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Maximum Lifetime Data Aggregation Problem in Wireless Sensor Networks

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Abstract
This paper studies energy efficient routing for maximum lifetime data aggregation problem in wireless sensor networks. We consider a network of energy-constrained sensors that are deployed over a region. Each sensor periodically produces information as it monitors its vicinity. The main process in such a network is the systematic aggregation and transmission of sensed data to a base station for further processing. During data aggregation process, sensors perform in-network aggregation of data packets enroute to the base station. The main challenge in data aggregation is to maximize the relative network lifetime, given the energy constraints of the sensors. Our goal is to maximize the lifetime of a wireless sensor network, given the location of n sensors and a base station together with the available energy at each sensor. We have done simulations for single and multiple base stations to solve the data aggregation problem with aggregation in wireless sensor networks. Our simulation results demonstrate that we obtain better performance than the existing approaches in terms of relative network lifetime.

Keywords: *sensor network, linear programming, aggregation, relative network lifetime*

1. INTRODUCTION

The past few years have seen the rapid proliferation of small wireless devices for personal communication. Such devices are achieving increasing levels of connectivity with large networks such as the Internet, and among themselves as peer-to-peer networks [22]. Alongside these recent advancements in wireless networks, there have been significant developments in low-power digital circuit design, sensing technology, and Micro Electro-Mechanical Systems (MEMS) [23]. The amalgamation of all these technologies has sparked great interest in creating miniature units that combine physical sensing and wireless communication - effectively, a wireless micro-sensor device. Large numbers of such sensor nodes can be disseminated in a region, and can automatically collect and analyze data from the physical environment. A large network of such nodes is collaborating their sensing efforts and it offers significant new opportunities in the study, monitoring, and maintenance of physical environments [8]. Like most wireless systems, sensor networks must effectively manage the power consumption of individual nodes to achieve satisfactory system lifetimes. It is imperative to design low-power hardware and power-aware operating systems so that power savings can be achieved at the node level.

The applications of sensor networks are many. They are used in military, health, environment, underwater, biological, and in many other fields where sensing of the data is required. The order of nodes may vary from a dozen in a home appliance to millions in a military field. How ever these wireless sensor networks differ from Ad-hoc networks. The differences between sensor networks and ad-hoc networks are outlined below:

- The number of sensor nodes in a sensor network can be several orders of magnitude higher than the nodes in an ad hoc network.
- Sensor nodes are densely deployed.
- Sensor nodes are prone to failures.
- The topology of a sensor network changes very frequently.

- Sensor nodes mainly use broadcast communication paradigm whereas most ad hoc networks are based on point-to-point communications.
- Sensor nodes are limited in power, computational capacities, and memory.
- Sensor nodes may not have global identification (ID) because of the large amount of overhead and large number of sensors.

  The protocols which are being currently used for the traditional Ad-hoc Networks can not be used for the sensor networks because:
- The topology of a sensor network changes from time to time.
- Sensor networks use broadcast communication while Ad-hoc networks use point-to- point communication.
- The failure rate of the nodes is quite high.
- Because of large scalability, nodes can not have a global ID as in Ad-hoc networks.
- Power consumption is of critical importance in sensor networks.

As the number of nodes in a sensor networks is very high, multi-hop communication gives more advantage than traditional single hop communication as it consumes less power. Again power consumption of each node is critical, while a compromise is made on Quality of Service [16]. Also the node architecture should be flexible in the sense that the user must have an option of extending the network lifetime at the expense of lower efficiency or higher transmission delay. Recent years have witnessed a growing interest in the application of wireless sensor networks in unattended environments. Nodes in such applications are equipped with limited energy supply and need careful management in order to extend their lifetime. In order to conserve energy, many of the routing protocols proposed for wireless sensor networks reduce the number of transmitted packets by pursuing in-network data aggregation. Almost all of the aggregation schemes presented in the literature strive to save sensor's energy while considering unconstrained data traffic. However, aggregation extends the queuing delay at the relay nodes and can thus complicate the handling of latency-constrained data.

Data fusion or aggregation has emerged as a basic tenet in sensor networks. The key idea is to combine data from different sensors to eliminate redundant transmissions, and provide a rich, multi-dimensional view of the environment being monitored. This paradigm shifts the focus from address-centric approaches finding routes between pairs of end nodes to a more data-centric approach finding routes from multiple sources to a destination that allows in-network consolidation of data [3]. There are several approaches to save the lifetime of the wireless sensor network. Out of those approaches data aggregation turns out to be one of the outstanding approaches which promises to be considerable energy saving, as it has emerged as a basic approach in WSN's in order to reduce the number of transmissions among sensor nodes and base station and hence minimizing the overall power consumption in the network. Data aggregation is affected by several factors such as the placement of aggregation points, the aggregation function, and the density of the sensors in the network. The determination of an optimal selection of aggregation point is extremely important. The number of packets transmitted from one node to another also affects the battery lifetime of the networks. The TinyOS operating system that can be used by an ad-hoc network of sensors locates each other and route data. The implementation of five basic database aggregates, i.e. count, min, max, sum, and average, based on the TinyOS platform and such a generic approach for aggregation leads to significant power (energy) savings. A class of aggregation is particularly well suited to the in-network regime. Such aggregates can be expressed as an aggregate function f over the sets a and b, such that $f\ (a \cup b) = g(f(a), f(b))$ [18]. We have to minimize the energy expended by the sensors during the process of data gathering. Directed diffusion is based on a network of nodes that can co-ordinate to perform distributed sensing of an environmental phenomenon. Such an approach achieves significant energy savings when intermediate nodes aggregate responses to queries [9]. The SPIN protocol uses meta-data negotiations between sensors to eliminate redundant data transmissions through the network. In PEGASIS [19], sensors form chains so that each node transmits and receives from a nearby neighbor. Gathered data moves from node to node, gets aggregated and is eventually transmitted to the base station. Nodes take turns to transmit so that the average energy spent by each node gets reduced. A hierarchical scheme based on PEGASIS that reduces the average energy consumed and delay incurred in gathering the sensed data. Lindsey et al [31] describe a hierarchical scheme based on PEGASIS that reduces the average energy consumed and delay incurred in gathering the sensed data. The rest of this paper is organized as follows. Modeling and problem formulation has been done in section 2. Section 3 presents the approach to solve MLDA, linear program formulation, and algorithms. Section 4 presents simulations results and performance analysis. Section 5 concludes the paper. Sections 6 and 7 present the related work and figures.

2. MODEL AND PROBLEM FORMULATION

2.1 System Model

To solve any practical problem in this world, we need to model the system properly. To solve this MLDA problem, the wireless sensor network is modeled as follows. Consider a network of n sensor nodes 1, 2, 3 …. , n and a base station node t labeled $n + 1$ distributed over a region. The locations of the sensors and the base station are fixed and known prior. Each sensor produces some information as it monitors its vicinity. We assume that each sensor generates one data packet per time unit to be transmitted to the base station. For simplicity, we refer to each time unit as a round. We assume that all data packets have size k bits. The information from all the sensors needs to be gathered at each round and sent to the base station for processing. We assume that each sensor has the ability to transmit its packet to any other sensor in the network or directly to the base station. Further, each sensor i has a battery with finite, non-replenishable energy E_i. Whenever a sensor transmits or receives a data packet, it consumes some energy from its battery. The base station has an unlimited amount of energy available to it. Our energy model [15] for the sensors is based on the first order radio model. A sensor consumes **E**elec = 50nJ/bit to run the transmitter or receiver circuitry and **E**amp = 100pJ/bit/m² for the transmitter amplifier.

Thus, the energy consumed by a sensor i in receiving a k-bit data packet is given by,

$$Rx_i = E_{elec}.k \quad (1)$$

while the energy consumed in transmitting a data packet to sensor j is given by,

$$Tx_{i,j} = E_{elec}.k + E_{amp}.d_{i,j}^2.k \quad (2)$$

where $d_{i,j}$ is the distance between nodes i and j.

2.2 Problem Statement

Data aggregation performs in-network fusion of data packets, coming from different sensors enroute to the base station, in an attempt to minimize the number and size of data transmissions and thus save sensor energies. Such aggregation can be performed when the data from different sensors are highly correlated.

Given the location of sensors and the base station and the available energy at each sensor, we are interested in finding an efficient manner in which the data should be collected and aggregated from all the sensors and transmitted to the base station, such that the system lifetime is maximized. This is the maximum lifetime data aggregation (MLDA) problem.

3. MAXIMUM LIFETIME DATA AGGREGATION

3.1. Solving MLDA (One Base Station)

The lifetime T of the system is defined to be the number of rounds until the first sensor is drained of its energy. A data gathering schedule specifies, for each round, how the data packets from all the sensors are collected and transmitted to the base station. For brevity, we refer to a data gathering schedule simply as a schedule. Observe that a schedule can be thought of as a collection of T

directed trees, each rooted at the base station and spanning all the sensors i.e. a schedule has one tree for each round. The lifetime of a schedule equals the lifetime of the system under that schedule.
The solution to this problem is obtained as organized in the following steps given below.

1. We need to find out the edge capacities between different nodes with constraint that the battery lifetime of every node is maximized.
2. Obtain the corresponding aggregation tree for each round.

The edge capacities between different nodes for the given network with the given constraint that the battery lifetime of each node is maximized, is obtained by solving linear programming of that network with that given constraint. After solving the linear program, get the corresponding aggregation trees.

3.2 Linear Program Formulation for WSN

[1] Consider a schedule S with lifetime T rounds. Let $f_{i,j}$ be the total number of packets that node i (a sensor) transmits to node j (another sensor or base station) in S. Since any valid schedule must respect the energy constraints at each other sensor, for $i = 1, 2, 3 \ldots, n$, is given by

$$\sum_{j=1}^{n+1} f_{i,j}.Tx_{i,j} + \sum f_{j,i}.Rx_i \leq E_i \qquad (3)$$

Each sensor, for each one of the T rounds, generates one data packet that needs to be collected, possibly aggregated, and eventually transmitted to the base station. The schedule S induces a flow network $G = (V, E)$. The flow network G is a directed graph having as nodes all the sensors and the base station, and having edges (i, j) with capacity $f_{i,j}$ whenever $f_{i,j} > 0$.

Theorem [1]. Let S be a schedule with lifetime T, and let G be the flow network induced by S. Then, for each sensor s, the maximum flow from s to the base station t in is $G \geq T$.
The corresponding linear programming for the given constraint is given in [1] in which some other constraints to ensure the flow conservation of the packets at each node are also included.

3.3. Obtaining Aggregation Tree

After solving the linear programming, the aggregation tree for the network is obtained as follows [1]. Given an admissible flow network G with lifetime T and a directed tree A rooted at the base station‘t’ (A need not span all nodes in G and not necessarily aggregation tree) with lifetime f, we define the (A, f)-reduction G' of G to be the admissible flow network that results from G after reducing by f, the capacities of all of its edges that are also in A., G' = (A, f). This reduction of the G' is possible if maximum flow from a node to the base station‘t’ in G' is $\geq T - f$ for each vertex ‘v’ in the G'. Note that A does not have to span all the vertices of G, and thus it is not necessarily an aggregation tree. Moreover, if A is an aggregation tree, with lifetime f, for an admissible flow network G with lifetime T, and the (A, f)-reduction of G is feasible, then the (A, f)-reduced flow network G' of G is an admissible flow network with lifetime $T - f$. Therefore, by using a simple iterative procedure, we can construct a schedule for an admissible flow network G with lifetime T, provided we can find such an aggregation tree A.

GETTREE Algorithm

GETTREE (Flow Network G, Lifetime T, Base Station t)

- initialize $f \leftarrow 1$
- let $A = (V_0, E_0)$ where $V_0 = \{t\}$ and $E_0 = \phi$
- while A does not span all the nodes of G do
- for each edge $e = (i, j) \in G$ such that $i \notin V_0$ and $j \notin V_0$ do
- let A' be A together with the edge e

- // if the $(A',1)$-reduction of G is feasible
- let G_r be the $(A',1)$- reduction of G
- if MAXFLOW$(v,t,G_r) \geq T-1$ for all nodes v of G
- // replace A with A'
- $V_0 \leftarrow V_0 \cup \{i\}, E_0 \leftarrow E_0 \cup \{e\}$
- break
- let $c_{\min}$ be the minimum capacity of the edges in A
- let G_r be the $(A, c_{\min})$–reduction of G
- if MAXFLOW$(v,t,G_r) \geq T - c_{\min}$ for all nodes v of G
- $f \leftarrow c_{\min}$
- replace G with the (A, f)-reduction of G
- return f , G , A

The GETTREE algorithm is used to get an aggregation tree A with lifetime $f \leq T$ from an admissible flow network G with lifetime T. Throughout this algorithm, we maintain the invariant that A is a tree rooted at t and the (A, f)-reduction of G is feasible. Tree A is formed as follows. Initially A contains just the base station. While A does not span all the sensors, we find and add to A an edge $e = (i, j)$, where $i \notin$ A and j $\in$ A, provided that the (A', f)-reduction of G is feasible. Here A' is the tree A together with the edge e, and f is 1 or the minimum of the capacities of the edges in A'.

3.4. Obtaining the Schedule

Next, how to get a schedule from an admissible flow network is discussed. A schedule is a collection of directed trees that span all the sensors and the base station, with one such tree for each round. Each such tree specifies how data packets are gathered and transmitted to the base station. These trees are called aggregation trees. An aggregation tree may be used for one or more rounds; the number of rounds is indicated by f , that an aggregation tree is used, by associating the value f with each one of its edges; f is called to be the lifetime of the aggregation tree.

Finally, a collection of aggregation trees from an admissible flow network G with lifetime T can be computed by using the GETSCHEDULE algorithm as given below, such that T data packets from each of the sensors are aggregated and transmitted to the base station t.

GETSCHEDULE Algorithm

GETSCHEDULE (Flow Network G, Lifetime T, Base Station t)

$$
\begin{array}{l}
S \;\leftarrow\; 0 \\
\textit{while } T > 0 \textit{ do} \\
\quad [f, G, A] \;\leftarrow\; GETTREE(G, T, t) \\
\quad S \;\leftarrow\; S \cup \{A\} \\
\quad T \;\leftarrow\; T - f \\
\textit{return } S
\end{array}
$$

This means that the GETSCHEDULE algorithm can always find a sequence of aggregation trees that can be used to aggregate and transmit T data packets from each sensor to the base station.

3.5. Solving MLDA (Two Base Stations)

The Concept of Multiple base stations is a new concept and seems like a complex process, but we are going to prove that it is one of very nice, innovative concept in Wireless Sensor Networks. The performance of the MLDA is calculated by determining the optimized relative lifetime of the network for different number of nodes in the network. From the plot 1 in which relative lifetime of the network against the number of nodes was plotted, it is evident that as the number of nodes in the network is less than 500, the relative lifetime of the wireless sensor network will be reasonable. On the other hand, as the number of nodes in the network increases, then the Optimum life time of wireless sensor network decreases. This degradation in performance of WSN can be improved by incorporating multiple base stations.

Here the solution to this problem is obtained in modified way as compared to that of single base station. Each node in the network sends its packets to one of the base station, i.e., for two base stations we will get two sets of nodes. Deciding a particular node to which particular base station it belongs is as follows.

1. For each node i, determine the number of hops required to send its packets to the two base stations.
2. After determining the number of nodes, include the node ' i ' in the set of nodes belonging to one of the two base stations to which minimum no. of hops is required to reach it.
3. For two base stations, there are two sets of dissimilar nodes.

The data aggregation trees for two base stations are obtained similar to single base station scenario. The data aggregation tree is obtained follows.

1. We need to find out the edge capacities between different nodes with constraint that the battery lifetime of every node is maximized.
2. Obtain the corresponding aggregation tree for each round.

The edge capacities between different nodes for the given network with the given constraint that the battery lifetime of each node is maximized, is obtained by solving linear programming of that network with that given constraint. After solving the linear program, get the corresponding aggregation trees.

3.6. Solving MLDA (Three Base Stations)

Here the solution to this problem is obtained in modified way as compared to that of single base station. Each node in the network sends its packets to one of the base stations, i.e., for three base stations we will get three sets of nodes. Deciding a particular node to which particular base station it belongs is as follows.

1. For each node i, determine the number of hops required to send its packets to the three base stations.
2. After determining the number of nodes, include the node ' i ' in the set of nodes belonging to one of the three base stations to which minimum no. of hops is required to reach it.
3. For three base stations, there are three sets of dissimilar nodes.

The data aggregation trees for three base stations are obtained similar to single base station. The data aggregation tree is obtained follows.

1. We need to find out the edge capacities between different nodes with constraint that the battery lifetime of every node is maximized.
2. Obtain the corresponding aggregation tree for each round.

The edge capacities between different nodes for the given network with the given constraint that the battery lifetime of each node is maximized, is obtained by solving linear programming of that network with that given constraint. After solving the linear program, get the corresponding aggregation trees.

4. SIMULATION RESULTS AND ANALYSIS

4.1. Simulation Model

The simulation was carried out with MATLAB 7.1. For solving the linear programming, Optimization toolbox of MATLAB was used.

This procedure of solving MLDA is classified in steps. First of all, solving any problem on a particular system requires the system to be modeled. In this simulation model, a network of 'n' sensor nodes 1, 2, 3,…., n and three base stations t_1, t_2, t_3 labeled $n+1$, $n+2$, $n+3$ distributed over a region was considered. The locations of the sensors and the base stations are fixed and known prior. We assume that each sensor generates one data packet per time unit to be transmitted to any of the base station. We assume that all data packets have size k =1000 bits. We assume that each sensor has the ability to transmit its packet to any other sensor in the network or directly to the base stations. Further, each sensor i has a battery with finite, non-replenishable energy E_i =1J. Whenever a sensor transmits or receives a data packet, it consumes some energy from its battery. The base stations have an unlimited amount of energy available to it. Our energy model for the sensors is based on the first order radio model. A sensor consumes E_{elce}= 50nJ/bit to run the transmitter or receiver circuitry and E_{amp} = 100pJ/bit/m² for the transmitter amplifier.

For single base station, all the nodes send their packets to that single base station. For two base stations, all the nodes separate between two base stations depending on their distance to both. This also applies to three base stations.

4.2. Results for Single Base Station

The performance of the MLDA is calculated by the relative lifetime of each node in the network. The relative lifetime of a sensor node is defined as the ratio of the average lifetime of a node after being a part of the network to the lifetime of an isolated node. The average lifetime of a node after being a part of network is nothing but the number of packets a node can generate and it is always less than that of isolated node. This reduction is due to extra overhead resulting from the reception of packets from other nodes which are far away from base station as compared to it and transmission of its packets to the higher level nodes. This average lifetime of the network is plotted against the number of nodes as shown in Figure 1. From the plot, it is evident that as the number of nodes in the network are less than 250, the average lifetime of the wireless network increases. On the other hand, as the number of nodes in the network increases, then the average lifetime of wireless sensor network decreases. So this problem of decreasing lifetime should be avoided through improving or modifying this MLDA algorithm. The Relative Network lifetime comparison between MLDA for single base station and LRS is illustrated in Figure 2. The simulation results show that MLDA for single base station reaches almost 2.32 times relative network lifetime than LRS. It proves that the route strategy for MLDA leads to more balanced energy consumption and consequently increases nodes lifetime as well as network lifetime.

4.3 Results for Two Base Stations

For this case also, the performance of the MLDA is calculated by determining the relative lifetime of each node in the network. This relative lifetime of the network is plotted against number of nodes as shown in the Figure 3 for both single and two base stations case. From the graph, it is evident that as the number of nodes in the network is less than 600, the average lifetime of the wireless network remains almost constant, which showing a significant improvement in performance. On the other hand, as the number of nodes in the network increases beyond 600, then the average lifetime of wireless sensor network decreases. The performance of MLDA in WSN for two base stations is significantly improved as compared to the single base station.

4.4 Results for Three Base Stations

For this case also, the performance of the MLDA is calculated by determining the relative lifetime of the network as defined in the section 4.3. This relative lifetime of the network is plotted against number of nodes as shown in the Figure 4, for all three cases of base stations i.e., single, two and three. From the graph, it is evident that as the number of nodes in the network is less than 700, the average lifetime of the wireless network remains almost constant, which showing a significant improvement in performance. On the other hand, as the number of nodes in the network increases beyond 700, then the average lifetime of wireless sensor network decreases. By observing the Figure 4, it is very clear that the performance of MLDA in WSN for three base stations is slightly improved as compared to that of two base stations case. However this performance improvement highly depends upon the relative locations of base stations with respect to each other which were discussed broadly in the next section showing the importance of base station location.

4.5 Fixing Base stations Locations

This multiple base stations concept works well when the placement of base stations is done in proper location. This performance improvement what we got in the multiple base stations case i.e., two and three respectively, highly depends upon the relative locations of base stations with respect to each other.

Placing the base stations optimally is done as follows. The two or three base station locations are varied throughout the network. Now calculate the number of nodes sending their packets to each of base stations. Determine the locations of base stations where the number of nodes sending packets to a particular base station are equal to that of nodes sending their packets to other base station. Place the base station at those locations with some tolerance. The tolerance should be with in the limits such that the number of nodes sending packets to a particular base station is approximately equal to that of nodes sending their packets to other base station. When this situation is achieved, the overhead on each of the node is approximately halved as compared that of single base station case which resulting in improvement in the average life time of the network. For two base stations case, the plot is shown in Figure 5, and the corresponding base locations are given below.

Base Station Locations B1 (x1, y1) = (84.6882, 17.9276),
B2 (x2, y2) = (17.5809, 14.202)

For three base stations case, the plots are shown in Figure 6 (a) and (b), and the corresponding base locations are given below. During the simulation, we observed that locating three base stations is very difficult in the network because as we keep on varying the base stations location, the condition that "the number of nodes sending packets to a particular base station is equal to that of nodes sending their packets to other base station" is approximately satisfied. But for three base stations case, the placement of the three base stations becomes very critical i.e., placement should be done very carefully. Otherwise, as we said earlier the advantage of multiple base stations becomes useless.

From the plots shown in Figures 6(a) and 6(b) for three base stations case, the corresponding base locations are given below.

Base Stations Locations B1 (x1, y1) = (84.6882, 17.9276)
B2 (x2, y2) = (17.5809, 54.2025)
B3 (x3, y3) = (47.8761, 88.5463)

These locations are obtained by placing the base stations where the number of nodes sending their packets to a particular base station is equal to that of nodes sending their packets to other base station is approximately satisfied. The three base stations should be placed in it.

5. CONCLUSIONS

Conserving the energy consumption of sensor node battery is a very important issue in WSNs because nodes have limited battery energy which is non-replenishable. The existing approaches such as PEGASIS and LRS (Hierarchical PEGASIS) showed their dominance in saving the sensor node energy. But these approaches are resulting poor performance in terms of delay incurred due to waiting of packets at a particular node for the arrival of packets from other nodes, and energy overhead on the intermediate nodes. However, our MLDA is a new, different and innovative idea of conserving the energy of a sensor node. The MLDA provides the balancing of the load of packets from other nodes at intermediate nodes which in turn increases the lifetime of the network. Through simulations for single base station, we observed that for smaller sensor networks the MLDA algorithm achieves system lifetimes that are 1.15 to 2.32 times better when compared to an existing data gathering protocol LRS.

However, the performance with single base station case can be significantly improved by having multiple base stations. We simulated the MLDA problem for two and three base stations case. Through simulations for multiple base stations, we observed that the lifetime of the network increases significantly in terms of nodes. And it is observed that the location of the base station affects the lifetime significantly. So we did work on this fixing of the base stations which gives the location of base stations with respect to the given WSN. For base stations more than 3, localizing the base stations with respect to given WSN is very difficult.

The proposed approach has been simulated and shown to improve the energy consumption significantly in comparison to the existing algorithms. As it is said in the above conclusion, the location of base stations influences the performance significantly and for base stations more than 3, it is very difficult to locate the base stations. Still some of questions like "how many base stations are required for optimal performance?" and "how to locate more than 3 base stations" remain unanswered. Future work should emphasize on these special issues for further improvement of lifetime of the network.

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7. FIGURES

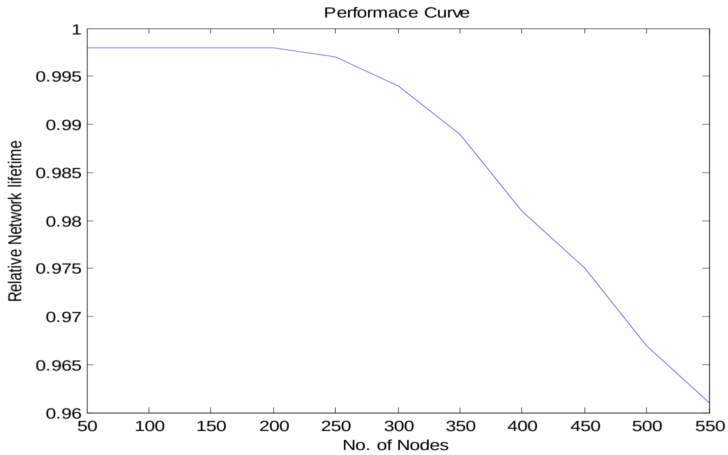

Figure 1. Relative Network Lifetime Vs No. of Nodes One BS)

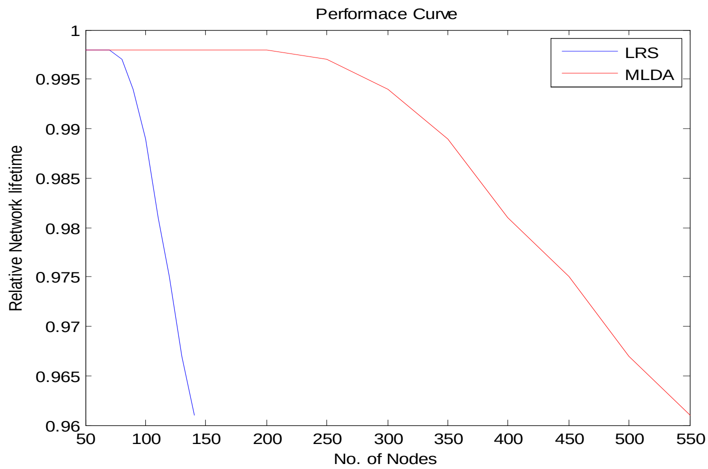

Figure 2. Relative Network Lifetime Vs No. of Nodes (MLDA One BS vs. LRS)

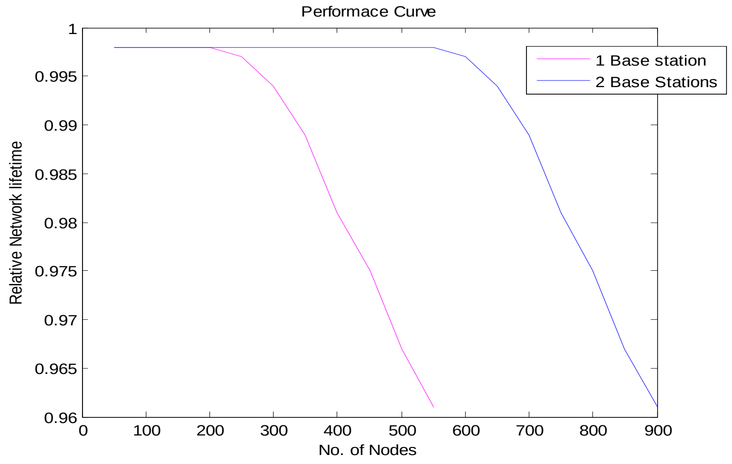

Figure 3. Relative Network Lifetime Vs No. of Nodes (Two BS)

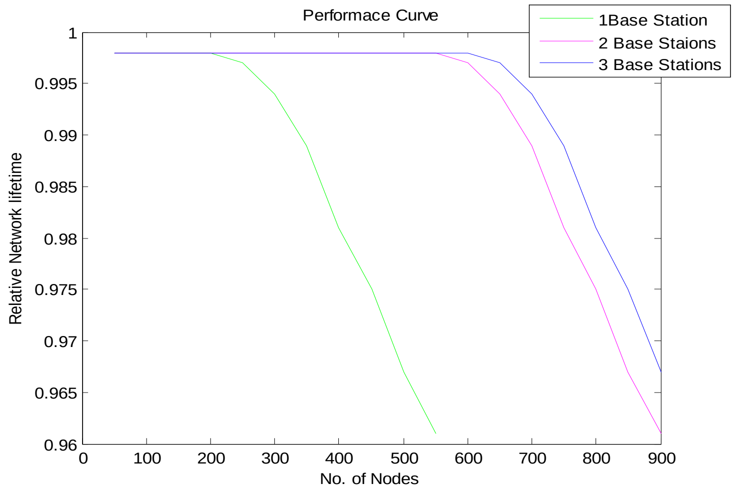

Figure 4. Relative Network Lifetime Vs No. of Nodes (Three BS)

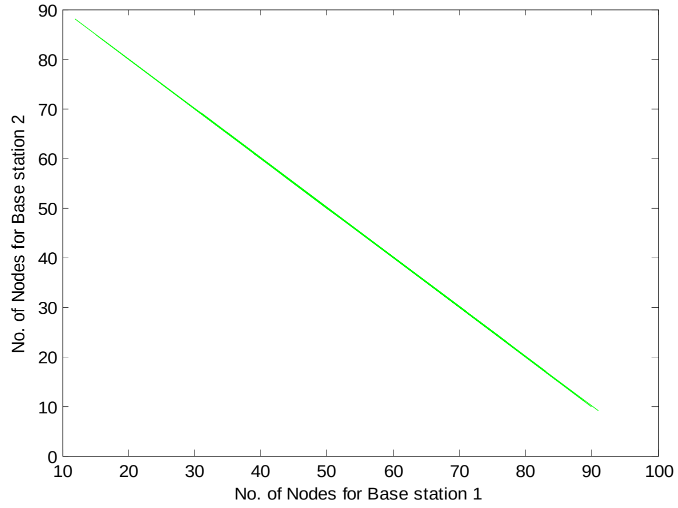

Figure 5. Base station placement (Two BS)

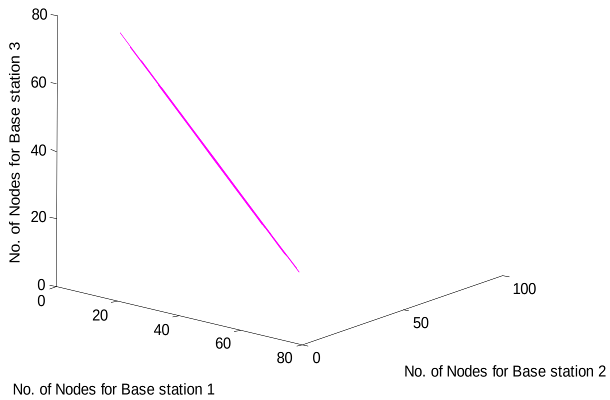

Figure 6 (a). Plot for the three base stations for placement in one angle

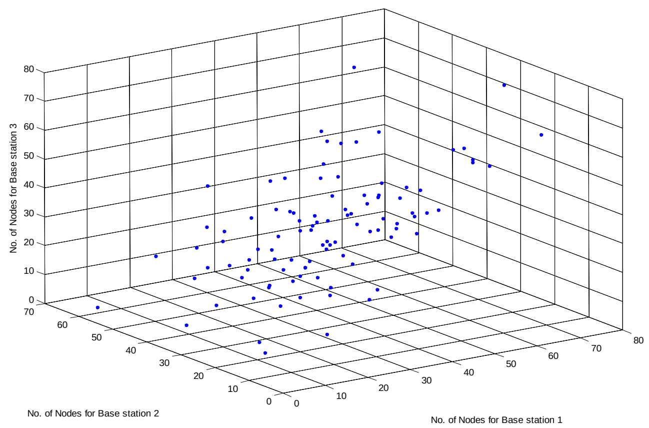

Figure 6(b). Plot for three base stations placement in another angle