# Cooperative Communication for Energy Efficiency in Mobile Wireless Sensor Networks*

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**Abstract.** The inherent challenges which static sensor networks face such as energy constraints, are also faced by mobile sensors. In this work, we present a hierarchical cooperative clustering architecture for ad hoc wireless sensor networks. Communication cost is a crucial factor in depleting the energy of sensor nodes. We propose a framework in which nodes cooperate to form clusters at each level of hierarchy ensuring maximal coverage and minimal energy expenditure with relatively uniform distribution of load within the network. Performance is enhanced by cooperative multiple-input multiple- output (MIMO) communication. We test our framework using TOSSIM over TinyOS-2.0.x on MICAz motes. We implement and compare the proposed framework with cooperative clustering scheme (CMIMO) and traditional multihop Single-Input-Single-Output (SISO) routing approach. Performance is evaluated on the basis of energy consumption. Experimental results show significant energy conservation as compared to existing schemes.

## 1 Introduction and Motivation

Wireless sensor networks (WSNs) demand energy conserving techniques from MAC to application layer. One of the main design challenges in wireless sensor networks is coping with resource constraints placed on individual sensor devices. Energy constraints end up creating limitations such as computational power and limited coverage which are an impediment to achieve the overall objective of a sensor network [1].

In large networks, data is communicated to sink via multihop routing. Typically, in static networks, nodes closer to sink get depleted off energy, despite energy conservation techniques. This is because these nodes are more loaded than other nodes in the network i.e. the reach back problem [2]. They act as relay nodes between sink and the network. If sink is mobile, the number of hops to communicate data can be reduced. This is because a mobile sink can reach in the vicinity of nodes in the sensor network. Similarly, because redundancy

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requirement (*'connectivity'*) in sensor nodes can be relaxed by introducing one or several mobile sinks, therefore, a sparse network architecture may be considered. In a dense network deployment, nodes may die out or the connectivity is disrupted due to physical obstacles or damages; in such scenarios mobile sinks can effectively collect data from the sensory nodes.

Mobile wireless sensor networks also face the inherent design challenges which static WSNs face. Since sensor nodes are energy-constrained, network longevity is a major concern in designing topology protocols, especially for applications deployed in harsh environments. Communication models such as hierarchical models [3] and [4], cooperative schemes [5], planer design [6] have been proposed in literature, for energy efficient clustering. Combined clustering and routing has also been considered for maximizing networks lifetime [7].

In this work, we focus on two scenarios: sensor nodes are static with a fixed basestation and a second scenario where there is a mobile sink in the network. The mobile sink is a light weight airborne plateform containing one or more sensor nodes. It serves as the data sink.Most sensor networks are static in nature but in emergency scenarios such as after an earthquake or during a fire (in buildings or forest fires) it is impossible to safely deploy a traditional static sensor network. In such events, it may be unsafe for the rescue teams to enter the buildings and enclosed spaces. Light weight airborne sensor networks can be used in such situations to detect survivors and send alerts to rescue teams. In recent years, cooperative Multi-input multi-output (MIMO) has been proposed as a communication model to be used in ad hoc wireless sensor networks [5], [8], [9]. MIMO technology has the potential to increase channel capacity and reduce transmission energy consumption. Since large network deployments necessitate energy efficient communication techniques, a concept known as cooperative MIMO has attracted a growing interest. In a cooperative MIMO network, a group of sensor nodes cooperate to transmit and receive data. The participation of multiple transmitters and receivers in a transmission saves significant energy in long-range communication [10]. Energy can be conserved if nodes are allowed to cooperatively transmit data just like in MIMO mode of communication. In our previous work [11], we showed that energy is conserved for a single transmission when data is routed via hierarchical cooperative routing. We extend that work by deploying our scheme on a more complicated network where clusterheads are aggregating data from a number of nodes and sending it to mobile/static sinks. Results show an extension in network lifetime in a communication intensive network. We exploit the benefits of cooperative communication for relaying data in static nodes as well as on airborne sensory platform.

### 1.1 Contributions

The main contributions of this paper are as following:

– A novel architectural framework for energy efficient routing to be used with cooperative MIMO communication in ad hoc WSNs.

– Performance analysis of our framework which minimizes energy consumption by employing an energy efficient cooperative clusterhead(CH) selection/routing algorithm.

### 1.2 Organization

The remainder of this paper is organized as follows. Section 2 gives an overview of existing literature. In section 3 we explain our framework; in section 4 and 5 we present our network model and experimental results. Section 6 summarizes our conclusions.

## 2 Related work

In the past few years, MIMO has surfaced as a reliable and energy conserving technology in the field of wireless networks. Various studies have focused on use of MIMO in sensor networks in order to improve energy conservation, network throughput and reliability in fading channels. In [12], authors propose a multiple-input multiple-output (MIMO) technique where multiple nodes within a cluster cooperate in signal transmission and reception. A cross-layer design is applied to optimize routing in order to minimize the energy usage and delay. For the cooperative MIMO scheme, routing is optimized based on an equivalent single-input single-out (SISO) system, where authors have treated each cooperating cluster as a super node.

Recently, lightweight airborne sensor networks have gained considerable attention as an area of research, Sensorflock[13] and Sensorfly[14] being two examples. An airborne wireless sensor network provides the capability to enhance many applications of interest to scientific community. This is provided by three-dimensional sampling of phenomena of interest that would otherwise be infeasible. One such class of applications is chemical dispersion sampling. A deployment of a flock of airborne sensors sensing and communicating their data back to a network of ground stations enables scientists to study the rate of dispersion of a natural or man-made toxin, pollutant, or chemical[13]. Another protocol, MobiRoute [15], supports routing in wireless sensor networks (WSNs) with a mobile sink. The authors theoretically prove that moving the sink can improve network lifetime without sacrificing data delivery latency. In MobiRoute, simulation results show that a mobile sink, in most cases, improves the network lifetime with only a modestly degraded reliability in packet delivery.

To our knowledge, little work exists in cooperative clustering for sensor networks with mobile sinks. An on ground MIMO based protocol TwinsNet [16],is proposed which shows gains, in terms of link loss rate. The improved link loss rate implies greater availability of critical data where the authors assumed that continuous data is required by the application. A uniform model for link quality is unrealistic for complex, unstructured environments but simulation results show a decrease in link loss rate. Authors assumed random movements of robots in the network. However, in TwinsNet protocol, energy consumption for the network is not explored.

## 3 Hierarchical Cooperative MIMO

In conventional networks where on ground sensory systems are deployed, as the system size gets smaller, the antennas get closer to the ground. This detunes the antennas, reduces line-of-sight, and increases multi-path problems [16].Airborne sensors offer better reception and transmission. However, when the sensors are deployed on light weight platforms, which are mobile, battery conservation becomes an important concern.

In this work, we propose Hierarchical MIMO (HMIMO), a novel clustering topology framework with MIMO capabilities for mobile sinks. To our knowledge, cooperative MIMO gains in lightweight airborne sensory devices has not been addressed in past.

MIMO offers three types of gains: Multiplexing, Capacity and Diversity gain. In this work we focus on diversity gain. Diversity gain is the slope of average bit error rate (BER) curve versus signal-to noise ratio (SNR). Diversity gain for a targeted BER offers energy conservation in static sensor networks. In networks consisting of mobile nodes, next hop destination changes from time to time. Each time the nodes transmit data, they do not recalculate a path which consumes least energy. This is because, such a task is very energy intensive. In clustered networks, the clusterheads communicate with mobile sinks. Everytime nodes transmit data to the mobile sink, the energy consumption differs based on the distance between the mobile sink and clusterhead. When mobile sinks are in close vicinity of clusterheads, they communicate via SISO approach. As the distance changes a distance dependent transmission protocol is followed in which CHs communicate with mobile sinks using cooperative MIMO approach.

### 3.1 Architecture

Our network is a heterogenous hierarchical network as illustrated in Figure 1. Network consists of ordinary sensor nodes, clusterheads, cooperative nodes, beacon nodes and airborne sensors (ABS).

When the algorithm starts, each ordinary node sends its neighbor node a HELLO message broadcast at a low power level. The aim of using low power is to send message to only one hop neighbors which are in close geographic vicinity. The second goal is to save energy. Every node calculates its weight on the basis of neighborhood information which is the normalized sum of clustering parameters. The first parameter is the transmission range of a sensory node. A node is able to communicate with any other node within a given transmission range. As we increase transmission range, there is also an increase in the radius of a cluster. For sparse networks we may have to increase the transmission range but for dense networks the transmission range is kept less so as not to burden the clusterheads. The second parameter is the residual energies of nodes. A node with a higher amount of energy is a better candidate for becoming a clusterhead. The third factor is link quality. HELLO message consists of node ID, its weight and a list of its neighbors. The nodes continue to exchange this information for a finite number of rounds.

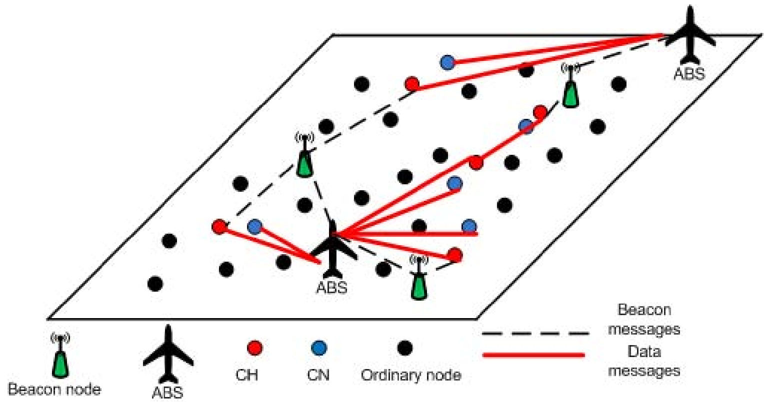


**Fig. 1.** HMIMO with mobile airborne sinks

**Clusters formation.** Clusters formation consists of following steps. It is discussed in a greater detail in our previous work [11].

**Step 1:** Each node compares its weight with that of its neighbors. If a node $v$ has greatest amount of weight in it's neighborhood, it declares itself a clusterhead. If there is a tie, it is resolved on the basis of node ID.

**Step 2:** If $v$ is not the best node then it sends a "Clusterhead message" to the node with the highest residual energy to become a clusterhead in case the best node has not already declared itself a clusterhead.

**Step 3:** After sending the "Clusterhead message" to the best node, node $v$ waits for a fixed duration of time($\delta$) for the best node to reply back.

– If that best node and not any other node in the neighborhood sends a "Cluster formation" message then after a fixed time ($\delta$), node $v$ declares it self to be a clusterhead.
– Each clusterhead selects a cooperative node (CN).

**Airborne sinks.** We have assumed airborne sinks as sensory units consisting of two sensor nodes. The airborne sinks have the capacity to fly across the sensor network. In emergency situations where there is buildings debri or many obstacles, ABS cannot move in a fixed path. Therefore, in such scenarios they follow a random movement. We have also considered scenarios where ABS can move in a predefined path. After collecting data from the ABS send this data to the basestation which is assumed to be outside the network.

**Beacon nodes.** Few nodes in the network are assigned the duty of beacon nodes. Whenever an ABS comes in the vicinity of beacon nodes, this information is communicated to neighboring clusterheads.

### 3.2 Routing

For hierarchical routing, clusters join to form bigger clusters. Once clustering process at first level is completed, clusters may join to form bigger clusters for routing called Routing Clusters. The neighboring clusterheads exchange a ROUTE message. In this message, clusterheads announce the cluster ID of the cluster whose clusterhead possesses the highest residual energy. Such a cluster becomes a routing cluster. Routing clusterheads announce their presence to all neighbor CHs in the network. The clusterheads update their routing tables. If it takes less energy from a CH to send data to ABS then it send data directly to ABS, otherwise, it send data to its Routing CH [11]. In this work we consider only three levels of hierarchiy, i.e static sensor nodes, clusterheads and some routing clusters.

**Reclustering.** Topology maintenance is critical for a clustered network. At certain times an update is required in a cluster. Reclustering can happen in any of the following cases:

- A clustering update is required when a link is created between two nodes.
- When an existing link between two nodes is broken:
  - If one of the nodes is a clusterhead and the other is an ordinary sensory node then both the nodes trigger clustering again.
  - If both the nodes are ordinary nodes then both nodes announce their new weights to their clusterheads and all the neighbors. This would make the clusterheads update the neighbor list of their neighbors.
- When the residual energy of a clusterhead reaches a threshold value(an energy parameter), clusterhead delegates the responsibility to another node in the cluster who has high enough energy to become a clusterhead. If some of the neighbors of old clusterhead cannot communicate with the new clusterhead then either they retrigger clustering or join neighboring clusters.

### 3.3 Energy Consumption

Since the ABS are far from CHs, presumably the energy consumption follows the multi-path model. Therefore, energy per bit consumed in a cluster where there are $N/k$ nodes in a cluster ($N$ is the total number of nodes in the network and $k$ is the number of clusters), is given by [17]:

$$E_{CH} = (\frac{N}{k} - 1)E_{circuit} + \frac{N}{k}E_{DA} + E_{circuit} + \epsilon_{mp}(d^{*}_{u,v})^{4} \tag{1}$$

where $E_{circuit}$ is [5]:

$$\begin{aligned} M_t(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn} + \\ M_r(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC}) \end{aligned} \tag{2}$$

and $\epsilon_{mp}(d^*_{u,v})^4$ is given by:

$$(1+\alpha)(\gamma(M_t, M_r)N_oBN_fG_oM_l(d^*_{u,v})^4) \quad (3)$$

where $\gamma(M_t, M_r)$ is the required SNR at the receiver. In this case (where we have single input and single output at the transmiter and receiver ends) $M_t$ and $M_r$ are both one. $P_*$ are power consumption values.$E_{DA}$ is energy consumed for data aggregation ($d^*_{u,v}$, is the optimum distance between two communicating nodes $u$ and $v$,. Rest of the notations are explained in table 1.

## 4 Network Model

Nodes have unique IDs and have some location coordinates namely x and y. Initially all the nodes have same amount of energy. Sensor nodes are deployed using a uniform random distribution. Two nodes are called neighbors if they are within the transmission range of each other. Mobile Airborne sinks vary from 1 to M. To test our framework, we have averaged our results on 100 different runs for varying distribution of nodes.

**Table 1.** System Parameters

| Parameter | Meaning | Value |
|---|---|---|
| $R_b$ | Bit Rate | 1 Mbps |
| $P_{DAC}$ | Digital-to-Analog converter | $15mW$ |
| $P_{ADC}$ | Analog-to-Digital converter | $15mW$ |
| $P_{mix}$ | Mixer | 30.3 mW |
| $P_{filt}$ | Active filters at transmitter | 2.5 mW |
| $P_{filr}$ | Active filters at receiver | 2.5 mW |
| $P_{syn}$ | Frequency synthesizer | 50 mW |
| $P_{LNA}$ | Low noise amplifier | 20 mW |
| $P_{IFA}$ | Intermediate frequency amplifier | 2 mW |
| $B$ | Bandwidth | 10 KHz |
| $N_0$ | PSD | -171 dBm/Hz |
| $M_l, N_f$ | Link margin, Receiver noise figure | 10 dB |

For energy analysis we consider communication on Rayleigh fading channel. We analyze our scheme for a target BER of $10^{-3}$. Signal to Noise Ratio (SNR) are the same as in [5]. All other values are assumed as mentioned in Table 1, otherwise stated. All nodes generate packets independently. We have used poisson distribution($\lambda$) for packets generation. Packets are generated according to poisson distribution per 10 seconds. We assume basestation to be located outside the square field (sensor nodes deployment) unless stated otherwise. The BS is equipped with multiple antennas. ABS transmit data to the basestation. We implement two version of our framework, one for static network with a single basestation and the other version with mobile sinks. We compare our framework with hop by hop MIMO called CMIMO [5], which is the most recent state-of-the-art work on cooperative communication in sensor networks, and traditional multihop SISO approach [4].

We choose these two schemes because of two reasons. Firstly, we show that our scheme is energy efficient as compared to SISO clustering approach. Secondly, we also show that hierarchical routing when used in conjunction with cooperative MIMO gives better results in terms of energy conservation as compared to existing multihop cooperative MIMO clustering/routing approaches in mobile airborne sensor networks.

## 5 Results and Discussion

### 5.1 Transmission Modes

Figure 2 shows a topology of a network with $k = 100$, (k is the number of level-one clusters). In this figure, at this particular instance the ABS/basestation lies at the center of square grid. The four different colored links show communication modes between clusters. Figure 2 shows various communication modes for routing in CMIMO.

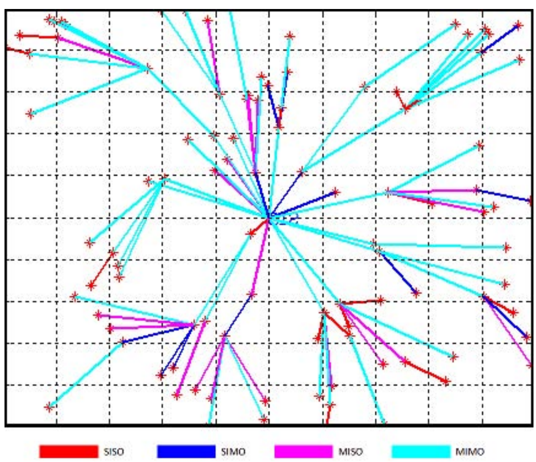


**Fig. 2.** Routing in CMIMO

In figure 3, packets are routed via HMIMO. In the previous approaches all the $k$ number of clusters were involved but in our approach the number almost reduces to $log(k)$. Therefore, there are less number of hops in hierarchical cooperative communication as compared to the traditional CMIMO approach. The figure also shows that MIMO mode of communication is dominant in the network which is indicates less energy consumption.

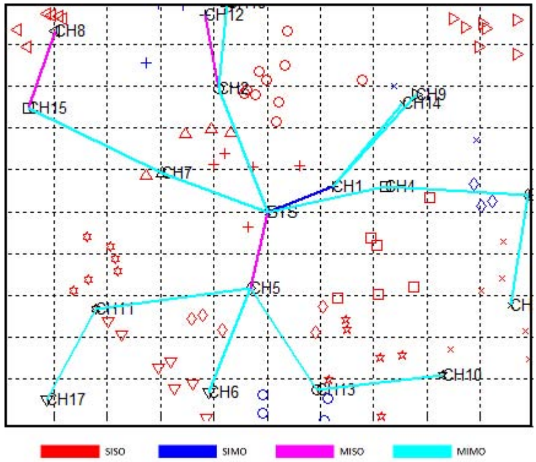


**Fig. 3.** Routing in HMIMO via backbone Clusterheads

### 5.2 Static Network with Hierarchical Cooperative Communication

In this experiment there are 100 nodes which are randomly deployed within a square region. Figure 4 shows a comparison between hierarchical MIMO with static nodes (HMIMO), CMIMO and traditional SISO. For this set of simulations we varied the size of the grid from $100 \times 100$ to $1000 \times 1000$ and Intercluster range is 33 % of the grid size. In HMIMO, data is forwarded via hierarchical routing. For the sake of simplicity, we have assumed a cost based link state routing for the other two algorithms. We alter the pathloss exponent between 2.7(semi-furnished rooms) and 3 (densely furnished buildings) [18]. For smaller grid sizes the performance of all the three algorithms is similar. This is because the intracluster distance between the clusterhead and sensory nodes and the intercluster distances between the communicating clusterheads is less. For shorter distances our algorithm and CMIMO uses SISO mode of communication. As we increase the grid size traditional multihop SISO continues to provide communication via SISO approach. However, the other two algorithms start switching to cooperative modes. In such scenarios, HMIMO outperforms CMIMO because number of hops for the data to reach basestation are less in HMIMO. The reason for decrease in number of hops is the hierarchical nature of our algorithm. As mentioned earlier, for small networks our scheme is using energy comparable to CMIMO. As we increase the network area, there is an upto 15-20% energy saving.

In state-of-the-art CMIMO (described in section 2), as the intra-cluster range increases, fewer clusters are formed. Thus, transmission distances between CHs become larger and circuit energy becomes less significant than transmission energy, which results in making other modes than SISO more favorable. A decrease in number of clusters increases number of nodes in each cluster which over

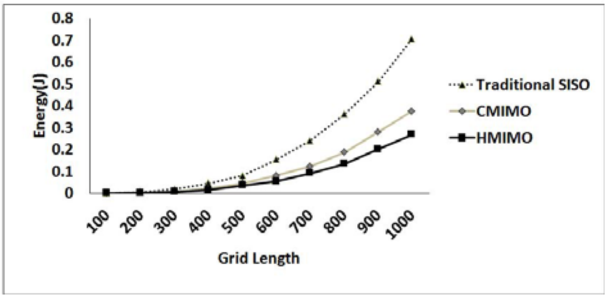


**Fig. 4.** Energy (J) consumption in HMIMO vs. Traditional approaches

burdens the clusterheads which are the communication centers. In our scheme, clustering parameters are not changed for the purpose of saving energy in routing. Distance dependent routing takes place by selecting appropriate nodes as routing clusterheads with the purpose of energy conservation. The advantage of our scheme is that routing and clustering jointly conserve power.

### 5.3 Energy Consumption with Mobile ABS

In this experiment, 100 nodes are randomly deployed within a square region. Figure 5 shows a comparison between HMIMO, hop by hop MIMO and traditional SISO. For this set of simulations we obtained results on a grid size of $1000 \times 1000$ meters. The Intercluster range for the first level clustering is taken as 33 % of the grid size. In HMIMO, data is forwarded via hierarchical routing. For the sake of simplicity, we have assumed a cost based link state routing for the other two algorithms.

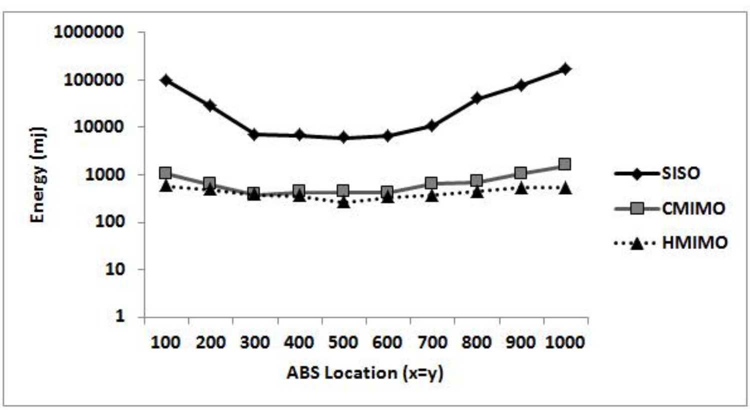


**Fig. 5.** Energy consumption with mobile ABS

ABS moves diagonally from one corner of the field to another. For shorter distances our algorithm and hop by hop MIMO uses SISO mode of communication. As the distance between ABS and majority of clusters decreases, i.e. when ABS is almost in the centre of the grid, HMIMO consumes less energy. The cooperative algorithms start switching to cooperative modes when distance between a clusterhead and ABS greater than the threshold value. In such scenarios, HMIMO outperforms hop by hop MIMO because number of hops for data to reach ABS are less in HMIMO. HMIMO utilized the distance dependant tradeoff. The reason for decrease in number of hops is the hierarchical nature of our algorithm. For small networks our scheme is using energy comparable to hop by hop MIMO. Aggregate energy consumption, when ABS moves from source to destination is the least in HMIMO. Results show approximately 10% energy conservation in HMIMO as compared to hop by hop MIMO. For same target BER Multihop SISO consume maximum energy because it requires maximum number of hops all using a single-input-single-output mode.

In another simulation we find energy expenditure by varying the number of airborne sensors 6. HMIMO outperforms tradtional approaches. When CHs are relatively equidistant from ABS, overall energy consumption in the network decreases.This is attributed to the fact that there is a decrease in number of hops and ABS are now in the ideal *distance-range* to cooperatively communicate with CHs. Even when there the number of ABS increases, HMIMO still outperforms tradtitional approaches because ABS send the data to base station via MIMO communication. This decreases the burden on static nodes deployed in the field.

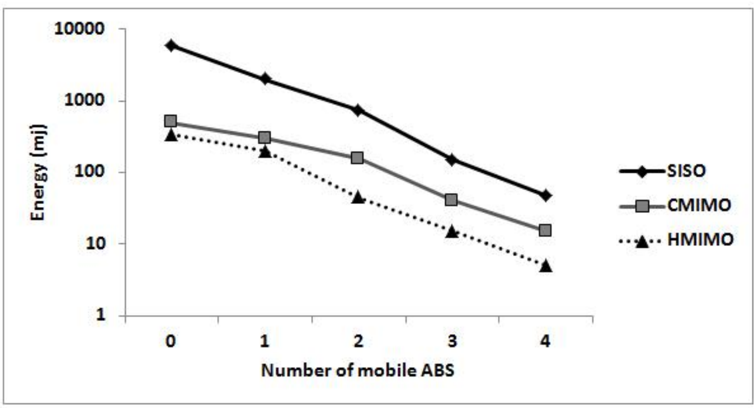


**Fig. 6.** Energy consumption with multiple ABS

## 5.4 Network Lifetime

In this experiment we measure network life time. We calculate network lifetime based on how much a node is used for communication. We analyze this performance metric on the basis of an energy parameter (an arbitrary threshold value).

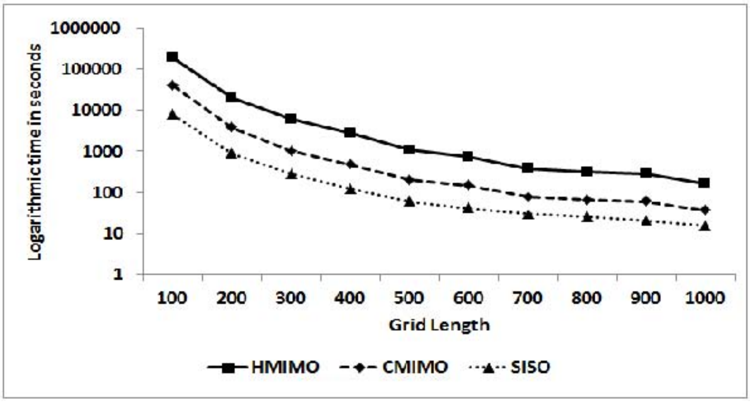


**Fig. 7.** Increase in network lifetime

We measure and compare the algorithms depending upon the time when 50% of nodes reach this threshold value. We introduce a mobile ABS in the network. Figure 7 shows a comparative analysis. Network employing Hierarchical cooperative clustering has a longer life time as compared to CMIMO and SISO. [1] An improvement in energy conservation at the communicating clusters elongated network lifetime manifolds. There is initially an increase in network lifetime with an increase in grid length because the intercluster distance increases which makes MIMO a more favorable communication mode. Nevertheless, when grid length is stretched beyond 500m, the total number of hops also increases, this results in a decrease in network lifetime for our algorithm as well as CMIMO.

## 6 Conclusion

In this work, we presented clustering/routing framework for mobile sinks (airborne sensors) in wireless sensor networks. Our framework uses cooperative MIMO techniques to communicate data to Airborne sensors. Each airborne sensor is equipped with two sensor nodes in order to carry out cooperative communication with clusterheads. Beacon nodes are deployed in the network for synchronization between clusterheads and Airborne sensors. We compared our results with a multihop MIMO and traditional multihop SISO techniques. For a target BER, there is energy conservation when data is routed via HMIMO. We tested our framework for fixed and random movements of ABS for a different number of ABS. Experimental results show approximately 15% energy gain as compared to CMIMO and more than 50% energy savings as compared to traditional SISO.

[1] When comparing the algorithms, distribution of nodes and packets generation is the same.

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