A Power Graded Data Gathering Mechanism for Wireless Sensor Networks[1)]

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Abstract The data gathering manner of wireless sensor networks, in which data is forwarded towards the sink node, would cause the nodes near the sink node to transmit more data than those far from it. Most data gathering mechanisms now do not do well in balancing the energy consumption among nodes with different distances to the sink, thus they can hardly avoid the problem that nodes near the sink consume energy more quickly, which may cause the network rupture from the sink node. This paper presents a data gathering mechanism called PODA, which grades the output power of nodes according to their distances from the sink node. PODA balances energy consumption by setting the nodes near the sink with lower output power and the nodes far from the sink with higher output power. Simulation results show that the PODA mechanism can achieve even energy consumption in the entire network, improve energy efficiency and prolong the network lifetime.

Key words Wireless sensor network, energy balance, power grade, data gathering

1 Introduction

Recent advances in micro-electro mechanical systems (MEMS) have led to the development of large-scale sensor networks for military affairs, environment monitoring and so on[1]. Sensor nodes are deployed densely near or in the sensing area to collect and transmit information to the sink node in a multi-hop fashion. Sensor nodes usually have non-replenishable energy resource, which causes energy efficiency to be an important consideration for sensor network design.

In the sensor networks for data gathering applications, data congregates to the sink node and this makes the nodes near the sink become hotspots in the network. As data transmission consumes most energy of a node, this would rupture the network and stop data transmission to the sink, and the network lifetime is reduced thereby. In another aspect, we noticed that the energy consumption is proportional to the distance of communication. We can adjust the energy consumption for the node to transfer the same amount of data by changing the node′s communication radius. At the same time, the modern wireless communication technologies have made it easy for nodes to adjust their output power in multiple levels. Thus, the method of changing a sensor node′s communication radius by adjusting its output power has been adopted by many researchers to balance the energy consumption of sensors nodes[2∼4]. However, most of the researchers only considered at node level, without utilizing the advantage of adjustable communication radius of nodes adequately.

This paper presents a new data gathering mechanism called PODA (Power-graded data gathering), which takes the adjustment of output power at system level in consideration to tackle the hotspot problem in wireless sensor networks for gathering data in large areas. Making nodes far from the sink use higher output power than those near the sink, all the nodes in the network can consume energy evenly so as to improve the energy efficiency and prolong the network lifetime. PODA protocol has the following characters. Firstly, energy consumption of nodes is even in the whole network. Secondly, the protocol is simple with low protocol cost, and easy to implement.

The rest of the paper is organized as follows. Section 2 presents some previous work about data gathering protocols for wireless sensor networks. Section 3 describes our mechanism in detail. Section 4 gives out the experimental results. Section 5 discusses some issues in implementation. Finally, we conclude this paper in Section 6.

2 Related work

Many previous data gathering mechanisms adopt different means to save node energy and prolong the network lifetime. Directed Diffusion[5] is a typical gradient-based data forwarding mechanism that can form a data-reporting tree in the network. It reduces the unnecessary data transmission

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by suppressing the redundant data packets. Directed diffusion has a relatively heavy communication cost, as it not only needs to rebuild the topology periodically to maintain the gradient, but also has to maintain more than one path to sink node for each data source to transfer multi-copy messages. Energy aware routing (EAR)[6] builds multiple paths from the data source to the sink node. Using a stochastic approach, it selects sub-optimal next hop for each node, so it can only gain energy balance locally. Though dynamic energy aware routing (DEAR)[7] can consume energy more evenly than EAR, it cannot avoid bringing hot spot near the sink node either. The authors of [8] tried to find an energy-balanced solution for data propagation in wireless sensor networks, but they did not adequately make use of the output power adjusting function of nodes. Besides, their algorithm is too complex to take into practice. In [4], the authors gave a re-clustering strategy and a redirection scheme for cluster-based wireless sensor networks The method of dynamic transmission power adjustment is introduced into their protocol to control the number of neighbors for each node, yet their protocol can only guarantee the local energy balance within a cluster. Without considering the traffic characteristie of the whole network in a data gathering application, all these protocols can hardly meet the requirement of energy balance on all the nodes in the networks. Based on the analysis of the traffic, we present a new data gathering mechanism in this paper to achieve this goal by exerting the function of output power adjustment on nodes adequately.

3 Power-graded data gathering

In this paper, we assume a wireless sensor network model, which is similar to data gathering applications such as environment monitoring, with the following properties:

1) A larger number of energy-constrained sensor nodes are deployed uniformly in the network area and are equipped with power control capabilities to vary their output power.

2) A fixed sink node is located in the center of the network area.

3) Each sensor node sends fixed-length data packets to the sink node periodically.

In such a sensor network, most sensing data gathers to the sink node hop by hop, as it is energy inefficient to transmit data to the sink directly. Nevertheless, the nodes near the sink have to forward data for other nodes besides their own data reporting. The closer to the sink, the more data they have to forward. Since the energy consumption of a sensor node depends mainly on communication and is proportional the distance of communication, if all the nodes in the network use a same communication radius, they will have the same energy consumption in transmitting a data packet. Therefore, nodes near the sink consume more energy because they have to transmit more data, and this decreases their lifetime dramatically.

Fig. 1 (a) illustrates a traditional network using a uniform output power. All the nodes that have a same hop-count to the sink form a nodes set, which we call a hop-grade. The nodes within the 1-hop-grade take charge of transmitting the data of nodes in all other sections of the network. In PODA, nodes near the sink adopt a short radius for communication, while nodes far from the sink adopt a longer one. Fig. 1 (b) shows a network using the proposed PODA mechanism of classifying output power, and the width of each graded ring increases along with hop-counts. For the nodes in higher hop-grades, although they consume more energy to transmit a data packet than those in lower hop-grades, the amount of data needed to transmit is much smaller. As a result, this makes the energy

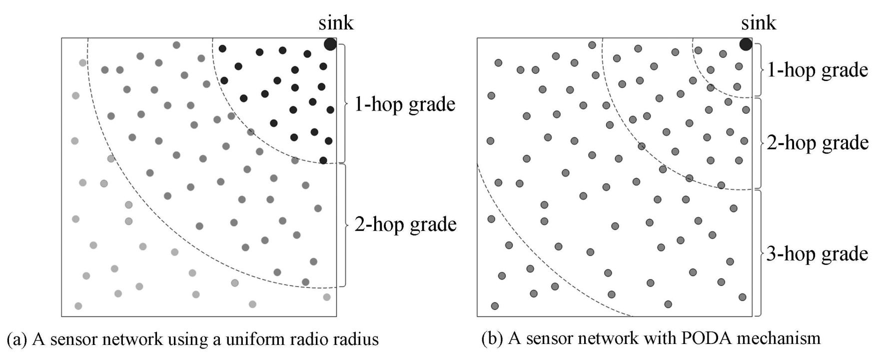


Fig. 1 Hop-count grades in wireless sensor network

consumption almost equal among nodes in different hop-grades in a long time running network, which can improve the energy efficiency and prolong the network lifetime by avoiding making the nodes near the sink as hotspots.

Another advantage provided by PODA mechanism is that it can shorten the delay incurred in gathering data with a multi-hop pattern. There always exists a tradeoff between delay and energy consumption during gathering data in wireless sensor networks[9~11]. With the network traffic model we assumed, the bigger the communication radii of the nodes, the shorter the delay of the data, but the higher energy cost for transmitting a data packet. In PODA mechanism, communication radii of the nodes increase along with hop-count from the sink, thus the data packets can arrive at the sink with less hop-count, but without wasting energy.

3.1 Output-power-grade

In this section, we describe the network traffic model, which is used in PODA mechanism, based on the sensor network model mentioned above.

In PODA, we assign an output-power-grade to each hop-grade. The nodes in a same output power grade transmit data using the same output power, so they have the same communication radius. Aiming at balancing the energy consumption of all the nodes in the network, we need to carefully design the communication radius used by nodes in each hop-count grade to get a table of output-power-grades corresponding to hop-count.

In Fig. 2 (a), the sink node uses R_0 as its communication radius and informs the nodes within this area as 1-hop-grade nodes. All the 1-hop-grade nodes (*e.g.* Node A in Fig. 2) use R_1 as their communication radius, and then they announce their hop-grades information to the nodes within their communication range to make them 2-hop-grade nodes. Similarly, all the 2-hop-grade nodes (*e.g.* Node B) use R_2 as their communication radius, and so forth. Assuming the nodes distribute uniformly, Fig. 2 (a) can be predigested to Fig. 2 (b) in which nodes that have the same hop-count form a ring area. We call each ring area an output-power-grade and denote them as $\{G_i\}$. Especially, the first output-power-grade G_0 is a round area with the sink node as its center. We can see that the hop-count from nodes in the i-th grade, G_i, to the sink node is $i+1$.

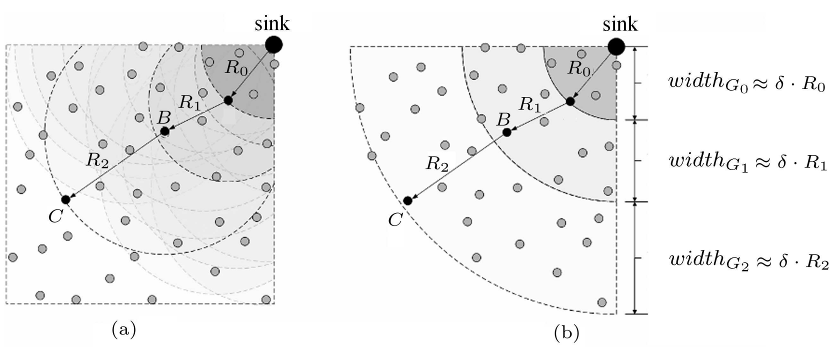


Fig. 2 Output-power-grades in a wireless sensor network

Let R_i denote the communication radius used by nodes in grade G_i. In PODA, starting from the sink, each node′s hop-grade is confirmed hop by hop. To make the nodes communicate with that in neighboring grades in both directions, we should have

$$R_{i+1} \geqslant R_i, \quad i \geqslant 0 \tag{1}$$

As shown in Fig. 2 (b), the communication radius is R_{i+1} of nodes in grade G_i. Therefore, the width of the ring area of G_i is decided by R_i:

$$W_{Gi} = \delta \cdot R_i, \quad i \geqslant 0 \tag{2}$$

where δ is a parameter in $(0, 1]$, which is decided by the deployment density of nodes, communication channel quality and topology building algorithm in the specified network.

Let us consider a data-gathering network that covers a round area and has a sink node at the centre. Let R denote the radius of the entire network. Then

$$R = \sum_i W_{Gi} = \delta \cdot \sum_i R_i, \quad i \geqslant 0 \tag{3}$$

Assuming the nodes are deployed uniformly and the deployment density is ρ, the amount of nodes in the network is $\rho \cdot \pi \cdot R^2$. All the sensor nodes periodically send data packets having a length of L-bit to the sink. Especially, in one report period, the amount of packets generated by nodes in grade G_0 is

$$D_{G0} = \rho \cdot \pi \cdot W_{G0}^2 \tag{4}$$

Due to (2), we have

$$D_{G0} = \rho \cdot \pi \cdot (\delta \cdot R_0)^2 = \rho \cdot \pi \cdot \delta^2 \cdot R_0^2 \tag{5}$$

Nodes in grade G_0 communicate with the sink directly, thus they have to transmit data generated by nodes in all the other grades

$$T_{G0} = \rho \cdot \pi \cdot R^2 - D_{G0} = \rho \cdot \pi \cdot R^2 - \rho \cdot \pi \cdot \delta^2 \cdot R_0^2 \tag{6}$$

For nodes in grade G_i, the amount of packets generated in each report period, which is also the amount of nodes in G_i, is

$$\begin{aligned} D_{Gi} =& \rho \cdot \pi \cdot (\sum_{k=0}^{i} W_{Gk})^2 - \rho \cdot \pi \cdot (\sum_{k=0}^{i-1} W_{Gk})^2 = \rho \cdot \pi \cdot [(\sum_{k=0}^{i} \delta \cdot R_k)^2 - (\sum_{k=0}^{i-1} \delta \cdot R_k)^2] = \\ & \rho \cdot \pi \cdot \delta^2 \cdot [(\sum_{k=0}^{i} R_k)^2 - (\sum_{k=0}^{i-1} R_k)^2] \end{aligned} \tag{7}$$

Nodes in grade G_i, which are near the sink, have to transmit data generated by the nodes in grade $G_j (j > i)$, which is far from the sink

$$T_{Gi} = \rho \cdot \pi \cdot R^2 - \rho \cdot \pi \cdot (\sum_{k=0}^{i} W_{Gk})^2 = \rho \cdot \pi \cdot R^2 - \rho \cdot \pi \cdot \delta^2 \cdot (\sum_{k=0}^{i} R_k)^2 \tag{8}$$

Based on the analysis of the network traffic characteristic mentioned above, we can assign the communication radius R_i in each output-power-grade to make nodes in different grades have almost the same energy consumption in data reporting. In the following sections, we will firstly introduce the energy model we adopt and then expatiate on calculating R_i.

3.2 Energy model

In this section, we present the energy model for communication in PODA mechanism. However, what should be pointed out is PODA mechanism does not restrict the energy model employed, but it can work with diverse energy models that are adapted to different applications.

We adopt the practical radio energy model described in [12]. In this model, the transmitter needs energy to run the radio electronics and the power amplifier, and the receiver needs energy to run the radio electronics. For relatively short distances, the propagation loss is modeled as inversely proportional to d^2, whereas for longer distances, the propagation loss is modeled as inversely proportional to d^4. Power control can be used to invert this loss by setting the power amplifier to ensure a certain power at the receiver. Therefore, to transmit and to receive an L-bit packet in a distance d, the radio expends the following energy, respectively.

$$E_{Tx}(L, d) = \begin{cases} L \cdot E_{elec} + L \cdot \varepsilon_{friis-amp} \cdot d^2, & \text{if } d < d_{crossover} \\ L \cdot E_{elec} + L \cdot \varepsilon_{two-ray-amp} \cdot d^2, & \text{if } d \geqslant d_{crossover} \end{cases} \tag{9}$$

$$E_{Rx}(L) = L \cdot E_{elec} \tag{10}$$

Here $d_{crossover}$ is the cross-over distance for Friis and two-ray ground attenuation models. E_{elec} is the electronics energy and depends on factors such as digital coding, modulation, and filtering of the signal before it is sent to the transmit amplifier. The parameters $\varepsilon_{friis-amp}$ and $\varepsilon_{two-ray-amp}$ depend on the required receiver sensitivity and the receiver noise figure.

For packets generated by the node itself, only one sending operation is needed, whereas a receiving and a sending operations are needed to transmit packets for higher grades. Especially, the energy consumed by the first output-power-grade G_0 in a report period is

$$E_{G0} = E_{Rx} \cdot T_{G0} + E_{Tx} \cdot (D_{G0} + T_{G0}) = E_{Rx} \cdot (\rho \cdot \pi \cdot R^2 - \rho \cdot \pi \cdot \delta^2 \cdot R_0^2) + E_{Tx} \cdot \rho \cdot \pi \cdot R^2 = \rho \cdot \pi \cdot R^2 \cdot (E_{Rx} + E_{Tx}) - \rho \cdot \pi \cdot \delta^2 \cdot R_0^2 \cdot E_{Rx} \tag{11}$$

where the former item denotes the energy consumed in transmitting data of the entire network, and the latter denotes that nodes in Grade G_0 don′t need to receive the data generated by themselves.

Similarly, the energy consumed by Grade G_i in reporting data is

$$\begin{aligned} E_{Gi} = & E_{Rx} \cdot T_{Gi} + E_{Tx} \cdot (D_{Gi} + T_{Gi}) = E_{Rx} \cdot \rho \cdot \pi \cdot [R^2 - \delta^2 \cdot (\sum_{k=0}^{i} R_k)^2] + \\ & E_{Tx} \cdot \rho \cdot \pi \cdot \{\delta^2 \cdot [(\sum_{k=0}^{i} R_k)^2 - (\sum_{k=0}^{i-1} R_k)^2] + R^2 - \delta^2 \cdot (\sum_{k=0}^{i} R_k)^2\} = \\ & \rho \cdot \pi \cdot R^2 \cdot (E_{Rx} + E_{Tx}) - \rho \cdot \pi \cdot \delta^2 \cdot E_{Rx} \cdot (\sum_{k=0}^{i} R_k)^2 - \rho \cdot \pi \cdot \delta^2 \cdot E_{Tx} \cdot (\sum_{k=0}^{i-1} R_k)^2 \end{aligned} \tag{12}$$

We can comprehend the three items in E_{Gi} like this: The first item denotes the energy consumed in transmitting data of the entire network. The second item denotes that nodes in grade G_i do not need to receive the data generated by themselves or by the nodes closer to the sink than them. The third item denotes that nodes in grade G_i do not need to transmit the data generated by the nodes closer to the sink than them.

Since increasing communication range will cause more collision, which waste more energy on both receiving and transmitting data packets, the data amount transmitted by the nodes is actually more than that in (12). Therefore, we amend (12) as

$$\begin{aligned} E_{Gi} = & \alpha_{Rx} \cdot E_{Rx} \cdot T_{Gi} + \alpha_{Tx} \cdot E_{Tx} \cdot (D_{Gi} + T_{gi}) = \\ & \rho \cdot \pi [R^2 \cdot (\alpha_{Rx} \cdot E_{Rx} + \alpha_{Tx} \cdot E_{Tx}) - \delta^2 \cdot \alpha_{Rx} \cdot E_{Rx} \cdot (\sum_{k=0}^{i} R_k)^2 - \delta^2 \cdot \alpha_{Tx} \cdot E_{Tx} \cdot (\sum_{k=0}^{i-1} R_k)^2] \end{aligned}$$

where α_{Rx} and α_{Tx} are proportionality coefficients for the increase of energy consumption on receiving and transmitting respectively. The values of the two coefficients depend on the link layer protocol adopted and the scheduling mechanism used in the network, also variate with the increased communication range; however, this is beyond the scope of this paper. For simplicity, we assume $\alpha_{Rx} = \alpha_{Tx}$ in this paper, and unify them as α_i, so E_{Gi} can be expressed as

$$E_{Gi} = \rho \cdot \pi \cdot \alpha_i \cdot [R^2 \cdot (E_{Rx} + E_{Tx}) - \delta^2 \cdot E_{Rx} \cdot (\sum_{k=0}^{i} R_k)^2 - \delta^2 \cdot E_{Tx} \cdot (\sum_{k=0}^{i-1} R_k)^2] \tag{13}$$

3.3 Communication radius

In this section, we explain how to deal with the communication radii of nodes in each output-power-grade with PODA mechanism.

The main purpose of the PODA mechanism is to make the energy consumption on communication equal among nodes in each location in the network under the precondition of knowing the network radius R. To achieve the purpose, we assign the communication radii of nodes in each hop-grade and require the average energy consumption per node to be equal. As mentioned in Section 3.1, D_{Gi} can also denote the number of nodes in Grade G_i, thus the following formula should be satisfied:

$$\frac{E_{Gi}}{D_{Gi}} = \frac{E_{Gi-1}}{D_{Gi-1}} = \cdots = \frac{E_{G0}}{D_{G0}} \tag{14}$$

In PODA, we need to choose the sink′s communication radius R_0 and the communication radius R_1 for nodes in the 1-hop-grade. To satisfy (1), we can generally set R_0 and R_1 to small ones among the values in communication scope of nodes′ RF communication modules. Due to (9), (10), and (11), we have

$$E_{G0} = E_{Rx} \cdot T_{G0} + E_{Tx} \cdot (D_{G0} + T_{G0}) = E_{Rx} \cdot (\rho \cdot \pi \cdot R^2 - \rho \cdot \pi \cdot \delta^2 \cdot R_0^2) + E_{Tx} \cdot \rho \cdot \pi \cdot R^2 = \\ \rho \cdot \pi \cdot R^2 \cdot (E_{Rx} + E_{Tx}) - \rho \cdot \pi \cdot \delta^2 \cdot R_0^2 \cdot E_{Rx} = \lambda \cdot [R^2 \cdot (2 \cdot E_{elec} + \varepsilon_1 \cdot R_1^{n_1}) - \delta^2 \cdot R_0^2 \cdot E_{elec}] \tag{15}$$

where $\lambda = \rho \cdot \pi \cdot L$, ε_1 and n_1 meet the following values.

$$\begin{cases} \varepsilon_1 = \varepsilon_{friss-amp} \text{ and } n_1 = 2, & \text{if } R_1 < d_{crossover} \\ \varepsilon_1 = \varepsilon_{two-ray-amp} \text{ and } n_1 = 4, & \text{if } R_1 \geqslant d_{crossover} \end{cases}$$

Since nodes in grade G_1 use R_2 as their communication radius, according to (13) we have

$$\begin{cases} E_{G1} = \rho \cdot \pi \cdot \alpha_1 \cdot [R^2 \cdot (E_{Rx} + E_{Tx}) - \delta^2 \cdot E_{Rx} \cdot (R_0 + R_1)^2 - \delta^2 \cdot E_{Tx} \cdot R_0^2] = \\ \qquad \lambda \cdot \alpha_1 \cdot [\varepsilon_2 \cdot R_2^{n_2} \cdot (R^2 - \delta^2 \cdot R_0^2) - \delta^2 \cdot E_{elec} \cdot ((R_0 + R_1)^2 + R_0^2) + 2 \cdot R^2 \cdot E_{elec}] \\ \dfrac{E_{G1}}{D_{G1}} = \dfrac{E_{G0}}{D_{G0}} \end{cases}$$

Then we can calculate the value of R_2 as

$$R_2 = \left\{ \frac{\frac{\eta}{\alpha_1} \cdot [(R_0 + R_1)^2 - R_0^2] + \delta^2 \cdot E_{elec} \cdot [(R_0 + R_1)^2 + R_0^2] - 2 \cdot E_{elec} \cdot R^2}{\varepsilon_2 \cdot (R^2 - \delta^2 \cdot R_0^2)} \right\}^{\frac{1}{n_2}} \tag{16}$$

where

$$\eta = \frac{R^2}{R_0^2} \cdot (2 \cdot E_{elec} + \varepsilon_1 \cdot R_1^{n_1}) - \delta^2 \cdot E_{elec}$$

and

$$\begin{cases} \varepsilon_2 = \varepsilon_{friis-amp} \text{ and } n_2 = 2, & \text{if } R_2 < d_{crossover} \\ \varepsilon_2 = \varepsilon_{two-ray-amp} \text{ and } n_2 = 4, & \text{if } R_2 \geqslant d_{crossover} \end{cases}$$

We can see that R_2 has no relation with the nodes density ρ and the packet length L. Therefore, we can calculate the communication radius R_{i+1} of nodes in output-power-grade G_i iteratively.

$$R_{i+1} = \left\{ \frac{\frac{\eta}{\alpha_i} \cdot [(\sum_{k=0}^{i} R_k)^2 - (\sum_{k=0}^{i-1} R_k)^2] + \delta^2 \cdot E_{elec} \cdot [(\sum_{k=0}^{i} R_k)^2 + (\sum_{k=0}^{i-1} R_k)^2] - 2 \cdot E_{elec} \cdot R^2}{\varepsilon_{i+1} \cdot [R^2 - \delta^2 \cdot (\sum_{k=0}^{i-1} R_k)^2]} \right\}^{\frac{1}{n_{i+1}}} \tag{17}$$

where

$$\begin{cases} \varepsilon_{i+1} = \varepsilon_{friis-amp} \text{ and } n_{i+1} = 2, & \text{if } R_{i+1} < d_{crossover} \\ \varepsilon_{i+1} = \varepsilon_{two-ray-amp} \text{ and } n_{i+1} = 4, & \text{if } R_{i+1} \geqslant d_{crossover} \end{cases}$$

3.4 Network deployment

The purpose of the PODA mechanism is to balance the energy consumption among all the nodes in the network by making nodes adjust their output power adaptively according to the hop-count from themselves to the sink. In this section, we introduce two main methods utilizing the PODA mechanism to deploy a sensor network.

3.4.1 Method 1. Fixed configuration output-power-grades

This method is to plan the output-power-grades and calculate the communication radius of each grade if the network scope can be determined in deployment preparation stage. With this method, nodes can only hold a mapping table of node′s hop-count and communication radii, thus they can decide the proper output-power settings according to their own hop-count.

We can set up a mapping table of nodes′ hop-count and output-power register settings of RF module, and the process setting up this mapping table is described as follows.

1) Using the formulas above, we can calculate the communication radii of the nodes in each output-power-grade, and then we can get a mapping table of hop-count and communication radii.

2) Obtain the corresponding settings of node′s hop-count and output power based on the mapping table of communication radii and output power, which can be estimated by formula (9) or generated by practical measurement.

3) Referring to the datasheet of RF chip, convert the corresponding relationship between hop-count and output power to that between nodes′ hop-count and register settings.

4) Write this mapping table into nodes′ configuration memory, *e.g.* a Flash memory, as configuration information.

This method is simple to implement, and nodes do not have to carry out complex calculation. Besides there would be little overhead involved. Since the configuration of output-power-grades is suited for certain specific network, recalculation may be needed when deploying another sensor network with different character.

3.4.2 Method 2. Dynamic configuration output-power-grades

This method is to implement (17) on nodes, so they can compute the proper communication radii after getting the input parameters when running in a network. The method is useful in the situation that the dimension of the network cannot be determined before deployment or may change after deployment. According to (17), R, R_0, R_1, and δ should be considered as input parameters, and a mapping table of nodes′ hop-count and output-power register settings is needed, which can be built in the same way described in Section 3.4.1.

This method provides enough flexibility for nodes to work in different networks or reset their output power at any time needed. The tradeoff is that nodes have to perform some calculation, and the input parameters for calculation should be diffused in network in topology constructing stage. Nevertheless, these overheads are negligible in long time running networks.

3.4.3 Topology construction

Whichever method above is employed, a topology construction stage is needed to set up output-power-grades in network. The process of topology construction is described as follows.

1) Sink node sends a setup packet using R_0 as its communication radius to start the process of topology building. The setup packet includes sink′s ID and the hop-count to the sink, which is zero at this time. If the second configuration method is adopted to make nodes decide their output power dynamically, the setup packet should also include the four parameters: R, R_0, R_1, and δ, which are used as input for calculation on nodes.

2) When a node uninitiated receives setup packets, it chooses one of the senders as its parent node. The algorithm for choosing a parent node is not restricted, but it should be noted that the algorithm would affect the value of δ.

3) After choosing a parent node, the node sets its hop-count as its parent node′s hop-count plus one. Meanwhile, it adjusts its output power according to the mapping table of hop-count and register settings in the configuration information.

4) The node makes up a new setup packet, which includes its ID and hop-count and sends the packet using the output power configured.

By flooding setup packets in the network, every node will be assigned a certain output-power-grade. In order to adapt the topology to node failure, etc, sink node can perform the topology rebuilding process periodically with a long interval.

4 Performance evaluation

In this section, we present the results of our simulation experiment, which are obtained from a packet-level simulator written in C++. In the simulation, 500 sensor nodes are distributed randomly in a rounded area, which has a radius of 200 m and has a sink node at the center. In our simulated data-gathering application, each node reports a data packet to the sink every 30 seconds. The simulation parameters are listed in Table 1.

We adopted a modified DEAR[7] protocol to set up the network topology in the simulation. DEAR is a routing protocol we proposed for wireless sensor networks that take into account both the hop-count to the sink and the minimum residual energy of that path and can obtain satisfying performance on consuming energy evenly and locally. In DEAR, it is possible that nodes send their data packets in the directions away from the sink to balance energy consumption among the neighbors, but it may influence our simulation experiments on data delay, so we modify the routing strategy such that a node′s next-hop candidate must have a less hop-count than the node. In the simulation, we will first compare DEAR with DEAR-PODA, which combines DEAR with PODA mechanism, on the performances of whole network energy equilibrium and network lifetime, and then analyze the influence of parameters δ on PODA.

Table 1 Simulation parameters

Network radius (R)		200 m
Number of nodes		500
Length of the data packet (L)		80 bytes
Time interval for reporting data		30 s
Initial energy for each node		0.5 J
Proportionality coefficient (α_i)		R_i^2/R_0^2
Energy model	E_{elec}	50 nJ/bit
	$d_{crossover}$	87 m
	$\varepsilon_{friis-amp}$	500 pJ/bit/m^2
	$\varepsilon_{two-ray-amp}$	0.065 pJ/bit/m^4

4.1 Energy balance

Fig. 3 shows a statistical histogram for lifetimes of nodes that run DEAR and DEAR-PODA, respectively with different distances from sink in networks. The scale of horizontal axis is the range of distances to sink node, *e.g.* (40, 80] denotes the statistics of nodes having the distance that is more than 40 meters and less than or equal to 80 meters from the sink, and the height of square columns denotes the average lifetime of nodes in a certain gap in distance. We performed the simulation three times for each different configuration, and picked up the nodes within the same distance gaps from all the results to calculate the average lifetimes.

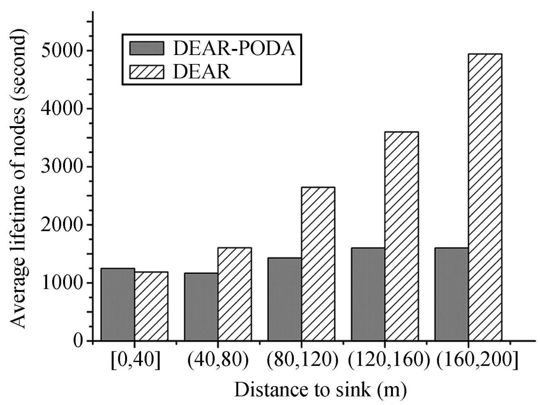
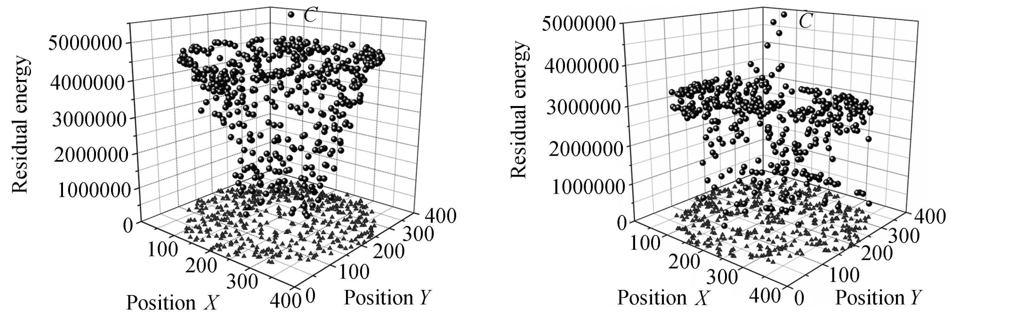


Fig. 3 Lifetime of the nodes with different distances to the sink

As shown in Fig. 3, in the network which adopts DEAR mechanism, the lifetimes of nodes near the sink are obviously shorter than those of nodes far from the sink. However, in the network that adopts DEAR-PODA, the differences of nodes′ lifetimes are much smaller. The main reason for the existence of these differences is that while estimating the communication radius of each power grade, we assume the nodes in the network are deployed uniformly, but nodes in our simulated networks are distributed randomly, which is more close to the real application situations. It is notable that the lifetimes of the nodes within the gap nearest to the sink are almost equal under the two mechanisms, which is caused by that these nodes have to forward all the data for the whole network and they use the same output power in each round of the simulation.

Fig. 4 is the snapshots of the nodes′ residual energy during the simulating processes of DEAR and DEAR-PODA. In the figures, axes X and Y decide the location of a node, while axis Z denotes the residual energy of the node at this time. Therefore, we can know the residual energy of the nodes from the position of the solid balls. The small triangles are the projections of the blue balls on the X-Y dimensions. Fig. 4 (a) was captured when about 20% of the nodes were dead in the network using DEAR. The highest node in each figure is the sink, which is marked a letter C besides it. Obviously, the nodes that are near the sink depleted their energy faster than the nodes far away from the sink. Fig. 4 (b) was captured at the time when about 20% of the nodes were dead in the network using

DEAR-PODA. Looking at the distribution of the red triangles in Fig. 4 (b), we can find out that the nodes disappeared evenly on the whole. We can see that the overall energy of the nodes in Fig. 4 (b) is lower than that in Fig. 4 (a) because the nodes far from the sink used higher output power to transmit data.



(a) DEAR (20% of nodes are dead, R=40m) (b) DEAR-PODA (20% of nodes are dead, R_0=40m, R_1=50m)

Fig. 4 Snapshots for the nodes′ residual energy during the simulating processes

4.2 Network lifetime and data delay

In this paper, the network lifetime is defined as the time that the first node dies[13,14]. Fig. 5 gives the comparison of network lifetimes between DEAR and DEAR-PODA varying with the initial radii used by 1-hop-grade nodes. It shows that DEAR-PODA can hardly postpone the death time of the nodes if the 1-hop-grade nodes in DEAR-PODA use the same initial radius as that used by all the nodes in DEAR. This is due to the fact that PODA mechanism aims to balance the energy consumption in nodes far and near to avoid wasting energy, but not to lighten the traffic burden of the 1-hop-grade nodes. However, PODA can shorten the data gathering delay by reduce the hop-count experienced by data packets, and we should note that the network lifetimes decrease along with the increase of the initial radii since using higher output power to transmit data makes the 1-hop-grade nodes die earlier. Therefore, the network, deployed with DEAR mechanism, has to adopt a large radius to achieve an equivalent delay performance than the network using DEAR-PODA with a small radius. Fig. 6 shows the comparison of network lifetimes in different requirements of delay performance, and shows that DEAR-PODA is preponderant obviously. Consequently, considering the data gathering delay, we can conclude that DEAR algorithm which combines with PODA can prolong the network lifetime.

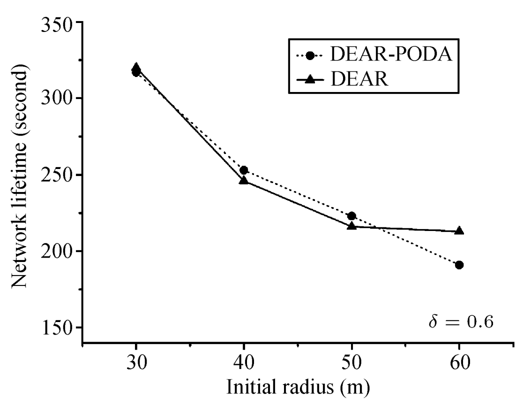


Fig. 5 Lifetime performance of DEAR-PODA

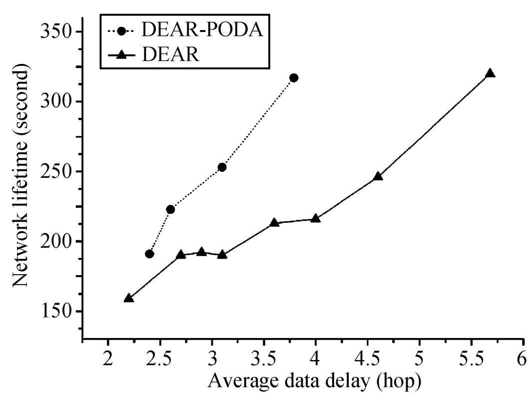


Fig. 6 Network lifetime vs. data delay

4.3 The influence of the parameter δ

In this section, we give some experiments results to illustrate that PODA can perform well with different δ. PODA can combine with various routing protocols where they would make δ different. Although distribution status of nodes and the link quality can affect δ to certain extent, the algorithm for choosing parents is dominant for a given network. Fig. 7 shows a part of network that is in topology construction stage. In Fig. 7, using a radius configured just now, Node A in the upper output-power-grade sends a setup packet to its neighbors, which include Nodes B and C. Using different algorithm to select a parent node, the nodes near the communication margin of Node A, like Node C, would have great disparity in the probability to choose Node A as the parent node. As a result, the width of the grade would be different, namely different δ.

Fig. 8 shows the influence on PODA′s performance when δ adopts five various values from 0.5 to 0.9, but R_0 and R_1 are fixed to 30 and 40 meters separately. We can conclude from the figure that the influence of δ on PODA′s performance on network lifetime is negligible. That is, PODA can obtain nice results when working with various parent-choosing algorithms.

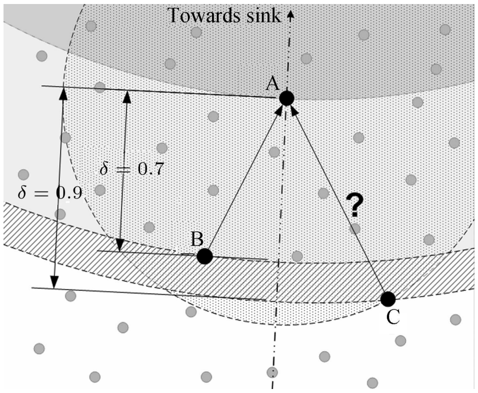


Fig. 7 The influence of the algorithm for choosing parents on the parameter δ

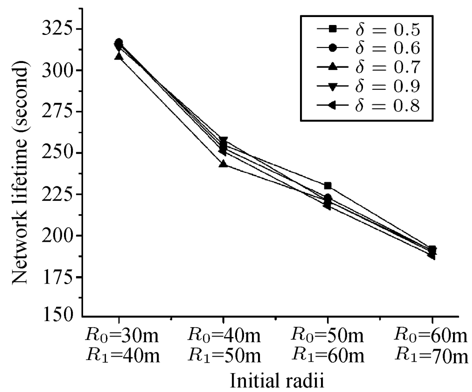


Fig. 8 The influence of the parameter δ on PODA

5 Discussion

In practice, the output power of RF chips is not continuously adjustable. For example, the sensor node we developed uses CC1000 as its RF module, and its output power ranges from -20 dBm to 10 dBm with a step of 1dB. It is probable that the nodes cannot tune their output power to match all the communication radii calculated in PODA exactly, so sub-optimal radii have to be chosen, and the performance may be affected. Another fact should be considered is that a node′s communication radius cannot be increased to arbitrary long distance, thus PODA is suitable for the sensor networks not very large. Nevertheless, a hierarchical structure that has multiple sink nodes can be used to deploy a large-scale network. In this situation, PODA mechanism can apply to each cluster to achieve even energy consumption in the whole network. Consequently, the capability to adjust the output power in sensor nodes should be taken into account when implementing PODA in actual circumstances.

6 Conclusion and future work

This paper presents PODA, an energy balanced data gathering mechanism, for data-gathering wireless sensor networks, in which all the nodes should send data to the sink periodically. In PODA, it makes full use of the function that the output power of the RF chips is dynamically adjustable to achieve energy balance in the whole network. This mechanism makes nodes near the sink adopt smaller communication radii, while nodes far from the sink use larger communication radii. In this scene, although nodes near the sink have to transmit more data, the energy consumed in transmitting a data packet is lower, and the situation in nodes far from sink is in reverse. Therefore, we can achieve even energy consumption in the entire network, improve energy efficiency and prolong the network lifetime notably. PODA is very easy to be implemented with little protocol overhead. Moreover, it can combine with many existing routing mechanisms, or run alone as a topology building mechanism.

For the future work, we will carry out evaluation aiming at the influence of PODA on packet loss rate in network because a more real physical layer model may affect the performance of routing protocols dramatically[15]. Besides, we will do more work on energy balancing problems when nodes are not distributed uniformly and when the sink node is not at the center of the network.

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