

Effective Location Management of Mobile Actors in Wireless Sensor and Actor Networks

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Abstract—Recent years have witnessed an increasing availability of heterogeneous sensor networks that consist of a large number of resource constrained nodes (sensors) and a small number of powerful resource rich nodes (actors). Such heterogeneous Wireless Sensor Actor Network (WSANs) offer improvement of sensor networks' capacity/coverage, energy conservation and network lifetime. This paper investigates the case where sensors are organized into clusters and mobile actors are used for maintaining an energy efficient topology by periodically manipulating their geographical position. We present an elegant technique that allows actor nodes to find an optimal geographical location with respect to their associated cluster heads such that the overall energy consumed is minimized. The proposed technique includes a weighted cost function based on the residual energy levels of cluster heads that allows the mobile actor to optimally fine-tune its geographical location. We present simulation results that demonstrate a significant increase of network lifetime over the traditional cluster based WSN deployments.

Index Terms—wireless sensor actor networks, mobile actors, clustering, energy efficiency, network lifetime.

I. INTRODUCTION

Wireless Sensor Actor Networks (WSANs) have emerged as the-state-of-the-art technology in data gathering from remote locations by interacting with physical phenomena and relying on collaborative efforts by a few resource rich devices and a large number of low cost devices [2]. In WSANs sensors are low cost resource constrained devices that have limited energy, communication and computation capabilities [3]. Once deployed, sensor nodes collect the information of interest from their on board sensors, perform local processing of these data including quantization and compression, and forward the data to a base station (BS) through a cluster head or a gateway node. Actors, on the other hand are resource rich nodes that are equipped with better processing power, higher transmission power, more energy resources and may contain additional capabilities such as mobility.

Despite the tremendous technological advancements in the field of wireless sensor network (WSNs), energy conservation is still one of the fundamental challenges in WSN system design. In a sensor node, energy is consumed in sensing, computation and processing, however the wireless transceiver consumes a significant amount of energy as compared to all other sources. Most of the WSN deployments are based on application specific data gathering i.e. a large number of sensor nodes send their data to the BS. Clustering is employed as a standard approach for achieving energy efficiency and scalable performance in WSNs [4, 5]. Sensor nodes can be organized hierarchically by grouping them into clusters, where the data is collected and processed locally at the cluster head. Single-hop clustering protocols follow a two-tier architecture, consisting of sensor nodes and cluster heads. In tier one communication, each sensor node sends its data to its local cluster head. The cluster head performs data aggregation, compression and data fusion. In tier two the cluster heads send the processed data to the BS. In protocols where the cluster head selection is performed randomly, the distribution of cluster heads is not well controlled.

Most protocols based on the two-tier architecture use direct communication for sending cluster head data to the BS. For a similar traffic pattern from cluster members, the amount of energy consumed in a cluster head located far away from the sink will be greater than that of the one located closer to the sink [6]. Such a variation in the level of energy consumed among different cluster heads leads to a situation where some cluster heads dissipate far more energy than the others compromising the network life. Intuitively, deployment of resource rich actor nodes could offset some of the higher transmission costs incurred by cluster heads in data transmission to the BS. In such a case, each elected cluster head will associate with an actor node which will forward cluster heads' data to the BS. Since random clustering involves election of new cluster heads in each round, therefore deployment of static actor nodes will not be energy efficient. Such inefficiency may result from variations in distances between the actor node and its associated cluster heads and their respective residual energy levels. The concept

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of mobility solves this dilemma by effective location management of actor nodes thus providing the enhanced energy savings. Mobile platforms equipped with sensor nodes can be utilized to address the connectivity and network lifetime problems in WSN [7]. Fig. 1 illustrates a scenario where mobile actors are used for enhanced energy savings as well as maintaining optimal connectivity in $sensor \rightarrow CH \rightarrow Actor \rightarrow BS$ communication.

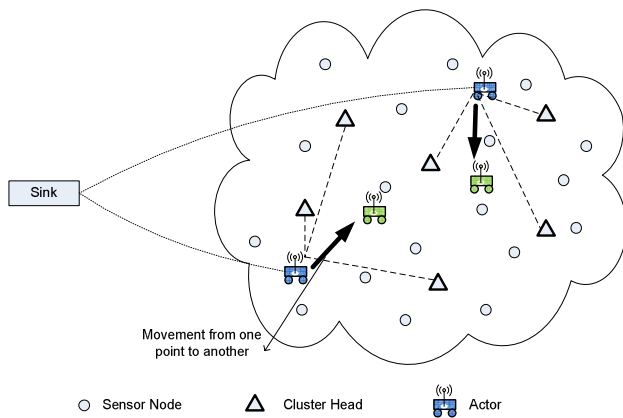


Figure 1: Example of Sensor Field with Cluster Heads and Mobile Actors

This paper proposes a methodology where a mobile actor node relocates itself in each round such that the energy consumed by its associated cluster heads is minimized. A weighted cost based function that accounts for the residual energy levels of associated cluster heads is used to find the new location of the actor nodes.

The rest of the paper is organized as follows. A brief summary of related work is presented in Section II. Section III presents system model and assumptions. Section IV presents details of our proposed technique for location management of mobile actors. Simulation results are discussed in Section V. Finally, our main conclusions and future research directions are highlighted in Section VI.

II. RELATED WORK

The concept of mobile nodes in WSN is relatively new and has been proposed in various contexts. One of the earliest proposed researches used the concept of data mules [8]. Data mules are referred to as mobile entities that collect data from sensors as they pass by the sensor nodes buffer the collected data and drop the data off to the wired access point. Data mules were primarily aimed at collection of non real-time data. The system architecture consisted of fixed wireless sensor nodes at the bottom tier, mobile nodes (Data Mules) at the intermediate layer and access point at the third tier. Data mules at the intermediate layer are considered as serendipitous agents who's movement cannot be predicted in advance. The transport of data from the sensor nodes is dependent on the movement of Data mules. Although such an architecture promises a little overhead and routing free data transport, however, the

transported data is prone to high and variable delay because of unpredictable and random movement of the data mules. In addition to large and unpredictable delays, any unexpected Data Mule failure could result in complete communication breakdown.

Message ferrying is introduced in [9, 10] where a set of special mobile nodes (message ferries) provide communication service for nodes in sparsely connected networks. The transport of data from the sensor nodes to the BS is facilitated by movement of message ferries along predetermined routes where data is collected from the sensor nodes and ultimately dropped off at the BS. Sensor nodes use the knowledge of ferry routes and can adapt their trajectories for transmitting or receiving data. Each sensor node communicates only with the message ferries, therefore all communication costs are reduced to a short distance single-hop communication at the expense of increased message delay.

Research in [11, 12] used mobile nodes for data collection in sparsely connected network. The authors focus on Mobile Element Scheduling (MES) problem [13] which is defined as the scheduling the visits of mobile nodes to the stationary sensor nodes such that there is no buffer overflows or data loss in the stationary sensor nodes. The authors proposed a two-step approach using partitioning-based scheduling. First nodes are partitioned into several groups with respect to their data generation rates and location. Then the schedule for each group is created using the Traveling Salesman Problem (TSP) [14] by calculating a minimum cost tour such that each stationary node receives exactly one visit from the mobile node. As a last step schedules from individual groups are linked to form the entire schedule. Research in [15] investigates the issue of navigating mobile actors within a SANET in response to dynamic sensing events to optimize specific networking performance and/or to balance the actuation workload. The authors investigated the actor navigation problem based on the snapshots of the network topology and proposed a polynomial-time algorithm that computes optimal position of actor nodes in terms of the minimum average hop-count with complete location information.

Mobile actors have also been proposed for data collection in underwater sensor network [16]. The strategy proposed by the authors consists of three major algorithms deal with area partitioning, actor scattering, sub-region optimization, and virtual cluster formation. In the proposed technique, virtual cluster are formed by the local sensor nodes as the mobile actors approach. Each sensor node sends data to its closest cluster head. The work proposed in this paper uniquely addresses the problem of location management of mobile actors in cluster-based WSNs. The main contribution is this paper is focused on devising a simple and effective technique that allows mobile actors to form a topology where cluster heads achieve balanced energy dissipation. The strength of our technique lies in its simplicity that allows mobile actors to optimally calculate their location rendering enhanced energy savings.

III. SYSTEM MODEL AND ASSUMPTIONS

We make the following assumption for our sensor network:

1. The network consists of a large number of resource constrained nodes (referred to as sensing nodes) and small number of resource rich nodes (referred to as actor nodes) with enhanced communication capacity, the ability to recharge their energy source and mobility.
2. We assume that all nodes have means to find out their geographical position.
3. Nodes are dispersed in a 2-dimensional space following a uniform distribution.
4. The base station is located outside the deployment region and has no energy constraints.
5. Once deployed the sensor nodes remain stationary and continue to operate until they completely exhaust their batteries.
6. We use the energy model presented in [17]. In this model the energy required to run the transmitter or receiver electronic circuitry E_{elect} is 50 pJ/bit and ϵ_{amp} the energy to run the transmitter amplifier is 100 pJ/bit/m². The energy expended by a node in transmitting an l -bit message a distance of d is given by,

$$E_{Tx} = lE_{elect} + \epsilon_{amp} d^2 \quad (1)$$

The energy expended in receiving an l -bit message is given by,

$$E_{Rx} = lE_{elect} \quad (2)$$

VI. LOCATION MANAGEMENT OF MOBILE ACTORS

In this section we present our rationale and algorithm for location management of mobile actors. The presented technique is based on the motivation that all cluster heads should have a balanced energy dissipation rate. This objective is achieved by introducing a cost function that allows the actor nodes to adjust their geographical location in such a manner that the overall energy of its associated cluster heads is minimized.

To further elaborate, let's consider the example illustrated in Fig. 2. Four cluster head A, B, C and D are associated with an actor node. The location of each node

is shown below in 'x' and 'y' coordinates. Fig. 2a shows the initial location of actor node and its associated cluster heads. Since the distance from each cluster head to the actor node is different, it is impossible to have comparable energy consumption for all cluster heads. Intuitively, finding a centroid as illustrated in Fig. 2b with respect to all cluster head locations would provide a position where an actor node is at the minimum distance from each cluster head. However, finding a centroid would still lead to an uneven energy consumption rate if the residual energy levels of all associated cluster heads are different. To account for the residual energy levels we introduce a weighted cost based function that allows actor nodes to fine-tune its location based on the residual energy level. Fig. 2c shows the actor node's updated location where it moves closer to the node A that has minimum residual energy.

Now we describe calculation of the cost factor. Table 1 outlines the notation used in the following sections. We assume that cluster heads can be elected using any generic single-hop clustering protocol such as [4, 18, 19]. Once elected, each cluster head will listen for the *Actor Advertisement Messages* (sent by actor nodes). Each cluster head then finds a least cost actor node and sends an *Association Message* to the selected actor node indicating its location coordinates and residual energy level. Upon receiving the *Association Message* the actor node knows that it will forward the cluster heads' data to the BS.

TABLE 1: NOTATIONS USED

Set of actor nodes	A
k^{th} node in A	a_k
Target location coordinates of a_k	(X_k, Y_k)
Set of cluster heads	CH
i^{th} node in CH	ch_i
Location of i^{th} cluster head	(x_i, y_i)
Residual energy of i^{th} cluster head	e_i
Cost factor for i^{th} cluster head	ϵ_i

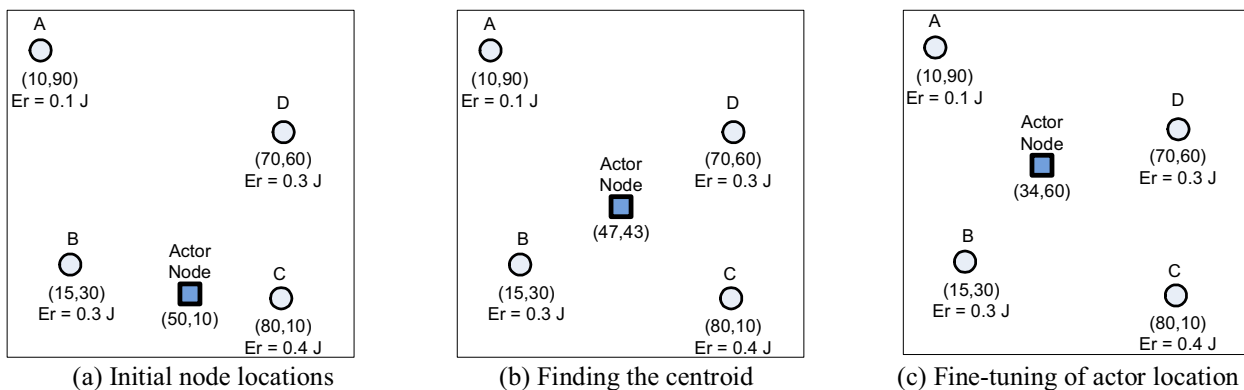


Figure 2: Example illustrating location management of actor node using weighted cost function

Once the actor node receives an *Association Message* from all cluster heads it calculates the cost factor for each cluster head i as follows,

$$\varepsilon_i = \frac{(e_{\max} - e_i)^2 + e_{\min}^2}{(e_{\max} - e_{\min})^2 + e_i^2} \quad (3)$$

Where,

$$e_{\max} = \max(e_i) \quad \text{for } i \in CH^k$$

$$e_{\min} = \min(e_i) \quad \text{for } i \in CH^k$$

The calculated cost factors are used to find the new location coordinates X_k and Y_k from equation (4) and (5) respectively.

$$\frac{d}{dx} \sum_i \varepsilon_i (x - x_i)^2 = 0 \quad (4)$$

$$\frac{d}{dy} \sum_i \varepsilon_i (y - y_i)^2 = 0 \quad (5)$$

The pseudo code of the steps used for location management in cluster based environments is outlined in Algorithm-I.

Algorithm-I:

Begin

$\forall ch_i \in CH$

1. Receive Actor Advertisement Messages
2. Find least cost Actor Node
3. Send Association Message

$\forall a_k \in A$

4. Send Actor Advertisement Message
5. While Timer 'T' is valid
6. Receive Association Messages from cluster heads
7. end While
8. Calculate weighted energy cost ε_i for all associated cluster heads
9. Calculate new X_k and Y_k
10. Move to new position (X_k, Y_k)

End

V. SIMULATION RESULTS

This section presents the performance analysis of our proposed technique. We assume ideal conditions at the physical level such that the probability of wireless interference is negligible. The network simulation model was built using MATLAB. We use the clustering algorithm presented in [18]. We also assume that the network consists of a small number of actor nodes (ranges from 1% to 3% of the network size). Simulation proceeds in data collection rounds. Each data collection round consists of cluster set up and actor node selection phase. In each round, each non cluster head node sends one data packet to its cluster head. The cluster head

performs in-network processing by aggregating the data received from its member nodes and forwards this data to the actor node. Finally, the actor node forwards data received from its associated cluster head to the BS. We also assume that the actor nodes do not transmit any data while they are moving from one location to another. Mobility feature is only used to optimize the energy conservation. To evaluate the effectiveness of the proposed technique, we use a number of performance metrics related to network life and energy conservation. The most important performance metric is network lifetime. We measure network life in data collection rounds. The second performance metric is average cluster head energy consumed per round. We also provide results that demonstrate the evidence for balanced energy dissipation. Table 2 summarizes the important simulation parameters used.

TABLE II: SIMULATION PARAMETERS

Sensor Deployment Area	100 x 100 m
BS Location	(50,175) m
Number of Nodes (N)	200 , 400
Data Packet Size	4000 bits
Control Packet Size	25 bytes
Initial Energy of Actors	10 J
Initial Energy of Sensors	0.5 J
Number of Actor Nodes	1 % to 3% of N
E_{elect}	50 nJ/bit
ε_{mp}	100 pJ/bit/m ²

We first evaluate the performance of the proposed algorithms with respect to the network lifetime metric. We measure the network life in number of data collection rounds till very first node runs out of its energy or a percentage of nodes completely exhaust their battery and die. Fig. 3 and 4 shows the network life in data collection rounds plotted against the number of active nodes for network size of 200 and 400 nodes respectively.

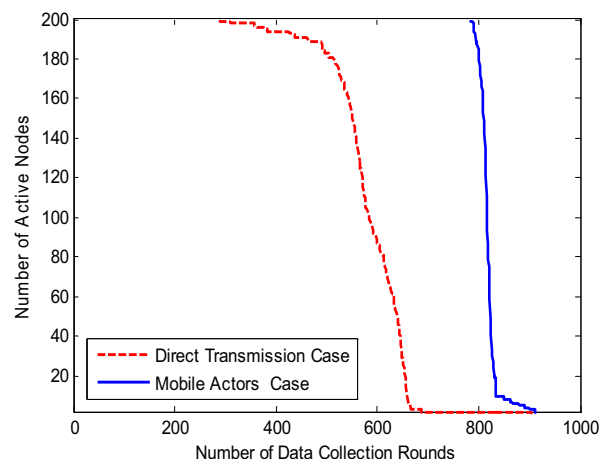


Figure 3: Network life (200 Nodes Network)

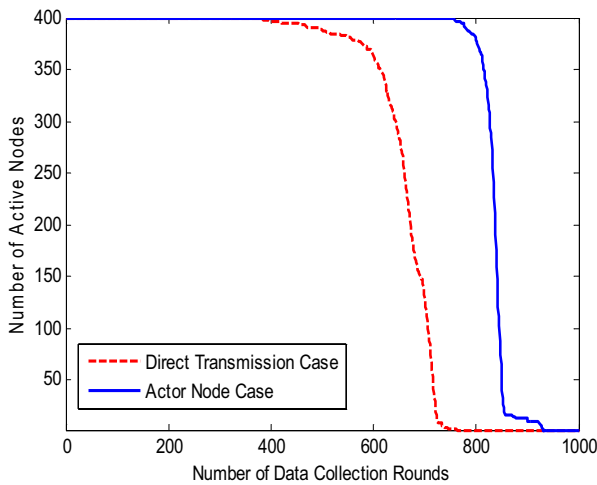


Figure 4: Network life (200 Nodes Network)

It can be observed from Fig. 3 and 4 that by using mobile actors the network lifetime (measured to the first node death) is increased more than 100% as compared to the direct transmission case. As discussed in Section 2,

cluster heads consume energy at a higher rate compared to plain sensor nodes because of high transmission and processing costs. Mobile actors contribute to reduction in transmission cost by allowing CHs to transmit at a short distance. The cost function proposed in this paper allows mobile actors to optimize their location with respect to energy minimization while considering residual energy level. It is also worth noticing the sharp slope for mobile actor’s case which is result of balanced energy dissipation in the sensor nodes.

Fig. 5 shows the distribution of residual energies of sensor nodes in the form of contour and surface plot along with their x and y coordinate for network sizes of 200 and 400 nodes. These measurements are collected at the first node death. The residual energy is represented by E_r . It can be clearly observed that there are no significant variations of residual energy levels in sensor nodes in the deployment region. The level of surface plots is indeed plain and there is no gradient with respect to the distance to the BS. A gradient is normally observed in unbalanced energy dissipation case.

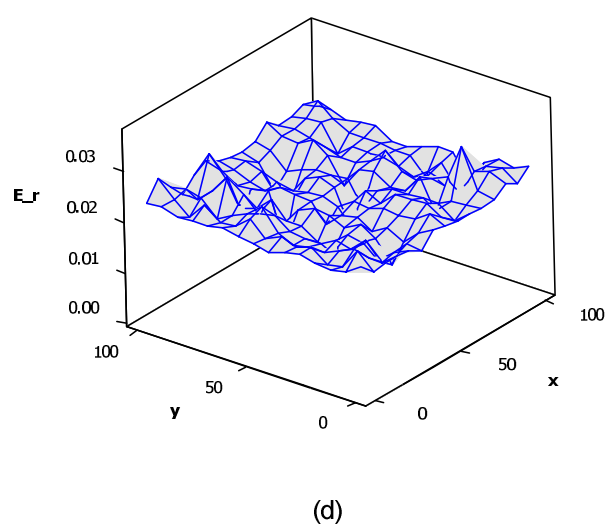
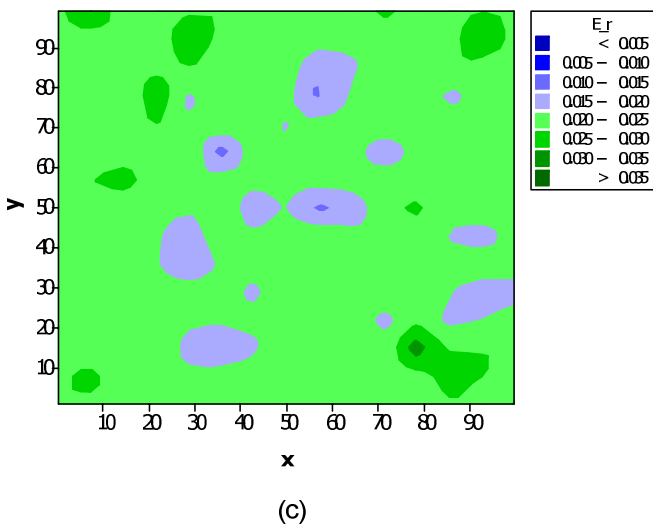
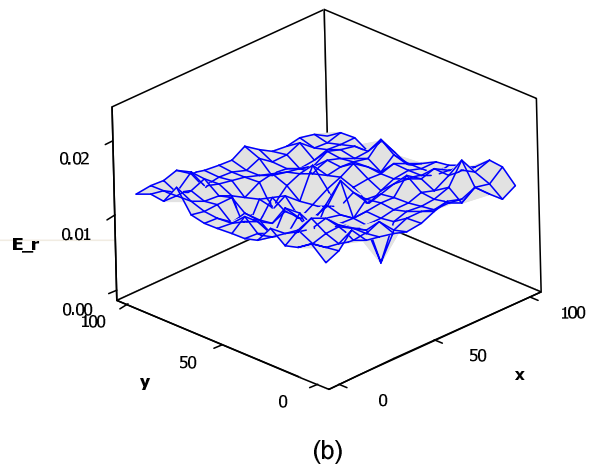
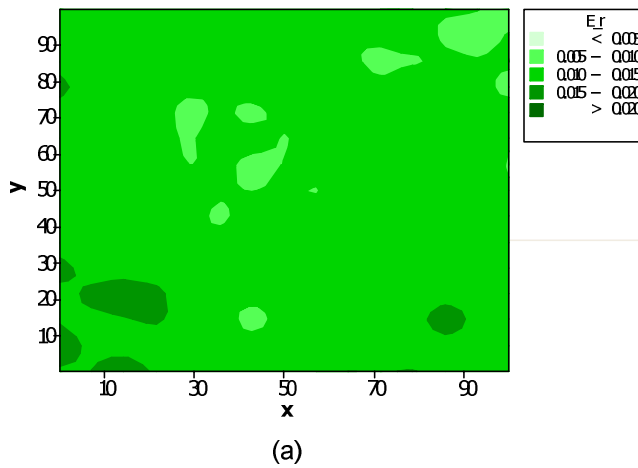


Figure 5: Contour and surface plots showing distribution of residual energy levels in sensor nodes at first node death, (a) and (b) Network size = 200 nodes, (c) and (d) Network size = 400 nodes

Such a scenario occurs because sensor nodes close to the sink will have more energy than that of those located far from the BS. By strategically mobilizing the actor nodes every clustering round aid in minimizing the variance of energy consumed by each cluster head. As a result, the overall energy dissipation in the network remains balanced.

The claim of balanced energy consumption as a result of using mobile actors is further exemplified by recording the standard deviation of residual energy levels of sensor nodes. Fig. 6 illustrates the standard deviation of residual energy levels in sensor nodes at each round. Balanced energy consumption in the network is also related to the spread of energy levels (measured by standard deviation). It can be clearly observed that as the rounds advance, no significant change in standard deviation is noted. For the network size of 200 and 400 nodes the standard deviation stays around .0038 J and .006 J respectively.

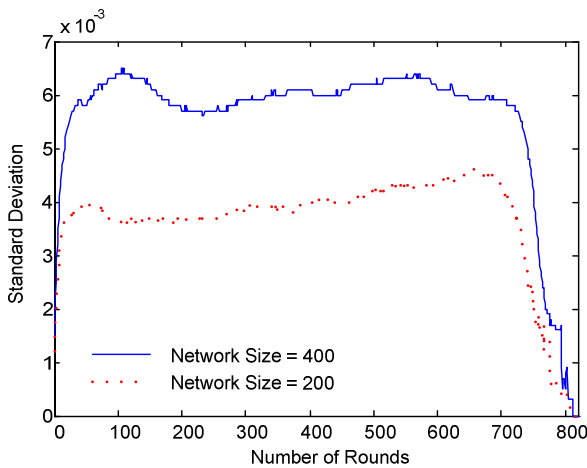


Figure 6: Standard deviation of residual energy levels in sensor nodes

We also investigated the optimal number of actor nodes for the two network sizes of 200 and 400 nodes. Fig. 7 and 8 show how network life is affected as a result of varying the number of actor nodes. The x-axis denotes the number of mobile actors in the system and the y-axis denotes the number of rounds when the first node runs out of its energy. The number of mobile actors is varied from 1% of network size to 3.5% of the network size. It can be observed from both Fig. 7 and 8 that a value of 2% (4 in 200 nodes network and 8 in 400 nodes network) provides the best results. When the number of mobile actors is 1% of the network size the number of associated cluster heads per actor node is large. Hence it may lead to situations where the resultant topology cannot be further optimized. Therefore adding a small number of actor nodes further increases energy savings resulting in enhanced network lifetime. Conversely, a relatively large number of actor nodes will result in more overhead messages. Hence it is desirable to have a minimum number of actor nodes that provide optimal coverage per cluster head. From the simulations we conclude that the best value for network lifetime is given by when the number of mobile actors is 2% of the network size.

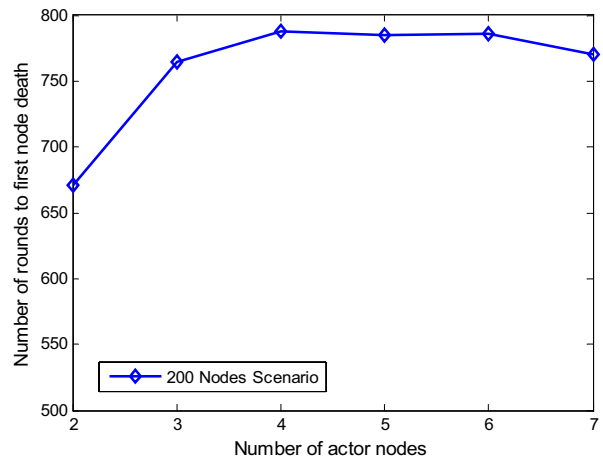


Figure 7: No. of actors vs. network life in first node death (200 Nodes Networks)

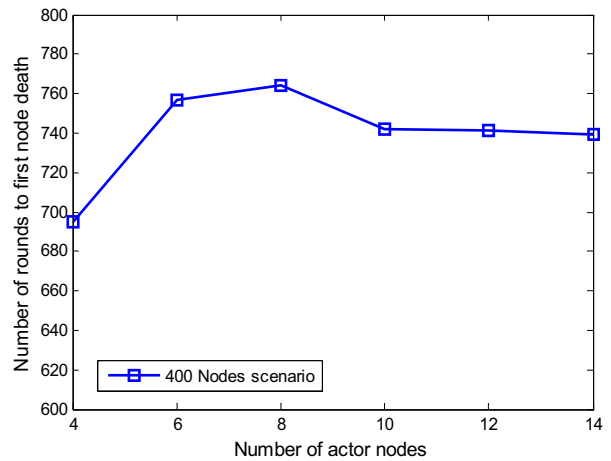


Figure 8: No. of actors vs. network life in first node death (400 Nodes Networks)

Fig. 9 illustrates the mean cluster head energy consumed per round for mobile actors and direct communication scenario. The statistics are collected using 100 independent runs. It is clearly observed that the cluster heads in former case consume far less energy (almost 50%) because of shorter distance transmission to the mobile actors as compared to the direct communication case. Hence the overall effect in network lifetime gain is quite significant.

VI. CONCLUSIONS AND FUTUREWORK

In this paper we have presented a simple and elegant technique to use mobile actor nodes for extending the network lifetime in cluster-based WSNs. We have shown that by deploying a small number of resource-rich mobile nodes the network lifetime can enhance in excess of 100% as compared to flat single-hop clustering. We presented a weighted cost based function that allows mobile actors to fine-tune their location by considering the residual energy levels of associated cluster heads. Strategic movement of actor nodes allows load balancing among the cluster head resulting in reducing the energy consumption and enhancing the network life. We will incorporate accurate radio interference model and means

for estimating link reliability. Such modifications will allow modeling a realistic communication environment. We intend to investigate effects of different mobility models in our future research.

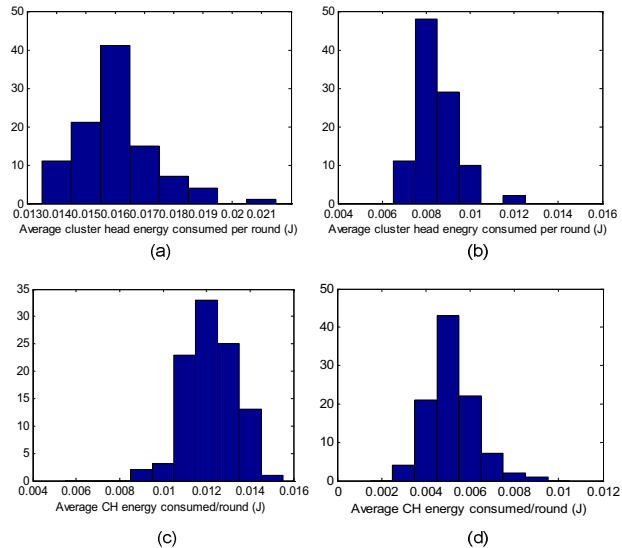


Figure 9: Histogram for average cluster head energy consumed per round (J). (a) 400 Nodes Direct communication case (b) 400 Nodes with mobile actors (c) 200 nodes with direct communication case (d) 200 Nodes with mobile actors.

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