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Load-Balancing Deployment of Sensors in Multi-sink Wireless Sensor Networks

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Abstract. A multi-sink wireless sensor network (WSN) is composed of a large number of sensors deployed in a wide area and there are some special sensors referred as sinks which play the role of data collector. Sinks are connected to internet so that they can forward data to the data collecting server. Thus each sensor can forward the information they sensed to any one of these sinks. Since sensors located in different positions may bear different communication responsibilities, e.g. forwarding the data generated by some other sensors, the loading or energy consumption of each sensor in network is heterogeneous. Obviously, some sensors may die earlier than the others and thus cause the bottleneck phenomenon in the network. When the bottleneck phenomenon occurs, most of the data from sensors cannot be delivered successfully to the sinks. In this paper, we evaluate the energy consumption as well as the load distribution of sensors deployed uniformly in multi-sink WSNs. With the knowledge of load distribution of a network, we find that not only sensors located near around the sinks but also those in the forwarding paths from the farthest sensors to the sinks will consume more energy. A forwarder selection method is proposed to leverage the loading of sensors in the longest forwarding path. Moreover, a sensor deployment strategy by density control is also proposed to balance the loading of sensors in different tiers, prolong the network lifetime, and increase the successful data delivery as possible. Simulation results show that the data delivery and survival rates are significantly improved by the proposed methods.

Keywords: bottleneck, data delivery, forwarder selection, load distribution, multi-sink wireless sensor networks, sensor deployment

1 Introduction

A multi-sink wireless sensor network (WSN) is composed of sensors and sinks. This kind of networks can be used for monitoring the area where the fixed network infrastructures do not exist, such as battle fields and rain forests etc. [1-2]. Sensors usually use battery as their power supply, thus how to prolong the lifetime of each sensor in the network to retain complete surveillance of the watched area and successfully deliver the monitored data to sinks become important issues of multi-sink WSNs. Each sink serves as a gateway which forwards the data collected from sensors to the server through the Internet. By using multiple sinks, sensors can forward data to the nearest sink to save power [3-4]. In the meantime, the dispersion of data packets or events also achieves the goal of load balance [5].

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While the sensing range is fixed, sensors will transmit the information directly to sinks or via other sensors which are nearer to sinks. The forwarding paths can be built in many gradient based protocols [6]. In this paper, a sensor is in *i*-tier if it is *i* hops away from a specific sink. Thus, in addition to the information generated by sensors in the network, the sensors in lower tiers also have to forward the data of other sensors in higher tiers to the sink. That is, sensors in lower tiers have to bear more communication responsibilities than those in higher tiers [7-9]. Therefore, sensors closer to the sink will lose their battery power very soon. While many sensors in low tiers die, most of the data transmitted from those in high tiers will not reach the sinks. This situation causes low data delivery and leads to bottleneck in network [7]. Since the sinks are not located in the center of the monitored area, the farthest distances from a sink to the boundaries in different directions are different. It means that the loadings of sensors located near around the sink are also different.

Because of the loading of a sensor is influenced by the relative direction or distance from sinks, to the best of our knowledge, there are no literatures proposed to deal with the deployment problem in such a multi-sink WSN. In this paper, we evaluate the energy consumption of sensors in different positions by considering the distance in hops of sensors away from the sinks and the direction relative to the sinks. Once the loading of sensors can be estimated according to our evaluations, more sensors will be deployed in the area where the loading is heavier in order to balance the loading of sensors. For the load distribution of network is balanced, higher data delivery is achieved, and hence the availability of network is also improved.

The rest of paper is organized as follows. Section 2 introduces some related work. Section 3 evaluates the sensor and load distributions in a network, and proposes a load-balancing deployment method. Section 4 presents the simulation results of our method and some previous studies. Finally, the conclusions are given in Section 5.

2 Related Work

Many papers have investigated in multi-sink WSNs [3-5, 7, 10]. In these researches, sensors chose the nearest sink as their destination of data packets. Since packets reached sinks through the shortest path, these schemes pursued the least energy consumption in the whole network. Some scholars proposed the gradient based data forwarding protocols [6, 11]. Once the gradient data were built for each sensor, source sensors could easily transmit data to the sink according to the descendent gradient values. However, some sensors might suffer from heavy burden for being a common sensor of two or more paths from source sensors to sinks, and these sensors would be drained out of their energy quickly [7].

Padmanabh, Gupta and Roy thought that the density of sensors required depended upon the distance from the sinks, probability of event occurrences, the transmission range of sensors and the coverage area [12]. If any of these parameters was changed, the required density of the sensors would also change. Increasing the number of sensors placed around the sink would decrease the doughnut effect. By converting the 2-dimensional problem into multiple identical 1-dimensional problems in data forwarding, the analysis of doughnut phenomenon in single-sink wireless sensor network would underestimate the loading of sensors in low tiers. Also, they did not discuss how to deal with the doughnut phenomenon in multi-sinks WSNs.

Authors in [3] proposed a routing protocol by forwarding data toward the nearest sink. To implement load-balancing, the proposed protocol would select the next nearest sink while the energy level of nodes in the original path fell below a certain threshold. However, designing the performance evaluation experiments for WSNs is faced with a number of practical and conceptual difficulties.

A systematic evaluation for energy consumption of sensors in multi-sink WSNs is useful for understanding the load distribution of sensors in networks. To the best of our knowledge, there are almost no similar studies proposed. With the knowledge of the load distribution or energy consumption of sensors in networks, we develop a deployment strategy and a routing protocol to prolong the network lifetime and enhance the network availability.

3 Sensor and Load Distributions

In this Section, a model is proposed to describe the operations of multi-hopped routing protocols in the multi-sink WSNs. Assume that sensors with fixed sensing range are uniform randomly deployed in the network field of regular polygon and the density of sensors is high enough. In the following discussions, sinks are located at vertices of the regular polygon.

A general wireless sensor network with n sinks, can be viewed as the random deployment (uniformly distributed) of $N(\bullet)$ sensors in a regular polygon. And the distance between each sink and the center of the polygon is assumed to be R. If a sensor is in i-tier, it is i hops away from a specific sink. Clearly, the sensor may be different hops away from different sinks at the same time. Since the sensing range, denoted as r, is fixed for each sensor, the corresponding width of tier is equal to r approximately. The distance between two adjacent sinks, is assumed to be $2Kr$. For sinks are deployed regularly on the circumference of a circle with radius R, K is equal to $h\times\cos((n\text{-}2)\pi/(2\times n))$ where h is equal to R/r.

3.1 Sensor Distribution in Network

The amount of energy consumption for data delivered from sensors to sinks depends on the number of hops from sensors to sinks. Thus, to evaluate the load distribution, we have to find that how many sensors in different tiers will deliver data to a specific sink. For the uniform deployment of sensors in a regular polygonal network, the number of sensors in an area is positively proportional to the area. Therefore, the areas of tiers are computed in this subsection, and the energy consumption of the network is evaluated in the next subsection.

As is well-known, sensors closer to a specific sink, namely A for abbreviation, than the other sinks should deliver their data to A for the sake of energy efficiency. For a regular polygonal network, assuming that all sinks are located on the vertices, the network can be split into n non-overlapping quadrangles which are similar to Voronoi polygons [13]. In each quadrangle, sensors are closer to the same sink than the others. Also, tiers are diagramed as the concentric circles with their center at a sink approximately.

Since all quadrangles are similar, we only need to compute the sensor distribution corresponding to one sink. Take Fig. 1 for example, A, B, and C are three sinks in the network. $A1$ and $A2$ are the middle points of line segments AB and AC respectively. Clearly, $\angle A1,A,A2$ is equal to $[(n\text{-}2)\pi/n]$ which is one of inner angles of a regular polygon with n vertices. Some geometric properties corresponding to sink A in its corresponding quadrangle are illustrated in Fig. 1 for the following computations.

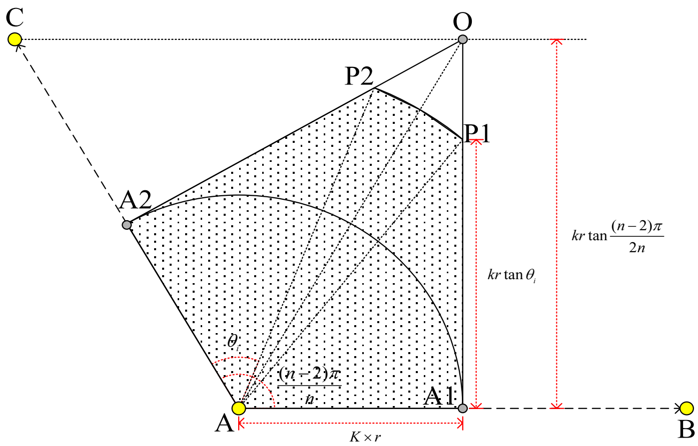


Fig. 1. Some geometric properties in the quadrangle corresponding to the sink A

The gray area, denoted as $S_n(A, i)$ in Fig. 1, represents a specific area of the quadrangle corresponding to sink A. Every sensor in $S_n(A, i)$ is not less than i hops away from sink A. Clearly, the area of i-tier with respect to sink A, denoted as $R_n(A, i)$, is equal to $S_n(A, i)$- $S_n(A, i\text{-}1)$. In a network in shape of regular polygon with n vertices, the area of $S_n(A, i)$ can be obtained by (1).

$$Area(S_n(A,i)) = \begin{cases} \pi(ir)^2 \dfrac{n-2}{2n} & for\ i = 1\ to\ K \\ (Kr)^2(\tan\theta_i) + (\dfrac{\pi}{2} - \dfrac{\pi}{n} - \theta_i)(ir)^2 & for\ i = K+1\ to\ h-1 \\ (Kr)^2(\tan\dfrac{(n-2)\pi}{2n}) & for\ i = h \end{cases} \quad \textbf{(1)}$$

$$where\ \theta_i = \cos^{-1}\frac{K}{i}\ and\ h = \left\lceil \frac{K}{\cos(\frac{(n-2)\pi}{2n})} \right\rceil .$$

3.2 Energy Consumption Analysis

Assume the energy consumed for receiving and transmitting one bit are ξ_R and ξ_T respectively. According to the radio model proposed in [14], we have (2).

$$\begin{aligned} \xi_R &= E \\ \xi_T &= E + E_{amp} \cdot d^2 \end{aligned} . \quad \textbf{(2)}$$

The constant E and E_{amp} in (2) are the energy for running the transmitter/receiver circuitry and the transmit amplifier respectively. The energy for transmitting one bit is assumed to be proportional to the square value of distance d.

With respect to sink A, the average energy required for a sensor in i-tier to forward packets from all sensors in x-tier, namely where $0 < I \leq x$, will be computed first. Assume that V events are uniform randomly triggered among sensors; the expected amount of packets triggered and transmitted by a sensor is V/N. We use $\rho = V/N$ for abbreviation. The number of events sensed and packets transmitted by the nodes in x-tier is $\rho \times N(x)$, thus the energy consumed for transmitting these packets to (x-1)-tier is $\rho \times \xi_T \times N(x)$. Equation (3) shows the average energy consumed for each node in x-tier.

$$E_x(x) = \frac{\rho \xi_T N(x)}{N(x)} = \rho \xi_T . \quad \textbf{(3)}$$

All packets transmitted from x-tier are received totally by sensors in (x-1)-tier. And all received packets are re-transmitted to sensors in (x-2)-tier. So that the average energy consumed for each node in tier x-1 to receive and forward all the packets transmitted from x-tier is shown in (4).

$$E_{x-1}(x) = \frac{\rho \xi_R N(x) + \rho \xi_T N(x)}{N(x-1)} = \frac{\rho N(x)}{N(x-1)}(\xi_R + \xi_T) . \quad \textbf{(4)}$$

Equation (5) is a general form for the nodes in i-tier where i is in [1, x-1] to bear the communication responsibility for sensors in x-tier.

$$E_i(x) = \frac{\rho N(x)}{N(i)}(\xi_R + \xi_T) . \quad \textbf{(5)}$$

The overall energy consumption of a sensor in i-tier, denoted as $E(i)$, after V events are triggered among the network, includes the energy required for transmitting its own data to a sensor in (i-1)-tier and forwarding data generated by sensors in x-tier where x=i+1 to h', h' is the biggest hop count in the forwarding path. That is,

$$E(i) = \sum_{x=i}^{h'} E_i(x) \text{ where } 1 \leq i \leq h'. \quad \textbf{(6)}$$

In Section 4, an example 4-sink WSN is used for the analyses and simulations. As noticed, the loading of sensors in the first tier is many times more than that in the farthest tier such that it is easy to cause bottlenecks near around the sinks.

Nevertheless, if the forwarding path is longer, sensors in that path will consume more energy. The sensors located in vicinity of the connecting line from the source node to the sink will be along the forwarding path in high possibility. It is obvious that sensors reside near the center line, i.e. the connecting line from the center of network to a sink, will suffer more energy consumption.

Assume the number of sensors in i-tier with respect to sink A in the fan-shape network is denoted as $N_\theta(i)$. The average energy required for a sensor located in i-tier within a fan-shape with respect to sink A to forward data generated from sensors in x-tier, denoted as $E_\theta(x, i)$, where $0<i\le x$ and $x\le h_\theta$ where h_θ-tier is the highest tier in the fan-shape. It is easy to find that

$$E_\theta(x,i) = \frac{\rho N_\theta(x)}{N_\theta(i)}(\xi_R + \xi_T) \text{ where } i = 1..\,x\text{-}1. \quad \textbf{(7)}$$

And the overall energy consumption of a sensor in i-tier within the fan-shape, denoted as $E_\theta(i)$, after V events are triggered among the network will be

$$E_\theta(i) = \sum_{x=i}^{h_\theta} E_\theta(x,i)\,. \quad \textbf{(8)}$$

Since the hop counts of the farthest tiers in different directions with respect to sink A are different, the load distributions within different fan-shapes are different. Let us denote the center line as $Line(A, O)$. Sensors in i-tier will be located in the area spanned from the angle $L_\theta(i)$ to $H_\theta(i)$ shown in Fig. 2. For $i\le k$, all sensors in i-tier span the whole inner angle of the regular polygon, i.e. from $L_\theta(i) = -\frac{(n-2)\pi}{2n}$ to $H_\theta(i) = -\frac{(n-2)\pi}{2n}$. And for $i>K$, sensors in i-tier span from $L_\theta(i) = -\frac{(n-2)\pi}{2n} + \theta_i$ to $H_\theta(i) = \frac{(n-2)\pi}{2n} - \theta_i$ where $\theta_i = \cos^{-1}\frac{K}{i}$ illustrated in Fig. 2.

Clearly, we can sorted all the bounded angles as a sequence, denoted as S_θ, which contains $L_\theta(1) = L_\theta(2) = \ldots = L_\theta(K) < L_\theta(K+1) < \ldots < L_\theta(h) \doteq H_\theta(h) < \ldots < H_\theta(K+1) < H_\theta(K) = \ldots = H_\theta(2) = H_\theta(1)$. As noticed, $L_\theta(h)$ is almost equal to $H_\theta(h)$.

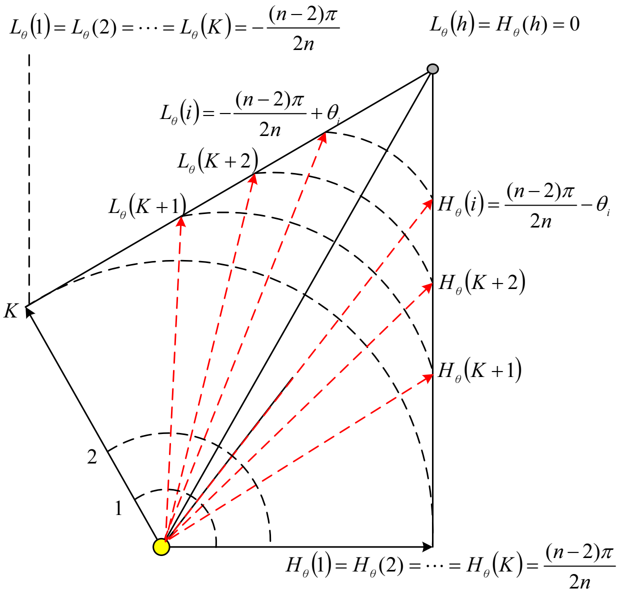


Fig. 2. The sequence of bounded angles

Since the energy consumption of sensors depends on the responsibilities of forwarding, i.e. the more data packets received from other sensors, the more energy consumption they need. Sensors in the same tier may bear different forwarding responsibilities depending on their angles away from $Line(A, O)$. In

Fig. 2, two adjacent angles in sequence S_θ, e.g. $L_\theta(j\text{-}1)$ and $L_\theta(j)$ where $L_\theta(j\text{-}1) < L_\theta(j)$ or $H_\theta(j)$ and $H_\theta(j\text{-}1)$ where $H_\theta(j) < H_\theta(j\text{-}1)$, construct a fan-shape with sink A at the vertex and the farthest tier is j-tier, i.e. $j=h_\theta$. Sensors in i-tier, where $1 \le i \le h_\theta$, of the fan-shape forward the data generated from sensors in x-tier where $i \le x \le h_\theta$ in high possibility. The load distribution of network is shown in Fig. 3. Clearly, the loadings of sensors located near around the sink or in the vicinity of $Line(A, O)$ are heavier.

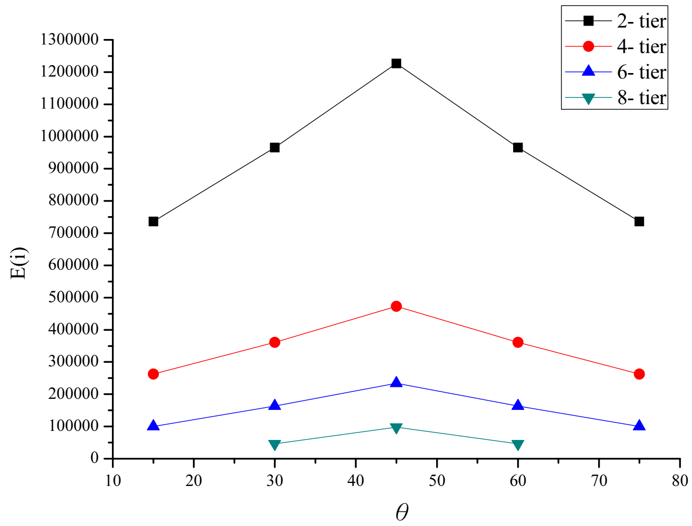


Fig. 3. The load distributions of different tiers in a network

Through the energy model mentioned above, we can estimate the energy consumption of sensors in different tiers and different angles away from $Line(A, O)$. Similar to the case in a single-sink WSN, sensors near around the sinks spend much more energy than those far from the sinks. Many literatures considered that the network will be load-balanced if the number of sinks in network can be increased. In fact, by considering the subnetwork with respect to one of sinks, i.e., sensors in the corresponding Voronoi polygon with respect to the sink, the sensors near around the sink still spend more energy than others. Of course, from the deviations of load distribution, we have the same conclusion that the more number of sinks in networks, the more load-balancing of sensors. Besides, since the forwarding paths in the subnetwork is not equivalent in all directions, the loading of sensors located in the longer forwarding path will suffer the higher energy consumption.

3.3 Linear Descent Selection

In this section, a linear descent selection is proposed such that data packets transmitted from sensors in i-tier received uniformly by sensors in $(i\text{-}1)$-tier to prohibit the load-balancing problem in different direction with respect to sinks in multi-sink WSNs. That is, in normal case, a sensor located in i-tier whose descent may be located in the direction from the sensor to sink A in high possibility. Fig. 4 shows an example relationship between sensors in i-tier and $(i\text{-}1)$-tier without losing generality. If a sensor in i-tier with angle θ_1 away from the center line transmits its data to the sensor in $(i\text{-}1)$-tier with angle θ_2 away from the center line satisfying the linear mapping, i.e.

$$\theta_2 = \frac{H_\theta(i-1)}{H_\theta(i)} \times \theta_1 \text{ or } \theta_2 = \frac{L_\theta(i-1)}{L_\theta(i)} \times \theta_1 . \quad \textbf{(9)}$$

Thus, the forwarding responsibilities is distributed evenly among sensors in $(i\text{-}1)$-tier and the loading of sensors in the same tier can be balanced.

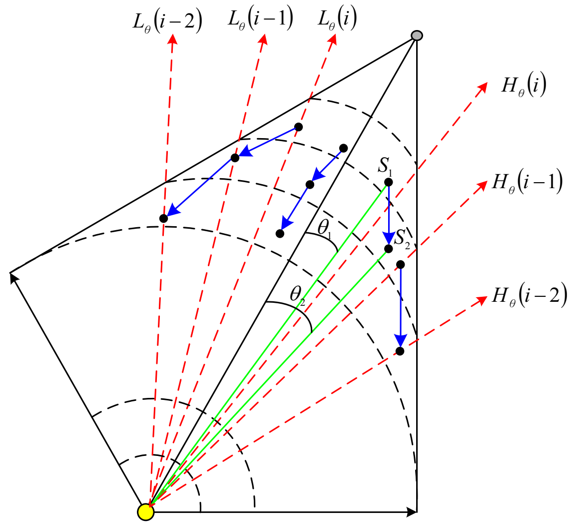


Fig. 4. Linear mapping from a sensor, S_1, in *i*-tier to a sensor, S_2, in (*i*-1)-tier

3.4 Sensor Deployment by Density Control

The densities of sensors deployed in different tiers can be determined by the loading of sensors in different tiers. Assume the density of sensors in *i*-tier is denoted as $D(i)$ where $1 \le i \le h$. In order to balance the loading of sensors in network, $D(i)/D(h)$ is set to be $E(i)/E(h)$. That is, if the loading of sensors in some tier is many times of that in the farthest tier, the corresponding density in that tier will be the same times of the density of sensors in the farthest tier such that the average loading of sensors in each tier will be the same. Effectively, this setting prolongs the lifetime of sensors near around the sinks such that the data generated from sensors can be successfully delivered to the sinks.

4 Simulation Results

To verify the analysis results obtained in Section 3, some simulations are tested in this section. The simulation program is written by Borland C++ 6.0 and executed in a personal computer with an Intel core 2 6300 CPU and 2G ram.

In each simulation scenario, 1000 stationary sensor nodes are uniformly distributed in a square area and 4 sinks are set up at the corners of the area. To simulate the network operations, 10000 events are randomly triggered among sensors which need to deliver a fixed-length packet to the sink. To simplify the parameter setting, we set the packet length to 1 bit in the simulations. Following the energy model used by Heinzelman, Chandrakasan and Balakrishnan, the E and E_{amp} in (1) are 50 nJ/bit and 0.1 nJ/bit/m2 respectively [14].

We assume sensors are homogeneous and initially have the same 10000 nJ energy. The R and r mentioned in previous section are set to 640 and 80 meters respectively. By gradient-based algorithm proposed in [6], each sensor can determine its hop count away from the nearest sink and keep the status of the upstream neighbor sensor with respect to the sink.

In Fig. 5(a) and (b), take the higher tiers for example, the loading of sensors located in different angles with respect to the center line *Line*(*A*, *O*) get smoother after the linear descent selection. Besides, the loading of sensors in low tiers is significantly larger than those in high tiers.

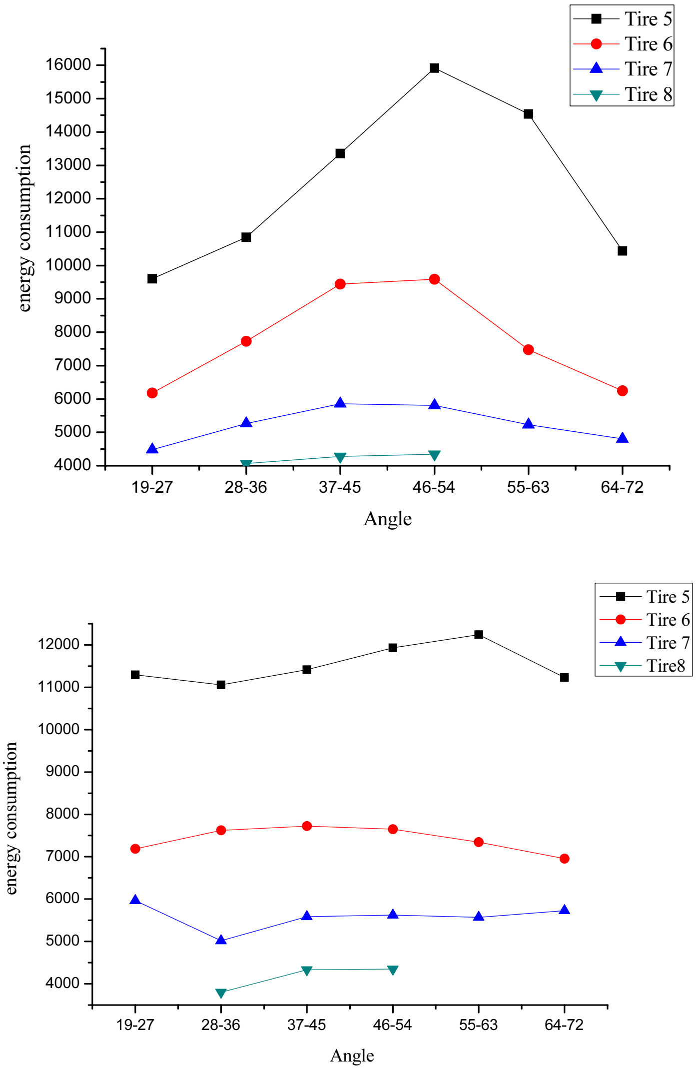
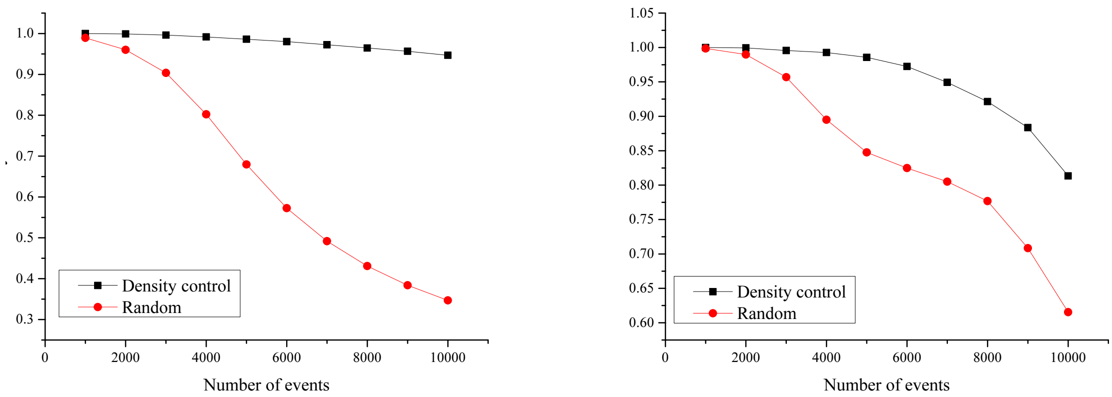


Fig. 5. The loading of sensors located in different angles with respect to the center line (a) before linear descent selection and (b) after linear descent selection

According to the analysis result, we have the value of $E(i)/E(h)$. Clearly, the more load-balancing the network, the bottleneck phenomenon is less severe, so that many sensors will not die earlier to cause the unsuccessful data delivery. Thus we have two testing sensor deployment maps: Density control and Random. In Density control testing maps, the sensor density of tier i is controlled to be $D(i)$ and $D(i)/D(h) = E(i)/E(h)$. As expected, for the loading of sensors is balanced, the density controlled deployment of sensors outperforms uniform randomly deployment in data delivery and survival rate significantly shown in Fig. 6.

5 Conclusions

The amount of energy consumption of sensors after network operations in multi-sink WSNs depends on many factors such as the distance from the sinks, probability of event occurrences and the transmitting range. In this paper, a model for multi-sink WSNs is proposed to simulate the operations of routing in the networks. Sensors located in different tiers or different angles away from the center line may suffer different communicational responsibilities. The energy consumption of sensors is systematically analyzed to derive the load distribution of sensors and the total energy required in multi-sink WSNs thoroughly. With the help of directional routing mechanism, the heavier loading for sensors in the



(a) (b)

Fig. 6. Comparing (a) the data delivery rate and (b) the sensor survival rate for three kinds of testing maps

vicinity of the center line can be released by distributing the data packets transmitted from some tiers to their decent tiers uniformly.

Deploying sensors by density control where the density and loading of sensors in each tier are proportional such that the loading of sensors will be balanced. In other words, the energy required for sensors in network are similar during the network operations. Therefore, the network lifetime is prolonged and the data delivery rate is increased correspondingly. Simulations show that the proposed deployment of sensors outperforms uniform deployment in data delivery rate and survival rate significantly.

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