CERIAS Tech Report 2005-92

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Controlled Mobility for Efficient Data Gathering in Sensor Networks with Passively Mobile Nodes

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Abstract

A large class of sensor networks is used for data collection and aggregation of sensory data about the physical environment. Since sensor nodes are often powered by limited energy sources, such as battery which may be difficult to replace, energy saving is an important criterion in any activity. Some deployments of sensor networks have *passive mobile* nodes, that is, nodes that are mobile without their own control. For example, a node mounted on an animal for bio-habitat monitoring, or a light-weight node dropped into a river for water quality monitoring. Passive mobility makes the activity of data gathering challenging since the positions of the nodes can change arbitrarily. As a result the nodes may move too far from the data aggregation point, such as a base station, making the data transmission extremely energy intensive. In extreme cases, the nodes may become disconnected from the rest of the network making them unusable. We propose a sensor network architecture with some nodes capable of *controlled mobility* to solve this problem. Controlled mobility implies the nodes can be moved in a controlled manner in response to commands, with a determined direction, speed, etc.. We present the different categories of nodes in our architecture and mobility algorithms for the two classes, called *collector* and *locator*, that have controlled mobility. It is well accepted that efficient data gathering benefits from the knowledge of locations of nodes. Passive mobile nodes makes location determination (i.e. localization) a crucial problem. We propose the use of the locators for this through a novel scheme based on triangulation. We provide theoretical and simulation based analysis of the mobility algorithms with respect to the metrics of energy, latency, and buffer space requirement.

Index Terms

Sensor networks, data gathering, passive mobility, controlled mobility, location determination.

I. INTRODUCTION

Sensor networks are a particular class of wireless ad hoc networks in which the nodes have small components for sensors, actuators and RF communication components. Sensor nodes are dispersed over the area of interest, called sensor field, and are capable of short-range RF communication (about 100 ft) and contain signal processing engines to manage the communication protocols and for data processing [1]. The individual nodes have a limited processing capacity, but are capable of supporting distributed applications through coordinated effort in a network that can include hundreds or even thousands of nodes. Sensor nodes are typically battery-powered. Since replacing batteries is often very difficult, reducing energy consumption is an important design consideration for sensor networks. Because transmitting power is proportional to the square or quadruple of the transmission range, the range of a sensor node is constrained in most deployments.

In sensor networks, the final data gathering and analysis station, called the base station, is sometimes placed far from the sensing nodes. This may be because the sensing field is in a hazardous environment, such as enemy territory, or a physically harsh environment, with high temperature, etc. It may be impossible to locate a protected, high-end base station with large computational and communication capabilities in such a hazardous environment. Since the transmission range of the individual nodes is limited, the large separation between the sensing region and the base station implies long distance and multi-hop transmission has to occur. This architecture is difficult to deploy and maintain with regular sensing nodes acting as relay nodes.

Some nodes in the network may be mobile, either in a controlled or in an uncontrolled manner. Uncontrolled mobility, referred to as *passive mobility* implies the nodes move but not of their own volition. Examples include nodes embedded into animals, nodes carried by human beings who move according to other considerations, and light-weight nodes carried by physical processes such as running water, glaciers, or wind. Nodes with passive mobility make data collection more challenging. Some nodes may move far away from the data aggregation point, such as a base station or a cluster head, and even become disconnected from the rest of the network. With

mobility, routing data to the nodes may become inefficient since many sensor network routing protocols rely on position knowledge [2], [10]. Hence, traditionally, mobility has been looked on as an adversary to efficient deployment of sensor networks due to degradation of the topology affecting parameters such as connectivity and coverage [3] or due to increased failure rates of wireless links [21]. We turn this argument on its head and propose to use "controlled mobility" of certain nodes in the network to our advantage. Controlled mobility implies the ability to control the movement of an entity (direction, velocity, etc.) by sending it control commands.

Several studies combine controlled mobility and sensor networks. LaMarca et al. [11] suggested using mobile robots to deploy and calibrate sensors, to detect their failures, and to recharge nodes using radio frequency or infrared signals. They built a prototype of sensor networks for house plants with a mobile robot. Sibley et al. [20] built miniature robots with sensors, called Robomotes. These sensors were quipped with wireless communication, odometer, infrared object sensors, and solar cellars. Each robomote is only 47 cm^3. Rybski et al. [19] presented a system for reconnaissance and surveillance using two types of robots: scouts and rangers. A scout is a mobile robot smaller than a soda can. A ranger can carry 10 scout and launch each 10 scout up to a distance of 30 meters. These examples demonstrate the practicability of combining sensor networks and robots. On the other hand, they have not fully addressed the issues encountered in large-scale sensor networks with passively mobile nodes. Miller et al. [15] explained that the slow motion of the Mars rover was not due to the limitation of technology; instead, it was mainly the concern of safety and the long communication delay between the Mars and the Earth. Hence, it is possible to construct sensory robots with controlled movement for data collection.

In this paper, we demonstrate the use of controlled mobility to solve the problem of energy efficient data collection in sensor networks that have a large geographical spread, and management of nodes that exhibit passive mobility. Since mobility is an energy expensive process itself, our solution equips only a small fraction of nodes with the ability for controlled mobility and for one class of nodes, enables its energy source to be periodically recharged. We propose a network architecture with five classes of nodes. The first class consists of ordinary *sensing nodes* that are dispersed over the sensor field and have the constraints of communication, computation, and energy traditionally associated with sensor nodes. Some of these nodes may exhibit passive mobility, while the rest are stationary. The network is divided into clusters with each sensing node assigned to a cluster. Each cluster has a set of *cluster heads*, only one of which plays that

role at a time. The cluster head buffers data from the sensing nodes awaiting further transmission. The cluster heads are off-the-shelf sensor nodes with one addition – they have larger memory for storage of the sensed data. The third class of nodes is the *data collector*. A data collector has the capability for controlled motion and visits the cluster heads according to a pre-determined schedule, collecting the sensed data from them and transmitting the data to the base station. The data collectors have the option of occasionally returning to the base station for recharging their energy source. The fourth class of nodes is called *locators* which are assigned to a cluster. These nodes move within the cluster helping the passively mobile sensing nodes determine their locations and assigning them to the closest cluster head. The locators have a hardware device, such as a GPS receiver, that enables them to determine their own location. The final class of nodes is the *connectors* which exhibit controlled mobility in order to maintain certain topological properties of the network, such as, connectivity and coverage. The role of connectors will form the topic of a separate publication and is not discussed further here.

The goals of our solution using the five classes of nodes are the following.

1) Reduce the distances for data transmission, and therefore, the energy expended in communication of sensed data.

2) Determine the locations of the sensing nodes with passive mobility so that data can be gathered from them efficiently.

An alternate architecture may be proposed which spreads many nodes between the sensing nodes and the base station to act as relay nodes. The data is then communicated through multi-hop communication from the sensing nodes to the base station. This architecture poses several challenges. The terrain may be such that placement of the intermediate relay nodes is difficult or infeasible. For example, consider marshy lands or water bodies. In such an environment, an unmanned aerial vehicle (UAV) can act as a collector and will likely be easier to deploy. Another challenge is the maintenance of the relay nodes. They will likely be identical to the ordinary sensing nodes since many of them will have to be deployed. Their constraints, including energy drain, will be a matter of concern. The nodes close to the base station will face the funneling effect whereby larger and larger fraction of the network data gets funneled through them. This will lead them to drain their energy rapidly. Our target deployment has a large sensor field and therefore many relay nodes will have to be used. This will make it challenging to provide

deterministic bounds on the data latency for the end-to-end transmission of sensed data from the sensing node to the base station.

The focus of this paper is the controlled mobility algorithms for the data collectors and the locators. The mobility algorithms are evaluated with respect to the energy expended, the buffer usage, and the end-to-end latency of sensed data. A set of mobility algorithms are proposed which differ in their degree of prescience of the network and the parameter that they optimize for. For example, one algorithm assumes knowledge of the size of each cluster and the data rate of the nodes in the cluster. Another algorithm optimizes the energy expended in the motion of the data collectors at the expense of higher data latency. The location determination algorithms are evaluated with respect to the above parameters plus rate at which the location information is disseminated and the accuracy and precision of the location estimate. The evaluation is performed analytically and through simulation with ns-2 as the simulation environment.

The rest of the paper is organized as follows. Section II describes the network architecture with the roles and capabilities of the different classes of nodes. Section III gives the algorithms for motion of the collectors and the locators, and the location determination protocol using the locators. Section IV presents the experimental set up and the simulation results. Section V concludes the paper with some ideas for future work.

II. Network Architecture

The sensor network architecture being targeted comprises large number of sensing nodes which collect information about the physical parameters of their environment. They are embedded in situ in the sensor field and dispersed over a sensor field which has a large geographical spread. The sensor field extends far from the base station to which the sensed data ultimately needs to be communicated back for processing and long-term storage. Some of the sensing nodes may move due to passive mobility.

Apart from the sensing nodes, there are four classes of special nodes introduced in Section I — collectors, locators, cluster heads and connectors. The different classes of nodes and their characteristics are summarized in Table I. A schematic of the network without the four special classes of nodes is shown in Figure 1 and a network with the specialized nodes is shown in Figure 2. The classes of nodes which are capable of controlled mobility have control interfaces to which commands can be sent for the purpose of directing their motion. The collectors can be

type	number	capability	mobility	limitation
sensor node	many	sensing data	passive or static	limited memory and energy
collector	few	collect data from heads	active, high	energy for long-distance movement
connector	some	improve network	active, low	limited energy
locator	some	GPS-equipped	active, low	limited energy
cluster head	some	large data buffer	no	stationary, limited energy

TABLE I

DIFFERENT TYPES OF NODES AND THEIR CHARACTERISTICS.

mounted on fast aerial vehicles or slower moving surface vehicles. They have two interfaces—a low range low bandwidth RF communication interface for communication with the cluster head and a longer range higher bandwidth GPRS-like communication interface for communication with the base station. The purpose of the collectors is to make all wireless transmission from the sensing nodes and the cluster head short range and energy efficient. In this way, they are analogous to mailmen collecting mails from mailboxes. By using the postal service, people do not have to deliver mail by themselves—they only need to walk short distances to the mailboxes. Each locator is attached to a particular cluster and moves within the cluster for helping the sensing nodes determine their locations. They are equipped with location determination hardware, such as GPS receivers. The cluster heads have larger stable storage compared to the sensing nodes in order to hold the sensed data before handing it over to the collector. Adding cluster heads makes data collection more efficient. The collectors do not have to visit each node; instead, the collectors only need to visit the cluster heads. This is analogous to using mailboxes at the corners of streets to collect mail so that the mailmen do not have to visit every house. In this architecture, only the collectors have high mobility and need to travel large distances, possibly at high speeds. Therefore, they have the provision of returning to the base station for recharging their energy source. The locators move within the extent of their respective cluster and are therefore considered to have low mobility. Their energy source may also be charged through the collectors. The locators may be made to return to their cluster head to coincide with the collector visiting the head.

Let us look at the general use scenario of the five classes of nodes in a typical deployment of the
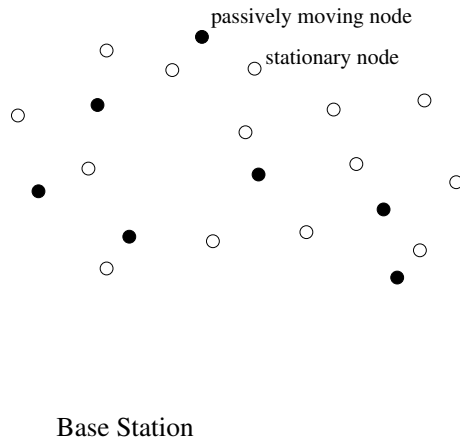
Fig. 1.   When the station is far away from all the sensor nodes, the last-hop problem occurs.
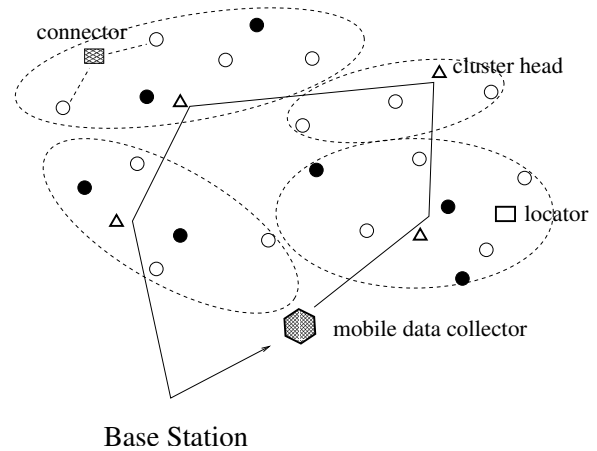
Fig. 2.   Four types of special nodes are added: data collectors, network connectors, locators, and cluster heads.

network. Initially, the nodes are deployed either through precise placement, such as manually placed at precise pre-determined and known locations, or through pseudo-random placement, such as light-weight nodes airdropped from a moving aerial vehicle. The network is divided into multiple clusters based on geographical boundaries, a cluster head elected in each cluster, and the nodes assigned to different clusters using a high energy beacon broadcast by each cluster head. Each sensing node collects data about its immediate environment and transmits the data to the cluster head, which is located much nearer to it than the base station. The mobile data collectors visit the cluster heads and collect the data of the entire cluster stored there. The data is then transmitted back by the collector to the base station. Within each cluster, the cluster head role is rotated between the candidate set of nodes, triggered by energy getting drained or for proximity to higher data producing nodes. The locators are equipped with GPS receivers and move through its cluster helping the cluster heads and the passively mobile sensing nodes determine their location. The location information for the cluster head is used by the collector to decide its movement pattern, while the location information of the sensing nodes is used to assign it to the closest cluster head for efficient gathering of its sensor data.

III. Mobility Algorithms

A. Collector mobility algorithm

Let us consider initially that the nodes are static and there is a single collector which moves through the network and collects data from the cluster heads. For the moment, we assume that the cluster heads are fixed. We are given n cluster heads which, following the collector's natural traveling path (e.g. based on the geography of the sensor field), are numbered $0, \ldots, n-1$, such that the collector follows the cycle of $0 \to 1 \to \ldots \to n-1 \to 0$.

The cluster heads hold sensed data before the collector arrives. Since it can take a long time — possibly hours or days — for the collector to revisit a head, it is important to determine whether the memory in the heads is bounded. If the collector arrives later than the scheduled time, more memory is needed in the heads. Moreover, it takes longer to transmit the data from the heads to the collector. This requires the collector to stay longer at each cluster and further delays the arrival of the next trip. This "positive feedback" may cause the required memory to grow unbounded. The following analysis shows that the memory does not grow indefinitely and hence can reach a stable schedule.

Let r_i be α_i/β_i, for $i \in [0, n-1]$, where α_i is the sensor data accumulation rate at cluster head i and β_i is the data collection rate of the mobile collector when visiting i. Let d_i be the time for the collector to travel from i to $i+1$ (modulo n) and D be the sum of d_i. We have the following linear system in terms of variables t_i which represents the time taken for the collector to collect data from each node i:

$$T = D + \sum_i t_i \tag{1}$$

$$t_i \geq r_i T \tag{2}$$

$$t_i \geq 0 \tag{3}$$

where Ineq. (2) is from the requirement of $\alpha_i T \leq \beta_i t_i$.

We first study the feasibility of the system defined above. Take the sum of Ineq. (2) over all i, we have

$$\sum_i t_i \geq \sum_i r_i T, \text{ or } \quad T - D \geq \sum_i r_i T \tag{4}$$

$$\text{viz.} \quad T(1 - \sum_i r_i) \geq D. \tag{5}$$

which is possible only if $\sum_i r_i < 1$. To show that $\sum_i r_1 < 1$ is also a sufficient condition for the system to be feasible, we derive the solution for t_i which minimizes T. (This solution minimizes the required total buffer size for all cluster heads, since the required buffer size on each cluster head grows linearly with T. Furthermore, minimizing T also minimizes the latency of data, assuming that the motion of the collector takes much more time than data communication, i.e. $D \gg \sum_i t_i$.) Suppose $\sum_i r_i < 1$ is satisfied. We let $T = \tilde{T} \equiv D/(1 - \sum_i r_i)$ and $t_i = \tilde{t}_i \equiv r_i \tilde{T}$. $\tilde{T}$ and $\tilde{t}_i$ satisfy Ineqs. (2), (3) and Eq. (1) and are hence the solution which minimize T.

Next, we want to see whether the solution for t_i is stable. This is important because occasionally the collector's motion schedule may be delayed unexpectedly due to transient communication slow-down with a certain cluster head or due to changes in the travel conditions (e.g. changing weather). It t_i increases at each delay and does not return to its previous value, then the entire motion schedule may be lengthened without an upper bound, which is an unstable situation. We define the stability in the sense that, if the collector meets an unexpected delay at a node, the system shown above is still feasible and t_i will eventually return back to $\tilde{t}_i$. Let $t_i = \tilde{t}_i \kappa$, where $\kappa > 1$. To show that t_i is still a feasible solution, we observe that $T = D + \kappa \sum_i \tilde{t}_i < \kappa \tilde{T}$. Hence, $t_i = \kappa \tilde{t}_i = \kappa r_i \tilde{T} \geq r_i T$, satisfying Ineq. (2).

If the collector is delayed unexpectedly by an amount of time L, then each cluster head will accumulate an additional amount, αL, of data, suppose the cluster heads have extra buffer space to store this additional amount and thus avoid data loss. As soon the collector reaches the next cluster head (with delay L), the cluster head empties the buffer in time $\kappa_0 \tilde{t}_i$, for some $\kappa_0 > 1$. The collector then continues to complete the current cycle. When the next cycle begins, the collector no longer needs to spend $\kappa \tilde{t}_i$ at each node i. Instead, it suffices to spend $t_i = r_i(D + \kappa \sum_i \tilde{t}_i)$. The new ratio of t_i over $\tilde{t}_i$ equals

$$\kappa = \frac{D + \kappa_{old} \sum_i \tilde{t}_i}{D + \sum_i \tilde{t}_i}, \tag{6}$$

which is less than κ_{old}. Hence, κ is a decreasing positive value. Take the limit on both sides of Equation (6), we see that κ approaches 1. In other words, t_i returns to $\tilde{t}_i$. This proves the stability of the round-robin routine.
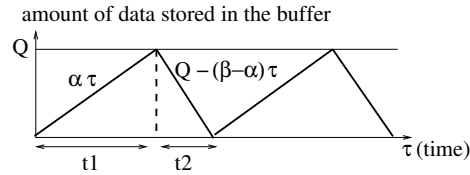
amount of data stored in the buffer

Fig. 3.   The amount of data stored in the buffer rises first when the transmitter is off and then declines after it is turned on.

B. Energy considerations for buffering at cluster head

Let α be the sensing rate and β be the transmission rate. We can use a buffer to store the sensed data during t_1 in Figure 3 before transmission. The amount of stored data grows at rate α. During t_2, the transmitter is turned on. The data stored in the buffer decreases at rate $\beta - \alpha$. At the end of t_2, the buffer is empty so the transmitter is turned off again. We assume that $\alpha < \beta$; otherwise, the buffer will definitely overflow. Intuitively, a larger buffer allows the transmitter to stay off longer so more energy can be saved. However, the buffer itself also consumes power so we have to find an appropriate buffer size which causes the most energy savings. Let p_b be the power consumed by the buffer per MB and k be the energy overhead to turn on and off the transmitter. The buffer size Q is $(\alpha - \beta)t_1 = \beta t_2$. We can express the value of Q as $\frac{\beta}{\alpha}(\alpha - \beta)(t_1 + t_2)$. During a period, the additional energy consumed by buffer insertion includes the buffer's energy $Qp_b(t_1 + t_2)$ and the overhead k for power management. The average power if $\frac{Qp_b(t_1+t_2)+k}{t_1+t_2} = \frac{\beta}{\alpha}(\alpha - \beta)p_b(t_1 + t_2) + \frac{k}{t_1+t_2}$. Our earlier study shows that the minimum power occurs when the length of a period $t_1 + t_2$ is $\sqrt{\frac{\alpha k}{\beta p_b(\alpha-\beta)}}$ and the buffer size Q is $\sqrt{\frac{\beta k}{p_b}(1 - \frac{\beta}{\alpha})}$ [4].

C. Different mobility algorithms for collector

The collector moves among the cluster heads using one of three possible schedules—the Round Robin schedule, the Data Rate based schedule, and the Min Movement schedule. In the *Round Robin schedule*, the collector visits each cluster head to collect data in a round robin manner. In the *Data Rate based schedule*, the collector visits the cluster heads preferentially. The frequency of visiting a cluster head is proportional to the aggregate data rate from all the nodes in the cluster. For example, take four clusters whose aggregate rate of data generation (number of nodes times the data rate of each node) is in the ratio 1:2:3:4. Define the period

for which the collector stays at a cluster head is a *slot* and a consecutive number of slots over which scheduling decisions are made as a *round* . With the data rate based schedule, in a round of 10 slots, the collector will visit the cluster heads in the order 1, 2, 3, 4, 4, 3, 2, 4, 4, 3. In the third schedule called the *Min Movement schedule*, the collector visits the cluster heads in the proportion of the aggregate data rate, but also with the goal of optimizing the distance traversed. Thus, in a round of 10 slots, the collector stays at a cluster head for multiple slots continually, the number of slots being calculated as above depending on the aggregate data rate at the cluster. In our simulation, this schedule gives the visit order of the cluster heads as 1, 2, 2, 3, 3, 3, 4, 4, 4, 4. The length of a slot is the time it takes for the cluster head to transfer *all* the data accumulated at the cluster head till the moment the collector arrives.

D. Analysis of cluster head to collector communication

The cluster head communicates the data collected from the nodes in the cluster to the collector. In the base case, this communication takes place once the collector reaches the cluster head. This minimizes the transmission energy spent by the cluster head. However, as the analysis in Section III-B shows, energy is also spent in buffering the data at the cluster head. We explore the possibility of the cluster head transmitting some of the data to the collector as soon as the two are within RF communication distance. In this scheme, the cluster head continues to transmit data to the collector as the collector moves closer. The collector transmits this data to the base station continually. This is possible since the collector uses two different communication interfaces for communicating with the cluster head and the base station – a low bandwidth RF interface for cluster head communication and a higher bandwidth and longer range interface for communicating with the cluster head (such as, GPRS). The scheme has the possible advantage of saving energy expended by the cluster head depending on when it transmits to the collector. It has the decided advantage of reducing the data latency since the collector immediately transmits the received data to the base station.

Let us analyze the distances over which the cluster head should transmit its data to the collector to save the energy. We consider energy saving to be the primary concern and the latency reduction as the consequence. We perform the analysis for one cluster without loss of generality since the cluster specific parameters (number of nodes and rate of data generation by a node in the cluster) are taken into account in the analysis. Let the number of nodes in the cluster be n, the rate of

data generation by each node be ρ. Let the critical distance for the data transmission be θ_{th} such that it is energy efficient for the cluster head to transmit only after the collector is closer than this distance. The time for the collector to traverse distance θ_{th} is $t_{th} = \theta_{th}/v_c$, where v_c is the velocity of the collector. The energy for transmission at the cluster head has two components – one due to the transmission circuitry which needs to be expended independent of the distance over which the data needs to be sent, and the second component due to the power amplifier whose energy need depends on the distance. The energy due to reception at the collector is due to the receiver circuitry. Let the energy per bit for the two transmission components at the cluster head be E_{tx_elec} and E_{PA} and that for reception at the collector be E_{rx_elec}. Let the energy expended at the power amplifier grow with the square of the transmission distance. Thus, the energy per bit of transmission over distance d is $E_{tx}(d) = E_{tx\_elec} + E_{PA} * d^2$. We consider an energy efficient memory at the cluster head where the unused banks of memory may be turned off. Thus, offloading some of the data to the collector enables the cluster head to selectively turn off parts of its buffer thus saving its energy [5], [8], [13], [17].

Let the energy spent to keep one bit in buffer be p_b. The data generated in time t by the nodes in the cluster is $n\rho t$. This is the amount of data buffered at the cluster head. Over the time duration t_{th}, the total energy due to buffering is $\int_0^{t_{tx}} p_b(n\rho t)dt$. The amount of data transmitted (and received) while the collector moves over a distance $d\theta$ is $n\rho d\theta/v_c$. The energy expended for this data, integrated over the entire distance, is $\int_0^{\theta_{th}}(E_{tx\_elec} + E_{PA}\theta^2 + E_{rx\_elec})n\rho/v_c d\theta$. Solving the two definite integrals and equating the two sides (energy due to buffer on LHS and energy due to RF transmission/reception on the RHS), we get the critical distance to be

$$p_b \cdot \frac{\theta_{th}^2}{2v} = E_{tx\_elec}\theta_{th} + E_{PA}\frac{\theta_{th}^3}{3} + E_{rx\_elec}\theta_{th} \tag{7}$$

For the radio used in [7], [12], $E_{tx\_elec} = E_{rx\_elec} = 50nJ/bit$ and $E_{PA} = 100pJ/bit/m^2$. From [5], $p_b = 0.012W/MB$. For the collector, we use two different models – one is a fast aerial vehicle of speed 30 m/s and the second a robot in our lab of speed 0.1 m/s [14]. The fast collector covers the distance over which RF communication is possible for the sensor nodes in such a short time that it is not worthwhile for the cluster head to begin transmitting. Therefore, we do the calculation for the slow collector. Putting these values in eqn (7), we get a quadratic equation which we solve to get the two roots for θ_{th} of 210.00 m and 14.23 m. For all practically available sensor nodes, the RF antennas cannot communicate reliably over 210 m. We take that

communication starts at a distance of 100 meters (from the spec sheet for Berkeley Mica2 motes [9]) and continues till a distance of 14.23 m. This is explained by the fact that a high distance of separation makes the communication between the cluster head and the collector too energy expensive and therefore, the cluster head buffers the data. Below the threshold distance, the cluster head has gotten rid of most of the data and has very little data to buffer. Therefore, it is more energy-wise to buffer the data than transmitting it to the collector. The curves for the energy due to buffering and RF communication are shown in III-D. The threshold distance is when the ratio reaches 1.
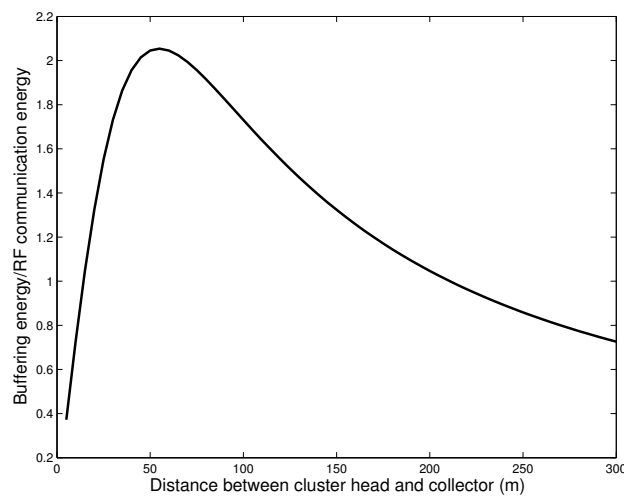

Fig. 4.   Relative energy spent due to buffering at cluster head and RF communication between cluster head and collector

E. Locator mobility algorithm

Let us consider initially that the nodes are static and there is a single locator which moves through the network and aids in the determination of positions of each node in the network. Location determination requires multiple reference points whose locations are known by, for example, GPS. Equipping many sensor nodes with GPS can be too expensive as well as make the sensing nodes heavy and unwieldy. Therefore, we use mobile locators that move around the sensor nodes as multiple reference points. First, the field is partitioned into *locator cells* which

are disjoint rectangular regions that satisfy a necessary condition (condition 1) and an optional condition (condition 2).

1) The maximum separation of two nodes in the cell is less than the transmission range of the nodes (Necessary).

2) The number of nodes in a cell is greater than a threshold, denoted by η_τ (Optional).

A cell which satisfies both conditions is called a *complete cell*, and one which satisfies only the necessary condition is called an *incomplete cell*. Note that a cell is different from a cluster. A cell is purely for the purpose of determining locator movement, while a cluster is an aggregate of nodes which have a cluster head that collects and possibly processes data from all the cluster nodes. A cluster comprises multiple cells. A cell is a square region of dimension $<$ (transmission range)$/2\sqrt{2}$.

The given parameters for the sensor network under consideration are the following.

- *Allowable error in location estimation (ε_τ)*. Each node should determine its location with less than ε_τ error on an average. The error arises due to errors in the model correlating physical measurement with distance between one-hop neighbors. This is a requirement imposed on the localization system. The error is given in terms of distance units that the calculated location can differ from the actual location.

- *Velocity of locator (v_l)*. This is the maximum speed with which the locator can navigate within the cluster.

- *Epoch (ζ_S)*. This is the average duration between successive movements of a passively mobile node.

The locators are mobile and each locator can act as multiple reference points for location estimation by communicating with a sensing node at different time points. The locators are looked upon as mobile entities that roam the sensor field, periodically broadcasting beacon messages with their own locations. An intermediate node when it receives a beacon message, it forwards it after incrementing the hop count. Thus, receiving a beacon message, a passively mobile node can estimate the number of hops it is away from the locator. The sensing nodes collect the beacon messages and after an *appropriate* number of beacon messages perform triangulation to determine their locations. A sensing node knows the number of beacon messages required in order for the location estimation error to be below ε_τ. The error in the estimation (ε) is a function

of the number of beacon messages (η_b) and the distance between the node and the locator for each reference point ($\delta_{l,n}$). The distance can be approximated by the product of the number of hops separating the locator and the node ($h_{l,n}$), and the transmission range of each node (r_T). The locator has the same kind of RF communication device as the sensing nodes and hence, its transmission range is considered identical to that of the sensing nodes.

$$\varepsilon = F(\delta_{l,n}, \eta_b) = F(h_{l,n} \cdot r_T, \eta_b) \tag{8}$$

F. Determination of Localization Error

We wish to determine the number of beacon messages that should be collected by a sensing node to guarantee a desired accuracy in its location estimate. The guarantee will however be probabilistic, i.e., the guarantee will be stated in terms of a probability that the error in location estimate will be bounded by a desired value. We will start with some background for location estimation. We will present this discussion in terms of a sensing node being surrounded by multiple neighbors each of which knows its own location. The neighbors send beacon messages to the sensing node using which it determines its location. Our environment where there is a single locator that moves and sends beacon messages from multiple positions is easily mapped to this model. The minimum number of neighbors required for location estimation in an n dimensional plane is $(n + 1)$. Thus, in our special case of a 2-dimensional plane, 3 neighbors are required, under perfect conditions, namely, where individual distance measurements from a neighbor are completely accurate. Localization with respect to three neighbors gives the following set of equations.

$$
\begin{aligned}
(x_1 - u_x)^2 + (y_1 - u_y)^2 &= r_1^2 \\
(x_2 - u_x)^2 + (y_2 - u_y)^2 &= r_2^2 \\
(x_3 - u_x)^2 + (y_3 - u_y)^2 &= r_3^2
\end{aligned}
\tag{9}
$$

In this set of equations, (u_x, u_y) is the position of the sensing node that we intend to locate and (x_i, y_i) is the location of the ith neighbor. Solving equation 9 we get u_x to be of the following form.

$$u_x = k_1 r_1^2 + k_2 r_2^2 + k_3 r_3^2 + k_4 \tag{10}$$

where $k_i \in R$. Similarly, u_y can be expressed in a form like equation10. One simple relation for measuring error in u_x and u_y is to differentiate both sides of the equation to get $\Delta u_x = 2k_1 r_1 \Delta r_1 + 2k_2 r_2 \Delta r_2 + 2k_3 r_3 \Delta r_3$. However, this is dependent on topology and no obvious bounds exist for the error. We choose to work with variances as a measure of the error in estimation. The range measurements are error prone, and this leads to the error in location estimation of the sensing node. If we assume that the errors in range measurements are uncorrelated, then from equation10, we get the variance of the estimated location in the following form.

$$Var(u_x) = k_1^2 Var(r_1^2) + k_2^2 Var(r_2^2) + k_3^2 Var(r_3^2) \tag{11}$$

For the purpose of estimating the error, we consider the neighbors to be divided into groups of 3. Triangulation is performed as above for each such group. Each triangulation gives a sample value for u_x and u_y and the location of the sensing node is finally determined by taking an average of all these u_x and u_y values. For simplicity we consider the number of neighbors to be an integral multiple of 3. Thus, the number of sample values of u_x and u_y is $p = N/3$ where N is the number of neighbors. The expected value of the calculated location (i.e., the sample mean) is the same as the expected value of the population mean and thus the technique gives an unbiased estimate of the location. The variance of the estimated location is given by.

$$Var(u_{xp}) = Var(u_x)/p \tag{12}$$

Note that $Var(u_{xp})$ is the *ensemble variation* in space over neighbors that form an *ensemble*, while the variance $Var(u_x)$ computed in equation11 is the time variance. Consider that the measurements of the range vector $[r_1, r_2, r_3]$ represent a stochastic process in time. So the averaging for determination of u_x and u_y is done over time and therefore the variance in equation11 is a time variance. On the other hand, in averaging over $p = N/3$ samples, we are averaging over the neighbors of the sensing node and this is an ensemble average. The corresponding variance is also the ensemble variance. If we assume ergodicity of the mean and the variance, then the time average and variance can be replaced by the ensemble average and variance that we need for our subsequent analysis.

Chebyshev's inequality gives that for a random variable X with a distribution having finite mean μ and finite variance σ^2, $P(|X - \mu| \geq t) \leq \sigma^2/t^2, t \geq 0$. Applying this to the random variable u_{xp} we get Probability (Error in location estimate (for the x-axis) $\geq$ Error bound in distance units) as follows.

$$P(|u_{xp} - E(u_{xp})| \geq \epsilon) \leq 1/\epsilon^2 \cdot Var(u_{xp})$$

$$P(|u_{xp} - E(u_x)| \geq \epsilon) \leq 1/(p\epsilon^2) \cdot Var(u_x) \tag{13}$$

Equation13 gives a bound on the probability of error in estimated location exceeding a desired threshold in terms of the number of neighbors. Given a desired accuracy, we can make the probability of error exceeding the desired accuracy to be as small as we like by increasing p, i.e., by extension, increasing the number of neighbors. Next, we have to determine the variance in u_x to complete the analysis. In equation11, if we take that the errors in the three range measurements r_1, r_2, r_3 are equal, then the variance in u_x can be written as.

$$Var(u_x) = (k_1^2 + k_2^2 + k_3^2)Var(r^2) \tag{14}$$

In general, the coefficients k_1, k_2, k_3 are dependent on topology, i.e., the relative placements of the neighbors with respect to the sensing node. The upper bound for the sum is infinity (when the three neighbors are collinear) and the lower bound is achieved when the triangles formed by the neighbors with the sensing node are equilateral. We perform an analysis on the topology shown in Figure 5. For values of angle θ subtended by the neighbors at the anchor node ($\angle CAD = \angle BAC = \theta$) between $\frac{5}{36}\pi(25°)$ and $\frac{1}{3}\pi(60°)$, it can be shown that $k_1^2 + k_2^2 + k_3^2$ lies close to $0.2/R$ where R is the distance between the neighbor and the sensing node. By our algorithm, the locator sends beacon messages when it is either in the cell or in the adjacent cell to the sensing node and therefore $R \leq r_T$, where r_T is the transmission range.

Next, we compute $Var(r^2)$. Consider the error in range measurements and let the upper bound on the relative error be e. This means that if the actual distance between a neighbor and the sensing node is d, the measurement lies between $d \pm e \cdot d$. Assume that the range measurements follow a Gaussian distribution. Therefore, almost all the points (99.74% to be exact) lie within $\mu \pm 3\sigma$. Equating, $\sigma = ed/3$. The upper bound for this is $er_T/3$. Thus, $Var(r) \leq (er_T/3)^2$. Then, $Var(r^2) = E(r^4) - (E(r^2))^2$. The higher order expectations can be calculated using the moment
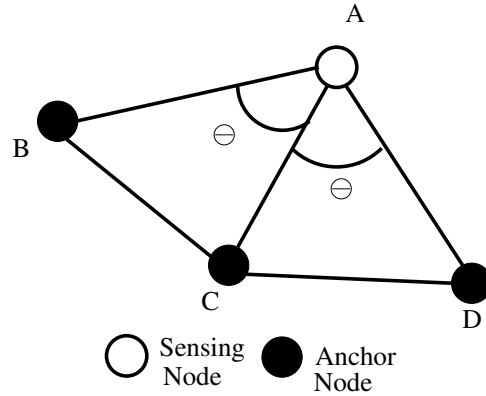
Fig. 5.   Topology of sensing node and 3 neighboring anchor nodes. Triangulation is done by the sensing node using distance measurements from the three anchor nodes.

generating function of a Gaussian distribution with mean μ and variance σ^2 $M(t) = e^{\mu t + \sigma^2 t^2/2}$. $E(r^2)$ and $E(r^4)$ can be derived by differentiating M(t) respectively twice and four times and evaluated at t=0. Simplifying, we get from equation14 the Probability (Error in location estimate (for the x-axis) $\geq$ Error bound in distance units) as

$$P(|u_{xp} - E(u_{xp})| \geq \epsilon) \ \leq \ 1/(p\epsilon^2) \cdot 0.2e^2 R^3 (2.47X10^{-2}e^2 + 4.44X10^{-1}) \tag{15}$$

For our environment, we pick $p = 24$ to restrict the error in location estimation in each dimension to 10 meters. Note that the above bound can be made much tighter for smaller distances between the neighboring node and the sensing node and for particular topologies. This value of p corresponds to a total of 72 beacon messages by the locator for the nodes in one cell. This means that the number of beacon messages sent out by the locator from each cell (the cell itself and its 8 neighboring cells) is 8.

Once the required number of beacon messages are received by a sensing node, it determines its location. The sensing node then informs the locator of its location. The locator verifies this location using the received signal strength from the node. Then, it assigns the node to the appropriate cluster. In a majority of cases, the node will be assigned to the cluster to which the locator is coupled. Only if the node has moved far away will it be reassigned to a possibly closer cluster head.

Again considering cell i, the locator sends a beacon message while located in cell i. The cells

in C_{i_1} are ordered according to the metric (Number of nodes in the cell - Distance of the cell from the current position). The complete and incomplete cells are ordered separately with all the complete cells being ordered above the incomplete cells. The locator picks the next cell to visit in order from the ordered list. Next, the cells in C_{i_1} are ordered, and so on. The movement is stopped when any node in the cell indicates that it has the requisite number of beacon messages.

A constraint for the movement of the locator is that all the η_τ beacon messages must be received by a node before it moves. Let the distance between two cells c_i and c_j be given by $\delta_{i,j}$. The locator has sent η_c beacon messages for cell i and in time t_c. The locator is currently in cell m and the next cell in the ordered list is cell n. The condition that the locator seeks to enforce is $(\eta_\tau - \eta_C) \cdot \frac{\delta_{i,j}}{v_l} < (\zeta_S - t_c)$. If the condition is violated for cell n, the locator moves to another position within the same cell m and sends another beacon message. This probabilistically assures that all beacon messages are received in the time in which it is useful, i.e. between two movements of a node.

IV. EXPERIMENTS AND RESULTS

We perform simulations using the NS-2 simulator [22]. The simulation environment is set up as follows. There are four clusters that are separated over a distance such that any two nodes from different clusters are not able to communicate between each other. Each cluster has a cluster head that collects data from its own cluster. Since the cluster head does not have the capability to send the collected data to the base station, there is a mobile data collector which moves to and collects data from each cluster head. The mobile collector then sends the data to the base station for analysis. The large inter-cluster distance and the separation from the base station underline the need for a mobile collector as opposed to multiple relay nodes between the cluster heads and the base station.

In each simulation, a cluster sends data, at a constant rate, to its own cluster head. The cluster head stores the data in its buffer until the data collector arrives (either physically, or within the energy-efficient communicable distance) and collects the data via wireless communication. The data collector follows a predetermined movement schedule to visit each cluster head. The collector periodically goes back to the base station if it does not have enough energy to serve another cluster head. Each cluster is characterized by the position of the cluster head, the number of nodes in the cluster, and the aggregate data rate of the cluster. In our simulation, we consider

Cluster Parameter	#1	#2	#3	#4
Cluster head coordinate (m)	(1,800)	(1,1)	(800,1)	(800,800)
(Base station is at (400,1500))				
Data rate per cluster node	2 bps	4 bps	6 bps	8 bps
Number of nodes in cluster	500	500	500	500

TABLE II

CHARACTERISTICS OF CLUSTERS

heterogeneous clusters. For the simulation, the cluster head is considered non-rotating. Since the geographical spread of the cluster is much smaller than the inter-cluster distance, we believe this will not have much effect on the results. The four clusters with the positions of the cluster heads and the base station is shown in Figure IV. The spread of only cluster number 2 is shown. The characteristic of the four clusters is summarized in Table II.
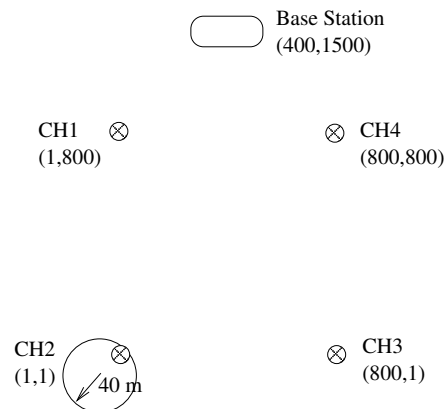

Fig. 6.   Topology of the four clusters and the base station used for simulation

The energy model used for the cluster head is the same as for the radio used in [7], [12]. The energy has two components—one due to the transmit-receive circuitry and the other due to the power amplifier. The latter component depends on the distance over which the data is transmitted. The amount of energy to send n bits of data over a distance d is given by $n(E_{TxRx} + E_{PA}d^2)$. The bandwidth for the cluster head to collector communication follows the value for the Berkeley

Parameter	Value
Cluster head tx/rx circuitry (E_CH_{TxRx})	50 nJ/bit
Cluster head power amplifier (E_CH_{PA})	0.1 nJ/bit/m^2
Collector tx circuitry (E_Coll_{TxRx})	1000 nJ/bit
Collector power amplifier (E_Coll_{PA})	0.008 nJ/bit/m^2

TABLE III

ENERGY PARAMETERS FOR CLUSTER HEAD AND COLLECTOR

motes [9] of 38.4 kbps. The collector to base station communication happens using GPRS with a range of over 1 km and a bandwidth of 135 kbps. The GPRS energy model also has the two components. The values are substantially different and taken from the energy for the GSM model [6]. The energy model parameters are summarized in Table III.

A. Fast and Slow Collector

In the simulation we use two collector models—a fast collector and a slow collector. The fast collector is based on the Aerosonde model from NASA [16] and the slow collector is based on a a commercial mobile robot called the Palm Pilot Robot Kit (PPRK) which was originally designed at Carnegie Mellon University [18] and is currently used in our lab [14]. These collectors are henceforth referred to as the *fast collector* and the *slow collector* respectively. The detailed parameters of these two models is shown in Table IV. We assume that the slow collector's initial energy is ten times less than the Aerosonde's to keep the endurance (time between recharges) approximately equal for the two models since for a given travel distance the slow collector consumes approximately one-tenth of the energy of the fast collector. The rationale behind selecting these two models is that the Aerosonde may be used if the data is time sensitive, such as pertaining to rare event detection by the sensing node, and the mobile robot may be used if there is a budget constraint for the deployment ($40K versus $300 per collector in the two cases).

Parameter	Fast Collector	Slow Collector
	(Aerosonde)	(Mobile Robot)
Speed	30 m/sec	0.1 m/sec
Energy consumed	10 Joule/sec	0.97 Joule/sec
	$\simeq 0.33$ Joule/m	$\simeq 9.7$ Joule/m
Initial energy	1.44 MJoule	144 KJoule

TABLE IV

CHARACTERISTICS OF FAST AND SLOW COLLECTOR USED IN THE SIMULATION

For the simulation, in the slow collector case, the cluster head transfers data to the collector through wireless RF communication for the optimal distance range as calculated in Section III-D. For the fast collector, however, this distance is traversed so fast that we make the simplification that cluster head only transfers data to the collector, once the collector arrives at the cluster head.

B. Collector Movement Schedule

Recollect that the collector moves among the cluster heads using one of three possible schedules—the Round Robin schedule, the Data Rate based schedule, and the Min Movement schedule. In a round of 10 slots, the collector will visit the cluster heads in the order 1, 2, 3, 4, 1, 2, 3, 4, 1, 2 in the Round Robin schedule; 1, 2, 3, 4, 4, 3, 2, 4, 4, 3 in the Data Rate based schedule; and 1, 2, 2, 3, 3, 3, 4, 4, 4, 4 in the Min Movement schedule. The length of a slot is the time it takes for the cluster head to transfer *all* the data accumulated at the cluster head till the moment the collector arrives (either physically arrives at the cluster head or data transfer through RF communication starts).

We also consider the possibility of variation in the physical conditions of the environment affecting the speed of the collector. The collector may face an obstacle in its path and may have to deviate from part of its pre-calculated route. Also, the physical conditions, such as wind speed, may change thereby affecting the collector speed. In order to take such variations into account, the speed of the collector is varied according to a normal distribution, such that the speed can vary by $\pm$ 40% of the average speed. This means that the 3σ limit of the Normal distribution is taken as $\pm$ 40% of the average.

C. Output Parameters

We collect the following output parameters from the simulation of the collector.

- Buffer size at the cluster head
- Data latency for data generated by the sensing nodes
- Time between recharges of the collector

The output parameters are calculated based on 50 rounds of collector movement *after* the initial transient period ends. The initial transient period is characterized by continuous growth in the buffer occupancy at the cluster heads. Each round is defined as 10 slots of movement. The buffer size in bytes is the buffer required at the cluster head for the data generated by the sensing nodes before it is handed over to the collector. Due to the variation in the speed of the collector, the buffer size also varies between rounds. We take the maximum buffer size over all the rounds after throwing out the outliers that lie beyond the 2σ range. The maximum buffer size is the relevant metric since the cluster head will have to provision for a buffer of that size to prevent data loss due to overflow. Throwing out the outliers is needed to eliminate the statistical noise and to draw useful conclusions from the results. The data latency is measured as the average of the time gap between the data generated by the sensing node and the data reaching the base station. We approximate the time the data is generated by the sensing node by the time the data reaches the cluster head. The collector returns to the base station when it estimates its energy will run out before it can reach the next cluster head and collect all its data. The third output parameter is the average time between successive visits of the collector to the base station for recharging.

D. Experiment Set 1: Fast Collector

In the fast collector, we observe the collector has a very high endurance and rarely returns to the base station for recharge. Therefore, the output parameter of average time between recharges is omitted for this set of experiments. The results are presented in Table V.

In the Data Rate based schedule, the buffer size that cluster head 1, 2, and 3 need is almost similar, but not for cluster head 4. The increasing amount of buffer size in the Data-Rate based scenario for cluster heads 1, 2, and 4 compared to the Round Robin schedule is because the maximum the number of cluster head(s) that a collector needs to visit before successive visits to

		Round Robin	Data Rate based	Min Movement
Buffer Size (KBytes)	CH_1	22.43	50.88	44.30
	CH_2	44.93	54.62	80.00
	CH_3	66.53	63.30	107.22
	CH_4	87.92	111.56	124.37
Data Latency (sec)	CH_1	75.04	181.29	153.79
	CH_2	75.11	93.18	76.99
	CH_3	75.05	62.19	51.36
	CH_4	74.93	46.61	38.55

TABLE V

RESULTS FOR FAST COLLECTOR WITH THREE DIFFERENT MOVEMENT SCHEDULES

cluster head 1, 2, and 4 is 9, 4, and 4 respectively. This is higher than the successive visits in the Round Robin schedule (3 for all the cluster heads). On the other hand, the gap between successive visits for cluster head 3 is 2 which leads to the decreasing amount of buffer needed. The same reasoning happens in the Min Movement scenario since the successive visits to each cluster head are spread farther apart than the Round-Robin and so is the amount of buffer needed to hold the data. The decrease of average latency in Data Rate based and Min Movement compared to Round Robin is because both these schedules consider the data rate of each cluster—the higher the data rate, the more often the cluster is visited by the collector. The latency is averaged over the entire data and is therefore improved.

E. Experiment Set 2: Slow Collector without Distance Transmission to the Collector

In this set of experiments, we consider the slow collector that waits for the collector to arrive at its location before transferring data to the collector. The buffer size, latency and time between recharges is shown in Table VI.

In this result, the buffer size needed by each cluster is higher compared to the fast collector case in Table V. The reasoning is that the collector speed is much slower such that each cluster produces more data between successive visits which also increases the data collection time of the collector. The frequency of recharge in Round-Robin schedule is higher compared to the other two schedules since the collector has to move each time it has finished collecting all the data

		Round Robin	Data Rate based	Min Movement
Buffer Size (MBytes)	CH_1	8.60	19.53	16.30
	CH_2	16.75	22.02	29.63
	CH_3	24.29	24.91	37.88
	CH_4	33.62	43.02	46.19
Data Latency (hrs)	CH_1	7.16	17.91	15.11
	CH_2	7.20	9.14	7.55
	CH_3	7.18	6.11	5.03
	CH_4	7.19	4.57	3.77
Time between recharges (hrs)	CH_1	43.96	48.52	78.45
	CH_2			
	CH_3			
	CH_4			

TABLE VI

RESULTS FOR SLOW COLLECTOR WITH THREE DIFFERENT MOVEMENT SCHEDULES UNDER NO DISTANCE TRANSMISSION

TO COLLECTOR

at a cluster head. In the Data-Rate Based schedule, there are 2 occasions in a round where the collector continues staying at cluster head 4 to retrieve more data. This reduces the movement energy consumption of the collector thus lengthening the time between recharges. In the Min-Movement schedule, the collector conserves even more movement energy such that the average time between recharging is even higher.

F. Experiment Set 3: Slow Collector with Distance Transmission to the Collector

In this scenario, the cluster head starts data transmission when the distance between the collector and itself is 100m, and stops the transmission when the optimum distance d is reached. In our case, as shown in Section III-D, d is 14.23 m. Below the optimum distance, the collector continues to move towards the cluster head and once it arrives at that cluster head, data transmission resumes again.

Since the cluster head is allowed to start data transmission early, this scenario reduces the average data latency on the three schedules as shown in Table VII in comparison with Table VI. There is also a decrease in buffer requirement for the same reason. The percentage of

		Round Robin	**Data Rate based**	**Min Movement**
Buffer Size (MBytes)	CH_1	7.60	17.33	16.28
	CH_2	15.21	19.46	28.43
	CH_3	21.94	22.27	37.08
	CH_4	29.16	39.33	45.73
Data Latency (hrs)	CH_1	6.37	16.08	14.36
	CH_2	6.37	8.25	7.17
	CH_3	6.35	5.49	4.78
	CH_4	6.34	4.12	3.59
Time between recharges (hrs)	CH_1	45.83	49.21	79.83
	CH_2			
	CH_3			
	CH_4			

TABLE VII

RESULTS FOR SLOW COLLECTOR WITH THREE DIFFERENT MOVEMENT SCHEDULES UNDER DISTANCE TRANSMISSION TO

COLLECTOR

improvement is shown in the Table VIII.

In Table VIII, the Min-Movement schedule has less improvement due to distance transmission because the collector often stays at a particular cluster head for consecutive slots. The fraction of time over which distance transmission happens in the Min-Movement schedule in relation to the time the collector spends at a cluster head is smaller than in the other movement schedules. Hence, the relative improvement due to the distance transmission is smaller.

The Round Robin schedule helps the recharge interval more than the other schedules. This can be explained by the observation that for cluster 1, the lowest data rate cluster, the collector does not *always* have to physically arrive at the cluster head. In some cases, all the data is communicated to the collector through distance transmission. In that case, the collector directly goes to the next cluster in its schedule (cluster 2). The distance traversed to go to cluster head 2 is less in this case compared to reaching cluster head 1 and then proceeding to cluster head 2. This is thus energy efficient and lengthens the time period between recharges of the collector.

		Round Robin	Data Rate based	Min Movement
Buffer Size	CH_1	11.64%	11.24%	0.15%
	CH_2	9.22%	11.65%	4.04%
	CH_3	9.70%	10.61%	2.10%
	CH_4	13.28%	8.56%	1.00%
Data Latency	CH_1	11.01%	10.21%	5.02%
	CH_2	11.57%	9.77%	5.02%
	CH_3	11.56%	10.15%	5.06%
	CH_4	11.84%	9.77%	4.94%
Time between recharges	CH_1			
	CH_2	4.25%	1.42%	1.76%
	CH_3			
	CH_4			

TABLE VIII

IMPROVEMENT FOR SLOW COLLECTOR WITH DISTANCE TRANSMISSION TO COLLECTOR

G. Experiment Set 4: Locator

For the locator, we use a commercial mobile robot (PPRK) ([14], [18]) (same as the one used for the slow collector), equipped with the Global Positioning System (GPS) carrying a regular sensor node with capability for short range RF communication. The locator moves in the cluster with 500 sensing nodes randomly distributed in the cluster spread. All the sensing nodes need to determine their own positions with the help of the locator. The cluster is divided into cells of size 10m x 10m and the size of the cluster is taken to be a square region of dimension 80m x 80m which inscribes the circular cluster region. The locator is capable of broadcasting its own position to the neighboring sensing nodes within a range of 30m. Thus, a locator in a cell can reach all the nodes in its own cell and in the 8 adjoining square cells (diagonal length = $2 \cdot \sqrt{2} \cdot 10 < 30$ m. The locator is unaware of the locations of individual sensing nodes. However, it knows the boundary of the cluster.

With this information, the locator moves from one cell to another in an "S" pattern as shown in Figure 7. The number of sensing nodes in each cell is shown by the number in the lower right corner in each cell. During the course of its movement, the locator broadcasts 8 beacon

messages in 8 different random positions within each cell. Each beacon message contains the position information of the locator. Since the size of each beacon message is 36 bytes (default packet size in TinyOS [9]) and the locator's bandwidth is 38,400 bps, the locator stays in each position for broadcasting a beacon for 7.5 ms. In order to simulate a real world situation, we vary the locator's speed by using a normal distribution, where on an average the locator moves 10cm/s with a variance of $\pm 40\%$ (same as for the land robot for the slow collector). Each sensing node needs to receive 72 beacon messages in order to determine its position with error in each dimension of less than 10 m.
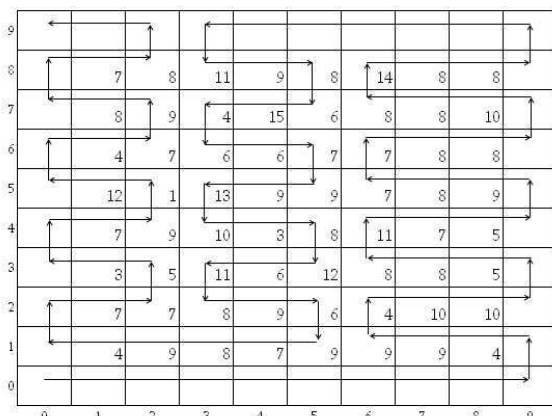

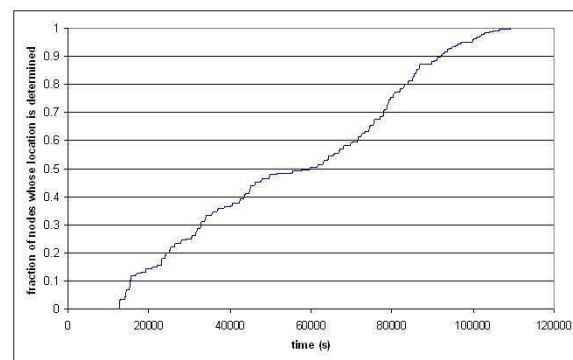Fig. 7.   Movement of the locator within a cluster

Fig. 8.   Rate of dissemination of location information among sensing nodes in a cluster

We are interested in three output parameters for the locator. The first is the rate at which location information is disseminated in the cluster. This is shown in Figure 8. The x-axis is the time elapsed since the locator started its movement in the cluster. The y-axis is the fraction of the nodes in the cluster that have determined their location. The second parameter of interest is the total time measured from the time the locator starts moving in the cluster such that all the nodes in the cluster know their position. For our simulation, this is 109,359.65 seconds ($\simeq$ 30.38 hours). This can be read off from the curve in Figure 8 by considering the time for the y-axis value to be 1.0. This time can be looked upon as the worst case initial latency when none of the nodes know their location to start with. In the steady state, only a few of the nodes will move and an incremental location determination will be needed. For this reason, we are interested in the third parameter, which is the time for a node to determine its location once the

locator arrives in its vicinity. This is given by the time to move among the cell in which the node is located and the 8 adjoining cells and broadcast 8 beacon messages from each cell. For our simulation, this time is 2882.39 seconds (= 0.8 hours). This is also the time for which the node will have to be stationary for the location determination to be useful. This number appears high and is due to the slow speed of the locator (0.1 m/s) compared to the transmission range (30 m). In a network deployment, this will be determined by the estimated pause time in the movement of a node and a locator of an appropriate speed will be chosen.

V. CONCLUSION

In this paper, we have proposed an architecture for energy efficient data gathering in large scale sensor networks. Some sensing nodes in the network may be passively mobile which makes the problem more challenging. In the network model under consideration, the sensor field has a large geographical spread and many of the sensing nodes are far away from the base station. We introduce some special classes of nodes some of which have the capability of controlled mobility, i.e., mobility of the form that can be directed by sending control signals. The data collectors have the capacity for moving over long distances, possibly at high speeds for collecting data from the cluster heads and communicating the data back to the base station. The cluster heads aggregate the data from the nodes in the cluster and temporarily store them prior to transmission to the collector. In order to enable efficient data gathering from the passively mobile sensing nodes, they need to be associated with the closest cluster head and therefore, need to know their locations. This is enabled by GPS-equipped mobile locators which move through the cluster and broadcast beacon messages with location information that helps the sensing nodes determine their position.

In this paper, we propose algorithms for motion of the data collectors and the locators. We also propose an extension to the traditional triangulation approach for location determination using mobile locators. The algorithms are analyzed mathematically and simulated to bring out their important characteristics, such as energy consumption, data latency and cluster head buffer requirement (collector algorithm), and convergence time (locator algorithm).

For future work, we plan to consider the movement patterns of the passively mobile sensing nodes in a cluster. We wish to investigate what proactive information broadcast by these passively mobile nodes can benefit the algorithms by making them more informed about the sensor field,

such as the density of nodes in a region. We are also investigating the effect of failures of collectors or cluster heads on the data collection. A set of cluster heads can concurrently serve the role. Also cooperation between multiple cluster heads to overcome temporary periods of high data rate is possible. There may be multiple collectors in the network which may work cooperatively in servicing the different cluster heads. Alternately, there may be a set of collectors for emergency data gathering corresponding to rare events being detected by a sensing node. The mobility algorithms needs to take these classes of collector nodes into account.

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