A Heterogeneous-aware Cooperative MIMO Transmission Scheme in WSN

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Abstract— **A heterogeneous-aware cooperative MIMO transmission scheme (HAMS) is proposed to optimize the network lifetime and save energy for energy heterogeneous wireless sensor networks (WSN). This scheme extends the traditional low-energy adaptive clustering hierarchy (LEACH) protocol to enable the cooperative MIMO transmission between the sink and clusters. Through the adaptive selection of cooperative nodes and the cooperative MIMO transmission, HAMS can gain effective performance improvement in terms of taking advantage of the presence of node heterogeneity. Based on the energy consumption model developed in this paper, the optimal parameter to minimize the overall energy consumption is found. Simulation results exhibit that HAMS can effectively save energy and prolong the network time. Furthermore, HAMS displays more resilient in different degree of heterogeneous wireless sensor networks.**

Index Terms— **WSN, heterogeneous-aware, cooperative MIMO, energy efficient**

I. INTRODUCTION

As the development of MEMS-based sensor and low power, radio frequency design, Wireless Sensor Networks (WSN) draws more and more attention recently. WSN is composed of thousands of tiny, battery-powered and low-power sensor nodes. These sensor nodes are confined on-board processing and radio capabilities [1] [2] and they are usually distributed in remote areas where is hard to reach. In most applications, it is a very difficult process for people to replace the embedded batteries once these nodes have been deployed. Therefore, energy efficiency becomes one of the most dominating concerns.

Classical transmission schemes like Direct Transmission and Minimum Transmission Energy can not be guaranteed well-balanced scatter of the energy load in the midst of nodes of the sensor networks. By using Direct Transmission (DT), data from sensor nodes is transmitted directly to the sink, at last, the nodes that far distant from the sink would be dead firstly [3]. In other words, by using Minimum Transmission Energy (MTE), collected data is routed over the minimum-cost route, but the nodes close to the sink tend to exhaust faster. Under either DT or MTE, a part of monitored area will not be monitored for a significant part of the network lifetime, which result in the sensing process of the field be biased. W. Heinzelman [4] proposed a solution called LEACH (Low-energy Adaptive Clustering Hierarchy). By creating clusters dynamically, LEACH effectively distributed the energy load.

Recently, cooperative MIMO transmission schemes in WSN have also been studied intensively. W. Cheng [5] proposed a virtual MIMO based on Space Time Block Code (STBC), of which the training overhead demanded for the MIMO transmission is considered. Through the coordination between the multi-hop routing and the cooperative MIMO transmission, Y. Yuan [6] proposed a cluster-based cooperative MIMO scheme for multi-hop WSN. Under the same Bit Error Rate (BER) requirement and Signal-to-Noise Ratio (SNR), cooperative MIMO systems can be numerous reliable than SISO systems and require less transmission energy [7]. Moreover, on wireless fading channel transmission, cooperative MIMO has shown the potential of enhanced channel capacity [8].

However, most of the results for cooperative MIMO schemes are obtained based on homogeneous sensor networks (the nodes are equipped with the identical amount of energy). We refer them to heterogeneous-oblivious. Actually, in most applications, the sensor networks are not always homogeneous. For example, different types of nodes may, over time, consume different amounts of energy own to the communication characteristics of the radio. Moreover, random events like morphological characteristics or short-term link failures of the field (e.g. uneven terrain) can also cause the sensor nodes heterogeneous in terms of energy [9]. All these issues motivate us to present a new WSN communication protocol for prolonging the network lifetime organized by different levels of heterogeneous sensor nodes.

In this paper, we build an energy heterogeneous wire-

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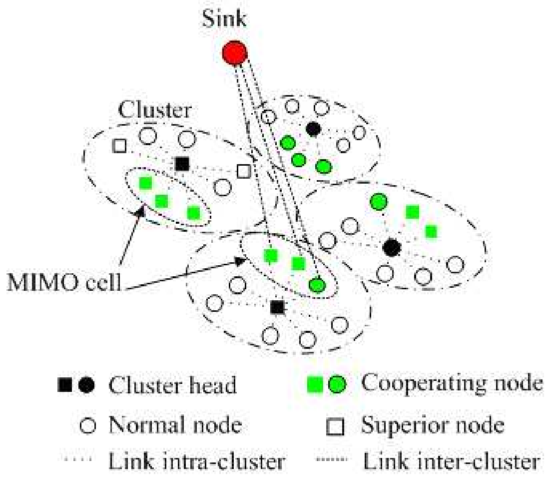

Figure 1. The architecture of HAMS.

less sensor network model. Based on this model, we propose a new transmission schemes called HAMS and provide the optimal number of cluster. Different from the existing protocols, HAMS is a heterogeneous-aware cooperative MIMO transmission scheme. In HAMS, the cooperative node and the cluster head are selected according to the nodes remaining energy adaptively. Simulation results demonstrated that HAMS could dramatically prolong the network lifetime. Furthermore, by studying the sensitivity to heterogeneity parameters, HAMS displays more resilient in different degree of heterogeneous wireless sensor networks.

The rest of the paper is organized as follows: Section II provides the system model and transmission schemes. In section III, we address the energy model and optimal clustering. Section IV presents the simulation results. In the end, we provide our conclusions in Section V.

II. SYSTEM MODEL AND SCHEMES DESIGN

In this section, we describe the system model and the transmission schemes of the heterogeneous WSN in terms of energy.

A. System Model

As the architecture of HAMS shown in Figure 1, in the model, all the nodes are randomly distributed in a square region. We assume some nodes are equipped with more energy resources than other nodes. We name these powerful nodes as superior node and the rest as normal node. All the nodes are divided into clusters like the LEACH protocol. In this model, we separate the nodes into three different roles, i.e., the Common Nodes (CN), the Cluster Head Nodes (CHN), and the Cooperative Transmission Nodes (CTN). We use the CTN and CHN inside the same cluster to form a virtual multiple antennas array (we call it MIMO cell). Binary Phase Shift Keying (BPSK) modulation scheme is also adopted because of its efficiency in cooperative MIMO design [10] [11] In the sake of keeping the model from being over complicated, we omit the base-band signal processing blocks, including source coding and pulse shaping. To simplify the problem we also make the following assumptions:

(1) The dimensions of the monitored region is known and all the nodes are randomly distributed, and they are static.

(2) The sink is equipped with multiple antennas located at the center of the field, and it is not energy limited.

(3) The STBC coding rate is 1.

(4) All the nodes are capable of operating in the following three operation modes: sleep, idle, and active. Nodes can transmit and receive data in active mode, but just receive messages when in idle mode. The energy consumption in idle mode is much less than that in active mode. When a node is in sleep mode, its antenna is in off mode to save energy.

B. Schemes Design

Similar to classical LEACH, the operation of HAMS is grouped into rounds. Each round consists of the following three phases: the cluster and MIMO cell formation phase, the intra-cluster transmission phase and the cooperative transmission phase.

1) Cluster and MIMO Cell Formation Phase: At the beginning of every round, some nodes will be elected as CHN or CTN according to a weighted probability. In order to optimize the network lifetime, HAMS attempt to maintain the constraint of well balanced energy consumption. Intuitively, the superior nodes have to become CHN or CTN more frequently than the normal nodes. Namely, new CHNs and CTNs must be elected with a weighted probability according to the rest of energy of the node. We assume that a percentage of the node population is equipped with more energy resources than remaining the nodes. Let $\alpha (0 \leq \alpha \leq 1)$ be the fraction of the sum of nodes n, which are equipped with λ times more energy than the rest $(1 - \alpha) \times n$ nodes [12].The same as the homogenous surrounding in classical LEACH protocol, the new heterogeneous setting has no effect on the spatial density of the network. Let E_0 be the original energy of each normal sensor, and then the total (initial) energy of the new heterogeneous setting is equal to: $nE_0(1 + \alpha\lambda)$.

The total energy of the system increased by a divisor of $1 + \alpha\lambda$. We regard the extra $n\alpha\lambda E_0$ energy as $n\alpha\lambda$ virtual nodes equipped with the same amount of energy as the normal nodes. Thus, the sum of nodes is increased to $n(1 + \alpha\lambda)$. In order to optimize the network lifetime, the weighted probabilities for normal nodes and superior nodes should respectively equal to:

$$p_{sup} = \begin{cases} \frac{1}{1+\alpha\lambda} \cdot \frac{k_{c-opt}}{n-k_{c-opt}[r \cdot mod(n/k_{c-opt})]}, & flag(i) = 1 \\ \hfill 0, & flag(i) = 0 \end{cases} \tag{1}$$

$$p_{sup} = \begin{cases} \frac{1+\lambda}{1+\alpha\lambda} \cdot \frac{k_{c-opt}}{n-k_{c-opt}[r \cdot mod(n/k_{c-opt})]}, & flag(i) = 1 \\ \hfill 0, & flag(i) = 0 \end{cases} \tag{2}$$

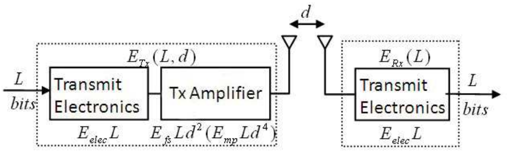

Figure 2. Radio Energy Dissipation Model.

Where n is the sum of nodes, k_{c-opt} is the optimal number of cluster (and the details are illustrated in the next section). r is the current round. If node i has been elected to be CHN or CTN in the most recent $r \cdot mod(n/k_{c-opt})$ rounds, the $flag(i) = 0$, otherwise $flag(i) = 1$. The probability for superior nodes is $1 + \lambda$ times as the normal nodes, which makes the energy load of superior nodes larger than normal nodes.

After the election of CHN and CTN, each cluster head will send a broadcast message to the other sensor nodes in the field using CSMA protocol. The message includes the cluster heads ID and coordinate. Sensor nodes (both CNs and CTNs) join in one of the clusters according to the RSSI (Received Signal Strength Indicator) and send a join-request message. Once received a join-request message from a sensor node, the CHN will record the ID, coordinate and the nodes type (CN or CTN). Then the CHN sets up a TDMA schedule for its cluster members and broadcasts it to each of its cluster members.

On the other side, the sink will broadcast polling message every round at the end of this phase. When the CHN received the polling message, it will reply an answer message, which contains the CHN and the CTNs ID and coordinate. While received a reply message, the sink will group the CHN and CTNs into a cooperative MIMO cell and build a TDMA schedule. The TDMA schedule decides which cooperative MIMO cell transmit first and which the second, etc. Hereto, a new cluster and MIMO cell is formed.

2) Intra-cluster Transmission Phase: Inside a cluster, the cluster member transmits its data to the CHN by multiple frames during its allocated time slot, and sleeps in other slots to save energy. Once received data from its cluster members, the CHN will perform data aggregation in order to remove the redundancy data .

3) Cooperative Transmission Phase: As soon as the CHN have received and aggregated all the data from its cluster members, and it will broadcast the aggregated data to the CTNs in the local cluster. The CHN and corresponding CTNs in the same MIMO cell then encode the transmission sequence by orthogonal STBC [13] code and transmit the data to the sink at the preestablished schedule time slot. We assume that if there are not enough CTNs to form MIMO cell the sink can adapt to form a SIMO system.

III. ENERGY MODEL AND THE OPTIMAL CLUSTERING

Figure 2 shows the radio energy dissipation model. To achieve an receivable Signal-to-Noise Ratio (SNR) within transmitting a $L - bit$ message over a distance d, the energy expended by the radio is given by:

$$E_{Tx}(l,d) = \begin{cases} L \cdot E_{elec} + L \cdot E_{fs} \cdot d^2, & d \le d_0 \\ L \cdot E_{elec} + L \cdot E_{mp} \cdot d^4, & d \ge d_0 \end{cases} \quad (3)$$

where $d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}}$.

According to the distance between the sender and the receiver, we use different amplifier model (E_{fs} or E_{mp}). E_{elec} is the energy dissipated per bit to operate the transmitter or the receiver circuit. In order to receive a $L - bit$ message, the radio expends $E_{Rx} = LE_{elec}$.

For simplicity, we make the following assumptions and constraints:

(1) There are n nodes randomly distributed (subject to uniform distribution) over an area $A = M \times M$ square meters, the sink is located at the center of the field, and the distance of any node to the sink or its cluster head is less than d_0.

(2) As the energy consumption spending on overhead is far less than that of data transmission, we ignore the energy consumption spending on dealing with overhead.

(3) The communication is contention-free and error-free, and the data collected by the CNs in the same cluster are redundant, consequently, it is unnecessary to retransmit all of them and it is reasonable to implement data fusion.

Accordingly, the energy dissipated in the CHN during a round can be given by the following expressions:

$$\begin{aligned} E_{CHN} &= L \cdot E_{elec} + \tfrac{n}{k_c} \cdot L \cdot R(i) \cdot E_{fs} d^2_{CHN-CTN} \\ &+ (\tfrac{n}{k_c} - 1) \cdot L \cdot E_{elec} + \tfrac{n}{k_c} \cdot L \cdot E_{DA} \end{aligned} \quad (4)$$

Where k_c is the amount of clusters, E_{DA} is the data aggregation cost per bit, $d_{CHN-CTN}$ is the mean distance between CHN and CTN, $R(i)$ is the data fusion rate which depends on the sizes of the clusters. If the size of the cluster is bigger, the CHN of this cluster receives more data and erases more correlated data. On the contrary, if the size of the cluster is smaller, its fusion rate is smaller. The fusion rate of the cluster i can be written as:

$$R(i) = \frac{b}{C_{nodes(i)}}, 1 \le b \le C_{nodes(i)} \quad (5)$$

Where $C_{nodes(i)}$ is the amount of the nodes in cluster i, b is an integer and it is independent of $C_{nodes(i)}$. The expected value of $R(i)$ is given by:

$$E[R(i)] = \frac{b}{E[C_{nodes(i)}]} = \frac{bk_c}{n}, 1 \le b \le C_{nodes(i)} \quad (6)$$

The energy consumed in the CN is equal to:

$$E_{CN} = L \cdot E_{elec} + L \cdot E_{fs} \cdot d^2_{CN-CHN} \quad (7)$$

Where d_{CN-CHN} is the average distance between CN and CHN. If the clusters are assumed to be partitioned on an average basis, the average number of nodes and area in each cluster will be n/k_c and M^2/k_c. If each cluster is assumed circular in shape and the CHN is located at the center of the cluster circle, its radius is equal to $M^2/\sqrt{\pi \cdot k_c}$. Based on the above depictions, the expected squared distance between CNs to its CHN is given by:

$$E(d^2_{CN-CHN}) = \iint (x^2+y^2)\rho(x,y)dxdy \tag{8}$$

Where $\rho(x,y)$ is the node distribution at an arbitrary point. In our model, nodes are evenly distributed throughout the field, hence $\rho(x,y)$ is a constant, i.e., $\rho(x,y) = 1/(M^2/k_c)$. Thus, the formula can be simplified as:

$$E(d^2_{CN-CHN}) = \frac{\rho M^4}{2\pi k_c^2} = \frac{M^2}{2\pi k_c} \tag{9}$$

We can also find that $E(d^2_{CHN-CTN}) = E(d^2_{CN-CHN})$. Thus, the energy consumes in the CN can be written as:

$$E_{CN} = L \cdot E_{elec} + L \cdot E_{fs} \cdot \frac{M^2}{2\pi k_c} \tag{10}$$

The energy consumes in the CTH is equal to:

$$E_{CTN} = E_{CN} + L \cdot R(i) \cdot E_{elec} + L \cdot R(i) \cdot E_{fs} \cdot d^2_{CTN-SINK} \tag{11}$$

Where $d_{CTN-SINK}$ is the average distance between the CTN (located at (x_i, y_i), $i = 1, 2, k_{co}$) and sink then the expected value of $d_{CTN-SINK}$ is given by:

$$\begin{aligned} E(d_{CTN-SINK}) &= \int_{-\frac{M}{2}}^{\frac{M}{2}} \int_{-\frac{M}{2}}^{\frac{M}{2}} \sqrt{x_i^2+y_i^2} \cdot \frac{1}{M^2} dxdy \\ &= 0.765 \cdot \frac{M}{2} \end{aligned} \tag{12}$$

The energy cost in a cluster is given by:

$$E_{cluster} \approx \frac{n-k_{co}}{k_c} E_{CN} + E_{CHN} + \frac{k_{co}}{k_c} E_{CTN} \tag{13}$$

Based on the above depictions, the total energy dissipated in the network is equal to: The energy cost in a cluster is given by:

$$\begin{aligned} E_{total} &= k_c \cdot E_{cluster} \\ &= (2n + k_{co}\tfrac{bk_c}{n})LE_{elec} + nLE_{DA} \\ &+ nLE_{fs}\tfrac{M^2}{2\pi k_c} + Lbk_cE_{fs}d^2_{CHN-CTN} \\ &+ k_{co}L\tfrac{bk_c}{n}E_{fs}(0.765\tfrac{M}{2})^2 \end{aligned} \tag{14}$$

We could find the optimal number of the CHNs by differentiating E_{total} with respect to k_c and equating to zero:

$$\begin{aligned} k_{co} &= \tfrac{M \cdot n\sqrt{E_{fs}}}{\sqrt{2\pi b}\sqrt{T}} \\ T &= k_{co}(E_{elec} + E_{fs} \cdot \tfrac{0.765^2 M^2}{4}) \end{aligned} \tag{15}$$

IV. SIMULATIONS

In this section, simulations are performed to evaluate the performance of the HAMS scheme. In the simulation, 100 nodes are randomly distributed on a $M \times M(M = 100m)$ field. The sink is located at the center of the field. The size of the message that cluster members send to their CHN is set to be 4000 bits. Each normal nodes is equipped with a equal energy E_0. Table I is the parameters in our simulations.

TABLE I.
SIMULATION PARAMETERS

Operation	Symbols	Values
Transmitter/Receiver Electronics	E_{elec}	$50nJ/bit$
Data Aggregation	E_{DA}	$5nJ/bit/report$
Data Amplifier if $d_{CTN-SINK} \le d_0$	E_{fs}	$10pJ/bit/m^2$
Data Amplifier if $d_{CTN-SINK} \ge d_0$	E_{mp}	$0.0013pJ/bit/m^4$

A. Network lifetime and distribution of alive node

Figure 3 shows that HAMS prolongs the network lifetime by 42.97% compared to E-MIMO protocol and LEACH protocol. The reason is that through assigning election probabilities of CHN and CTN weighted by the relative initial energy of nodes, HAMS guarantees well balanced distribution of the energy load among nodes of the network.

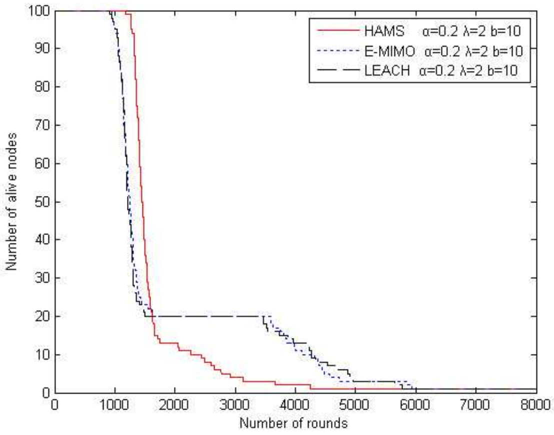

Figure 3. Comparison of NO. of alive nodes.

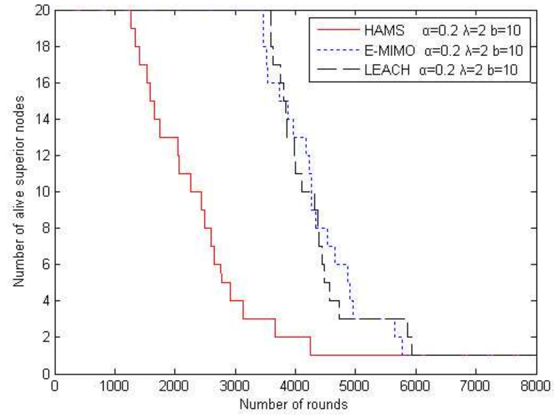

Figure 4. Comparison of NO. of alive superior nodes.

Figure 4 is a detail view of the number of alive superior nodes per round. In E-MIMO and LEACH, the number of alive superior nodes decreased in a very slow process. This is because that all nodes are elected as CHN or CTN according to the same probability. It just guarantees that each node tends to spend the same amount of energy. As a result, normal nodes tend to die fast. By contrast, HAMS guarantees that superior nodes are elected as CHN or CTN more often and tend to consume much more energy. It guarantees that the energy load is well distributed among all the nodes. Therefore, all the nodes die at almost the same speed.

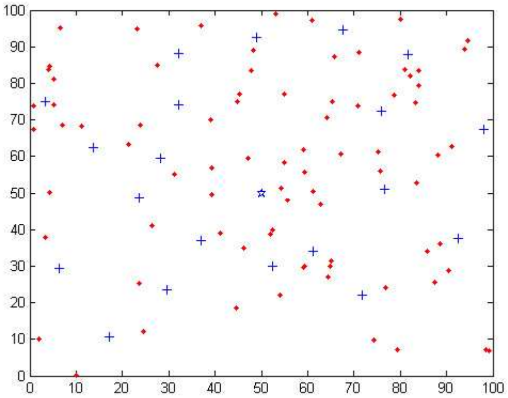

Figure 5. Distribution of alive nodes using HAMS in the presence of heterogeneity: $r = 3000$.

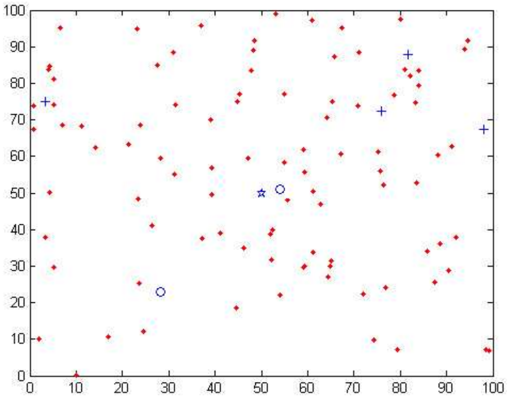

Figure 6. Distribution of alive nodes using E-MIMO and LEACH in the presence of heterogeneity: $r = 3000$

Figure 5 and Figure 6 show a more detail information about the distribution of alive nodes. When operated to 3000 rounds almost all nodes are died (denoted by the red point) except superior nodes in E-MIMO and LEACH (Figure 5). However in HAMS there are a few normal nodes still alive(Figure 6).

B. *Sensitivity for heterogeneity*

In Figure 7, as the value of λ increased, the network lifetime gained by HAMS increases obviously. However, little changes occurred while using E-MIMO and LEACH. The reason is that as the value of λ increased, the added energy to the network becomes bigger. Namely, the degree of the heterogeneity of the WSN becomes larger. HAMS could take full advantages of the extra energy to prolong network lifetime and it behaves more resilient in heterogeneous networks.

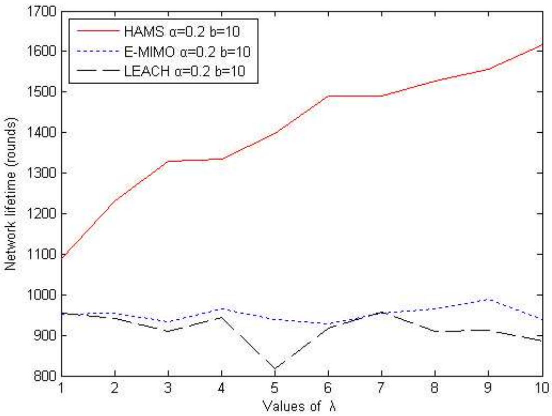

Figure 7. Sensitivity of HAMS, E-MIMO and LEACH for different values of λ

In Figure 8, the network lifetime in HAMS increase linearly with α. On the other side, the network lifetime in E-MIMO and LEACH also increased but more slowly. As the value of α approximate to 100%, the network lifetime in three protocols becomes almost the same greater values. This is because as the value of α increased, the added energy to the network increased accordingly. While α equals 100% the networks become homogeneous and the total energy increased to λ times at the same time.

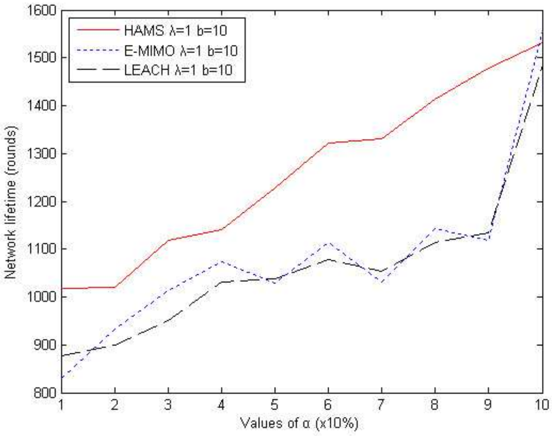

Figure 8. Sensitivity of HAMS, E-MIMO and LEACH for different values of α

Figure 7 and 8 show that in the situation of heterogeneous networks, HAMS displays more resilient than heterogeneous-oblivious protocols in terms of energy.

V. CONCLUSION

In this paper, we proposed HAMS for the application of cooperative MIMO communication in energy heterogeneous wireless sensor networks. In this scheme, nodes in different levels hierarchical network are independently elected as CHN or CTN according to their weighted probabilities. We developed the energy consumption model as well as the optimal number of cluster head based on HAMS protocol. Feasibility of the proposed protocol is verified by simulations. Simulation results show that compared to the existing protocols, HAMS could dramatically prolong the network lifetime. Furthermore, by studying the sensitivity of current protocols to heterogeneity parameters, HAMS displays more resilient in different degree of heterogeneous wireless sensor networks

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