On the Energy Hole Problem of Nonuniform Node Distribution in Wireless Sensor Networks

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Abstract— **In this paper, we investigate the theoretical aspects of the nonuniform node distribution strategy in wireless sensor networks, which aims to avoid the energy hole around the sink. We find that in a circular sensor network with a nonuniform node distribution and constant data reporting, the unbalanced energy depletion among the nodes in the whole network is unavoidable. This is because although all the inner nodes have used up their energy simultaneously, the outmost part of the network may still have energy left. In spite of this fact, a suboptimal energy efficiency among the inner parts of the network is possible if the number of nodes increases with geometric proportion from the outer parts to the inner ones. In our proposed nonuniform node distribution strategy, the ratio between the node densities of the adjacent $(i+1)$th corona and the ith corona is equal to $(2i-1)/q(2i+1)$, where q is the geometric proportion mentioned above. We also present a routing algorithm with this node distribution strategy. Simulation experiments demonstrate that when the network lifetime has ended, the nodes in the inner parts of the network achieve nearly balanced energy depletion, and only less than 10% of the total energy is wasted.**

I. Introduction

With the technological advances in MEMS, a mass production of tiny and economical sensors becomes possible. A sensor node can be used to measure temperature, humidity or other physical attributes of the phenomenon around it. A typical wireless sensor network is formed by a large number of tiny sensors and an information collector, called the sink node. These sensors could be deployed to collect information and monitor in real-time such scenarios as forests, farmlands, battlefields, and so on. Applications of wireless sensor network technology include habitant monitoring, precision agriculture and military use, among others.

In wireless sensor networks, energy efficiency is of great importance. The sensor nodes behave as both data originator and data router [1]. The data traffic follows a many-to-one communication pattern. Nodes nearer the sink have to take heavier traffic load. Therefore, nodes around the sink would deplete their energy faster, leading to what is called an *energy hole* around the sink. If this happens, no more data can be transmitted to the sink. As a result, the network lifetime ends soon and much energy of the nodes would be wasted. Experimental results in [4] show that when the network lifetime is over, up to 90% of the total initial energy of the nodes is left unused if the nodes are normally distributed in the network.

Li and Mohapatra [2] present an analytical model for the energy hole problem in wireless sensor networks. They assume a uniform node distribution and discuss the validity of strategies such as hierarchical deployment, data compression, etc.

Olariu and Stojmenović [3] first prove that under some conditions the energy hole problem is unavoidable in wireless sensor networks. They assume the nodes in the network are distributed uniformly and report data uniformly. Lian *et al*. [4] explicitly propose the nonuniform node distribution strategy to enhance the data capacity in wireless sensor networks. In [5], the authors also discuss the nonuniform node distribution by only considering energy consumed in data transmission and stating that a balanced energy depletion is possible.

In this paper, we further explore the theoretical aspects of the energy hole problem in wireless sensor networks with nonuniform node distribution. Different from [5], we consider both the energy spent on data transmission and data receiving, and hence obtain quite different results. We first prove that a totally balanced energy depletion among all the nodes is impossible. Then we propose a node distribution strategy in order to achieve a suboptimal balanced energy depletion. We observe that in a circular sensor network with nonuniform node dis-

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tribution, if the number of nodes grows with geometric proportion from the outer (peripheral) parts to the inner ones, then a suboptimal balanced energy depletion is possible. Under this strategy, the ratio between the node densities of the adjacent $(i+1)$th and the ith coronas is equal to $(2i-1)/q(2i+1)$, where q is the geometric proportion mentioned above. A routing algorithm is also proposed with the nonuniform node distribution strategy. This algorithm makes routing decisions only depending on the energy status of nodes.

The rest of the paper is organized as follows: Section II surveys the related work. Section III describes the assumptions and network model. Section IV theoretically analyzes the nonuniform node distribution strategy. A new nonuniform node distribution strategy and a routing algorithm is proposed in Section V. Section VI describes the simulation results of the proposed algorithm. Finally, Section VII concludes the paper.

II. Related Work

Various schemes have been proposed to address the energy hole problem in wireless sensor networks. Here we briefly summarize the existing work most relevant in our context. Some of them have already been introduced in Section I.

Li and Mohapatra [2] present a mathematical model, to analyze the energy hole problem, assuming the nodes are distributed uniformly in a circular network. Based on a traffic perspective, this analytical model examines the validity of several possible schemes aiming to mitigate or solve the energy hole problem. It is observed that in a uniformly distributed sensor network, hierarchical deployment and data compression have a positive effect. Increasing the data generating rate will deteriorate it while simply adding more nodes in the network makes little difference.

Olariu and Stojmenović [3] present the first theoretical work to analyze avoidance of the energy hole problem, assuming a wireless sensor network with uniform node distribution and uniform data reporting. They assume an energy model $E = d^\alpha + c$, where α is the energy attenuation parameter related to specific field, d is the distance between the data sender and receiver, and c is a technology dependent, positive constant. By further assuming that the transmission range of a sensor node is adjustable, they demonstrate that when all the coronas have the same width, the energy spent on routing is minimized. However, this would lead to an unbalanced energy depletion in the network. It has been proven in [3] that for $\alpha > 2$, the unbalanced energy depletion is preventable, but for $\alpha = 2$, the unbalanced energy depletion phenomenon is inevitable. In [5], the same authors discuss the nonuniform node distribution strategy in wireless sensor networks. Assuming an energy consumption model that considers only the energy spent on data transmission, they stated that a balanced energy depletion can be achieved when the node density ρ_i of the ith corona is proportional to $k+1-i$, where k is the optimal number of coronas. In their scheme, nodes near the sink have to send data with a lower rate.

To assign more nodes as energy reservoirs to the areas near the sink is an intuitive way to tackle the energy hole problem. Lian *et al.* [4] explicitly propose the nonuniform node distribution strategy in wireless sensor networks. Because of the unbalanced energy depletion among nodes in the network, more nodes are added to those areas with heavier energy load. And a routing algorithm is proposed in which some nodes sleep once in a while to save energy. In [6] a nonuniform energy distribution strategy and a new routing protocol with a mobile sink are presented. Nodes near the sink have more energy budgets in order to shoulder heavier energy burden.

In LEACH [7], UCS [8], EECS [9] [10], and EEUC [11], hierarchical structures of the sensor network are constructed and clustering schemes are proposed aiming to distribute the energy depletion among all the nodes. LEACH employs cluster head rotation to balance the energy depletion. Noticing that some cluster heads near or far from the sink take a heavier energy burden, the schemes UCS, EECS and EEUC, propose to form clusters with different sizes. These methods produce smaller cluster of which the cluster head consumes more energy for forwarding data to the sink.

Perillo *et al.* [12] summarize two cases in which energy holes could appear. In one case, the sensor nodes send data to the sink via a single hop, thus nodes farther away would deplete their energy faster. In the other case, data are forwarded to the sink via multiple hops. Therefore nodes near the sink have more traffic load and would die first. When the nodes use up their energy, energy holes form around them. The authors assume that each node can vary their transmission range and model the maximization of network lifetime as a linear optimization problem.

Other endeavors introduce mobility into the wireless sensor network to tackle the unbalanced energy depletion problem. Wang *et al.* [13] introduce a mobile relay to prolong the network lifetime. They state that to enhance the network lifetime by a factor of nearly four, the mobile relay only needs to stay within two hops away from the sink. They also propose two joint mobility and routing algorithms which are capable of realizing the stated results. Luo and Hubaux [14] use a mobile sink to improve the network lifetime. With a mobile sink, the nodes near the sink would change over time, thus avoiding energy holes around the sink. They prove that in order to achieve a high energy efficiency, the best position for the sink in a circular sensor network is the center of the network. The authors also demonstrate that using a mobile sink is beneficial and in this case, the mobility trajectory should follow the periphery of the network.

III. Assumptions and Network Model

In this section we describe our network model and basic assumptions. Similar to [13], we assume all the nodes are deployed in a circular area with a radius of R. But we do not introduce a mobile relay. The only sink is located at the center of the area (see Figure 1). All the sensors are homogeneous and have an ID number. The transmission range of all the nodes is fixed to 1 unit. We divide the area into R adjacent coronas with the same width of 1 unit. We denote the i-th corona as C_i. Obviously, the corona C_i is composed of nodes whose distances to the sink are between $(i-1)$ and i.

We assume a data logging application, where the sensors are required to send their sensed data at certain rate. For sake of simplicity, we assume that the sensor nodes generate and send L bits of data per unit time. Nodes belonging to coronas $\{C_i|i \neq R\}$ will forward both the data generated by themselves and the data generated by nodes from coronas $\{C_j|(i+1) \leq j \leq R\}$. The nodes in the outermost corona, C_R ,need not forward any data. We assume there is no data aggregation at any forwarding nodes. We also use a simplified energy model. The initial energy of each sensor is $\varepsilon > 0$. But the sink has no energy limitation. In our model, we consider the energy related to data transmission and receiving. We further assume that a node consumes e_1 units of energy when sending one bit while it depletes e_2 units of energy when receiving one bit such that $e_1 > e_2 > 0$. Note that the constraint $e_1 > e_2$ can be relaxed as shown in the following sections.

IV. Theoretical Analysis of Nonuniform Node Distribution Strategy

In this section, we theoretically analyze the nonuniform node distribution strategy from energy perspective. We first present the energy depletion model of the

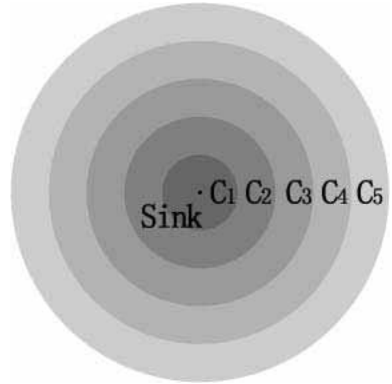

Fig. 1. A circular area consisting of coronas.

coronas. Then we prove that it is impossible to achieve a balanced energy depletion among the nodes in the whole network with a maximum energy efficiency. Nonetheless, we find that a balanced energy depletion among the coronas except the outermost one is possible. We then analyze the characteristics of node distribution under this condition.

A. Energy Depletion Analysis

Let N_i stand for the number of nodes in the corona C_i. And we use E_i to denote the energy consumed per unit time by the nodes in corona C_i. We assume that data can be transmitted to the next inner corona with one hop and to the sink with the minimum number of hops to achieve a high energy efficiency. Then we calculate the total energy consumed in each corona.

According to the above assumptions and network model, the outermost corona C_R only needs to forward data generated by themselves. The energy consumed per unit time by this corona is

$$E_R = N_R L e_1.$$

All the nodes in other coronas have to transmit data generated by themselves as well as data originated from outer coronas. Therefore,

$$E_i = L[\sum_{k=i+1}^{R} N_k(e_1+e_2) + N_i e_1], 1 \leq i \leq R-1.$$

Thus, we can formulate E_i as follows:

$$E_i = \begin{cases} N_R L e_1, & i = R \\ L[\sum\limits_{k=i+1}^{R} N_k(e_1+e_2) + N_i e_1], & 1 \leq i \leq R-1. \end{cases} \quad (1)$$

B. Impossibility of Balanced Energy Depletion

Ideally, when all the nodes of the network use up their energy at the same time, the network lifetime and the energy efficiency are maximized. In particular, there is no energy wasted when the network lifetime is

$$\frac{N_1\varepsilon}{E_1} = \frac{N_2\varepsilon}{E_2} = ... = \frac{N_{R-1}\varepsilon}{E_{R-1}} = \frac{N_R\varepsilon}{E_R}. \tag{2}$$

Theorem 4.1: A perfect and maximum energy efficiency is not achievable, in the sense that formula (2) can not hold in the proposed model.

Proof: Similar to [3], we use proof by contradiction. It is enough to prove Theorem 4.1 if we demonstrate that a balanced energy depletion is not attainable between the coronas C_{R-1} and C_R. Suppose

$$\frac{N_{R-1}\varepsilon}{E_{R-1}} = \frac{N_R\varepsilon}{E_R} \tag{3}$$

holds. By Eq. (1), we can write Eq. (3) as follows:

$$\begin{aligned} N_{R-1}\varepsilon E_R &= N_R\varepsilon E_{R-1}, \\ N_{R-1}\varepsilon N_R L e_1 &= N_R\varepsilon L[N_R(e_1+e_2) + N_{R-1}e_1]. \end{aligned} \tag{4}$$

After simplifying Eq. (4), we have

$$N_R(e_1+e_2) = 0. \tag{5}$$

Obviously, Eq. (5) is impossible, implying Eq. (3) can not hold. Hence the proof. ∎

It is easy to understand that this impossibility lies in the traffic pattern that nodes in the corona C_R only need to transmit their own data, but nodes in the corona C_{R-1} or other coronas need to forward their own data as well as those from outer coronas. In the next section we will prove a balanced energy depletion is possible among all the coronas except C_R.

C. Suboptimal Balanced Energy Depletion

Although Theorem 4.1 states that it is impossible to attain a perfect balanced energy depletion among the nodes in the whole network, a suboptimal balanced energy depletion is still very attractive. Here we define a suboptimal balanced energy depletion as a balanced energy consumption among all the coronas except the outermost one. We also call it a suboptimal energy efficiency. Let us prove the following result.

Theorem 4.2: A suboptimal energy efficiency of the whole network is theoretically possible. The system can achieve a maximum energy efficiency among all the coronas except C_R.

Proof: Let us first prove that the following equation can hold.

$$\frac{N_i\varepsilon}{E_i} = \frac{N_{i+1}\varepsilon}{E_{i+1}}, \qquad 1 \le i \le R-2. \tag{6}$$

The proof uses a deductive method. Suppose Eq. (6) is true. Therefore,

$$N_i E_{i+1} = N_{i+1} E_i. \tag{7}$$

Applying Eq. (1), we rewrite Eq. (7) as

$$\begin{aligned} &N_i L[\sum_{k=i+2}^{R} N_k(e_1+e_2) + N_{i+1}e_1] \\ &= N_{i+1} L[\sum_{k=i+1}^{R} N_k(e_1+e_2) + N_i e_1]. \end{aligned} \tag{8}$$

After simplification and basic transformations, we obtain

$$\frac{N_i}{N_{i+1}} = \frac{\sum_{k=i+1}^{R} N_k}{\sum_{k=i+2}^{R} N_k}. \tag{9}$$

Let $N = \sum_{i=1}^{R} N_i$ denote the total number of nodes in the network. By *Equal Ratios Theorem* we transform Eq. (9) into

$$\begin{aligned} \frac{N_i}{N_{i+1}} &= \frac{N - \sum_{k=1}^{i} N_k}{N - \sum_{k=1}^{i+1} N_k} \\ &= \frac{N - \sum_{k=1}^{i-1} N_k}{N - \sum_{k=1}^{i} N_k} \\ &= \frac{N_{i-1}}{N_i}, \qquad 2 \le i \le R-2. \end{aligned} \tag{10}$$

Therefore, if we make Eq. (10) satisfied, Eq. (6) can hold. This concludes the proof of Theorem 4.2. ∎

Lemma 4.3: If the number of nodes in coronas varies with a geometric proportion from the outer coronas to the inner ones in the whole network, the system achieves a maximum energy efficiency among all the coronas except C_R.

Proof: This condition makes Eq. (10) satisfied, thus proving the lemma. ∎

V. Routing with A Nonuniform Node Distribution Strategy

Our proposed strategy is similar to the one proposed in [4]. However, based on the above theoretical results, our strategy regulates the number of coronas in the network and aims to achieve a high energy efficiency. The main idea is that the nearer the corona is to the sink, the higher is its node density. Because in our network model, nodes belonging to inner coronas not only forward the data generated by outer coronas, but also transmit the data sensed by themselves. Thus, these kinds of nodes would deplete their energy much faster than their counterparts far away from the sink. Hence we assign more nodes to the inner coronas of the network. Different number of nodes may be needed in different coronas, depending on their distance to the sink. We assume that nodes in the corona C_i are distributed with a density of ρ_i. From the outermost corona C_R to the innermost corona C_1, the node density is decreasing. From the viewpoint of the whole network, the nodes are distributed nonuniformly. Therefore, we have

$$\rho_1 > \rho_2 > \rho_3 > ... > \rho_R. \quad (11)$$

In Figure 1, darker corona means that it has a higher node density. Note that all the nodes are assumed to generate data although node density is higher in the inner coronas. An applicable scenario is that in a battlefield more detailed information is needed around the headquarter where the sink is located at.

More importantly, based on the results derived in the previous section, we assume nodes are assigned a priori from the outermost corona to the innermost corona such that the number of nodes in the coronas increases with geometric proportion. We define the ratio between the numbers of two adjacent coronas as

$$\frac{N_i}{N_{i+1}} = q \qquad q > 1, 1 \leq i \leq R-1. \quad (12)$$

We assume that we have assigned nodes in such a way that each node in C_{i+1} can communicate directly with q different nodes in C_i. The distance between a given node in C_{i+1} and the corresponding q nodes in C_i is set to 1 unit, which makes it possible that a route can be constructed with the smallest number of hops from the outermost nodes to the inner ones and eventually to the sink.

Let S_i stand for the area of corona C_i. Then the node density is given by

$$\rho_i = \frac{N_i}{S_i} = \frac{N_i}{\pi(2i-1)}. \quad (13)$$

By Eq. (12), the ratio between the node densities of two adjacent coronas C_{i+1} and C_i is obtained as:

$$\frac{\rho_{i+1}}{\rho_i} = \frac{2i-1}{q(2i+1)} \qquad q > 1, 1 \leq i \leq R-1. \quad (14)$$

This implies that the ratio is only related to the geometric proportion of the network and which corona the nodes belong to.

Let us now sketch the routing algorithm. With the nonuniform node distribution strategy, any node in the network has q candidate relay nodes directing to the sink in the next inner corona. We assume that there is a network initialization process in which nodes find their upstream node and their q relay candidates and record the assigned node ID numbers. In order to gain a balanced energy depletion among the q relay nodes, the source node selects one relay node with maximum energy resource. When selecting the relay node with maximum remaining energy, the source node has to exchange energy information with all the q candidate relay nodes. If there are more than one candidates with the same maximum remaining energy, choose one of them randomly. After the source node selects the relay node, it forwards data of its own as well as those from the upstream node. For nodes which are data source, they just send their own data to the downstream selected relay node. And the selected relay node will repeat this process until the data arrive at a node in corona C_1, then the data will be sent to the sink. The pseudo-code of the routing algorithm is presented in Figure 2.

VI. Simulation Results

In this section, we evaluate the performance of the proposed routing algorithm with the nonuniform node distribution strategy. We use a simplified energy model stated in Section III and do not consider the MAC layer and physical layer issues. The basic simulation parameters are listed in Table I.

A. Remaining Energy of Each Node

Figure 3 shows the remaining energy of each node when the network lifetime ends. Nodes with smaller ID numbers belong to the outer coronas while those with larger ID number indicates nearer to the sink. The six fragments of lines stand for the remaining energy of

Algorithm: Routing with nonuniform node distribution

On receiving an ENERGY_QUERY_MSG from node i
if $IsParent(i) = TRUE$ **then**
  $AckEnergyInfo(ID)$
else
  $DiscardMsg$
end if

On receiving a DATA_FORWARD_MSG from node j
$k = SelectNextRelay(q)$
if $IsParent(j) = TRUE$ **then**
  $ForwardData(k)$
else
  $DiscardMsg$
end if
$ForwardOwnData(k)$
$AckEnergyInfo(ID)$

On receiving no message
$k = SelectNextRelay(q)$
$ForwardOwnData(k)$
$AckEnergyInfo(ID)$

Fig. 2. Pseudo-code of the routing algorithm

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Initial energy (ε)	100 units
Sending energy cost (e_1)	$0.75/10^4$ unit
Receiving energy cost (e_2)	$0.5/10^4$ unit
Length of unit data (L)	100 bits
Number of outmost nodes (N_R)	4
Ratio between number of nodes in two adjacent coronas (q)	2∼3
Radius of the network (R)	4∼9

the nodes belonging to the six coronas $C_6 \sim C_1$, from left to right, respectively. We clarify here that these six fragments are actually not straight lines, but there are very small variances in them (see Figure 4). This also shows that nodes belonging to the same corona have a nearly balanced energy depletion. We call a node in the network dies when it is unable to forward any data or send its own data. The network lifetime is defined as the duration from the very beginning of the network operation to until the first node dies. We see that when

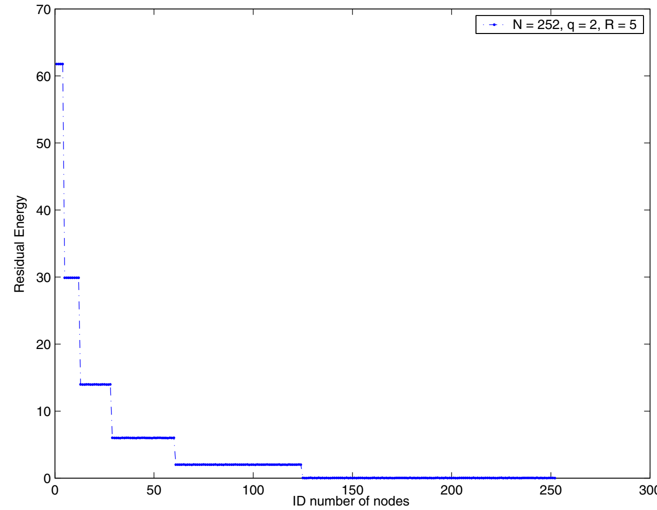

Fig. 3. Most nodes have little energy wasted.

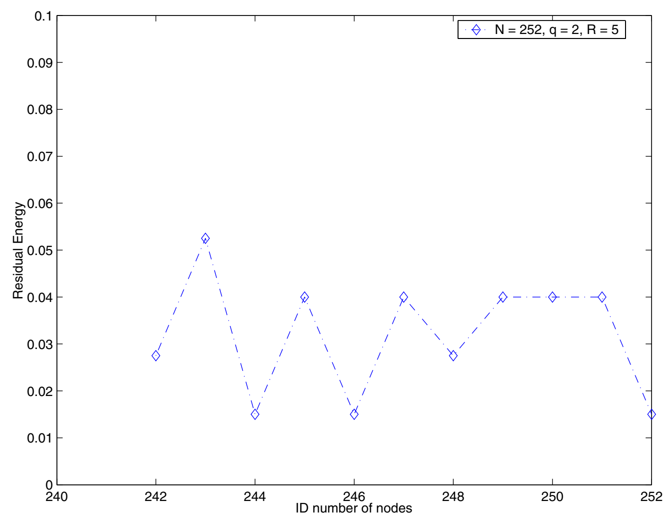

Fig. 4. Small variances in the fragments of Figure 3.

the network lifetime ends, the peripheral nodes have the most energy left, especially the nodes in the outmost corona. This is adherent to our theoretical analysis. Nodes except the ones from the outmost corona still have energy left because we stop the network operation once the first node dies. Besides, coronas farther away always have less energy load. In particular, most of the nodes belonging to $C_3 \sim C_1$ have less then 10 units of energy left. This demonstrates the routing algorithm with the nonuniform node distribution strategy achieves a high energy efficiency.

B. Residual Energy Ratio

Based on the previous analyses, we calculate the residual energy ratio in the following way.

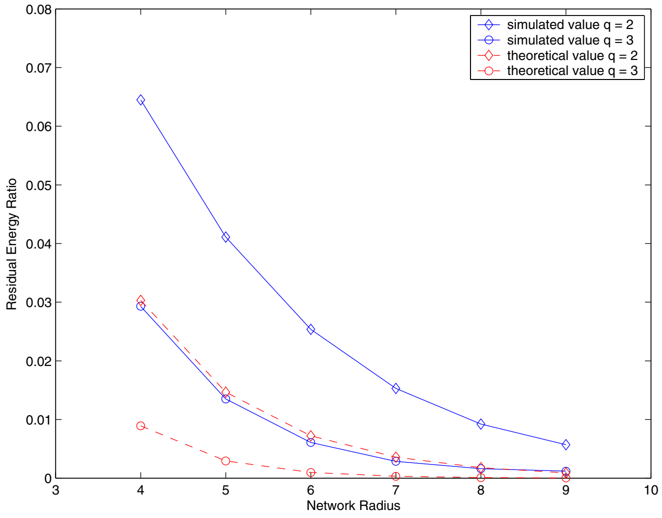

Fig. 5. Residual energy ratios as a function of network radius and q.

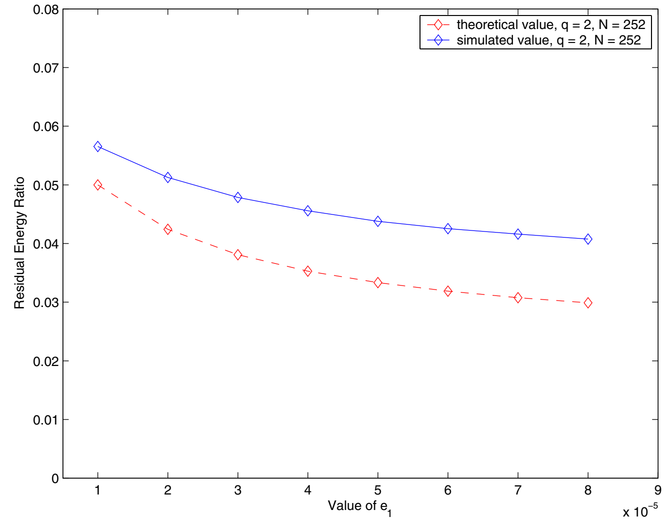

Fig. 6. Residual energy ratios of different values of e_1, where $e_2 = 0.5/10^4$unit.

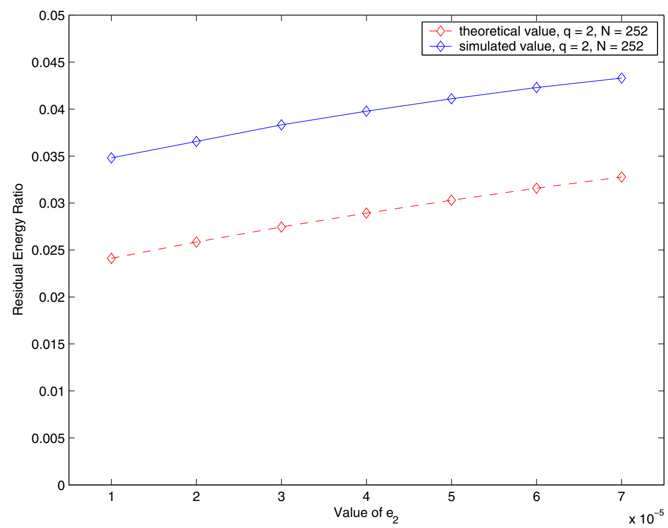

Fig. 7. Residual energy ratios of different values of e_2, where $e_1 = 0.75/10^4$unit.

When the network lifetime ends, the remaining energy is given by

$$E_{residual} = (\frac{N_R \varepsilon}{E_R} - \frac{N_{R-1}\varepsilon}{E_{R-1}})E_R.$$

From Eqs. (1) and (12), we obtain

$$E_{residual} = \frac{N_R \varepsilon (e_1 + e_2)}{(1+q)e_1 + e_2}. \tag{15}$$

And the total number of nodes can be computed as,

$$N = \frac{N_R(q^R - 1)}{q-1}, q > 1. \tag{16}$$

By Eqs. (15) and (16), the residual energy ratio is

$$\frac{E_{residual}}{N\varepsilon} = \frac{(e_1 + e_2)(q-1)}{[(1+q)e_1 + e_2](q^R - 1)}. \tag{17}$$

Clearly, from an energy perspective, the theoretical ratio of residual energy is only related to the values of e_1, e_2, q and the network radius R.

We illustrate the analytical and simulated values of the residual energy ratio in Figure 5 with different network radii. As expected, the ratios in the simulations are greater than the analytical values. But with the growth of the network radius, the tendency of residual energy ratios match well between the theoretical values and simulated ones. We explain the differences as follows. On one hand, we compute the theoretical values mainly from an energy perspective, without considering routing issues much. Hence the residual energy ratio decreases rapidly with the growth of network radius. On the other hand, the network stops operation when the first node can not receive or send any data. This is why the residual energy ratios in the simulations are greater. We also observe that the routing algorithm performs better when $q = 3$ than it does when $q = 2$ in our simulations. This is in accordance with the theoretical results. Furthermore, the remaining energy ratios of different network radii in our simulations are all below 10%. In Figures 6 and 7, we show the values of the residual energy ratio with different e_1 and e_2, respectively. The simulated values of residual energy ratio match well with the analytical ones; the slight gaps can also be explained as above. We observe that the residual energy ratio increases with the increment of e_2, but decreases with the growth of e_1. In fact, we notice that the network lifetime diminishes with larger e_1 or e_2, as each node consumes more energy. This provides some hints on wireless sensor network design, say, network lifetime improvement may sacrifice energy efficiency.

VII. Discussions and Conclusions

In this paper, we have explored the theoretical aspects of the nonuniform node distribution strategy which addresses the energy hole problem in wireless sensor networks. We find that it is impossible to achieve a balanced energy depletion among all the nodes due to the data transmission pattern of wireless sensor networks. Nonetheless, we demonstrate that with a nonuniform node distribution strategy, a very high energy efficiency is achievable. We formulate the ratio between the node densities of the adjacent $(i+1)$th corona and the ith one under this strategy. We present a new routing algorithm as well with the nonuniform node distribution strategy. In our simulations the system achieves a high energy efficiency and less than 10% of total initial energy is wasted.

The nonuniform node distribution has the potential to attain a very high energy efficiency in circular wireless sensor networks. However, it incurs some costs. With the number of nodes in the coronas increasing from outer the to the inner areas with geometric proportion, the total number of nodes in the network grows exponentially. Therefore, in order for this nonuniform node distribution strategy to be more realistic, the cost of sensor nodes needs to decrease significantly. Another possible solution is to employ nodes with different initial energy budgets [6]. Our theoretical analysis can be applied to this kind of scenario.

Additionally, a perfect MAC layer is needed to handle channel problems among the nodes. We also have to rely much on more sophisticated sensor manufacturing and sensor node deployment methods to guarantee nonuniform node distribution strategy possible. Here we ignored the energy consumption on MAC and network layers which we plan to include in our future work.

Acknowledgments

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