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Energy-efficient multipath routing in wireless sensor network considering wireless interference

Shujiang LI [1], Xin MA [2], Xiangdong WANG [1], Minghao TAN [1]

1.School of Information Science and Engineering, Shenyang University of Technology, Shenyang Liaoning 110870, China;

2.Qinhuangdao Audio-Visual Machinery Research Institute, Qinhuangdao Hebei 066000, China

Abstract: Due to the energy and resource constraints of a wireless sensor node in a wireless sensor network (WSN), design of energy-efficient multipath routing protocols is a crucial concern for WSN applications. To provide high-quality monitoring information, many WSN applications require high-rate data transmission. Multipath routing protocols are often used to increase the network transmission rate and throughput. Although large-scale WSN can be supported by high bandwidth backbone network, the WSN remains the bottleneck due to resource constraints of wireless sensors and the effects of wireless interference. In this paper, we propose a multipath energy-efficient routing protocol for WSN that considers wireless interference. In the proposed routing protocol, nodes in the interference zone of the discovered path are marked and not allowed to take part in the subsequent routing process. In this way, the quality of wireless communication is improved because the effects of wireless interference can be reduced as much as possible. The network load is distributed on multiple paths instead of concentrating on only one path, and node energy cost is more balanced for the entire wireless network. The routing protocol is simulated in NS2 software. Simulation result shows that the proposed routing protocol achieves lower energy cost and longer network lifetime than that in the literature.

Keywords: Energy efficiency; Wireless sensor network; Multipath routing; Wireless interference

1 Introduction

Wireless sensor network (WSN) is a promising new technology that can be applied to many fields such as emergency rescue, biological detection, environment measurement and real-time monitoring [1]. A WSN consists of many tiny low-power wireless sensors and does not have fixed network infrastructure. WSNs are usually mission-driven and application-specific, and must operate under a set of unique constraints and requirements. The nodes in WSNs are powered by batteries and usually cannot be recharged during operation. Because the energy of wireless sensors is limited, energy efficiency is a critical factor in routing protocol design.

There have been some research studies in the literature on multipath routing protocols to increase energy efficiency and prolong network lifetime. Among many techniques reported to tackle this energy resource constraint problem, distributed source coding (DSC) is a new technology that can achieve high energy efficiency and extend the lifetime of WSN applications. A multirate routing scheme based on cross-layer optimization between routing and DSC in WSN is proposed in [2]. The transmission rate assignment is based on remaining energy, and a joint rate and energy scheduling mechanism is proposed to meet energy constraints in the networks adopting DSC. The optimization scheme can achieve longer sensor network lifetime [2].

Statistical energy-efficient multipath routing protocol (SEEMRP) is proposed in [3]. The protocol tries to achieve a balance between energy efficiency and reliability by tagging the urgency of the information. The protocol introduces the concept of criticality factor of a message that determines the urgency of delivering the message. As a result, all packets are delivered to the destinations according to the criticality that the network administrator requires to associate with them. Therefore, the packet being delivered with a lower criticality factor may take a different, longer path to its destination. This spreads the energy cost over a larger part of the network instead of putting the entire load on the shortest path. Also, the protocol saves the energy of the shortest path for more critical messages should the need arise in future. The protocol may be able to allow a great number of nodes to participate in routing of packets, yet it may also significantly increase the network energy cost when the packets are routed on different, much longer paths to destination. However, the energy efficiency indexes such as energy cost are not compared in the simulation results of the paper.

Interference-aware and confidentiality-enhanced multipath routing is proposed in [4] that takes into account effects of interference and shows that using directional radio propagation properly can provide reduced energy cost at a reasonable level. Unfortunately, directional antennas require special hardware support, making them impractical for energy and resource-constrained wireless sensor network.

On-demand multipath routing algorithm based on probability (MRAP) is proposed in [5]. According to MRAP, different data generated at the same sensor node may take different transmission paths. The probability of this depends on various parameters, such as the hop distance from normal node to sink or normal node remaining energy. In this way, the energy usage balance among multipaths is achieved by MRAP.

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Maximal-minimal nodal residual energy multipath routing protocol (MMRE-AOMDV) is proposed for mobile ad hoc networks, which extends the multipath ad hoc on-demand distance vector (AOMDV) routing protocol [6]. The protocol automatically reselects a new route with greater residual energy to forward data packets. The MMRE-AOMDV protocol can balance battery power utilization and prolong the entire network's lifetime.

In situations when multimedia sensing data need to be transmitted in real time, there are strict demands for service quality and energy efficiency. Real-time and energy aware routing (REAR) is proposed that builds multiple paths by metadata instead of essential sensing data to save energy and to provide enough bandwidth [7].

One of the problems of directed diffusion is that it mostly leads to selecting the shortest path between destination and source nodes. This will lead to premature death of nodes on the path. To overcome this problem, greedy multipath routing algorithm (GMPR) using a greedy heuristic method is proposed in [8]. By using positive reinforcement packet and considering node remaining energy, efficient load balancing and energy aware routing are implemented.

In [9], multipath routing protocol for network lifetime maximization (MRNLM) is proposed for wireless ad-hoc networks. MRNLM sets energy threshold to optimize the forwarding mechanism and builds an energy cost function as the criterion for multiple path selection and energy balance.

In real situations, nodes in wireless sensor network may have different initial energy level at the deployment stage. Hence, the heterogeneous energy routing protocol (HER) based on ant colony optimization algorithm is proposed for wireless sensor network [10].

Some researchers propose cluster-based multipath routing protocols to exploit the redundancy and geometrical properties of the wireless sensor network. Clustered and leveled disjoint multipath routing algorithm for wireless sensor networks is proposed that improves the performance of directional flooding algorithm by processing and structuring of the network. The average energy consumed by each node and the total number of transmitted packets for routing are reduced [11].

Cluster-based load balancing multipath routing protocol (CLBM) is proposed in [12]. Space and time localization is used in the process of cluster head reselecting according to residual energy and the distance between the node and the event center area. Network lifetime is extended by achieving the load balance of networks.

Energy-aware multipath routing algorithm (EMRA) in wireless sensor networks is proposed that uses localized multipath algorithm to discover node disjoint paths between the source and the destination nodes. The load balancing algorithm is used to distribute the traffic over the multiple paths discovered and takes network reliability into consideration [13].

However, when there are simultaneous transmissions along multiple paths within physical proximity of each other, there is route coupling that is caused by wireless interference [14]. The above-mentioned routing protocols have not considered the effect of wireless interference between multiple paths.

Interference-minimized multipath routing protocol with congestion control in wireless sensor network (I2MRCC) is proposed in [15]. A technique is proposed to evaluate the quality of a path set for multipath load balancing, considering the effects of wireless interferences. I2MRCC protocol increases throughput by discovering zone-disjoint paths for load balancing, requiring minimal localization support. The congestion control scheme is also proposed in [15] that further increases throughput by loading the paths for load balancing at the highest possible rate supportable. The problem is I2MRCC protocol does not take the remaining energy of nodes into consideration. As a result, this will cause premature death of some network nodes and reduce the network lifetime.

In fact, most multipath routing protocols only use one or two paths for data transmission because more paths result in higher routing cost and wireless interference, hence negligible performance benefits [15∼17]. In this paper, we propose a multipath energy-efficient routing protocol for WSN that considers wireless interference between two paths. The proposed routing protocol searches for the shortest paths with the least interference, and nodes in the interference zone of the discovered first path are marked and not allowed to take part in subsequent routing process. In this way, the quality of wireless communication is improved because the effects of wireless interference can be reduced as much as possible. The network load is distributed on two paths instead of concentrating on only one path. In this way, more nodes take part in transmitting data packets, and node energy cost is more balanced for the entire wireless network.

The organization of this paper is given as follows: Section 2 gives network models and problem description. Section 3 describes the proposed energy-efficient multipath routing protocol considering wireless interference for wireless sensor network. Section 4 describes the simulation experiments followed by results and discussions. Section 5 gives the conclusions.

2 Network models and problem description

A large number of low-power normal sensor nodes and source nodes are randomly deployed in the monitoring region. Every node has its unique ID and knows its location. A number of high-energy nodes are arranged around the destination node. The energy of the source node is not limited. After capturing the required information, the source node establishes a path between the destination node and itself by the normal nodes and sends data to the destination node. The transmission range T and the interference range I are uniform for all nodes [15]. The interference range is equal to the transmission range.

The wireless sensor network can be expressed by a connectivity graph $G = (V, E, \Omega)$, where V is the set of N nodes, $V = R \cup S \cup D$, R is the set of normal nodes, S is the set of source nodes, and D is the destination node. M is the number of normal nodes. E is the set of all links connecting the nodes in V, and every link represents a communication link between two adjacent nodes. Ω is the set of weights of link set E. $l_{i,j} \in E$ is the link between node i and j [15]. It is assumed that there is only one link between two adjacent nodes. For any two nodes $n_i \in V$, $n_j \in V$, $l_{i,j} \in E$, $\omega_{i,j}$ is defined as the value of data transmission cost on $l_{i,j}$.

Consider the communication between a source node $n_{\mathrm{s}} \in$

V and a destination node $n_{\mathrm{d}} \in V$. A loop-free path k from n_{s} to n_{d} comprises of the source node n_{s}, the destination node n_{d}, and a set of normal nodes represented by $R = \{n_k^i\}$, where $1 \leqslant i \leqslant |R_k|$ and $\{n_k^i\}$ represents the ith normal node along path k. $|R_k|$ represents the total number of normal nodes along path k [15]. The goal of the routing protocol is to achieve the smallest network energy cost and balance the node energy cost in the network.

3 Energy-efficient multipath routing considering wireless interference

The energy cost is determined by the data packet size and radius of the transmission, and the energy cost model of the receiver module and the transmitter module is based on the first-order radio model. The energy cost for sending k-bit packet to a node with distance d and receiving k-bit packet is shown below:

$$\begin{aligned} E_{\mathrm{Tx}}(k,d) &= E_{\mathrm{Tx-elec}}(k) + E_{\mathrm{Tx-amp}}(k,d) \\ &= E_{\mathrm{elec}} \times k + \varepsilon_{\mathrm{amp}} \times k \times d^n, \qquad (1) \end{aligned}$$

$$E_{\mathrm{Rx}}(k) = E_{\mathrm{Rx-elec}}(k) = E_{\mathrm{elec}} \times k. \qquad (2)$$

$E_{\mathrm{Tx-elec}}$ is the energy cost of the transmitter, $E_{\mathrm{Tx-amp}}$ is the energy cost of the amplifiers and $E_{\mathrm{Rx-elec}}$ is the energy cost of the receiver.

The operation of the routing protocol in the wireless sensor network is generally divided into the stages of routing request (RREQ), routing reply (RREP), second path discovery, and data transfer.

1) The source node initiates the RREQ stage in order to find the first path from the source node to the destination node.

2) In the RREP stage, the interference zone of nodes on the first path is marked, and the source node finds the first path from the source node to the destination node.

3) In the second path discovery stage, nodes interfered by nodes in the first path are not included in the second path routing. In this way, the source node establishes the second path from the source node to the destination node.

4) When routing discovery is completed, the source node sends data using the two paths at the same time, and other nodes enter the sleep state until the start of the next task.

3.1 Routing request of the first path

The source node is monitoring a certain area of the region. After collecting the data, the source node sets the transmit radius d and transmits the data.

Nodes with omnidirectional antennas send RREQ data packet to surrounding nodes by flooding to find the destination node. RREQ packet includes node ID, remaining energy of node and message ID of RREQ.

Any node that receives RREQ sent by other nodes checks the message ID and searches the task table to ensure whether this RREQ is first received.

If the RREQ packet is received for the first time, the node sets reception time T and starts the timer. T is computed by

$$T = \frac{k}{\mathrm{Energy}_{\mathrm{node}}}, \qquad (3)$$

where k is a constant, and $\mathrm{Energy}_{\mathrm{node}}$ is the node remaining energy.

Nodes process the RREQ packet after set reception time T and record the remaining energy, ID and message ID of the node sending this RREQ in the recv_node list. The remaining energy and ID in this RREQ packet are replaced by this receiver node's remaining energy and ID. When the reception time arrives, RREQ packet is sent to the neighbors of this node.

If the RREQ packet is received after the first time, the node checks the arrival of the timer setting for this message ID. If the timer setting time T has not arrived, then the node will record the RREQ packet's remaining energy, node ID and other information under the current message ID number in the recv_node table. If the timer has passed the setting time T, the node drops the RREQ packet.

RREQ packets are sent to the destination node by flooding using this method. After the destination node receives the RREQ packet, it will examine the message ID number. If the RREQ packet is received for the first time, the destination node sets the timer reception time T and starts timing. At the same time, the destination node records in the recv_node table the node remaining energy and node ID and other information of the same RREQ the destination node received.

If the destination node receives the RREQ packet after the first time, the destination node checks if the reception timer time T has arrived. If it is past the reception time, the destination node discards the received RREQ packets. If the reception timer time T has not arrived, the node will record the node remaining energy, node ID and other information in the packets under corresponding message ID in the list. The path discovery process is shown in Fig. 1.

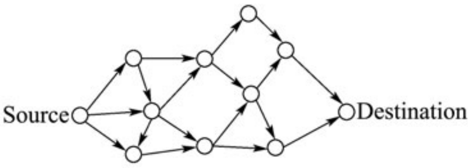


Fig. 1 Source node path discovery.

When the time T of the destination node timer arrives, the destination node searches recv_node table under the message ID how many nodes have sent RREQ packets, and the number of nodes is recorded as M. According to the following equation, the weight of including to the route the node under the message ID in recv_node table is calculated by

$$P_i = \frac{E_i}{\sum\limits_{j=1}^{M} E_j}, \qquad (4)$$

where P_i is the weight of node i in recv_node table, E_i is the remaining energy of node i in recv_node table, and M is the number of nodes having same message ID. According to $P = \{P_1, P_2, P_3, \cdots, P_M\}$, the destination node chooses the node with $P_{\max}$ to join the path.

3.2 Routing reply of the first path

After the routing node is selected for the path, the destination node sets the transmit radius and sends the RREP packet. The RREP packet includes the following information: receiver node ID number, sender node ID number, message ID number, RREP signs, etc. The packet format of the RREP is shown in Fig. 2.

RREP	RecvID	SelfID	MessageID

Fig. 2 Packet format of RREP.

Any node, after receiving the RREP packet, checks the data packet type. If it is the RREP packet, it checks the receiver node ID number to determine whether it is the receiver node. When the receiver node ID in the RREP is itself, the node checks and records the message ID number, checks node ID that sends the RREP packet, and sets this sender node ID to the next hop node. Node flag is set, calculates the number of nodes under the message ID in recv_node table and sets it as M. The weight of the node to be the routing node is calculated according to equation (4), and the next hop nodes are selected according to the weight. Then, the transmit radius is set, and the RREP packet is transmitted. The first path is established until the source node receives the RREP packets and done the appropriate processing. This process is shown in Fig. 3.

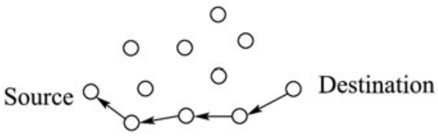


Fig. 3 Route establishing.

The network lifetime of the established routing is decided by nodes with the least energy in the routing path, as shown by:

$$T_{\text{route}} = \frac{E_{\min}}{T(i) + R(i)}, \tag{5}$$

where $E_{\min}$ is the remaining energy of the least energy node in the established routing. $T(i)$ and $R(i)$ are the node energy cost of transmitting and receiving. After the transmission distance and transmission data are determined, the node transmitting and receiving energy cost is determined. When $T(i) + R(i)$ is a fixed value, $E_{\min}$ is proportional to T_{route}. This means the path survival time is proportional to the remaining energy of the lowest energy node.

The relation between the routing survival time and the network life time is expressed as $T_{\text{net}} \propto \min T_{\text{rou}}$.

This means to maximize network life time, the shortest route running time should be minimized. Hence, selecting the nodes with most remaining energy in routing can maximize the network life time.

We assume that the interference radius is equal to the communication radius, and a node can only influence the nodes in its communication radius, as shown in Fig. 4.

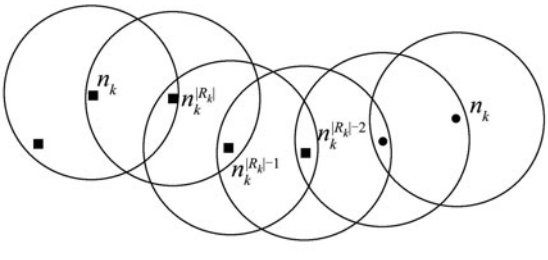


Fig. 4 Route establishing.

When the destination node has selected RREP packet's receving node, the node shall be included as the routing node. As shown in Fig. 4, $n_k^{|R_k|}$ is selected by the destination node as a routing node and to send an RREP packet. After receiving the RREP packet and detecting in this section of the packet the receiver node is itself, $n_k^{|R_k|}$ checks if its remaining energy is lower than the minimum energy threshold.

When the node remaining energy is below this minimum threshold, $n_k^{|R_k|}$ considers itself as a failure node and sends invalid message to inform the destination node that it does not participate in the establishment of routing. Destination node deletes its relevant information of $n_k^{|R_k|}$ under the message ID in the recv_node table after it receives invalid message from $n_k^{|R_k|}$. After it considers itself a failure node, $n_k^{|R_k|}$ no longer participates in the operation of the network and changes to sleep state.

When the remaining energy of $n_k^{|R_k|}$ is not below the minimum threshold value, $n_k^{|R_k|}$ sends confirmation message to the destination node to ensure the signal is received. If the destination node does not receive any signal from $n_k^{|R_k|}$ within a period, it will consider $n_k^{|R_k|}$ to be not available and will rechoose a routing node.

$n_k^{|R_k|}$ will set the destination node ID as the next hop node ID after sending a confirmation message to the destination node. Then, interference flag is set, and the RREP packet is processed, replacing node ID in the RREP packet with its ID and changing the receiver node ID. As shown in Fig. 4, $n_k^{|R_k|}$ selects $n_k^{|R_k|-1}$ as a routing node. Then $n_k^{|R_k|}$ will forward RREP message after setting the transmit radius.

After $n_k^{|R_k|-1}$ receives an RREP packet, it checks if the packet receiver node is set for itself. After $n_k^{|R_k|-1}$ confirms packet receiver node is set for itself, it sends confirmation message to the $n_k^{|R_k|}$ and sets interference flag. At the same time, $n_k^{|R_k|-1}$ completes the processing of the RREP packet and selects next-hop routing $n_k^{|R_k|-2}$, and forwards RREP packets.

When the RREP packet is forwarded to the source node, the source node checks the node ID in the RREP and records it in the task list table and sends confirmation message packets to the node. The nodes interfered by $n_k^{|R_k|}$ cannot be marked as an interfering node. The nodes in the area of the source node communication range can not be marked as an interference node.

As the node transmitting antenna is omnidirectional, nodes can receive the RREP within a communication radius of the routing node. After receiving the RREP packet, confirming the receiver ID is not itself, the node will not modify the interference flag. If the ID is itself, it will change the flag and will no longer participate in routing establishment later.

3.3 Establishing the subsequent paths

The method of establishing the subsequent path is similar to establishing the first path, but nodes with the interference flag set do not participate in the process of establishing the path.

The source node sends data to the destination node through these established paths when the routing is completed. The nonrouting nodes enter the sleep state until the next task begins and once again participate in the next route discovering.

The source node sets the amount of transmitted data each time. Every time the source node sends a data packet, it sets the same time interval and then sends the next packet.

4 Simulation experiments

4.1 Simulation environment

In the simulations, we assume two paths are discovered only in the routing protocol. In order to validate the performance of the proposed protocol, simulation experiments are conducted using the software NS2 which is based on a discrete event on the LINUX operating system. Node distribution is shown in Fig. 5. 200 sensor nodes are randomly arranged on a square area with a side length of 200 m. The communication radius of each node is set to 20 m, and the energy of each normal node is set to 2 J. The number of destination node is set to 1. The number of source nodes is set to 4. The MAC layer follows the IEEE 802.11 standard. The bandwidth of the channel is set to 1M byte/s. The energy cost of the receiver and the transmitter to deal with 1bit data is set to 50 nJ/bit. The number of bits sending by source is determined randomly by the source. The energy cost of transmission and reception is computed according to equations (1) and (2). The simulation time is set to 2000 s.

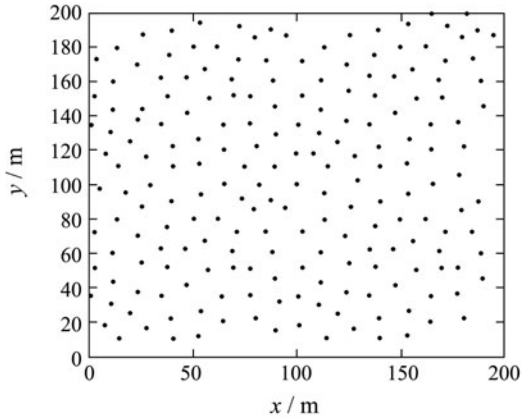


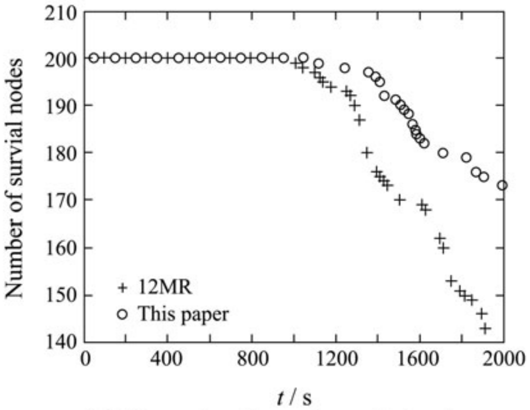
Fig. 5 Route establishing.

4.2 Simulation result and analysis

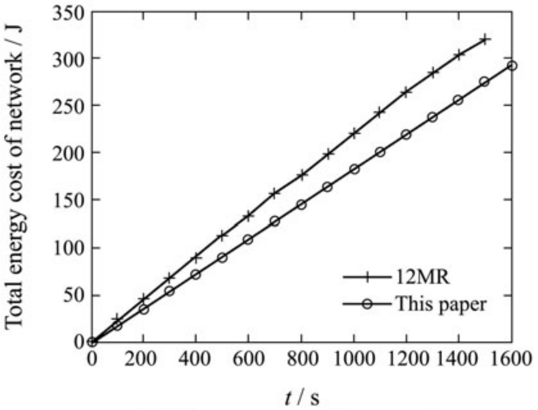
The indexes of this simulation are chosen as the number of network's survival nodes, the energy cost of the network and the routing energy cost. The total energy cost means the total energy consumed by all the nodes during the network lifetime; the routing energy cost means energy consumed for finding a route.

Fig. 6 shows the node survival time in the network, the total energy cost of the network when the network is running and the routing energy cost, respectively, when k is set 100. As is visible from Fig. 6 (a), the proposed routing protocol has more survival nodes than that with I2MR in the network. The total energy cost with the proposed routing protocol is lower than the I2MR. As is visible from Fig. 6 (c), the routing energy cost with the proposed routing protocol is lower than the I2MR.

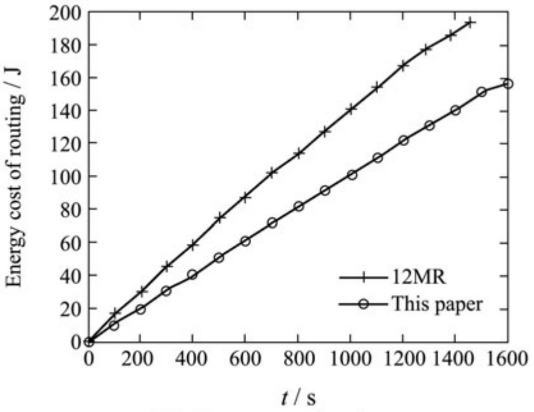
These figures show the result of comparing the I2MR and the proposed routing protocol of this paper. It is shown that survival time of nodes in the network of the proposed routing protocol is longer than that of I2MR; the first node death using the proposed routing protocol is later than that of I2MR. The network energy cost with the proposed routing protocol is less than I2MR. The routing energy cost is lower than that with I2MR. But the impact of different k-values on the proposed routing protocol on total energy cost and the energy cost of routing is not obvious. It only affects the death time of nodes.



(a) The number of networks survival nodes



(b) The energy cost of the network



(c) Energy cost of routing

Fig. 6 The performance comparison between this paper and I2MR ($k = 100$).

5 Conclusions

Energy-efficient routing is a crucial design concern for WSN applications due to energy and resource constraints of the wireless sensor node in WSN. This paper considers effects of wireless interferences and proposes a multipath energy-efficient routing protocol for wireless sensor network. Nodes in the interference zone of the discovered path are marked and not allowed to take part in subsequent routing process. In this way, the effects of wireless interferences can be reduced as much as possible. The network load is distributed on multiple paths instead of concentrating on only one path. In this way, more nodes take part in transmitting data packets, and node energy cost is more balanced for the entire wireless network. The simulation result in NS2 software shows that the proposed routing protocol achieves lower energy cost and longer network lifetime than that in the literature.

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Shujiang LI was born in 1966. He received his Ph.D. from the Northeastern University, China, in 1998. He was a research fellow with Nanyang Technological University, Singapore, from February 2001 to July 2004. Currently, he is a professor at the Shenyang University of Technology. His research interests include intelligence control and complex network control and applications. E-mail: lisj2005@126.com.

Xin MA was born in 1984. He received his M.S. degree from Shenyang University of Technology. His research interest is wireless sensor networks.

Xiangdong WANG was born in 1959. He received his Ph.D. from the Northeastern University, China, in 1998. He is a professor at the Shenyang University of Technology. His research interests include complex system control and swarm intelligence algorithms.

Minghao TAN was born in 1979. He received his Ph.D. from the Northeastern University, China, in 2004. He is an associate professor at the Shenyang University of Technology. His research interests include intelligence control and robust control.