Shenker, "Scheduling for reduced cpu energy," in *Proceedings of 1st USENIX Symposium on Operating System Design and Implementation*, November 1994, pp. 13–23.

[5] E. Shih, S. Cho, N. Ickes, R. Min, A. Sinha, and A. C. A. Wang, "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks," in *Proceedings of ACM MobiCom01*, 2001.

[6] C. Chen, J. Ma, and K. Yu, "Designing energy-efficient wireless sensor networks with mobile sinks," in *Sensys06*, 2006.

[7] G. N. Bravos and A. G. Kanatas, "Combining MIMO and Multihop Based Transmissions on Energy Efficient Sensor Networks," in *Proceedings of the Program for European Wireless*, 2007.

[8] S. Cui and A. J. Goldsmith, "Energy-efficiency of mimo and cooperative mimo techniques in sensor networks," *IEEE Journal on Selected Areas in Communications*, 2004.

[9] E. P. Freitas, J. P. C. L. Costa, A. L. F. Almeida, and M. A. M. Marinho, "Applying mimo techniques to minimize energy consumption for long distances communications in wireless sensor networks," in *NEW2AN/ruSMART 2012*, Springer-Verlag, Ed., 2012, pp. 379–390.

[10] M. A. M. Marinho, E. P. de Freitas, J. P. C. L. da Costa, A. L. F. de Almeida, and R. T. de Sousa Júnior, "Using MIMO Techniques to Enhance Communication Among Static and Mobile Nodes in Wireless Sensor Networks," in *IEEE 27th International Conference on Advanced Information Networking and Applications (AINA)*, 2013.

[11] M. A. M. Marinho, E. P. de Freitas, J. P. C. L. da Costa anda André Lima F. de Almeida, and R. T. de Sousa Junior, "Using Cooperative MIMO Techniques and UAV Relay Networks to Support Connectivity in Sparse Wireless Sensor Networks," in *Computing, Management and Telecommunications (ComManTel), 2013 International Conference on*, 2013.

[12] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," in *Signals, Systems and Electronics*, 1998.

[13] M. Biguesh and A. B. Gershman, "Training-based MIMO channel estimation: A study of estimator tradeoffs and optimal training signals," *IEEE Transactions on Signal Processing*, vol. 54, pp. 884–893, 2006.

[14] R. Trepkowski, "Channel estimation strategies for coded MIMO systems," Master's thesis, Virginia Polytechnic Institute and State University.

[15] D. Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," *Wirel. Netw*, vol. 11, pp. 419–435, 2005.

[16] W. Lou, W. Liu, and Y. Zhang, "Performance optimization using multipath routing in mobile ad hoc and wireless sensor networks," *Combinator. Optim. Commun. Netw.*, vol. 2, pp. 117–146, 2006.

[17] A. Woo, T. Tong, and D. Culler, "Taming the underlying challenges of reliable multihop routing in sensor networks," in *Proc. ACM SenSys 2003*, 2003.

[18] M. Bhardwaj and A. P. Chandrakasan, "Upper bounds on the lifetime of sensor networks," in *Proceedings of IEEE ICC01*, 2001.

[19] V. Mhatre and C. Rosenberg, "Design guidelines for wireless sensor networks: communication, clustering and aggregation," in *Elsevier Ad Hoc Networks*, 2004.

[20] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, "A multi-radio unification protocol for IEEE 802.11 wireless networks," in *BroadNets*, 2004.

[21] Y. Liang and Y. Feng, "An Energy-efficient Routing Protocol Based Dynamic Cooperative MIMO for Wireless Sensor Network," in *Third International Conference on Intelligent Networks and Intelligent Systems*, 2010.

[22] M. Z. Siam, M. Krunz, and O. Younis, "Energy-Efficient Clustering/Routing for Cooperative MIMO Operation in Sensor Networks," University of Arizona, Tech. Rep., 2008.

[23] S. Cui and A. J. Goldsmith, "Energy efficient routing based on cooperative MIMO techniques," in *Networks (ICON), 2012 18th IEEE International Conference on*, 2012.