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Avoiding Energy-hole in Wireless Sensor Networks with Hybrid Communication Model

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Abstract. In multi-hop wireless sensor networks, the sensors closest to the sink tend to deplete their energy faster than other sensors, which is known as energy-hole problem. To balance energy dissipation, we first investigate the location of the static sink in terms of energy efficiency. We study the mobile sink model, and conclude the best mobility strategy. We then consider jointly sink mobility and hybrid communication, and propose a hybrid communication model based on taking both static sink and mobile sink into account. We finally conduct extensive experiments and find that the number of alive sensors can be increased significantly as compared to not only the static sink but also the mobile sink.

Keywords: sensor network, lifetime, model, mobile sink

1. Introduction

Wireless Sensor Networks (WSNs) consist of a large number of low-cost and low-power sensors which a cooperatively monitor the environments surrounding them. It can be used for a wide range of applications such as military surveillance, industry control, traffic control and ambient conditions detection [1]. The typical application for WSNs is the sensors gathering data and reporting to sink.

Being different from the traditional wireless networks, each sensor is battery powered and has limited processing and memory capabilities. Therefore, prolonging network lifetime is a key issue in the design of the communication protocols used for data transmission from the sensors to the sinks [2].

Much work has been done during recent years to prolong the lifetime of the WSNs. There are energy aware protocols in the literature, generally using multi-hop paths to use the energy more efficiently. The important point to note is that minimizing the total energy consumed may not be optimal for network lifetime [3]. Specifically, in multi-hop sensor networks, the sensors that are closer to the sink have to act as relays for data packets from all other sensors in the network. As a consequence, their energy is soon depleted and the sink becomes unable to receive any further packet (energy-hole problem) [4] .

Intuitively, there are two solutions to the energy-hole problem. On the one hand, if some sensors withdraw from the network due to energy exhausting such that the network loses necessary connectivity, there must be other supplementary sensors deployed. On the other hand, the sensors should be capable of finding and reaching the sink in possibly different positions, whether there be multiple sinks or the sink be able to change its location.

In this paper, we will focus our efforts on the second one: to utilize mobile sinks. The idea is to make use of existing multi-hop routing protocols and to achieve further improvements in terms of network lifetime by exploiting the sink mobility. Using our analytical models, we first show that the energy consumption in staic sink is much more unbalanced. We then propose a hybrid model with mobile sink. We finally conduct

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extensive experiments and find that energy dissipation of sensor can be balanced significantly with the hybrid model.

The rest of this paper is organized as follows: Section II discusses the most related work. Section III gives the system model and assumeptions. Section IV proposes the hybrid communication model. Section V presents the simulation results to evaluate the performance of our proposed model. Finally section VI concludes this paper.

2. Related Work

Existing literature utilizes mobile sensors as mobile sinks to prolong network lifetime. In [5], the authors propose to take the advantage of the sink mobility for WSNs. Due to the sink mobility, the sensors in the network can take turns to become the neighbors of the sink so the energy can be consumed evenly among the sensors, and consequently the lifetime of the entire network can be prolonged.

Wang et al. propose a local update-based routing protocol in WSNs [6]. When the sink moves, it only needs to broadcast its location information within a local area rather than among the entire network, so it consumes less energy in each sensor and also decreases the probability of collisions in wireless transmissions, and thus can be used in large-scale wireless sensor networks.

The authors of [7], [8] propose to relocate mobile sensors to some appropriate locations in response to the sensor failure and lots of sensing area. In [9], the authors develop a centralized heuristic that runs in polynomial time given the solution to the linear program, which provides a provable upper bound to the problem of controlled mobility of multiple sinks.

Basagni et al. present analytical models as well as distributed heuristics for controlled single sink mobility that clearly show the power of moving the sink to places that are dictated by current network conditions. The results obtained by controlling the mobility of one sink are so encouraging that one wonders if and how much more improvement can be obtained by deploying multiple mobile sinks [10]. All these proposals, however, are developed for other purposes without considerations of the impact of the energy-hole problem.

3. System Model and Assumptions

3.1. Energy Consumption Model

We assume there is an energy-efficient MAC protocol in the underlying MAC layer, energy will be consumed only when performing sensing task, processing raw data, and transmitting and receiving data for itself and other sensors. The radio model discussed in [2] can be used to evaluate energy consumption of data transmission. In this model, a radio dissipates E_{elec} (*50 nJ/bit*), defined for the transmitter or receiver circuitry, and E_{amp} (*100 pJ/bit/m*^{2}), defined for the transmitter amplifier. The equations used to model energy consumption of a sensor for communi-cation are given below.

The energy consumption for transmitting sensor:

$$E_{TX}(len,d) = E_{elec} \times len + E_{amp} \times len \times d^2 \quad (1)$$

The energy consumption for receiving sensor:

$$E_{RX}(len,d) = E_{elec} \times len \quad (2)$$

Here *d* is the distance between two sensors, *len* is the number of bits of information sent, and *Eelec* and *Eamp* are the constants as previously defined. The energy dissipation is a second order function of distance. So the data routing with multiple shorter nearby hops will be more efficient than directly transmitting between two far sensors. The energy consumption is also a linear function of *len* which is bits of information transmitted through the sensor network.

3.2. Network Model and Assumptions

In this section we will describe our network models and basic assumptions. We assume that *N* sensors are densely deployed according to a Poisson point process in a circular area of center *O* and radius *R*. We assume that each sensor generates a raw data packet with the same size *len*. We also assume that the transmission radius of all the sensors is equal to r, all sensors have the same initial energy E_{init} and the energy of the sink is unlimited.

To facilitate our discussion, we divide senors to different sets according to their distance to the center *O*. The set P_i contains all the sensors which can reach the center *O* with minimal hop count *i*. The sensor S_n will be in the set P_k if $(k-1)\times r < dist(S_n, O) \le k \times r$, where $dist(S_n, O)$ is the Euclidean distance between sensor S_n and the center *O*. Thus, the sensors in P_k will be in the *k*-th annulus around the center *O*, as showed in Fig. 1.

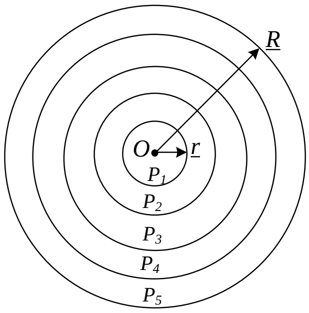


Fig. 1. Sensor network model

4. Hybrid Communication Model

4.1. Static Sink Model

In this section, we first investigate the location of the sink in terms of energy efficiency, then we show that the network lifetime is quite limited with a sink.

We assume the sink is at $B(x_B, y_B)$ and consider an small area *A* that the center is on (x, y) and the radius is R_A. Given the Euclidean distance $d=\sqrt{(x-x_B)^2+(y-y_B)^2}$ between the center of area *A* and *B*, the routing path length l (in hops) from *A* to *B* is approximately.

The total energy consumed to transmit data to the sink can be expressed as

$$E_{total} = \iint_A len(E_{elec} + emp \times d^2)dxdy \tag{3}$$

It is easy to see that minimizing E_{total} is equivalent to minimizing $\int_{-R_A}^{R_A}\int_{-\sqrt{R_A^2-y^2}}^{\sqrt{R_A^2-y^2}}\left((x-x_B)^2+(y-y_B)^2\right)$, which achieves the minimum value if $x_B=y_B=0$. Thus , the optimum location of the static sink is the center of area *A*.

Let us evaluate the network lifetme of the static sink model. It is clear that the energy consumption for the sensors which lie on a ring P_i will be equal. The total energy consumption of all sensors in P_i is

$$E_{total\_s\_i} = E_{s\_i\_EX} + E_{s\_i\_TX} = N(\pi R^2 - \pi(ir)^2)E_{elec}len/(\pi R^2) + N(E_{elec} + E_{amp}r^2)len \tag{4}$$

The average energy consumption of sensors in P_i can be expressed as

$$E_{aver\_s\_i} = \pi R^2 E_{total\_s\_i} / (N(\pi R^2 - \pi(ir)^2)) \tag{5}$$

The average lifetime of sensors in P_i is given by

$$T_{s\_i} = E_{init} / E_{aver\_s\_i} \tag{6}$$

As shown in Fig.2, the lifetime of a sensor increases dramatically with the increasing distance between senseor and the center *O*. This means that the sensors around the center *O* use up their energy much faster than other sensors, because they have to forward heavy traffic load.

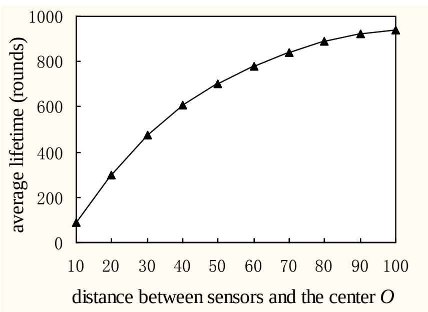


Fig. 2. Sensors lifetime with a centered static sink. We assume *R=100m*, *r = 10m*, *len=2000bit*, *N = 100*, and E_{init}= *1J*.

4.2. Mobile Sink Model

We first fix the optimum mobility strategy under the constraint that the sink should not move out of the network region. We believe that the movement on concentric circles in annuli, because it is the only symmetric strategy that we can have within the network region. We assume that the optimum symmetric strategy is the one whose trajectory is circle of radius R_{opt} and in P_i.

Since the sink can only receive data from the sensors in P_i, both the packet generated by sensors in P_i and not in P_i must pass through sensors in P_i at least once. This means that the sensors around the base station use up their energy much faster than other sensors. Therefore, the network lifetime is upper bounded by the lifetime of these sensors. Let us analysis the lifetime of sensors in $P_{i.}$ The total energy dissipation of all sensor sensors in P_i is given by

$$E_{total\_m} = E_{m\_EX} + E_{m\_TX} = N(\pi R^2 - \pi R_{opt}^2 + \pi(R_{opt} - r)^2)E_{elec}len/(\pi R^2) + N(E_{elec} + E_{amp}r^2)len \quad (7)$$

The average energy consumption of sensors in P_i can be expressed as

$$E_{aver\_m} = \pi R^2 E_{total\_m} / (\pi R^2 - \pi R_{opt}^2 + \pi(R_{opt} - r)^2)/N \quad (8)$$

It is easy to see that minimizing E_{total} is equivalent to maximizing $\pi R^2 - \pi R_{opt}^2 + \pi(R_{opt} - r)^2$. Thus, the optimum symmetric strategy is the one whose trajectory is circle of radius $R_{opt}=R$. The total energy dissipation of all sensors in P_i can be writen as

$$E_{total\_i} = N((i-1)r)^2 E_{elec}len/R^2 + N(ir)^2(E_{elec} + E_{amp}r^2)len/R^2 \quad (9)$$

The average energy consumption of sensors in P_i is

$$E_{aver\_m\_i} = R^2 E_{total\_i} / (N(R-r)^2) \quad (10)$$

The average lifetime of sensors in P_i is given by

$$T_{m\_i} = E_{init} / E_{aver\_m\_i} \quad (11)$$

As shown in Fig.3, the lifetime of a sensor decreases with the increasing distance between the sensor and the center *O*.

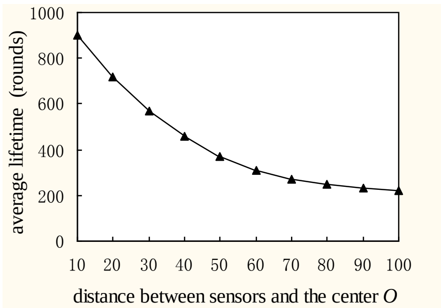


Fig. 3. Sensors lifetime with a mobile sink. We assume *R=100m*, *r = 10m*, *len=2000bit*, *N = 100*, and E_{init}= *1J*.

4.3. Hybrid Communication Model

We noted that in mobile sink model the sensors which are farthest from the center *O* have the highest energy consumption. On the other hand, in static sink model the sensors that are closest to the center *O* have the highest energy consumption.

In order to balance energy consumption, we propose a hybrid communication model which the transmission data alternate between the static sink and the mobile sink periodically, see Fig. 4. In the network deployment stage, the static sink broadcasts a "hello" message to all sensors at a certain power level. By this way each sensor can compute the approximate distance to the center *O* based on the received signal strength.

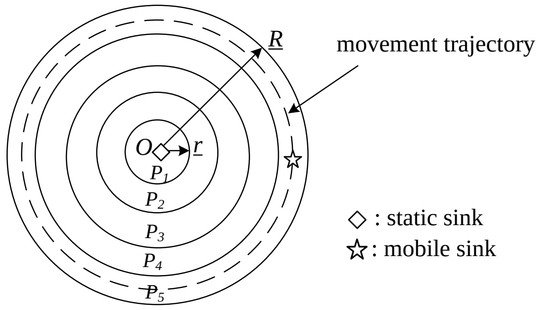


Fig. 4. Network model with a mobile sink and a static sink

We use a new system parameter $c \in [0,1]$ to measure how often the mobile sink is used. We define the lifetime T of the system to be the number of rounds. We set the parameter c using equation (12).

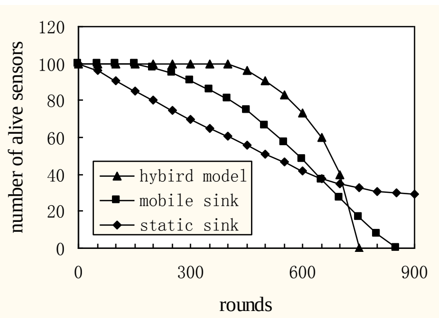
$$c = \begin{cases} 0, & D \le r \\ D/R, & r < D < R - r \\ 1, & D \ge R - r \end{cases} \tag{12}$$

where D denotes the distance between the sensor and the center *O*. Let $T_m = T \times c$ is the number of rounds that sensor transmit data to the mobile sink and $T_s = T - T_m$ is the number of rounds to the static sink.

5. Simulation and Results

We evaluate the performance of our proposed model via simulation in this section. For simplicity, we assume the probability of signal collision and interference in the wireless channel is ignorable. We consider the networks of 100 sensors randomly arranged in a circular observation region of radius 100*m*. The initial energy of sensors is 1*J*. The size of data packet is 2000 *bit*. In our simulation experiments, every simulation result shown below is the average of 50 independent experiments.

We use the number of alive sensors to evaluate the performance of sensor networks. We compare the number of alive sensors of hybrid communication model with static sink model and mobile sink model. We set the transmission radius $r = 10$. As can be found in Fig. 5(a), it coincide with our expectation that more sensors live longer in our hybrid communication model than in the static sink and the mobile sink model. By varying the transmission radius r, we can evaluate the performance of sensor lifetime. The average lifetime of sensors is illustrated in Fig. 5(b). It is worthy noting that increasing transmission radius will not lead to further prolong sensors lifetime. It is easily understood that more transmission radius will lead to more energy consumption and shorter lifetime.



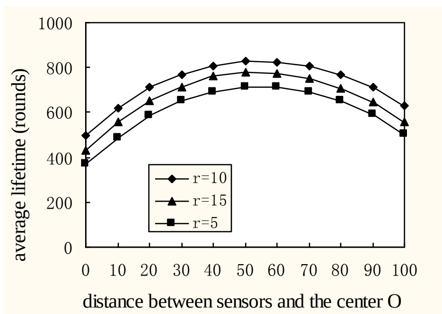


Fig. 5. (a) The number of alive sensors comparison; (b) The lifetime of sensors comparison

6. Conclusion and Future Work

In this paper, we first show that the sensors located close to the sink have higher relay workload than those of farther sensors, leading to the failure of sensors near the sink at the very beginning. We then consider jointly sink mobility and hybrid communication mode, and propose a new hybrid communication model based on taking both static sink and mobile sink into account. We conduct extensive experiments and find that the number of alive sensors can be increased significantly as compared to not only the static sink but also the mobile sink.

In the future, we intend to study how data aggregation can be efficiently integrated into the proposed model. We will also investigate other network models, including the observation fields having irregular shapes and multiple mobile sinks in the network.

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