Employing Sink Mobility to Extend the Lifetime of Wireless Sensor Networks

Viplavi Donepudi and Mohamed Younis

Department of Computer Science and Electrical Engineering
University of Maryland Baltimore County
Baltimore, MD 21250
`{donevip1,younis}umbc.edu`

Abstract. Wireless sensor networks (WSNs) often employs miniaturized battery-operated nodes. Since in most setups it is infeasible or impractical to replace the onboard energy supply, the design and operation of WSNs are subject to a great deal of optimization. Among the most popular strategies is the pursuance of multi-hop routes for forwarding collected sensor data to a gateway. In that case, the gateway becomes a sink for all traffic and the close-by nodes relay lots of packets and deplete their battery rather quickly. In this paper, the mobility of the gateway is exploited to balance the load on the sensors and avoid the overload on the nodes in the proximity of the gateway. A novel approach for defining a travel path for the sink is presented. The proposed approach is validated in a simulated environment and is shown to significantly boost the network lifetime.

Keywords: Wireless Sensor Networks, Energy Efficiency, Node Mobility, Network Longevity.

1 Introduction

Wireless sensor networks (WSNs) have been attracting a growing attention from the research community in recent years. A sensor node is equipped with a sensing circuitry to measure ambient conditions such as light, heat and pressure, and a radio for transmitting the collected data. Sensors operate on small batteries and become non-functional when the onboard energy supply gets depleted. A sensor node also has limited computation and memory capacity because of its miniature size. A WSN is composed of a large number of sensor nodes that probe their surroundings and send their data to a gateway for further processing. The gateway interfaces the network to remote command centers. Fig. 1 shows a typical WSN architecture. Applications of WSNs include disaster management, early detection of fires in forests, combat field surveillance and security [1-4]. In these unattended application setups energy consumption is a major concern since a sensor node fails when it runs out of energy and it is impractical to replace its battery in inhospitable environments. Therefore, energy-aware design techniques both at the node and network levels are usually pursued in order to extend the lifetime of the individual sensors.

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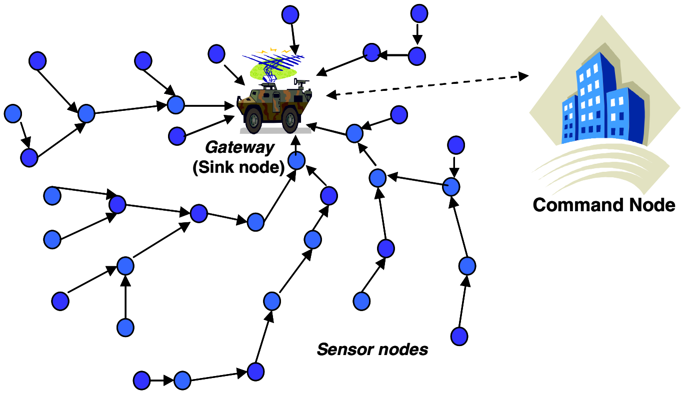


Fig. 1. A sample WSN architecture with the gateway acting as a sink for all traffic and interfacing the network to a remote command center

The quest for maximizing the node lifetime has made multi-hop data routing a very popular optimization scheme. Generally in order to achieve good signal to noise ratio, the output power of a radio at the sender has to be proportional to d^l where d is the distance to the receiver and $l \geq 2$. Therefore, to save energy, sensors data is usually relayed to the sink over multi-hop paths even if a sensor can directly reach the sink. Since in most WSN applications, data is forwarded towards a single sink node, the sensors close to this sink would get heavily involved in packet relaying and consume their energy reserve rather quickly. At the time when a sensor node "S_1" close to the sink runs out of energy, data paths are re-established and a node "S_2" that is further from the sink than S_1 becomes the closet hop. Such a scenario increases the total transmission energy and shortens the node's lifetime. Basically, S_2 will consume more energy to reach the sink than S_1 and dies soon after. Such effect spreads outward and may leave the sink unreachable to many sensors. Fig. 2 illustrates this problem.

The scenario described above is definitely damaging to the application and would cause the network to prematurely partition despite the availability of numerous sensors. This paper investigates means to counter the effect of accelerated energy consumption around the sink node and ensure a longer lifespan for sensors close to the sink node. The problem will be referred to thereafter as having void area around the sink. The proposed approach exploits the mobility of the gateway node. Basically the void problem is caused by the involvement of the neighbors of the gateway in data relaying at all time. Thus, if the gateway location continually changes, it always has new neighbors and the traffic forwarding load will be spread. The main question is what the travel path that the gateway should follow.

Mobility has become a hot research topic in WSN recently. In some of the considered network models, the sink moves around the deployment region and collects data from the sensor nodes. For example, in [5], mobile "Mules" are used as forwarding agents. Another protocol, called SEAD, has been introduced in [6] where access points are defined for the mobile sink to collect the data. In these approaches the sink node moves randomly in the deployment area without a known travel path. In fact, these approaches are geared for handling the sink motion rather than employing

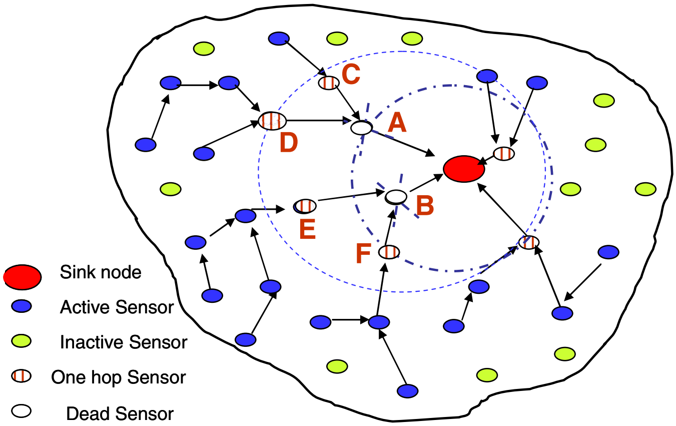


Fig. 2. Sensors close to the sink (inner circle) act as a relay for data sources upstream and deplete their energy at a high rate. Nodes A and B eventually exhaust their batteries and fail, forcing nodes C, D, E and F to become the closest hops to the sink node and to consume their energy at rate higher than before A and B fail given the increased distance. This problem spreads outward quickly creating a void around the sink.

such mobility to enhance the network performance. Unlike such work, this paper promotes mobility as a solution to the void around the sink problem. A novel Density-based Touring Strategy (DTS) is proposed where the sink node is programmed to travel through areas that are highly populated with sensors in order to enhance the performance.

This paper is organized as follows. The next section discusses the related work. The DTS approach is described in section 3. Section 4 describes the simulation setup and the performance results. Finally, the paper is concluded in Section 5.

2 Related Work

The wide variation in the node lifetime across the network has been noted by quite a number of studies [7-8]. The suggested solutions in the literature for tackling this issue can be categorized as precautionary or reactive. Precautionary schemes hope to prevent the problem from happening and often pursue non-uniform node deployment [8-9] and careful topology setup [10-12]. Reactive schemes, as the name indicates, respond to the fact that many sensors die in a particular region. The most notable reactive scheme is the relocation of nodes [13].

Node-placement based solutions strive to increase the sensor population close to the sink in order to ensure the availability of spares. These spares will naturally replace faulty nodes and thus sustain the network connectivity. Ishizuka and Aida [9] have investigated random node distribution functions, trying to capture the fault-tolerant properties of stochastic placement. They have compared three deployment patterns: simple diffusion (2-dimensional normal distribution), uniform, and R-random, where the nodes are uniformly scattered with respect to the radial and angular directions from the sink. The R-random node distribution pattern resembles the effect of an exploded shell and obeys the following probability density function for sensor positions in polar coordinates within a distance R from the sink:

$$f(r,\theta) = \frac{1}{2\pi R}, 0 \le r \le R, 0 \le \theta < 2\pi$$

The simulation results have shown that the R-random deployment is a better placement strategy in terms of fault-tolerance. A similar study has been conducted by Xu et al. [8], where a weighted random node distribution is proposed to account for the variation in energy consumption rate among the nodes. It is worth noting that neither [8] nor [9] has suggested practical means for implementing the proposed distribution.

On the other hand, some have tried to balance the energy consumption among the nodes using careful setup of the routing tree. For example in [10] the node's load, measured by average queue size, is factored in during the route selection. Shah et al. [11] have proposed an occasional use of sub-optimal paths in order to balance the load on nodes and increase their lifetime. Data routes are chosen by means of a probability function, which depends on the energy consumption on the possible paths. Meanwhile, in [12] the energy reserve at the individual nodes is considered in the route selection. However, these techniques cannot prevent the potential of the void around the sink problem since they still involve the sensors around the sink as relays all the time.

The work on sink node relocation [13] is one of the most notable efforts for dealing with the void around the sink problem. The main idea is to move the sink towards the sources of highest traffic. The performance of DTS is compared to this approach in Section 4. A similar idea is explored by Basagni et al. [14], where the sink makes a greedy move to neighboring areas whose sensors collectively have a higher residual energy. Another very recent work on countering the void around the sink problem is reported in [15]. Basically, a number of strategies for node deployment are studied. The main idea is place additional nodes, mainly sensors and gateways, in selected areas in order to prevent overloading some of the existing sensor nodes and to boost their lifetime. It is argued that a deterministic node placement is not feasible in many unattended WSN applications and it may be infeasible to apply such a solution. Nonetheless, the effectiveness of DTS is compared to these approaches through simulation is Section 4.

Employing a mobile sink has been pursued in a number of publications as a means for optimizing the performance of the WSN. Coverage and network longevity are the most popular objectives of the motion. Given the focus of this paper on the void around the sink problem, only work that targets the network lifetime is considered. The proposed approaches in the literature can be categorized based on the travel path into random, predictable and controlled, based on the network state as topology dependent and topology independent, and based on the data collection strategy into employing access points or pursuing direct interaction with sensor nodes. A random travel often fits the category of topology independent schemes and usually yield little benefits relative to the incurred overhead [16, 17]. A way to counter the excessive topology management overhead is to pursue predictable mobility solutions [18-20] where the sink travel path is fixed at the time of network setup. However, this is still topology independent and does not adapt to changes in the network state.

Controlled motion is seen by the research community as the better scheme since the travel path is predictable and the changes in the data dissemination tree due to the sink mobility are deterministic. In addition, the tour can be set based on the network state and the current topology, which makes it feasible to gear the sink motion for maximizing the performance. DTS fits in this category. The two most notable controlled mobility schemes are reported in [21] and [22]. Actually, the approach of [21] resembles those that pursue predictable sink motion. The difference is that the travel path is picked based on the network periphery. The use of network clustering and designating cluster heads are the base for defining the travel path of the sink node in [22]. Cluster heads act as a data storage depot that gets emptied when visited by the sink. In other words, the sink moves from one cluster head to the next and so on. Clearly this approach is mostly influenced by the criteria for clustering and setting intra-cluster data routes. One would argue that the approach in essence leaves the solution of the void around the sink problem to the clustering algorithm to address rather handling it through cleaver selection of the sink travel path.

3 Sink Mobility Strategy

As discussed earlier, the sensors close to the sink node tends to deplete their energy at a high rate and sometimes become traffic bottlenecks. This section describes how a controlled mobility of the sink node can be employed as a means to counter this problem. An algorithm for defining the travel path is presented and its effectiveness in extending the network lifetime is analyzed.

3.1 Design Issues

The essence of employing the sink mobility to counter the potential of the void around the sink problem is to spread the traffic load and prevent relaying bottlenecks from forming. In other words, the sink virtually extends its set of neighboring sensors by being at many spots. There are three major questions that are to be addressed:

1. What travel path to take: This is an intuitive question given the goal of the sink motion. One way to tackle this question is to identify a set of positions that the sink is to visit on a tour. It has been shown that optimal positioning of the sink can be mapped to the 1-center problem, which is NP-hard [23]. Basically, having an infinite solution space complicates the problem. Thus, heuristics ought to be pursued.
2. How fast the sink travels: Changing the sink position introduces two complications to the routing of data. First, the data may be ready while the sink is absent from the neighborhood. This may happen if the sink does not come back on time to the position that the sensors expect it to be at. The alternate option is for the data to follow the sink, which makes the establishment of the data paths unnecessarily complex and imposes significant control packets overhead that diminishes the optimization efforts the sink mobility is geared to achieve. The second complication is that data delivery may be late and the application may get

negatively impacted. Since the sink travel speed may be subject to some physical constraints, e.g., the capabilities of the motors on the sink, the travel path has to be carefully defined in order to cope with the data freshness constraints.

3. How to find the sink: When the position of the sink changes, the sensors may not know how to reach it. Thus, the sink either has to keep broadcasting where it is or the sink position has to be somewhat predictable. Continual update of the sink position makes the network topology too dynamic and unnecessarily complicates the data routing given that the sensors are stationary and the sink motion is to optimize the performance. Predictable sink availability at certain spots makes it easier to establish data routes. Basically, a sensor tries to set up a route to the closest spot that the sink is scheduled to visit.
4. How data is collected: There are potentially two options for the sink to receive the data. In the first some sensor nodes play the role of cluster heads or aggregation nodes. A local routing tree is formed to forward the data to the closest aggregation node. The sink will then harvest the data from aggregation nodes while it is coming within their communication ranges. In other words, the aggregation points act as data access points or data storage depots. This model is not preferred though since it may overload the aggregation nodes and shorten their lifetime. The second option, which is adapted by DTS as explained below, establishes a local routing tree based on a virtual gateway. The virtual gateway basically represents where the sink node will be when it is in the vicinity. Sensors forward their data towards the virtual gateway and the sink will receive the data from the neighbors of the virtual gateway when it comes to the area.

3.2 Density-Based Touring Strategy

The goal of DTS is to find the shortest and most effective travel path for the sink node. To counter the complexity of the sink placement problem discussed above, DTS identifies a set of positions to be visited. As the name indicates, the node density is a main factor considered by DTS for selecting the visited spots on the trip. The rationale is that highly populated areas will have ample routing resources and the relaying load will be split on multiple nodes. Such load sharing will extend the nodes lifetime, which is the objective of the sink mobility. In addition, passing close to nodes that transmit many packets most probably will yield good average delay and energy per packet, network throughput, and reliability [7, 13]. The travel path should actually be a tour after which the sink revisits previously travelled areas. Thus, sensors will wait for the sink to come back to deliver their data reports. Minimizing the travelled distance is important to lower the overhead incurred by the sink node and reduces the latency in data collection. A long tour will delay the sink arrival and affect the freshness of the sensor data and may cause it to miss some important data samples.

Since there are an infinite number of possible paths to be considered, the deployment area is partitioned into a two-dimensional grid of size $m \times n$. In theory the entire deployment area can be a search space. However, in practice it may be desirable to limit the travel distance and to prevent the sink from going too far while moving in order to shorten its tour. The boundary of the allowed travel area can be stretched to enable more flexibility by expanding the search space, especially if the void problem does exist in the network. The size of the cell is a design parameter which can be determined based on sensor's radio range. Sufficiently small cells make it possible for a sensor node to reach the sink when it visits its cell. In addition, appropriate selection of the cell sizes enable nodes in neighboring cells to reach each other and thus a node can pursues few hops to forward its data to the sink while passing a neighbor cell.

The cells in the grid serve as steps on the sink's travel path. In order to set up the path, first the most populated cells are picked. DTS then models the grid as a directed graph *G*. Each cell *c* is represented as a node in *G*. The problem now becomes finding a route that traverse the set of nodes *P* that corresponds to the picked cells. Two options can be identified. The first option is simply to use the distance between the centers of the cells as link costs on *G* and then find the minimal spanning tree for the sub-graph involving only the nodes in *P*. In the second option, DTS estimates a cost factor for each cell *c* that is inversely proportional to the number the nodes located within the cell *c* (i.e., $w(c)=\alpha/|c|$). Each cell c_i is connected to all its nine adjacent cells with inbound edges that have a cost $w(c_i)$. Now, the path selection can be easily mapped to the problem of finding the minimal (a least cost) spanning tree (or a cycle) for the nodes in *P*. In addition to the difference in the link cost calculation, the second option introduces potentially more cells on the travel path and may lengthen the travel distance. As indicated, the sink will travel longer distance and incur overhead. Obviously, selecting the right option is subject to a trade-off.

The intuitive question is how high the sensor population in a cell is in order for the cell to be considered a candidate. One extreme is when all cells are to be visited, which corresponds to the minimum spanning tree or cycle for the entire graph. Obviously this case increases the data collection latency and the motion overhead given the length of the tour that the sink makes. The other extreme is when no cell is

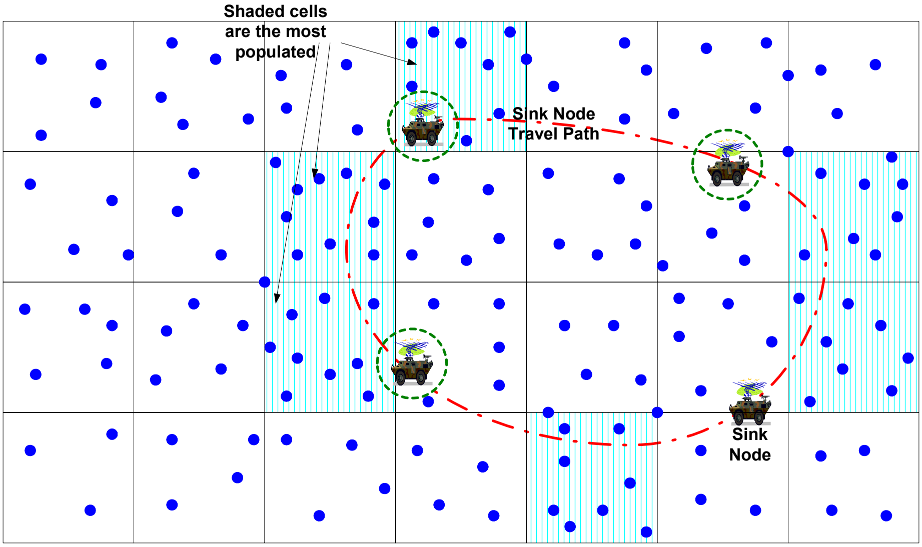


Fig. 3. The sink makes a tour that include the cells that are high populated with sensors

picked which corresponds to a stationary sink that does not move. A reasonable strategy is to set a threshold, i.e., to include the top *x%* of the cells in terms of the number of sensors in the cell. In Section 4 the effect of the threshold on the performance is studied through simulation. If a spanning tree is to be identified the sink may have to travel the tree from start to end and back. This may impact the freshness of the data for some sensors. For example, the first cell will be revisited after the sink visits all other cells on the travel path twice. A cycle will be a more appropriate choice. Fig. 3 illustrates the idea.

The DTS works as follows. First the cells that will be visited are identified based on the node population. A travel path is then selected according to the criterion for the inter-cell link cost in the graph representation of the grid. The nodes in the designated cells on the path set routes as if the sink is located at the center of the cell, i.e., by employing the virtual gateway model discussed in the previous section. Nodes in unvisited cells forward their data to the closest cell that is part of the sink tour. When the sink travels to go to the individual virtual gateway positions in the designated cells and receives the data. Fig. 4 shows a pseudo code summary of the DTS algorithm. It should be noted that the sink travel speed and the presence of data collection latency are not factored in this paper for simplicity of the presentation. The DTS algorithm can be easily extended to factor in data freshness constraints.

```
Algorithm Density-based sink touring (x)
-   Map the deployment area into a grid based on the communication
    range of the individual sensors
-   Sort the list of cells according to the number of sensors
-   Identify the set P of the top x% in the sorted list
-   Model the grid as a graph G and define the link costs
-   Find the minimal spanning tree for the set P of nodes
-   Set routes to the closest cell on the tour
-   Move the sink on the links of the minimum spanning tree
End;
```

Fig. 4. Pseudo code for the DTS algorithm for sink m

4 Experimental Validation

The effectiveness of DTS in dealing with the void around the sink problem has been validated through simulation. This section discusses the simulation environment and performance metrics and the experiments results.

4.1 Simulation Environment

A Java-based WSN simulator has been developed to handle numerous test cases. A varying number of sensor nodes is randomly scattered over a rectangular area. For a certain position of the sink node, data paths are set by applying Dijkstra's least cost routing algorithm using the square of the inter-node distance as a link cost. The idea of virtual gateways is used to associate sensors to a certain position of the sink on the tour. In that case, a sensor in a cell forwards its data to the closest cell to be visited by the sink. The simulator focuses only on the network layer and assumes collision free medium access.

Once the network has been created, events of interests, such as a rage of fires, are triggered at random spots in the area. The sink will then collect the data from those sensor nodes for which an event falls in their detection range. Sensors that cannot detect an event will not generate any packets. A simulation cycle denotes the time in which each sensor sending its data along the designated path until the data reaches the sink. Each time a packet is transmitted the energy consumed at the sender and receiver is tracked and the remaining battery life is adjusted. When a sensor completely depletes its onboard energy supply, it is considered dead, and the network topology is restructured.

4.2 Experiments Setup and Performance Metrics

In the experiments, the network consists of varying number of sensor nodes (50 to 500) that are randomly placed in a 100×100 m^2 area. The entire region is divided into cells. The size of the cell is varied to study its impact on the performance. Basically, the area is divided into 9, 16, 25, 36, 49, 64, 81 or 100 equal-sized cells. The mobile sink (gateway) travels through the cells based on the tour devised by the DTS algorithm. A free space propagation channel model is assumed [24]. A node is considered non-functional if its energy gets completely depleted. The maximum transmission and sensing ranges of a sensor node are assumed to be 10m and 20m, respectively. The radio range of the mobile gateway is 100m. All the sensors that can detect an event generate packets at the rate of 1 packet per simulation cycle. Each data packet has an energy field which is updated whenever transmission and reception of a packet takes place. The model of [25] is used for calculating the transmission and reception energy cost.

Simulation experiments have been conducted for different network sizes, grid configurations and selection criteria for the cells to be visited on the sink tour. It should be noted that varying the number of nodes while fixing the radio range and dimensions of the deployment area would capture the effect of the node density and yield topologies with different connectivity characteristics. Each experiment considers a new randomly generated network topology. When comparing to other approaches, each generated topology has been replicated to measure the performance under different parameters. Unless stated otherwise, the sink pursues the shortest travel path between the selected cells. The following metrics are used to assess the performance of DTS:

- *Average energy per packet:* This metric represents the average energy consumed until delivering a data packet to the sink node.
- *Average lifetime of a node:* This metric gives a good measure of the network lifetime by averaging the time a node stay functional.

4.3 Experimental Results

This section presents some of the obtained performance measurements. The results are grouped based on the parameter that is varied. A comparative assessment relative to prior approaches for countering the void around the sink problem is provided at the

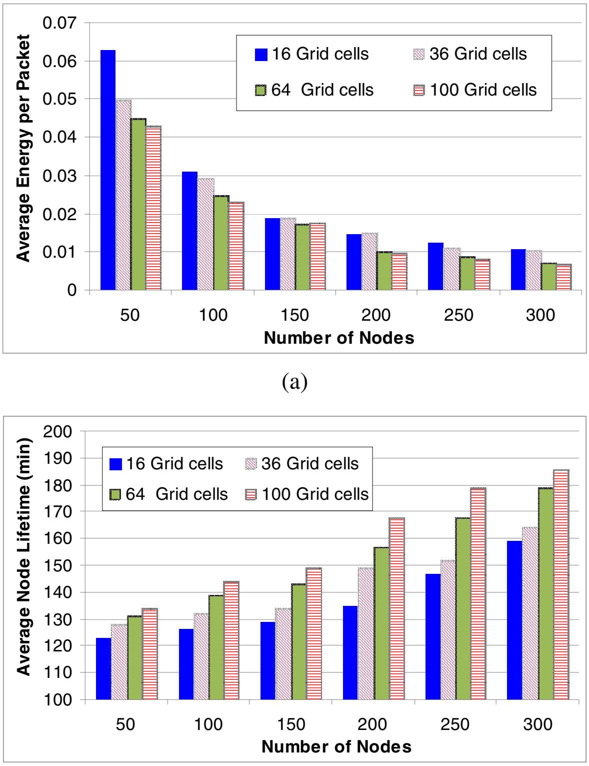
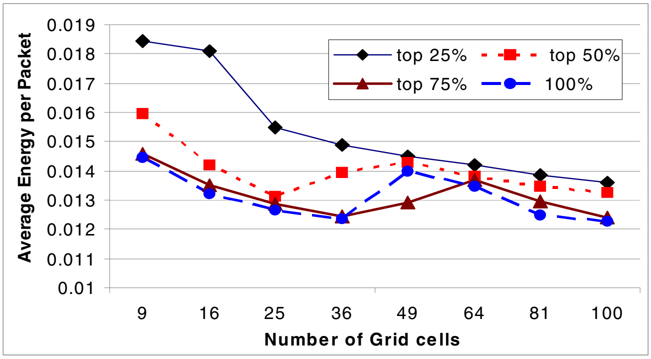


Fig. 5. The scalability of the performance gains achieved through the DTS approach and how the cell size influence it

tail of the section. The result of each experiment is the average of five executions. It has been observed that with 90% confidence level, the simulation results stay within 6%-10% of the sample mean.

Effect of the network size: Fig. 5 shows the performance of DTS as a function of the network size and the number of cells in the grid. The results show that the gains achieved through DTS scale very well for large networks. However, the gain appears to saturate for large networks given the increase in node density, which ensures the availability of sufficient routing resources in the network and makes the role of the sink mobility less important. The performance will be compared to other optimization strategies and to the case of stationary sink later in this section.

Fig 5 also indicates that the resolution of the grid, controlled by changing the number of cells, plays a role in the performance. When the cell size is large, i.e., having fewer cells, the performance of DTS is worse than using smaller cells. This is expected since it will be possible to identify the dense areas in the network with a higher resolution. This point will be elaborated in the next.



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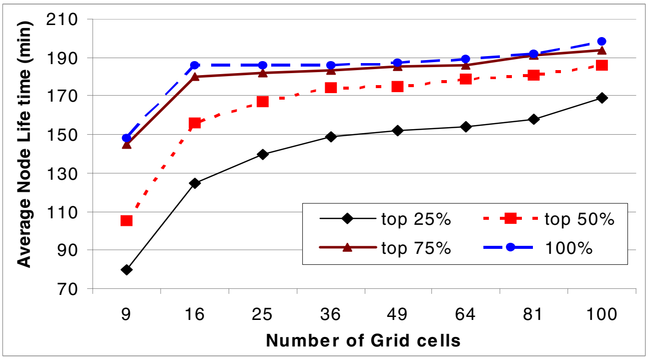
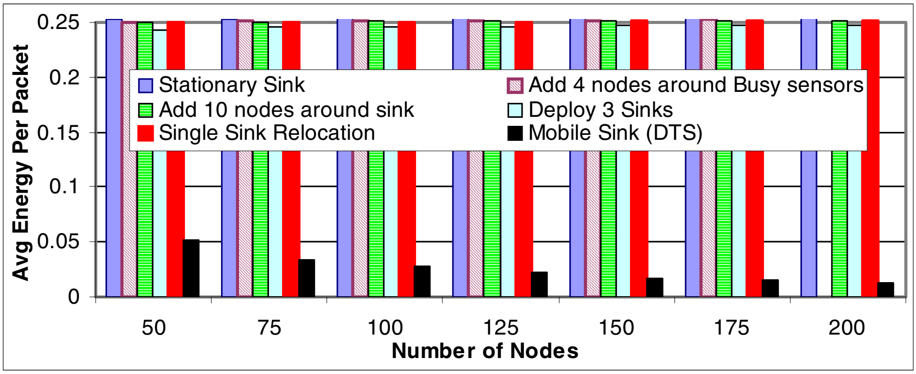


(b)

Fig. 6. The effect of the cell size and the density threshold for selecting the cells on the sink tour on the achieved performance

Effect of grid related parameters: This set of experiments validates how DTS is affected by the size of the cell and the number of selected cells to be on the sink travel path. The cell size is controlled by changing the number of cells in the grid. Basically, the experiments have considered slicing the grid into 9, 16, 25, …, 100 cells. In addition, the number of cells considered when setting the sink travel path has been varied. Recall, the DTS sort the cells based on the node density and picks the top *x*% of the list. The considered values of *x* are 25, 50, 75 and 100, which set the threshold for how high the density of a cell in order to be picked. Obviously, selecting 100% of the cells implies touring the entire network and is considered as an extreme case. In these experiments 200 nodes are deployed in the network and the communication range is assumed to be 20m. The simulation results are shown in Fig. 6.

The results indicate that the cell size is an influential parameter. Slicing the grid into few cells does not allow DTS to pinpoint the areas that need attention. The increase in the number of grid cells enables a fine grained analysis and a more accurate identification of highly populated spots that are worthy to be visited by the sink. Nonetheless, increasing the resolution too much does not help. For example,



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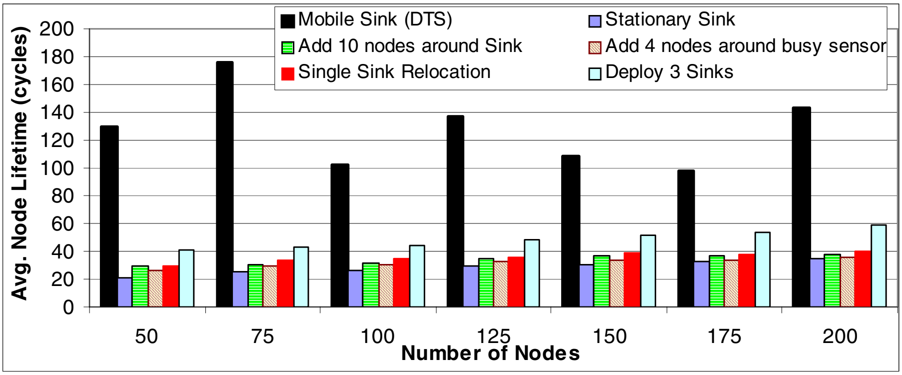

(b)

Fig. 7. When compared to other strategies for countering the void around the sink problem, the effectiveness of DTS is very distinct and its performance significantly dominates them

having 81 cells does not add much gain in performance compared to 49 cells. The performance graphs indicates that for a uniform distribution of nodes having a cell size that equals 2/3 the communication range seems to be a good choice. On the other hand, touring all cells indeed delivers the best performance. However, as discussed earlier, this choice maximizes the overhead incurred by the sink and increases the data latency. Actually, touring 75% of the cells yields a performance that is very close to that of touring all cells. The graphs indicate that selecting 50% of the cells is a very reasonable choice.

Comparison to other solution strategies: To assess the effectiveness of the sink mobility as a solution to the void around the sink problem relative to other solution strategies, the performance of DTS has been compared to the selective node deployment schemes proposed in [15] and the sink relocation approach of [13]. The comparison is based on the two metrics studied above, namely, the Average Energy per packet and the average lifetime of a node. The stationary sink results are used as a baseline. The sensor's communication range has been set to 10m. For DTS the grid is divided into 64 cells and the top 25% of the highly populated cells are visited on the sink tour. The travel path is formed by mapping the grid to a graph with the link costs defined based on the node population, as explained in Section 3. Thus effectively, the sink will visit additional cells during its tour.

The results are shown in Fig. 7. The results demonstrate the significant performance advantage achieved through DTS. Relative to the baseline case, the average energy per packet consumption has been reduced from 0.25 to 0.05, a gain of 400%. In fact, the contribution of the other strategies seems very marginal relative to DTS. The average lifetime of a node is more than doubled in most experiments. It should be noted that the variability in the average node lifetime in this experiments relative to the size of the network is due to the way that path is set compared to the earlier experiments, i.e. the use of a density-base rather than distance-based link cost.

5 Conclusion

This paper has investigated the use of mobile gateway to counter the problem of uneven energy consumption in wireless sensor networks. Basically, the gateway acts a sink for all traffic and their neighboring nodes tend to forward the most packets and thus deplete their energy rather quickly. By moving the sink, the set of neighboring nodes will change and the load is spread throughout the network. A novel approach is presented for defining an effective and efficient travel path for the sink. A density-based touring strategy (DTS) has been promoted for finding the spots that sink will pass to collect data. Each of these spots will be considered by the sensors in the vicinity to build a local routing tree.

The proposed DTS approach been validated through simulation. Two metrics have been pursued to assess the energy efficiency of the network; namely the average energy per packet and the average node lifetime. The simulation results have confirmed the effectiveness of DTS and its scalability for large networks. The experiments also have highlighted the effect of the various parameters on the performance and provided guidelines for the best configuration. The DTS approach is further compared to other strategies for countering the void around the sink problem, namely deploying additional nodes in selected areas and the relocation of the sink when deemed necessary. The comparison has demonstrated the distinction of DTS as a solution and the effectiveness of the sink mobility as a solution if the motion capabilities and overhead can be supported in the network design.

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