Using Cooperative MIMO Techniques and UAV Relay Networks to Support Connectivity in Sparse Wireless Sensor Networks

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Abstract— **One possible way to define the end of lifetime for a Wireless Sensor Network (WSN) is to set a threshold for the number of disconnections among the sensor nodes so that above this level the WSN becomes unable to provide the quality of services required by the users or even totally loses its ability to provide any service at all. Disconnections isolate sensors or group of sensors which cannot deliver their acquired data, thus constituting a sparse nonfunctional WSN, although some of its isolated or grouped sensors remain operational. A possible way to overcome such a problem is to provide an alternative reliable connection via other types of nodes to support the communication among isolated parts of a disconnected network. This paper proposes the use of cooperative multiple input multiple output (MIMO) techniques to support communication among static sensors in a sparse WSN and a relay network composed of Unmanned Aerial Vehicles (UAVs) keeping the WSN connected, thus extending its lifetime. Simulations of the proposed approach are performed and the acquired results highlight the benefits of this proposal.**

Keywords - wireless sensor networks; cooperative multiple input multiple output; energy efficiency; network connectivity; unmanned aerial vehicles relay network

I. INTRODUCTION

One of the main characteristics of WSNs is their integration with the environments which they are monitoring. In many cases, these environments present harsh conditions that may lead to a number of failures isolating sensor nodes or groups of them, hence compromising the network operation due to disconnection [1]. These failures can be of different types, being transitory or permanent, and in this last case, they may result in the end of the network lifetime [2]. Once deployed, most sensor networks are required to have their lifetime extended as long as possible, which is a goal threatened by network disconnection [3]. Eventually, the network will attain a disconnection state so generalized that it is not worth to be maintained anymore. However, the latter this moment happens, the better the overall cost-benefit indicators for the WSN.

Network disconnection is indeed a problem that WSNs have to face sooner or later, and a way to mitigate the drawbacks due to their occurrence is to provide alternative communication paths so that the sensor nodes are able to deliver their acquired data. These alternative paths can be created throughout relay nodes which may be additional sensor nodes or just message forwarding nodes.

Figure 1a presents an example of a sparse WSN containing groups of isolated nodes which are not able to deliver their data to the base station. To fix the broken connectivity in a WSN as in Figure 1a, different relaying solutions can be proposed, such as, for example, the use of mobile sinks [4]. There are several possible mobile sink based solutions, among them one possibility is to have one or more mobile sinks collecting data from the isolated nodes periodically or sporadically. In approaches that use this concept, the sensor nodes wait for a mobile sink to reach their communication range to collect data, as presented in [4]. Another possible solution is related to the concept of Delay Tolerant Networks [5] that enable the connections and disconnections of node to be controlled according to the need for communication.

Yet another possible solution is to have a number of mobile sinks that move in such a way that could cover the whole area in which a WSN is deployed [6]. This would allow the sensor nodes to always find a sink to deliver their data. Figure 1b illustrates the idea, where the mobile sinks are Unmanned Aerial Vehicles (UAVs) flying over the area where the WSN is deployed. The UAVs form a relay network that keeps the connectivity from any sensor node to the base station.
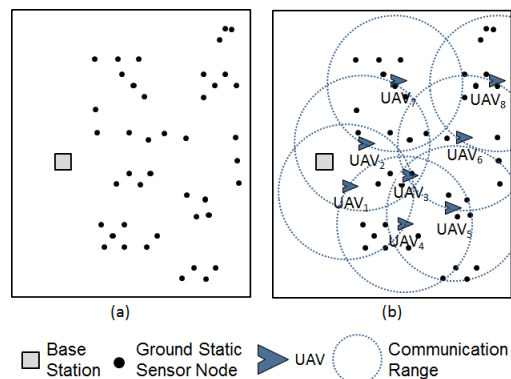

Figure 1. Cooperative MIMO communication between clusters of sensors and a mobile sensor.

Despite the usefulness of the solution presented in [6], it has two drawbacks. The first is the constrained mobility of the UAVs (the mobile sinks) and the second is related to the

system scale. Regarding the mobility constraint, it is implicitly imposed in the proposed solution, as the intended idea is to really constrain the movements of the UAVs in order to keep them close enough to maintain the connectivity among themselves. In relation to the system scale, the proposal may require a number of UAVs to cover a given area, depending on how sparse is the network of static sensor nodes, and how limited is the communication range of these nodes.

This paper proposes an extension of the work presented in [6], adding cooperative multiple input multiple output (MIMO) strategies [7] to address the mentioned drawbacks of the original approach. The central idea is to apply MIMO techniques in the islands of sensor nodes, so that their communication range can be extended. With this extension, these groups of nodes are able to reach the mobile sinks farther away, making it possible either to reduce the number of mobile nodes to cover an area as well as to reduce the constraints in their movement.

The remaining text is organized as follows: Section II presents related work in the area. Section III revisits the solution proposed in [6], adding the MIMO technique and providing the solution that represents the main contribution of the paper. Simulation results are presented and discussed in Section IV. Section V concludes the paper.

II. RELATED WORK

A proposal to handle intermittent connections in MANETs is reported in [8]. This proposal is based on a beacon-less strategy combined with a position-based resolution of bids when forwarding packets. A local database of nodes' locations is used, which is updated using broadcast gossip combined with routing overhearing. The similarity between this approach and the one proposed in this paper is related to maintaining the network of mobile nodes connected. However, our proposal does not handle disconnections as presented in the mentioned related work, but it avoids such disconnections to occur by extending the communication range of the islands of isolated nodes by means of the cooperative MIMO technique combined with the controlled movement of the mobile nodes.

An improved routing strategy to mobile sinks in WSN is presented in [4]. Considering the UAVs as mobile sinks, the idea to deliver sensed data to mobile sinks reported in [4] is comparable to our proposal. The main difference between the two works is that in [4] the intention is to optimize the route from a given sensor node on the ground to a few mobile sinks that move in the area. This does not provide a network that is fulltime connected. In our work on the other hand, the goal is to keep connection during the whole system runtime. Moreover, the use of the MIMO technique is another feature which is not covered in [4].

The employment of a MIMO technique for data collection by sinks in WSN is proposed in [9] whose authors present an approach in which polling stations are used to intermediate the communication between the mobile node and the MIMO clusters, along a predefined path of the mobile sink. In relation to our work, the two main differences are their usage of polling stations, which are not required in our approach, and their dependence on a predefined path in the mobile sink movement. This limitation regarding mobile nodes does not exist in our approach, which considers a random movement pattern.

III. PROPOSED APPROACH

To tackle the problem of disconnections in sparse WSN, the approach proposed in this work combines two ideas: the first is the usage of mobile nodes (Unmanned Aerial Vehicles - UAVs) as relay nodes to support the communication among islands of isolated static sensor nodes, and the second is the cooperation of these static sensor nodes by using MIMO techniques to extend their communication range. These two parts of the contribution and their combination are explained hereafter.

A. UAV Relay Network

As presented in [6], a network of UAVs works as a backbone to relay messages from isolated sensor nodes to a sink or base station. To achieve this goal, the UAV-backbone network has to keep its internal connectivity, i.e. the connectivity among all its members, as well as with the base station or sink destination of the messages. This means that any UAV must be able to reach the base station as well as any other UAV that composes the backbone network.

To keep this connectivity, beacon messages are periodically transmitted by the base station, which are received by the neighboring UAVs and forwarded to their neighbors. This beacon messages carry the identification of the sender UAV and its current distance in hops to the base station. Based in the information received in these beacons, the UAVs are capable to update their list of neighbors as well as their distance, in number of hops, to the base station. This a trivial way to discover neighbors and to maintain updated routing information towards the base station.

However, the UAVs are supposed to move, so they eventually reach situations in which they will be on the edge of the communication range of one another. At this point, an algorithm that monitors the received signal strength indication (RSSI) acts to interfere in the UAV movement. This algorithm defines that once a UAV has only one neighbor and the measures of the RSSI of the beacons received from this last neighbor indicates that the communication link is about the break, the UAV is forced to move towards this last neighbor that keeps it connected to the rest of the network. Each UAV acting according this simple movement control behavior results in a global system behavior that keeps the UAVs close enough, or as farther as possible to each other, so that the communication links are kept, thus the connectivity among them. Besides keeping the connectivity among the UAVs and the base station, it is enough that an isolated static sensor node reaches any UAV to deliver its data trusting that this data will eventually be received by the base station.

B. Cooperative MIMO to enhancing communication from static to mobile nodes

Static sensor nodes in WSN generally have short communication ranges, usually few hundreds of meters [10],

which may be an impediment for their communication with mobile nodes, as they have short time windows to deliver their data. Considering the omnidirectional propagation model, it is possible to observe in Figure 2 the half-sphere that is reached within the communication range of a static sensor node on the ground to deliver a message to a passing UAV.
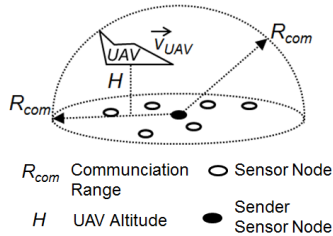

Figure 2. Representation of the space reached within the communication range of a static sensor node on the ground.

As mentioned above, considering the short communication ranges usually available for the sensor nodes, the space reached by their communication can be quite limited, which diminishes the opportunity to deliver their messages to the passing UAVs. This is even worst in cases in which the UAVs move in high speeds.

Observing the problem considered in this paper, in which islands of isolated sensor nodes form a disconnected WSN, and that these sensor nodes in each island are close together, there is an opportunity to take advantage of their proximity to enlarge their communication range so that they are able to reach UAVs farther way to deliver their messages. If they send their data each one by themselves, they would be limited by their communication range, but together they can extend their communication range by means of cooperative MIMO.

Taking advantage of the cooperative nature of the sensor network operation, cooperative MIMO can be introduced in these groups of isolated sensor nodes to provide a reliable and longer range communication among static and mobile nodes. In cooperative MIMO, instead of a conventional arrangement of multiple antennas in a single sensor which constitutes traditional MIMO, multiple sensors cooperate to transmit and receive data. Figure 3a illustrates the idea in which two groups of nodes form clusters and using cooperative MIMO (in this case a MISO – multiple input single output) send data to the mobile node, i.e. the UAV. Figure 3b illustrates the same situation, but showing also the UAV forwarding the message to sensor nodes members of another group. This situation will be further explored. Nodes within close range (defined by a threshold) exchange pilot signals to setup the MIMO cluster, as detailed in [7].

Within the general study domain on applications of cooperative MIMO to extend communication range of sensor nodes in WSN as presented in [7], the particular case of interest for the problem analyzed in this paper can be highlighted, which is the MISO case (cooperative n by 1 MIMO). Figure 4 presents an example in which two nodes send data to one receiver node.

In the example presented in Figure 4, the numbers indicate the sequential order of the events, first the

transmitting sensors exchange the information that needs to be transmitted, and then both sensors transmit the symbols at the same time slot to the receiver.
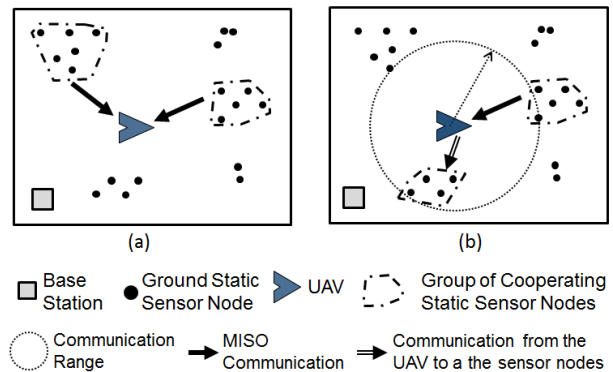

Figure 3. (a) Communication from groups of sensor nodes to a UAV, (b) UAV forwarding data from one group to another.
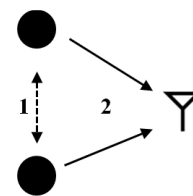

Figure 4. Example of a 2 × 1 MISO system.

C. Using cooperative MIMO to deliver messages from isolated static sensor nodes to the UAV Relay Network

Bringing together the proposals of the UAV relay network and the cooperative MIMO to enhance communications from the groups of isolated static sensor nodes to the UAVs, it is possible to build up a new solution for the disconnection problem in sparse WSN.

Despite the usefulness of the pure UAV relay network, it has the drawback related to the need of a number of UAVs so that they are able to stay in the communication range of the static sensor nodes to receive their data, as illustrated in Figure 2, and that they may have considerable constraints to maintain connectivity among themselves. By enabling the static sensor nodes in the islands to cooperate for a MIMO based communication, their grouped range is considerably extended, their sent data can reach farther UAVs. This way the solution allows the UAVs to ease movement constraints, as well as making it possible to reduce the number of UAVs needed to cover an area, compared to the case in which each sensor node sends its data alone.

Figure 3b presents an example in which a communication from a group of sensor nodes is forwarded by a UAV to another group of sensor nodes, as an application of the MISO presented in the previous subsection. Extending this approach, it is possible to have the UAV relay network performing multiple forwarding hops to deliver data from any island of sensor nodes that are able to reach a given UAV, without the severe restriction in the UAVs' movement caused by the limited communication range of a single sensor node. Figure 5 illustrates this situation.
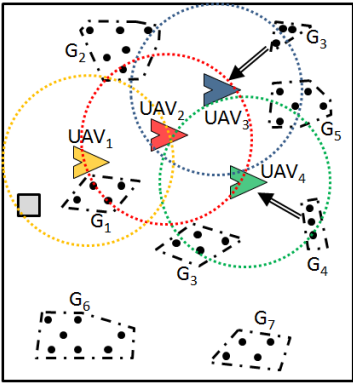
Figure 5. Use of the cooperative MIMO by the static sensor nodes to reach the UAV relay network.

In the example presented in Figure 5, groups of isolated sensor nodes, G_3 and G_4 have data to deliver to the base station, but as they have no neighbors that are able to forward their data towards the destination, they cooperate (using MISO) and together send the data to UAV_3 and UAV_4 respectively. These two UAVs are not by themselves able to reach the base station, but they have links with UAV_2, which is connected to UAV_1 which by its turn is connected to the base station. Following this forwarding sequence, the data sent by the sensor nodes members of groups G_3 and G_4 eventually reach the base station.

D. Adapting the UAV movement control algorithm to cooperative MIMO relay networks

The algorithm proposed in [6] does not take into account the usage of static nodes as part of the relay network formed by the UAVs, but consider them as data producers only. Thus, in order to further explore the combination of the benefits of the MIMO technique with the relay network, the algorithm that controls the movement of UAVs to keep them closer enough to maintain the network connected needs to be adapted to take into account the presence of static nodes (in MIMO clusters) and the maximum distance that they can stay from these clusters.

This is done by creating a measurement of the relative attraction that the UAVs have to the MIMO clusters, the UAVs among themselves. When a UAV is connected to nodes that have very short communication ranges, it moves more freely around the node, moving away from the group of nodes at a smaller pace, and eventually drifting a little beyond the maximum communication range. In contrast, when the UAV is connected to a group of nodes that has a large communication range, its movement is adapted to be more active in trying to keep the link and avoid that it breaks. This adaptation prevents the UAVs from having their movement restricted to a very small area around static nodes that have too short communication range, but it allows keeping connections with those with it worth, i.e. those with longer ranges. Considering that a UAV has only one neighbor, i.e. it has only one connection, the probability p of this UAV to move towards this last connected node (or group of nodes) if the communication link is about to break is given by:

$$p = \frac{n_{\max}}{d_{\max}}$$

Where $d_{\max}$ is the maximum communication range of the UAV and $n_{\max}$ is the maximum communication range of the node (group of nodes) or another UAV with it is connected. If the link is eventually broken the same probability is used to decide if the UAV will move towards the last know location of its last neighbor, preventing UAVs from getting stuck around nodes with too short communication ranges for long periods of time.

This allows both techniques to coexist over the same network, as the concentration of UAVs over a certain point depends on the maximum communication range of the islands of nodes, which is directed related to the number of MIMO members in a specific configuration.

IV. EXPERIMENTS AND RESULTS

A. Studied Scenario and Simulation Setup

The case study scenario is similar to the one presented in Figure 1b, in which islands of isolated sensor nodes have data to deliver to a base station or sink, and mobile sensor nodes (UAVs) from a relay network that connect those isolated nodes so that their messages arrive at the destination.

For the simulations an area of 10 km × 10 km is filled with 14 separate islands of sensor nodes. These islands are set so that they are in average 3000 m apart from each other. The UAVs are randomly distributed in the scenario at the beginning of each simulation run, and they follow the random waypoint (RWP) mobility model. Their average speed is 85 km / h. A base station is placed at the center of the simulation scenario acting as the sink destination of the data sent by the sensor nodes. Each simulation runs for 60 minutes (simulation time).

Cooperative MIMO configurations vary from a Noncooperative MIMO, allowing a maximum communication distance between nodes and UAVs of 350 meters, up to 7 cooperating nodes, allowing a communication to a distance of 2450 meters.

B. Results and Discussion

The assessed metrics measure the average number of nodes disconnected from the sink across different Cooperative MIMO configurations. Also the number of UAVs is varied so it is possible to show how the network connectivity varies according to the number of available UAVs. Energy consumption is an important parameter, but this aspect is not in the scope of this paper due to space limitations.

Figure 6 shows the average number of nodes disconnected from the sink during the simulations with 8 UAVs deployed in the area. It is possible to observe an increase in the connectivity that can be achieved with the usage of a higher number of nodes in the cooperative MIMO within the node islands. This is due to the fact that larger ranges are achieved with more cooperating nodes.

For the sake of comparison, Figure 7 shows the results for the average number of disconnected nodes when a

Noncooperative MIMO is used, but the number of UAVs in the simulation area increases.
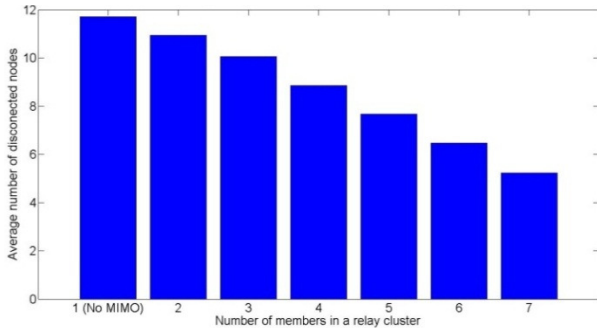

Figure 6.   Average number of disconneted nodes from the sink in relation to the increasing numbers of MIMO cooperating nodes and 8 UAVs.
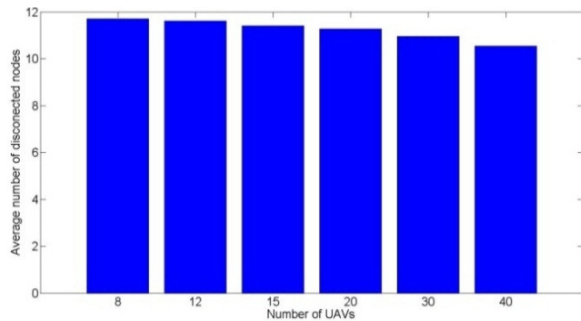

Figure 7.   Average number of disconneted nodes from the sink in relation to the increasing number of UAVs in the scenario.

It is possible to notice from the results presented in Figure 7 that even a large increase in the number of available UAVs has only a marginal effect on the overall network connectivity. Since node communication is extremely limited without Cooperative MIMO (350 m) the nodes that are located farther from the sink require the UAVs to form a relay chain connected to the sink. Since the random movement pattern is used by the UAVs, it is hard to make this connection stable for a long time. Even with the controlled random movement proposed in [6], in which the UAVs avoid to break the communication link with their close neighbors, it is difficult to achieve results as good as those presented in Figure 6 with so few UAVs.

However, the combination of cooperative MIMO and the increase in the number of UAVs can provide further improvements to the network connectivity. Figure 8 shows the results of the average number of nodes disconnected from the sink for a varying number of MIMO cluster members when 20 UAVs are distributed over the area.

Considering the improvement presented in Section III-D, in which the islands of nodes are able to act as relays over larger distances due to the usage of Cooperative MIMO, an important improvement can be noticed in the network as a whole. Nodes that are located far from the sink can now communicate using a combination of UAVs and intermediary groups of sensor nodes and no longer have a great dependency on the UAVs movement pattern. This means that a node that has a data packet that needs to be transmitted to the sink no longer has to wait for a set of

UAVs to properly align and provide a path towards the destination; this results in a decreasing latency across the network, especially for nodes located far from the sink. Figure 9 shows how the delay drops in relation to an increase in the number of cooperating nodes in the MIMO clusters that are formed in each island of nodes.
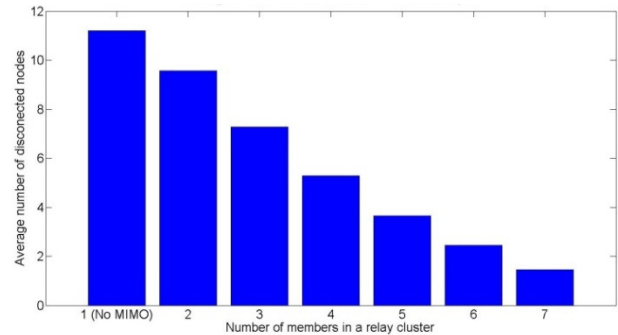

Figure 8.   Average number of disconneted nodes from the sink in relation to the increasing numbers of MIMO cooperating nodes and 20 UAVs.

Another problem that is minimized is the probability of link to be broken, as a smaller number of mobile participants (UAVs) are necessary, since the islands of static nodes also serve as long range relays, it is less likely that the connection will be broken before the node that originally transmitted the package can get a confirmation of its delivery. It is important to notice that, with the values established in the simulation setup, the islands of nodes are not able to connect among them, they only relay messages from and to UAVs that are connected to them. It is also important to highlight that the increased communication distance obtained with the Cooperative MIMO allows the UAVs to maneuver over a much larger area without breaking the connections.

The impact in the movement control of the UAVs to keep their connectivity is analyzed in the following. Figure 10 presents the average number of neighbors, mobile or islands, connected to a UAV during the simulations in which 8 UAVs are covering the area moving according to a Pure RWP and the controlled RWP proposed in [6].
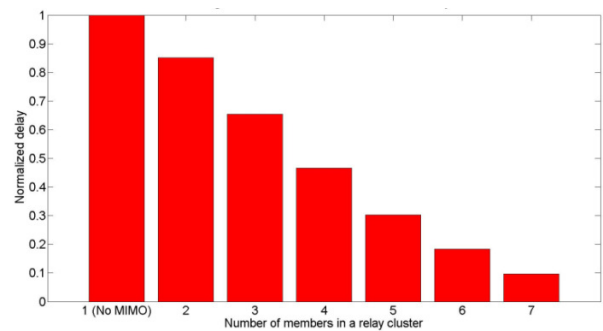

Figure 9.   Normalized delay in relation to the increasing numbers of MIMO cooperating nodes

The results show that at short communication ranges (no MIMO or MIMO clusters with few members) the movement control helps increasing the overall network connectivity. However, as the number of MIMO cluster member increases, and consequently the communication range, the algorithm

starts negatively impact the network connectivity. This is due to the fact that it may lead to eventual deadlocks in which the UAVs become stuck in given locations, or to one neighbor that is disconnected from the rest of the network. If two UAVs are connected only to each other, they will start to move towards each other when the RSSI starts to get weak, once close enough they will start to move randomly again, if no other connection is made the signal will eventually drop again and the process will be repeated, keeping both UAVs connected to each other but disconnected from the rest of the network. The same may happen to a UAV in relation to islands of nodes that have longer communication ranges. In this case the UAVs risk to become "anchored" to a given island. On the other hand, the UAVs moving with a Pure RWP can benefit from the longer communication ranges of the islands of nodes by being able to connect to other UAVs farther way, without the risk of the same deadlock mentioned above.

Using the adapted movement control described in III-D, the connectivity results are slightly better than those achieved by the pure RWP, resulting in lower numbers of disconnected nodes in average, as it is possible to observe in Figure 11.
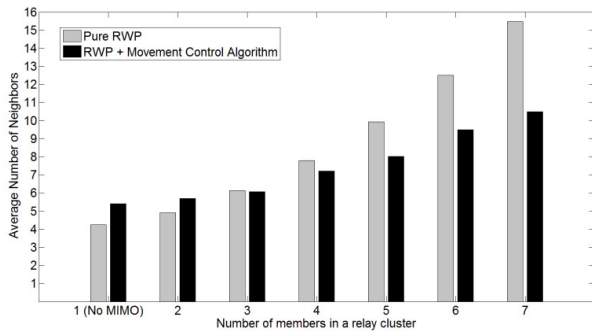

Figure 10. Average number of connected neighbors in relation to the increasing numbers of MIMO cooperating nodes and movement pattern
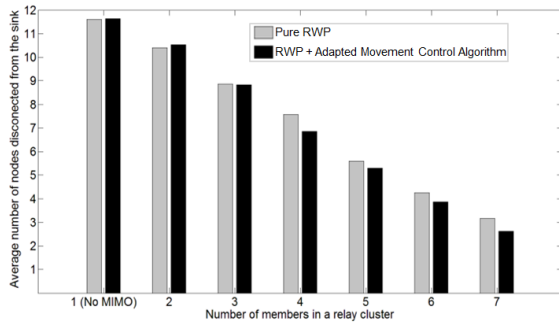

Figure 11. Average number of nodes disconected from sink in relation to the increasing numbers of MIMO cooperating nodes and movement patern

The usage of the adapted movement control algorithm allows benefiting from both the extended range provided by the use of cooperative MIMO and the controlled movement of the UAVs, without the drawbacks related to the movements constraints and deadlocks between UAVs, as it avoids the deadlocks between UAVs and static nodes by weighting the decision to move towards a static node by its maximum communication range.

V. CONCLUSION

This paper presents an approach that combines cooperative MIMO techniques and relay networks of mobile nodes to support connectivity in sparse WSN. The results provides evidence of the benefits in combining the two techniques, as they help to address the drawbacks of one another besides achieving better results in terms of network connectivity compared to the isolated usage of each of these techniques, besides the reduction in the communication delay. Future works are planned to improve the connectivity results even more by modifying the movement control algorithm, considering other movement patterns and other parameters that may affect the impact of the movement in the connectivity of the mobile nodes, and consequently the connectivity of the entire network. A study about the energy saving associated to the adoption of the approach and a direct comparison with related techniques are also planned.

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