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Routing to a mobile data collector on a predefined trajectory

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***Abstract*— In this paper, we propose a distributed scheme for data gathering using a mobile data collector in Wireless Sensor Networks (WSNs). In our scheme, a mobile data collector moves along a predefined track over the sensing field and data are forwarded to nodes whose transmission disks overlap with the trajectory of the data collector; these nodes are called relaying nodes. Data are classified into two categories: delay-sensitive data and delay-tolerant data. While delay-sensitive data are sent to the data collector directly, delay-tolerant data may be sent to a nearby relaying node, where they wait for the data collector to come and pick them up.**

We give a theoretical analysis to quantify the impact of data collector mobility on the lifetime of the network as compared to a WSN with a stationary data collector. Moreover, we use simulations to evaluate our scheme in practice. Simulation results show that our scheme has the potential to prolong the lifetime of the network significantly.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have many potential applications in commercial, environmental, and military domains. Extending the lifetime of WSNs is crucial to enable their use in this wide range of applications. Sensor nodes are characterized by their limited energy reserve. With this energy limitation, sensor nodes use multi-hop communication to deliver their data to a base station. Multi-hop communication results in an unbalanced energy load over the network; nodes near the base station are used as relaying nodes to deliver data generated all over the network to the base station. Therefore, nodes around the base station deplete their energy much faster than distant nodes [1] [2] [3]. This will not only stop those nodes around the base station from functioning, but will also render the base station unreachable by other nodes. Some proposals tried to solve the problem by placing more sensor nodes around the base station [4] [5]. However, this may result in an unbalanced sensing coverage over different parts of the field.

Using a mobile data collector seems to be a natural solution to this problem, yet only few proposals followed that direction [6][2][7][8][9][10]. Our work in [6] and the work in [2] use linear programming to find the optimal path for the data collector together with the optimal routes from sensor nodes to the data collector. While able to find optimal solutions, the schemes in [6] and [2] are centralized and suffer the high computational complexity of linear programming. In the work presented in [9] and [10], sensor nodes hold their data until the data collector becomes close enough to receive the data in one hop. This could bring significant energy savings at the cost of much longer delay. The authors in [7] exploit multi-hop communication to deliver data to the data collector at its current location. However, the scheme requires sensor nodes to be synchronized with the data collector in order to determine the latter's current location.

In this paper, we present a fully distributed and localized routing scheme that utilizes data collector mobility to distribute the load over different parts of the network. The data collector moves along a globally known trajectory. A sensor node whose transmission range overlaps with the trajectory of the data collector is called a relaying node. Relaying nodes receive data from other nodes and deliver them to the data collector when it becomes nearby. Data are classified into two categories: delay-sensitive and delay-tolerant. Delay-sensitive data are sent to a relaying node whose transmission range involves the data collector currently; we call such a node an active relaying node. Delay-tolerant data are sent to any relaying node where they wait for the data collector to come and pick them up. The scheme we present here does not require any kind of synchronization between sensor nodes and the data collector, and the delay encountered by delay-sensitive data is very similar to that in a network with a stationary base station. The novel contributions of this paper can be summarized as follows:

1) The routing scheme we present here is fully distributed in the sense that routes are created by the nodes themselves and not by a centralized entity, and it is localized in the sense that every sensor node makes its routing decisions based on local information.
2) Our scheme finds good solutions, rather than optimal ones, with a very low computational complexity (our scheme does not use any computation that takes more than a constant time).
3) In general, using a stationary base station minimizes the delay and using a mobile data collector distributes the load and prolongs the lifetime of the network. Our scheme combines the advantages of the two scenarios without any synchronization between the data collector and the sensor nodes.

To the best of our knowledge, this is the first scheme that supports on-line delivery of data to a mobile data collector in a distributed, localized, asynchronous fashion.

The remainder of this paper is organized as follows. Section

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II describes the model of the sensor network under study and gives a formal problem definition. In Section III, we present a lifetime and delay analysis to understand the impact of data collector mobility. Our routing scheme is described in Section IV. Section V shows the experimental results. Finally, in Section VI, we conclude by summarizing the contributions and pointing out some related future research directions.

II. SYSTEM MODEL AND PROBLEM DESCRIPTION

We consider a sensor network of N sensor nodes uniformly deployed in a sensing field. The network is assumed to be connected (i.e., there is at least one multi-hop path between any pair of nodes). Sensor nodes collect data from the surrounding environment and report them to the data collector. The transmission range of all sensor nodes is fixed to r m (i.e., each sensor node has a transmission disk of radius r m). The topology of the network is modeled as a connectivity graph $G = (V, E)$, where $V = \{n_0, n_1, ..., n_{N-1}\}$ is the set of N sensor nodes, and $(i, j) \in E$, if sensor nodes n_i and n_j are within the transmission range of each other.

As stated in the Introduction, a mobile data collector moves along a predefined trajectory that overlaps with the transmission disks of relaying nodes. At a given time, an active relaying node is one which is not more than r m away from the data collector.

We are interested in a delay-tolerant routing scheme to deliver delay-tolerant data to any relaying node and a delay-sensitive routing scheme to deliver delay-sensitive data to an active relaying node. The objective is to prolong the lifetime of the network, namely, the time until a particular proportion of the sensor nodes run out of energy.

III. LIFETIME AND DELAY ANALYSIS

Assuming a dense sensor network on a circular sensing field, we give simplified lifetime and delay comparisons between the following two scenarios:

1) A network with a stationary data collector located at the center of the sensing field. All data packets are destined to the data collector.
2) A network with a mobile data collector that moves along the boundary (i.e., the perimeter) of the sensing field[1]. Data packets are forwarded to relaying nodes, where they wait for the data collector to come and pick them up.

Figure 1 shows a graphical illustration of the two scenarios. To simplify our analysis, we make the following assumptions:

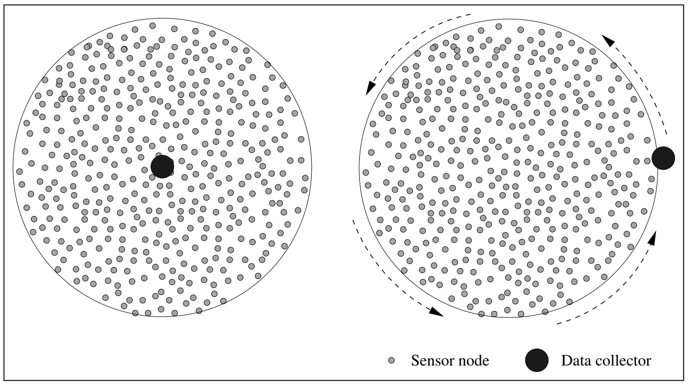

Fig. 1. A network with a stationary data collector (left) and a network with a mobile data collector (right).

1) All sensor nodes have the same data generation rate; every sensor node generates D packets per time unit.
2) Sensor nodes are uniformly distributed over the sensing field.
3) The sensing field is a circle of radius R.
4) Sensor nodes consume E_{tr} energy units to send one packet.
5) Every sensor node starts with an energy supply of E_{init} energy units.

A. Lifetime comparison

Here we compare the two scenarios in term of network lifetime. Network lifetime is defined as the time until the data collector is unreachable. Our comparison assumes that a perfect load balancing is exercised in both scenarios (i.e., the load is evenly distributed over relaying nodes). We also ignore the energy consumed to receive data; transmission is known to be the dominant energy consuming operation [1].

A stationary data collector: With multi-hop communication, the lifetime of the network is determined by the lifetime of relaying nodes (i.e., nodes whose distance to the data collector is not more than r m). Since sensor nodes are uniformly distributed over the sensing field, we should have $\frac{N\pi r^2}{\pi R^2} = \frac{Nr^2}{R^2}$ relaying nodes. Relaying nodes are in charge of delivering all data generated all over the network to the data collector. Therefore, they transmit DN packets to the data collector. With a perfect load balancing, each relaying node transmits $\frac{DNR^2}{Nr^2} = \frac{DR^2}{r^2}$ packets. Thus, the lifetime of a relaying node is $\left\lfloor \frac{E_{init} r^2}{DR^2 E_{tr}} \right\rfloor$ time units.

A mobile data collector: Since the data collector moves along the perimeter of the sensing field, we have $\frac{\pi(R^2-(R-r)^2)N}{\pi R^2} = \frac{(2Rr-r^2)N}{R^2}$ relaying nodes. With a perfect load balancing and a constant data generation rate, each relaying node will be in charge of transmitting $\frac{DNR^2}{(2Rr-r^2)N} = \frac{DR^2}{(2Rr-r^2)}$ packets. Thus, the lifetime of a relaying node is $\left\lfloor \frac{E_{init}(2Rr-r^2)}{DR^2 E_{tr}} \right\rfloor$ time units.

From this comparison, the lifetime of a network with a mobile data collector is longer than that of a network with a stationary data collector by a factor of $\frac{2R-r}{r}$. For example, if $r = 100$ m and $R = 1000$ m, the lifetime of a network with a mobile data collector is 19 times longer than the lifetime of the same network with a stationary data collector.

B. Delay comparison

The delay a packet encounters is proportional to the number of hops between the packet's source and destination. The

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[1] Our scheme is applicable to trajectories of any shape. However, the assumption of a circular trajectory is made to simplify the analysis.

number of hops between two points can be approximated to be a linear function of the Euclidean distance between them. Therefore, the delay a packet encounters can be expressed by $delay = \alpha L$, where α is a constant and L is the Euclidean distance between the packet's source and destination.

With a stationary data collector located at the center of the sensing field, the maximum delay a packet may encounter occurs when the source is at the perimeter of the sensing field; this results in a delay of αR. On the other hand, the maximum delay in a network with a mobile data collector is significantly worse. With a mobile data collector, the worst case occurs when a packet arrives to a relaying node which has just been left by the data collector; such a packet needs to wait for the data collector to complete a full round along the perimeter of the sensing field which depends on the speed of the data collector and on other factors. It is obvious that such a delay is much longer than that of a network with a stationary data collector.

To summarize, having a mobile data collector has a great potential to prolong the lifetime of the network, yet it suffers longer delay as compared with a stationary data collector. Accordingly, we are motivated to come up with a scheme that combines the lifetime of a mobile data collector network and the delay of a stationary data collector network.

IV. ROUTING SCHEME

Sensor nodes use two routing schemes to deliver their data to the data collector: delay-tolerant routing and delay-sensitive routing. In the delay-tolerant routing, data packets are sent to any relaying node where they wait for the data collector to come and pick them up. On the other hand, when a node has delay-sensitive data, it needs first to locate the data collector in order to send the data to an active relaying node.

A. Delay-tolerant routing

In order for sensor nodes to deliver their delay-tolerant data to the data collector, they need to have a path to at least one relaying node. To do so, relaying nodes broadcast their identity at the deployment stage and each sensor node keeps a record of the next hop towards some relaying node. Each sensor node n_i has a Relaying Node Record (RNR_i) which has the following fields:

> id: the id of the relaying node to which delay-tolerant data will be sent.
>
> $next\_hop$: a neighbor of n_i which is used as a next hop towards the relaying node.
>
> $number\_of\_hops$: the number of hops to the relaying node.

Algorithm 1 describes the process of setting the relaying node records of all sensor nodes, assuming that each sensor node uses the nearest relaying node. Note that this process will construct a tree for each relaying node; the tree of a relaying node n_i is rooted at n_i and involves all sensor nodes whose nearest relaying node is n_i.

After this initialization process, RNRs are used to forward delay-tolerant data to relaying nodes.

Algorithm 1: Setting relaying node records.

```
foreach sensor node $n_i$ do
    if $n_i$ is a relaying node then
        $RNR_i$.id=$i$;
        $RNR_i.next\_hop$=$i$;
        $RNR_i.number\_of\_hops$=0;
        broadcast $RNR_i$ to all neighbors of $n_i$ ;
    else
        $RNR_i.number\_of\_hops = N + 1$;
    end
end
when a sensor node $n_i$ receives a broadcasted $RNR_j$ :
    if $RNR_j.number\_of\_hops + 1 <$
    $RNR_i.number\_of\_hops$ then
        $RNR_i.number\_of\_hops =$
        $RNR_j.number\_of\_hops + 1$;
        $RNR_i.id = RNR_j.id$;
        $RNR_i.next\_hop = j$;
        broadcast $RNR_i$ to all neighbors of $n_i$ ;
    end
end
```

B. Delay-sensitive routing

Our delay-sensitive routing has two phases: locating the data collector and forwarding data to an active relaying node. To facilitate locating the data collector, announcements about the current location of the data collector are disseminated periodically to a subset of sensor nodes in the network. When a sensor node has delay-sensitive data, it sends a query to a subset of sensor nodes in the network. To guarantee that the query reaches a node which has received the most recent announcement, we use a simple and reliable direction-based approach: announcements cross the network vertically (i.e., north to south) and queries cross the network horizontally (i.e., east to west). A similar approach was used in the context of information discovery in large networks [11]. We assume that sensor nodes know their geographical location in a 2D space. To disseminate announcements and queries, we use the Greedy Perimeter Stateless Routing (GPSR) [12]. The GPSR uses a planar graph $G'(V', E')$ which is a subgraph of the connectivity graph $G(V, E)$ and has the same set of vertices as G (i.e., $V' = V$ and $E' \subseteq E$). G' partitions the space into several closed faces and one open external face. Border nodes are those nodes that form the external face. We exploit a nice property of the GPSR: when a packet is sent to an arbitrary location in the external face, it is delivered to a border node which is the closest to that location. Thereby, to send a query from a node at location (x, y) to the west, a query is sent to the location $(x-\alpha, y)$ where α is the diameter of the network[2] (i.e., $(x - \alpha, y)$ is outside the sensing field and to the west of it). Such a query will be delivered to a node at the west border of the network. To send a message to the north, the east, or the south, we use the destination locations $(x, y + \alpha)$, $(x + \alpha, y)$, $(x, y - \alpha)$, respectively.

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[2] The diameter of the network is the maximum Euclidean distance between two nodes in the network.

An announcement message has three fields: loc, $time\_stamp$, and $destination$. loc is the current location of the data collector in the form of (x, y), $time\_stamp$ is the time at which the announcement is made according to the data collector clock, and *destination* is either $(x, y+\alpha)$ or $(x, y-\alpha)$. Every sensor node maintains a Data Collector Record (DCR) to store the most up-to-date information it knows about the location of the data collector. DCR has two fields: loc and $time\_stamp$. Since all transmissions of the announcement messages are made through a wireless medium, all neighboring nodes of the sender will hear the announcement and update their DCRs accordingly. When an announcement message arrives to its final destination (i.e., a border node), that node broadcasts the announcement for the last time to tell its neighbors about the new information.

A query has two fields: $source$ and $destination$, where $source$ is the location of the sender, say (x, y), and $destination$ is either $(x-\alpha, y)$ or $(x+\alpha, y)$. When a query Q arrives to its destination, a reply R is sent back to $Q.source$. A reply has three fields: $destination$, loc, and $time\_stamp$, where $destination$ is the location of a node that initiated the query, loc is the location of the data collector according to the most recent announcement seen by the reply message, and $time\_stamp$ is the time stamp associated with that location. As it moves along its path to $Q.source$, R carries the most recent location of the data collector it has encountered. When R arrives to a node on its way to $Q.source$, it exchanges information about the location of the data collector with the DCR of that node before being forwarded to the next hop.

To summarize, the data collector will periodically disseminate announcements vertically, and when a sensor node has delay-sensitive data, it sends a query horizontally, waits for the replies to come back carrying the location of the data collector, and then sends the data to the data collector. Due to space limitations, we defer the formal correctness proof of this scheme to a full version of this paper.

V. EXPERIMENTAL RESULTS

We compare the scheme we propose with a static scheme that has a stationary data collector. We also show the difference between the network lifetime of our scheme and the optimal network lifetime obtained using linear programming in a centralized fashion [6]. In the static scheme, a data collector is placed in the center of the sensing field, and sensor nodes use shortest path routing to deliver their data to the data collector. We use the general energy consumption model presented in [1] which can be described as follows.

$$E_{Tr}(r, b) = b \times (e_{elec} + e_{amp} \times r^{\gamma}) \tag{1}$$

$$E_{Rc}(b) = b \times e_{elec} \tag{2}$$

where $E_{Tr}(r, b)$ is the energy consumed to send b bits over r m, $E_{Rc}(b)$ is the energy consumed to receive b bits, e_{elec} is the energy consumed by the transmitter (receiver) to send (receive) one bit, e_{amp} is the energy consumed by the transmission amplifier for one bit, and γ is the path-loss exponent. In our simulation, r is set to 50 m, e_{elec} is set to 50 nJ/bit, e_{amp} is set to 0.1 nJ/bit/m^2, and γ is set to 2. The packet size is 512 bits. Every sensor node has an initial energy of 50 J and generates 150 packets/round. 50% of the data is delay-sensitive and 50% is delay-tolerant.

Our simulations involve networks of size 200, 400, 600, 800, and 1000 sensor nodes randomly deployed in a 300 x 300 m^2, 400 x 400 m^2, 500 x 500 m^2, 600 x 600 m^2, 700 x 700 m^2 fields, respectively. For each network size, we test 20 instances and take the average.

To generate a trajectory for the data collector, we use a simple method. We divide the sensing field into four equal-size squares; the trajectory of the data collector is a quadrilateral that has a vertex inside each square.

Fig. 2 shows the lifetime comparison between the three schemes. The lifetime of a network with a mobile data collector is at least 3 times longer than that of a network with a stationary data collector. The ratio of the network lifetime using a mobile data collector to that using a stationary one is proportional to the size of the network as shown in Fig. 3. This is because the number of relaying nodes using a stationary data collector is the same regardless of the size of the network. This makes the load assigned to each relaying node proportional to the size of the network. On the other hand, the number of relaying nodes with a mobile data collector is proportional to the size of the network[3]; this means that with a larger network, the increase in the amount of data generated over the network is confronted with a similar increase in the number of relaying nodes. Fig. 4 shows a comparison of the average energy consumed per bit between different schemes. Besides load balancing, data collector mobility brings a decrease in the total consumed energy. This is a direct result of having more relaying nodes distributed over the sensing field; this results in sending delay-tolerant data over shorter routes.

The network lifetime of our distributed scheme is 50% to 75% of that of the centralized, optimal scheme. That is because of the careful placement of the data collector experienced in the optimal scheme. Furthermore, the optimal scheme is centralized, i.e., all information about the network is available to a centralized entity where the optimal routing and placement of the data collector is computed, and it is assumed that the optimal routes are delivered to sensor nodes at no cost.

An interesting result we have is that even though the optimal scheme has a longer network lifetime, it may consume a little more energy than the distributed one (as shown in Fig. 4). The reason is that the optimal scheme may choose a route or a data collector location that spends more energy for the sake of avoiding and reducing the load on sensor nodes with low residual energy. An energy-efficient route or data collector location that puts extra load on a sensor node with a critical energy level is not preferred in the optimal scheme.

VI. CONCLUSION

For the sake of load balancing and lifetime prolonging in WSNs, we propose a scheme for data gathering using a mobile data collector. The novelty of our scheme stems from its distributed nature and from exploiting data collector mobility

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[3] Here we assume that the size of the data collector trajectory is proportional to the size of the sensing field.

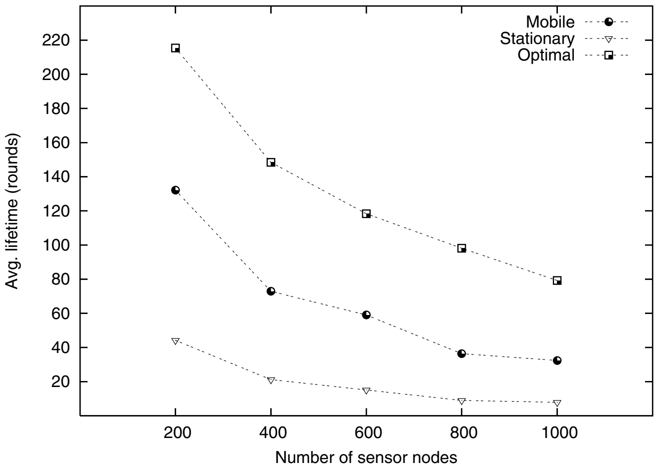

Fig. 2. Lifetime comparison.

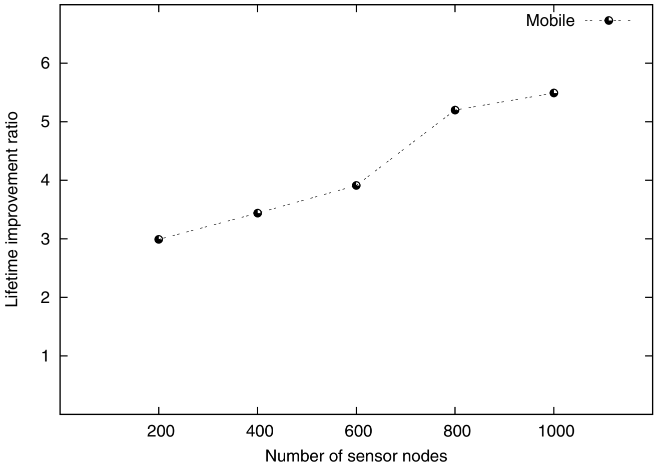

Fig. 3. Lifetime improvement ratio of data collector mobility.

with a reasonable data delivery delay. Furthermore, we do not assume any time synchronization between the data collector and the sensor nodes. The low complexity of our scheme, as compared to other schemes that use comprehensive optimization tools (e.g., linear programming), makes it practical and easy to implement in ad hoc WSNs. Simulation results show that our scheme has the potential to prolong the lifetime of a WSN significantly as compared with a classical WSN with a stationary data collector.

We currently study another scenario in which sensor nodes send requests to the data collector to come and pick the delay-tolerant data rather than using a fixed trajectory. In this case, we need to find a good route for the data collector to visit nodes which have sent data pick up requests.

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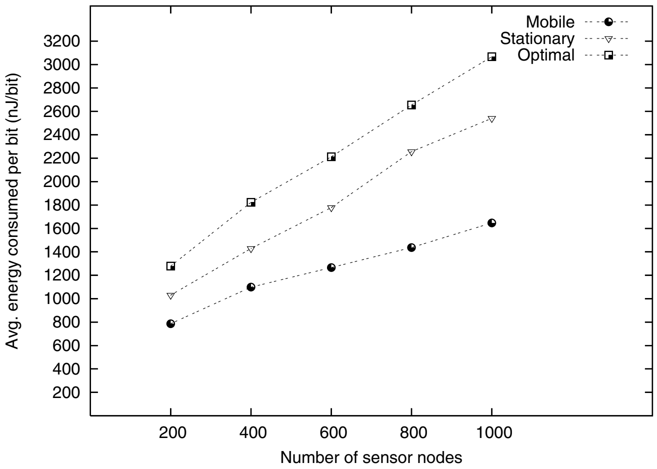

Fig. 4. Energy consumption comparison.

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