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Electrostatic Modelling of Multiple Mobile Sinks in Wireless Sensor Networks

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Abstract. Sensor networks are constituted by cheap devices with limited energy supply. Therefore, it is crucial to design algorithms that optimize the energy usage of these devices and thus prolong the lifetime of the network. In this paper we present a novel method to deploy multiple sinks optimally in a sensor network, based on an electrostatic model. We assign positive or negative charges to sensor nodes depending on their energy level, and positive charges to sinks. Different charges attract each other, while charges of the same type shove each other. We show that, by properly setting these charges, the sink nodes can reach a position of equilibrium. Furthermore, we study how to move these mobile sinks during the operation of the network by dynamically changing the charges assigned to the sensor nodes and sinks. By comparing our adaptive strategy to three other solutions we show that it outperforms all the other approaches as far as network lifetime is concerned.

Keywords: wireless sensor network, multiple sinks, electrostatic model

1 Introduction

Sensor networks consist of low-cost devices with limited resources, monitoring some physical environment and sending information about it to dedicated sink, which has several orders of magnitude more resources than the sensor nodes.

Since the sensors have limited energy supply and usually it is impractical to replace their batteries, it is crucial to design algorithms that optimize the energy usage of these devices and thus prolong the lifetime of the network. Sensors spend the most of their energy for communication, therefore it is important to design methods that minimizes the energy used for communication in a sensor network. In order to improve the lifetime of a sensor network multiple sinks may be used; this would decrease the average hop number a message has to pass through before being received and processed by a sink. Another way of optimizing the network lifetime is to adaptively move the sink nodes. This latter idea comes from the observation that the first sensors that get depleted in a multi-hop

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sensor network are always the ones next to the sink, since messages from all the other nodes in the network go through one of the neighboring nodes of a sink. Thus, if we periodically change the location of the sinks, the sensor nodes loaded with an amount of traffic larger than the average will change as well. Finally, a third solution to prolong the network lifetime is the usage of an optimal routing algorithm. However, we do not deal with routing techniques in this paper; we suppose that we already have a well performing routing method, which always finds the best route to the closest sink.

The usage of multiple sinks can prolong the lifetime of a sensor network. However, it is far from trivial to decide where to place these sinks in order to obtain the best possible result. In this paper we will show an optimization method that is based on the interaction between nodes loaded with different electric charges, which eventually define an electrostatic field. We assign positive charges to sinks, negative charges to nodes with an energy level above the average, and positive charges to nodes with an energy level below the average. In this model sinks will shove each other, they will be attracted by sensor nodes with enough remaining energy, and will be shoved away by sensor nodes with spare energy reserve. Thus, sinks will be distributed through the electrostatic field, being located close to sensors in good condition in terms of energy, but far away from nodes close to depletion.

The remainder of the paper is organized as follows. Section 2 presents the related work, specifically emphasizing the solutions based on electrostatic fields. Sections 3.2 and 3.3 describe in details the sink placement and movement algorithm; then, simulation results are presented in Section 3.4. Finally, Section 4 concludes the paper and identifies some open questions to be studied in the future.

2 Related work

Finding the optimal placement of multiple sinks in a sensor network is addressed in a dynamically growing number of papers, however, due space limitations here we mention only three of them. An often used way to find the optimal placement of sinks is to formulate it as a linear programming (LP) task and solve it[1][2]. [3] claims that finding the optimal placement for a given number of sinks is equal to the clustering problem and should be solved using a clustering algorithm.

Recently there are several proposals assuming to use an electrostatic model in the design and maintenance of sensor networks. [4] examines how to place the sensor nodes in the network in order to assure the traffic transport with a minimal number of nodes. Electrostatic model based optimal routing algorithms are introduced in [5][6], while [7] uses the magnetic model for the same purpose. Contrary to that, in this paper we propose an electrostatic model based method for finding the optimal placement of multiple sinks, which computational complexity is simpler than solving an LP problem. Furthermore, during the operation of the network the method controls adaptively and coordinated the movement of the sinks considering the state of the network.

3 Controlling multiple sinks in wireless sensor networks using an electrostatic model

In our work we propose a novel iterative method that uses an electrostatic model to find the places of the sinks minimizing the average distance between a sensor and the closest sink It is assumed sensors report only to the closest sink.

3.1 The electrostatic model

In our proposed method both the sensors and the sinks have a given amount of electric charge. Every sensor has the same initial negative charge ($Q_{sens_t}, t = 1..n$) and each sink has a positive charge ($Q_{sink_u}, u = 1..m$), which is set dynamically (see Sec. 3.2.); therefore, the sensors attract the sinks while the sinks shove each other. The positions of the sensors are fixed. We assume that each sink knows the coordinates and charges of all the sensors, and the coordinates and charges of the other sinks. We made these strict assumptions, since our goal is to examine the performance of the proposed method in idealistic circumstances.

The force generated by two charges in the electrostatic field is:

$$F_{ij} = \frac{Q_i * Q_j}{4\epsilon_0 \pi r^2}, \tag{1}$$

where Q_i and Q_j are the amount of charges, r is the distance of the charges and ϵ_0 is the dielectric permitivity constant. In our model we use an "electrostatic-like" field where the force generated by two charges is calculated though the simplification of (1), which is the following:

$$F_{ij} = \frac{Q_i * Q_j}{\sqrt{r}} \tag{2}$$

The force in our model has the same behavior as in the electrostatic field: two charges having the same sign generates a repulsive force, while charges having different signs generates an attractive force. The force between charge i and charge j is represented by the vector $\overrightarrow{p_{ij}}$, $F_{ij} = |\overrightarrow{p_{ij}}|$. The resultant force acting on charge i is determined by adding all the forces acting on it: $p_i = \sum_{j,j\neq i} p_{ij}$.

3.2 Optimal placement of multiple sinks

In the first step of the novel iterative method every sink calculates the resultant force acting on itself. For the sinks this can be written as follows:

$$\overrightarrow{p_s} = \sum_{t=1}^{n} \overrightarrow{p_{st}} + \sum_{u=1,u\neq s}^{m} \overrightarrow{p_{su}}. \tag{3}$$

Then, the vector of the resultant force is normalized and multiplied by a unit step, which gives the new place of the sink. The sink stops to change its position when the size of the force is below a certain threshold. At the end of each round every sink updates the coordinates of the other sinks. The iteration is done till all the sinks stop to change their positions.

The charges and the coordinates of the sensors are constant; therefore, the placement of the sinks is controlled through the setting of their own charges. Two important questions emerge here: how large should be the sum of the charges of the sinks, and how to distribute that amount among the sinks. Our goal is to minimize the average distance (in a geographic manner) between a sensor and the nearest sink , therefore minimizing the energy spent for communication. Supposing that each sensor communicates with the closest sink, the average distance is minimized if every sink serves an area of the same size (i.e. they serve the same number of sensors, since the sensors are placed uniformly in the network). For the minimization it is also necessary that the sinks are placed in the center of the area they are serving, since if two sinks are placed at the opposite margins of the network then they will serve the same number of sensors, thus their average distance from the sensors is not minimal. The number of sensors served by a sink is proportional to the charge of the sink. A sink with a bigger amount of charge will serve more sensors as it will be attracted more strongly to the center of the network by the sensors while, it will shove away more strongly the other sinks due to (2). Therefore, the sink will serve the same number of sensors when every sink has the same charge in the network. The location of a sink within its area can be controlled by the amount of charge distributed among the sinks.

Choosing the charges the sinks to be too low causes the sinks to move near the center of the network; since sensors will attract them more strongly to the center of the network than the sinks will shove away each other. On the other hand, choosing the charges of the sinks too high leads to the sinks shoving each other so hard that they will leave the area of the network. In order to find the ideal amount of charge for sinks we made experimental examinations. We put the sinks at randomly chosen initial places and distributed a given amount of charge among them. The distribution was done based on the next formula:

$$Q_{sink_s} = \frac{n_s^{-1}}{\sum_{u=1}^{m} n_u^{-1}} * \sum_{t=1}^{n} Q_{sens_t}, \tag{4}$$

where n_s denotes the number of sensors served by sink s. Setting the charges using this formula will result in the sum of the charges of the sinks remaining constant; their charges will be set for the next round inversely proportionally to the number of sensors served in the current round. After the initialization, the optimal places of the sinks were determined using the proposed iterative method and the average distance between the sensors and the sinks were measured. In every round the charges of the sinks were set dynamically based on (4). At the end of the iterative method the charges of the sinks were always almost equal.

Fig. 1 shows how the amount of charge of the sinks affects the average distance of the sensors to the sinks. The network was circle shaped, with a radius of $500m$, there were 1000 sensors deployed uniformly in the network, each sensor having 1 unit of electric charge. Thus, the sum of the charges of the sensors

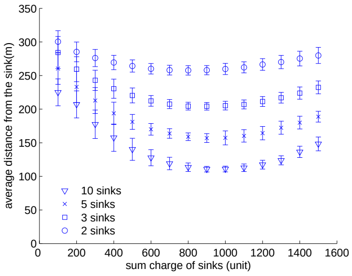

Fig. 1. Average distance of the sensors and the nearest sink.

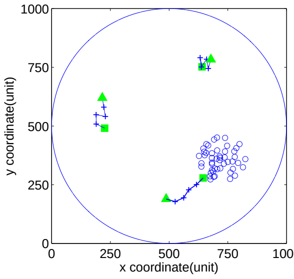

Fig. 2. Moving multiple sinks.

was 1000 units. The results clearly indicate that if the charges of the sinks are too low, they will move to the center of the network, causing a higher average distance. Choosing the charges of the sinks too high has the same effect on the average distance, since the sinks move to the periphery of the network. The optimal choice to minimize the average distance is to choose the charges of the sinks so as to ensure that their sum is roughly equal to the sum of the charges of the sensors.

Fig. 3 shows the optimal placement of the sinks determined by our iterative method in case of having 2,3,5 and 10 sinks in the network. The small circles show the places of the sensors and the squares show the sinks.

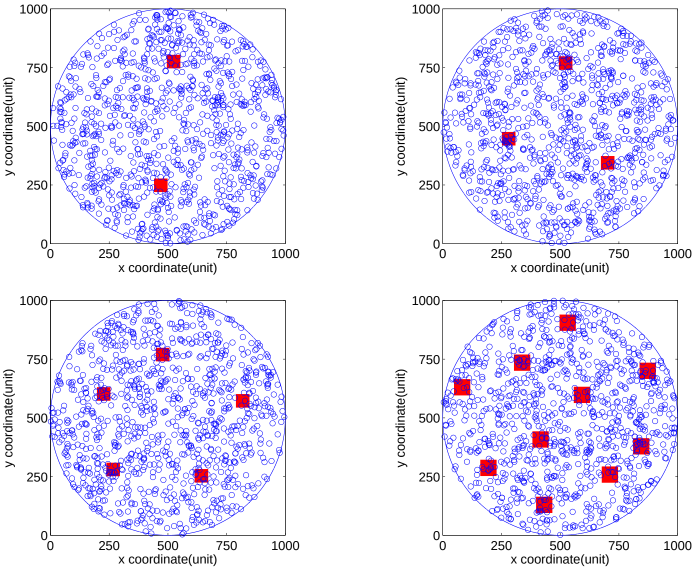

Fig. 3. The optimal placement of the sinks in case of 2,3,5 and 10 sinks.

3.3 Moving Multiple Sinks in the Network

The lifetime of a sensor network can be significantly improved using mobile sinks instead of fixed ones[8][9][10]. Our method not only finds the optimal places for the sinks, but it is also able to control the movement of these sinks.

In case of multihop communication the sensors close to the sink will get a huge load that depletes their batteries very fast. To avoid this, the sink has to move away to another place as soon as it detects that the sensors close to it are running out of energy. In order to achieve this, contrary to 3.2. the charges of the sensors can be set dynamically based on their energy levels: if their energy level falls to the half of its initial value, the amount of its charge also falls to the half of their initial value. This will cause the sensor to attract the sink less; therefore, the sink will move away from that sensor.

To amplify the effect of the depletion of a sensor's energy supply we propose the following method. Let us assume that every sink knows the charges of every sensor. Therefore, the sinks can calculate the average amount of charge of a sensor in the network. The charge of the sensors whose charge is under the average will be turned into a positive charge, while the charge of the sensors with charge over the average will be turned into a negative charge. Thus, sensors having less energy than the average energy level will shove away the sinks, while sensors having more energy than the average will attract the sinks.

Fig. 2 shows how the algorithm works in case that near one sink the sensors have depleted their energy too much. The small circles represents the sensors whose energy level is below the average energy level, thus their charges are set to positive values, therefore they shove away the sink. The movement of one sink also results in the other sinks moving away. The squares denote the initial places of the sinks and the triangles show their place after five steps. It can be seen that the sink near the sensors with low energy moves away; therefore, the amount of the traffic that has to be forwarded by these sensors will decrease and energy reserves will be saved.

3.4 Simulation Results

We investigated through simulations how the performance of the proposed method affects the lifetime of the sensor network. We used the Matlab environment. The shape of the network was a circle, with a radius of $500m$. There were 1000 sensors deployed uniformly but randomly in the network, each sensor's communication range was $80m$, it had $1000J$ unit of initial energy and the same amount of charge. During the simulation the charge of a sensor was always set equal to the value of the its energy level. Sending and receiving a packet cost a sensor $1mJ$ of energy. We assumed that the sinks have no energy constraints because they have large batteries or their batteries are rechargeable. The sensors communicated with the sinks in a multihop manner. We assumed an ideal shortest path routing algorithm to find the route to the sink closest to the sensor. For that purpose the Dijkstra algorithm was used. The sensor network was time-driven, i.e., every sensor sent data periodically to the sinks.

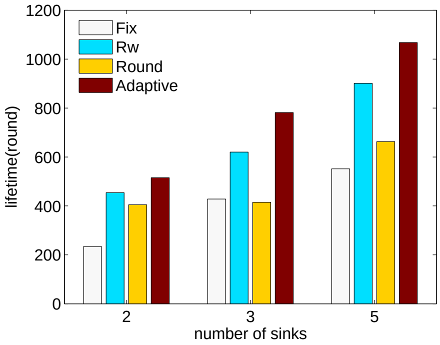

Fig. 4. The lifetime of the network in case of 2, 3 and 5 sinks.

We considered the network to be alive up until the moment when a sensor could send its data to the nearest sink. We investigated the performance of four strategies. The first one is called *Fix*: the sinks were fixed in the places determined by the iterative initialization method proposed in section 3.2. The new places in case of the mobile strategies were determined after 100 data periods. In case of the *RW* strategy the sinks were deployed randomly, then the sinks started to move following the random waypoint model[11], in one round each sink moved $40m$. The sinks were placed at equal distances on the periphery of the network in case of the *Round* strategy and they moved $40m$ in every round on the periphery of the network. Finally, in the *Adaptive* strategy that we propose, after the initial deployment phase described in section 3.2 the sinks started moving according to the mechanism presented in section 3.3.

Fig. 4 shows the lifetime of the network in case of the four strategies when there were 2, 3 and 5 sinks deployed. It can be seen that moving the sinks will prolong the operation of the network. The results show that our proposed algorithm had the best performance in terms of network lifetime. The results suggest that using more sinks results in a longer operation of the network since having more sinks results in a decrease of the average distance between the sensors and the sinks.

4 Conclusion and Future Work

In this paper we introduced a novel method to deploy multiple sinks in a sensor network based on an electrostatic model. The goal was to minimize the average distance between the sensors and the sinks, thus minimizing the energy spent for communication. We also extended that method in order to adaptively control the movement of multiple sinks. The initial examinations have shown that using the proposed method prolongs efficiently the lifetime of the network.

However, there are still several open questions related to the new method. In some aspects we assumed idealistic conditions: for example, in the simulations we assumed an ideal shortest path routing. It would be interesting to examine the performance of our method using some existing geographic routing algorithms. Another important question is how the performance of the method is influenced if the sinks do not have global information about the state of the network, e.g., they only know the charges of the sensors served by themselves. Also, the case of event-driven networks and the case of not uniformly deployed sensors could be examined. The not uniform deployment of the sensors would probably result in an even better performance of the *Adaptive* strategy compared to the other ones. The adaptivity of method proposed in section 3.3 can be enhanced, too: when the sink detects that every sensor in its area has depleted its energy too much, it can decrease its charge, in order to diminish the size of the area it serves. Thus, the amount of the traffic forwarded by the weak sensors will be decreased.

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