Deploying Multiple Mobile Sinks in Event-Driven WSNs

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Abstract—Deploying multiple mobile sinks is an attractive approach to enhance the performance of wireless sensor networks. In this paper, we address the scenario of two mobile sinks. The two sinks can travel in the same region or in the divided regions separately. The problems are formulated by a lattice-based network model. We deduce the network lifetime and delay of data delivery in different mobility patterns. The relation between network performance and number of mobile sinks is also discussed. Simulation results are provided to validate our theoretical analysis followed by performance comparison of different mobility patterns.

Index Terms—Wireless Sensor Networks, Multiple Mobile Sinks, Network Lifetime, Delay of Event Delivery, Optimal Mobility Trajectory

I. INTRODUCTION

Wireless sensor networks (WSNs) are networks usually comprised of a large number of nodes with sensing and routing capabilities [1]. Multi-hop routing is usually implemented for the transport of the sensed data to special data collection nodes (the sinks).

Recently, deploying multiple base stations as data sinks in order to enhance the lifetime of wireless sensor networks has received much research attention. The advantages include, among others, efficient routing (e.g., [2], [3], [4]), data dissemination (e.g., [5]), topology control (e.g., [6]), data aggregation (e.g., [7], [8]). Although all these protocols achieve their optimization goals under certain conditions, they always focus on the sensor nodes. We will show that further improvements on the performance of sensor networks can be achieved if we shift our focus to the behavior of sinks.

There are some research papers on how to find an optimal position for all the sinks in order to maximize the lifetime of the network (e.g., [9], [10], [11]). However, they assume sink to be stationary or make the sink move to the optimal positions. Currently, sink mobility has been exploited to extend the network lifetime, e.g., [12], [13], [14], [15]. They mostly focus on the mobility of single sink, or analyze the network performance with multiple random walk sinks. Hence, we will extend the research to the deployment of multiple mobile sinks.

Information gathering in sensor networks can follow different patterns, depending mostly on the specific needs of the applications. In a time-driven scenario all sensors send data periodically to the sink. As opposed to this, in the event-driven case sensors start communicating with the sink only if sensing an event, i.e., a situation that is worth reporting. Finally, in a query-driven scenario a sensor transmits its data only if the sink asks for it [16].

Most of the research papers (e.g., [14], [10]) in the area address the time-driven scenario, and provide energy-efficient solutions for homogeneous networks, with sensors having constant and equal amounts of data to send in all parts of the covered region. However, there are a large number of applications (e.g., intrusion detection, seismic activity monitoring, animal movement tracking) where an event-driven approach is more appropriate. Hence, in our paper we address only this scenario.

In this paper, we propose a solution that is significantly different from all the above approaches. We assume in an event-driven scenario, there exist multiple mobile sinks in the network. When a sensor node detects an event occurring, it sends data to the nearest sink via multi-hop routing. Our goal is to find a suitable deploying manner of multiple mobile sinks so as to shorten the delay of data delivery and prolong the network lifetime.

The rest of this paper is organized as follows. In Section II, we state the problem and the lattice-based network model. Section III analyzes the sensor networks with two and more mobile sinks based on previous research achievements. Simulation results are provided in Section VI. Finally, Section V concludes the paper.

II. SYSTEM MODEL

A. Network Model

We make the following simplifying assumptions in building the system model (Fig.1 illustrates the system model):

- Sensors remain stationary at the nodes of a bi-dimensional square grid composed of same-size cells.
Sensor nodes are homogeneous and wireless channels are bi-directional, symmetric and error-free.

Sensor nodes communicate with the sink by sending data via multiple hops along the shortest path; a hop is of one cell side length, i.e., the distance between two adjacent nodes in the grid equals the transmission range of nodes.

Data transmission and reception are the major energy consuming activities.

The sinks can move freely on the grid from one node to another in eight directions. After the sink arrives at a node, sensors can communicate with the sink. For analytical simplicity, the traveling time of the sink between two nodes is considered negligible, and the sojourn time of the sink visit at sensors is equal.

The event occurs at any grid cross point independently with stationary distribution.

B. Path Selection

If a sensor node $i$ is neither co-located with sink $k$ nor directly connected with it (i.e., if $k$ is not co-located with any of the nodes in $S_i$), then data packets generated at node $i$ have to be relayed through multiple hops to reach the sink. The sink can only be located at one node position in the grid (the sensor locations and the possible sink locations are the same). The sink keeps moving among grid positions until the maximum network lifetime is reached, which occurs when one sensor node’s residual energy drops below a predefined threshold required for it to operate (when this occurs the sensor “dies”). When a sensor node lies on the same horizontal or vertical line of the current position of the sink, a unique shortest path exists between the two nodes. Otherwise, multiple shortest paths exist. For example, six shortest paths exist between node $i$ and sink $k$ (Fig.1), each four hops long. Three of those paths are shown, path 1 and 2 along the perimeter of the rectangle defined by nodes $i$ and $k$, and path 3, one of the four interior paths. In our routing protocol we consider only the two paths along the perimeter of the rectangle, i.e., paths 1 and 2 in Fig.2. These two routes are taken at equal frequencies, or equivalently, the route alternates between the two paths.

C. Performance Metric

1) Network Lifetime: Network lifetime is one of the most importance performance metrics in WSNs. Usually, it is defined by the sustained time when the first sensor node runs out of its residual energy, thereby causing loss of network coverage. Hence, the lifetime of network is determined by the node which undertakes the heaviest load. According to our assumptions, the network is homogeneous. Therefore, the load of a sensor node can be calculated as the probability of the sensor node having data to relay. The energy model of sensor nodes is simplified, we define the power consumed in receiving and relaying one packet to be 1 unit. The Load is calculated as the total power consumption divided by the total number of packet generated. So the Load of network is the maximum value of the Load of sensor nodes. For the purpose of intuitive indication, we use $Life = \frac{1}{Load}$ to represent the network lifetime.

2) Delay of Event Delivery: In event-driven WSNs, many applications (e.g., intrusion detection, seismic activity monitoring, animal movement tracking) are critical of event delivery delay. The long delay of event delivery may cause the users to retrieve invalid or mistaken information due to rapidly changing environment. For simplification, the delay of event delivery is defined by the hop counts (AH) from the event occurs place to the sink, the packet queue time and process time in intermediate relay nodes are negligible.

III. THEORETIC ANALYSIS

A. One Sink

Due to space constraints, we omit the analysis process of one sink. The analysis process can be found in a previous publication [15]. We will list the following conclusions and formulas which can be cited in the next sections.

For one static sink with position $(x, y)$, the average hop counts (AH) are:

$$AH_{(x,y)} = \frac{L+W}{4} + \frac{1}{L}(x-\frac{L}{2})^2 + \frac{1}{W}(y-\frac{W}{2})^2$$

where $L$ is the length of rectangle, $W$ be the width.

In a square with grid size $N$, formula[1] is abbreviated as:

$$AH_{(x,y)} = \frac{N}{2} + \frac{1}{N}((x-\frac{N}{2})^2 + (y-\frac{N}{2})^2)$$

Considering the mobility of sink, a square trajectory rotated 45° with centre $O$ is the optimal trajectory (as shown in Fig.3).

When the sink move in this trajectory, the network load ($Load$) is lowest.

With a radius of $R$, the average hop counts are:

$$AH(R) = \frac{L+W}{4} + \frac{(L+W)R^2}{3LW}$$

The network load is (the centre of grid “O” has the heaviest network load):

$$Load(R) = \frac{1}{4R} + \frac{L+W}{4LW}$$
In a square with grid size $N$, equation[3] is abbreviated as:

$$AH = \frac{N}{2} + \frac{2R^2}{3N}$$  \hspace{1cm} (5)$$

Equation[4] is abbreviated as:

$$Load = \frac{1}{4R} + \frac{1}{2N}$$  \hspace{1cm} (6)$$

B. Two Sinks

1) Moving in the same region: It’s obviously that when the two sinks are stationary, a greater distance between sinks result in less average hop counts and smaller network load. Some previous works [10] have also get similar conclusion. Therefore, taking into consideration the scenario when two sinks are moving in the same region, a mutual trajectory and a stable distance between each other will have a relatively less average hop counts and smaller network load.

The moving trajectory of two sinks is shown in Fig.4.

![Fig. 4. Two mobile sinks in the same region](image)

As shown in Fig.4(a), sink 1 sojourns at position $A$ and sink 2 sojourns at $B$. The region can be divided into two part $RA$ and $RB$, one with shadow and the other not. If the event occurs in $RA$, the packet will be transferred to sink 1. Due to the symmetry, the average hop counts can be calculated as the $AH$ of the shadow region $RA$ with sink 1.

In that the position of $A$ is $(\frac{N}{2} - R, \frac{N}{2})$, the values of $L$ and $W$ are $N$ and $\frac{N}{2}$. Based on the formula(1), we get the following equation:

$$AH_A(R) = \frac{3N}{8} + \frac{2}{N}(R - \frac{N}{4})^2$$  \hspace{1cm} (7)$$

As shown in Fig.4(b), sink 1 sojourns at position $C$ and sink 2 sojourns at $D$. The region can be divided into two part, region $RC$ and region $RD$. Similarly, the average hop counts can be calculated as the $AH$ of the shadow region $RC$ with sink 1.

Suppose the position of sink in region $RC$ is $(x, N-x)$, we get the following equation:

$$AH(x) = \sum_{i=1}^{N} \sum_{j=1}^{i} \text{Hop}(j,i),(x,N-x)$$

$$= \sum_{i=1}^{N} \sum_{j=1}^{i} (|j-x| + |i-N+x|)$$

We use MATLAB to simplify the equation to:

$$AH(x) = 0.39N + \frac{5}{2N}(x - (0.3N - 1))^2$$  \hspace{1cm} (8)$$

As the position of $C$ is $(\frac{N}{2} - R, \frac{N}{2} + \frac{R}{2})$, hence $AH_C$ is:

$$AH_C(R) = 0.39N + \frac{5}{2N}(0.5R - (0.2N + 1))^2$$  \hspace{1cm} (9)$$

When the sinks sojourn between $A$ and $C$, the precise value of $AH$ is difficult to be solved. Since the values of $AH_A$ and $AH_C$ are nearly equal, for simplicity, the $AH$ approximately equal to $(AH_A + AH_C)/2$.

Obviously, the $AH_A(R)$ and $AH_C(R)$ are both concave functions, so the curve of $AH(R)$ exists a inflexion $R'$. When $R \leq R'$, the $AH(R)$ decrease as $R$ increases; when $R \geq R'$, the $AH(R)$ decrease as $R$ increases. In order to minimize the value of $AH(R)$ and find the inflexion $R'$, we make the derivatives of $AH(R)$ function equal to zero and solve $R$.

$$d(AH(R)) = \frac{1}{2}d(AH_A(R)) + d(AH_B(R))$$

$$= \frac{1}{2} \frac{4}{N}(R - \frac{N}{4}) + \frac{5}{2N}(0.5R - 0.2N + 1)$$

$$= 0$$

We solve the equation and get $R = \frac{6N-10}{23}$, and it belongs to the interval $[0.25N, 0.4N]$.

Now, we will analyze the network load under different trajectory parameters.

First, we want to find the point which has the heaviest network load. When the sinks sojourn at position $A$, based on previous conclusion in [15], the nodes near $A$ have heaviest load than other nodes, and the central node $O$ nearly has no load. When the sinks sojourn at position $C$, the loads of the nodes near $C$ are heavier than other nodes but smaller than $A$ in the former case. As the sinks travel along the trajectory, the nodes near $A$ have the highest probability to relay the packets.

![Fig. 5. The network load with mobile sinks](image)

As shown in the Fig.5, when the sink sojourn at position $A$, $B$, $C$, the loads are $Load_A = \frac{R}{2N}$, $Load_B = \frac{R}{2}$, $Load_C =$
\[
\frac{1}{2\pi^2} (N/2 - R + \alpha N/2). \quad (\alpha \text{ is a factor to adjust } \text{Load}_C, \text{ because in some position, the value of } \text{Load} \text{ is smaller than } \text{Load}_C, \text{ here we set } \alpha \text{ equal to } 0.5).
\]

The load is
\[
\text{Load} = \frac{1}{4R} (2\text{Load}_A + 4\text{Load}_B + (4R - 6)\text{Load}_C)
\]
\[
\approx \frac{1}{4N} + \frac{1}{8R} + \frac{1 + \alpha}{4N} - \frac{R}{2N^2}
\]

2) Moving in the divided regions: Moving in the divided regions is much more convenient to be analyzed than moving in the same region. As the two sinks are separated to individual regions, we consider the scenario as one sink moving in a rectangle region with length \( L \) and width \( W \).

Because the network load is decided by the maximum loads of nodes, based on the formula(4), the region should be half divided. So \( L = N \) and \( W = \frac{N}{2} \).

To minimize the network load, the trajectories should be square which rotated 45°.

Based on formula(3) and (4), we get the \( \text{AH} \) and \( \text{Load} \):
\[
\text{AH}(R) = \frac{3}{8} N + R^2/N \tag{10}
\]
\[
\text{Load}(R) = \frac{1}{8R} + \frac{3}{8N} \tag{11}
\]

here, \( R \leq \frac{N}{4} \)

As the packets are transferred via shortest path, when one sink moves to the zone which near the opposite region, some packets maybe be delivered to it. These will cause the theoretic \( \text{AH} \) greater than its actual value.

C. 3+ sinks

As the number of sinks grows, if the sinks moving in the same region, the space will be crowded. So this strategy will not increase the network performance noteworthy. Moving in divided regions separately looks like a better strategy here.

Suppose there are \( M \) sinks, we divide the region into \( \sqrt{M} \times \sqrt{M} \) subregions. The size of each subregions is \( N/\sqrt{M} \).

Being that the event occurs in each subregions with the same probability, the \( \text{AH} \) of the region equal to the \( \text{AH} \) of the subregion.
\[
\text{AH}(R) = \frac{N}{2\sqrt{M}} + \frac{2\sqrt{M}R^2}{3N} \quad \text{where } R \leq \frac{N}{2\sqrt{M}} \tag{12}
\]

Take \( \text{Load} \) into consideration, the probability of the event occurring at a designated region is \( \frac{1}{M} \). Hence, the \( \text{Load} \) of regions is \( \frac{1}{M^2} \) of the subregions’ \( \text{Load} \).
\[
\text{Load}(R) = \frac{1}{M} \left( \frac{\sqrt{M}}{4N} + \frac{1}{4R} \right) \quad \text{where } R \leq \frac{N}{2\sqrt{M}} \tag{13}
\]

As the number of sinks grows, the subregions are smaller and smaller. This will cause the \( \text{Load} \) of subregions be a large value, and the promotion seems like a drop in the bucket. From the simulation result in [15], we conclude the size of region be 40 is suitable.

IV. Simulations

In this section, we provide simulation results for the strategies presented in Section III. We also compare these results with their corresponding analytical results. The simulations are developed with a high level program language C++, which ignores the MAC and PHY layers effects.

Our scenario is such that whenever an event occurs, the sensor node generates event packets every 1 unit time slot, and the event will last 10 unit time slot. After the event ends, another event will occur at another random position, and there are 500 events occurring simultaneously. The sinks sojourn at one position for 1 unit time slot, the simulation scenario will last 3000 unit time slot. All these simulation parameters are set to ensure the stationary distribution of event and sink position. The counter of sensor node will be increased by 1 once it forward one packet. The hop counts of every event packets will also be accumulated. After the duration of simulation scenario terminated, we can get the load distribution of all nodes and the average hop counts of the scenario.

A. In the same region

We perform simulations for the strategy analyzed in Section III.B.1. The two mobile sinks walk along the trajectory as shown in Fig.4. By changing the value of \( R \) in 100 \( \times \) 100 networks, we compare the simulation results with the theoretic analysis results.

![Fig. 6. Two mobile sinks in the same region of 100 \( \times \) 100 Networks](image)

As shown in Fig.6, the simulation and theoretic results are almost coincided. From Fig.6(a), there exists an inflexion when \( R \) approximately equal to 0.3N. Fig.6(b) shows that the network lifetime increases as the \( R \) increases.

B. In the divided regions

In this section, we perform simulations for the strategy analyzed in Section III.B.2.

![Fig. 7. Two mobile sinks in the divided regions of 100 \( \times \) 100 networks](image)
As shown in Fig.7, both the average hops and the network lifetime increase as the $R$ increases.

C. Compare two mobile patterns

First we plot the network load distribution (Fig.8) to verify our conclusion on the positions of the nodes with heaviest network load. For the purpose of fairness, we set $R$ equal to the half of width of region in the two mobile manner. The $R$ respectively equal to $N/2$ and $N/4$.

![Image](image_url)

(a) Moving in the same region  (b) Moving in the divided region

Fig. 8. The network load distribution of 100 × 100 networks

Now, we will compare the $AH(R)$ and $Lifetime(R)$ of the two mobility patterns. Due to different trajectory radius, we utilize the proportion width of region to denote the radius.

![Image](image_url)

(a) Average Hop Counts  (b) Network Lifetime

Fig. 9. Compare two mobility patterns

As shown in Fig.9(b), the network lifetime of pattern III.B.1 has a longer lifetime than pattern III.B.2. With different radius, each pattern has its advantage on average hop counts (Fig.9(a)).

V. CONCLUSION

In this paper we first presented a system model to analyze the average hop counts from the place of event to sink and further analyze the load distribution of the network. Based on the model and some previous conclusion for one mobile sink, we discuss the scenario of two mobile sinks. When the two mobile sinks traveling along the same trajectory with fixed distance, the network load decreases as the radius of trajectory increases, and the average hops curve has an inflexion. When the two mobile sinks travel along the separate trajectory in divided regions, the network load decreases while the average hops increase as the radius increases. Comparing the two mobility patterns, we conclude that the first pattern has a smaller network load. This means two mobile sinks moving in the same regions is a better strategy in a sense.

Finally, we discuss the relation between the performance and the number of mobile sinks. The analysis shows that as the number of mobile sinks increases, the performance of network is also improved. Nonetheless, too more sinks provide less improvement.

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