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Research Article

An Efficient Data Collection Protocol Based on Multihop Routing and Single-Node Cooperation in Wireless Sensor Networks

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Considering the constrained resource and energy in wireless sensor networks, an efficient data collection protocol named ESCDD which adopts the multihop routing technology and the single-node selection cooperative communication is proposed to make the communication protocol more simple and easy to realize for the large-scale multihop wireless sensor networks. ESCDD uses the greedy strategy and the control information based on RTS/CTS to select forwarding nodes. Then, the hops in the multihop data transmission are reduced. Based on the power control in physical layer and the control frame called CoTS in MAC layer, ESCDD chooses a single cooperative node to perform cooperative transmission. The receiving node adopts maximal ratio combining (MRC) to recover original data. The energy consumption per hop is reduced. Furthermore, the total energy consumption in data collection process is shared by more nodes and the network lifetime is extended. Compared with GeRaF, EERNFS, and REEFG protocol, the simulation results show that ESCDD can effectively reduce the average delay of multihop data transmission, improve the successful delivery rate of data packets, significantly save the energy consumption of network nodes, and make the energy consumption more balanced.

1. Introduction

Multihop routing and cooperative multiple-input multiple-output (MIMO) have become the key technology to improve the energy efficiency of wireless sensor networks (WSNs) [1, 2]. The efficient multihop routing protocol is an important method to increase the WSNs energy efficiency. Because of high efficiency, low energy consumption, and good scalability, the multihop routing protocol based on geographic information has been widely applied in WSNs [3, 4]. Therefore, the multihop routing based on geographic information is mainly studied in this paper.

In order to minimize energy consumption of multihop wireless sensor networks, the present study work is to reduce the control overhead and the numbers of hops to improve the energy efficiency of routing. In addition, the performance of multihop data collection depends on the relay selection rules and the environment state. Because of the inherent space diversity gain feature, cooperative MIMO, a virtual multiple antenna technology, can significantly reduce the transmitting power of nodes in the fixed network throughput by using the distributed space-time coding (DSTC). Thus, the energy consumption of network nodes is saved and the network lifetime is prolonged. Cooperative MIMO is a feasible scheme to improve the energy efficiency of wireless sensor networks. Because of multiple nodes and distributed characteristic in wireless sensor networks, cooperative MIMO is suitable for application. Therefore, the application of cooperative MIMO in wireless sensor networks has attracted more and more attention from the academic circles [5–7]. In wireless sensor networks, cooperative MIMO, a combination of cooperative communication and MIMO, is regarded as one key technology to improve the robustness of transmission link and reduce the energy consumption.

Considering the constrained resource and energy in wireless sensor networks, an efficient data collection protocol named ESCDD which adopts the multihop routing and cooperative MIMO is proposed to make the data collection more simple and easy to realize for the large-scale multihop WSNs. The features of ESCDD protocol are as follows. An energy-saving node sleeping control strategy based on topology control is employed to control the node connectivity and reduce the idle listening. Similar to the GeRaF protocol, forwarding nodes are selected according to geographic information to minimize hops for data transmission on the basis of literature [8]. Source node chooses only one cooperative node every hop by using power control to perform cooperative MIMO, which is effective in reducing energy consumption of each hop data transmission and extending the lifetime of the WSNs. Otherwise, ESCDD does not require beamforming and DSTC, which make it easy to implement.

2. Related Work

There is much research on the high-efficient data collection protocol of multihop wireless sensor networks [1, 3, 6, 9, 10], which relates to every layer of communication protocol stack. Because this paper focuses on the physical, MAC, and routing layer, the work related to this paper is discussed in detail.

GeRaF proposed in [3, 4] is a greedy multihop implicit routing protocol based on geographic information. The data transmission of every hop is based on single-input single-output (SISO). GeRaF is characterized by dynamics, distributed characteristics, briefness, and easiness to implement. However, the performance of GeRaF is affected by the density of network because of the less information between node and its neighbor nodes. Meanwhile, the cooperative MIMO is not considered in the data transmission. The greedy geographic routing algorithm based on the two-hop neighbor information is used to further improve the routing efficiency [11]. But it increases the complexity because of choosing the next hop node using the two-hop neighbor information.

It can effectively increase the capacity of communication channel or significantly reduce the energy consumption of data transmission by applying the cooperative MIMO technology to WSNs. Cui et al. have proposed a cooperative MIMO communication model based on Alamouti coding in the single-hop WSNs [12]. The energy consumption and data transmission delay are analyzed. The total energy consumption of cooperative MIMO technology transmitting one bit is discussed at the same bit error rate (BER). The simulation result indicates that the energy consumption ratio of SISO system to cooperative MIMO system is gradually increased with the increase of transmission distance. Therefore, in view of energy efficiency and transmitting delay, cooperative MIMO is more suitable for long distance data transmission than SISO. On the basis of [12], the cooperative MIMO under the influence of parameters which are transmission distance, size of constellation modulation in node physical layer, path attenuation index, and control overhead caused by increasing the training sequence has been analyzed in [6]. It further proves that the communication mode of cooperative MIMO can save more energy than SISO technology by choosing appropriate parameters. At the same time, the cooperative MIMO can significantly reduce the transmission delay. Based on the LEACH clustering protocol in WSNs, a distributed virtual MIMO multihop cooperative communication protocol with STBC encoding has been proposed in [13]. It adopts the cross-layer method with the combination of cooperative MIMO, multihop routing, and hop-by-hop data recovery mechanism. In order to further reduce the control overhead and the protocol complexity, a method implementing the communication between remote cluster heads nodes through MISO technology has been mentioned in [14]. A plurality of transmitting nodes at the sending end is used to achieve cooperative transmission, but, at the receiving end, there is only one node for receiving. Same as [6], the cooperative transmission node also adopts distributed STBC encoding. An Energy Balance Routing Algorithm has been introduced into the cooperative MIMO communication structure in [15]. It is effective in reducing the energy consumption and therefore prolonging the network lifetime. Chung et al. have given a comparison of energy consumption between cooperative MIMO and the traditional multihop data transmission mode in WSNs [16]. The simulation result shows that the energy efficiency of these two data transmission modes depends on the density of network nodes, the state of the wireless channel, and the communication distance. When the parameters are limited in certain range, the cooperative MIMO is more efficient than the traditional multihop transmission mode. However, this cooperative MIMO here is the single-hop mode. The multihop cooperative MIMO is still not analyzed. By simplifying the complexity of cooperative MIMO technology application in WSNs, a communication mode of WSNs using single-node cooperation mechanism has been proposed in [8]. Compared with the traditional multiple nodes cooperation mechanism, single-node cooperation mechanism does not require the cooperative beamforming or the distributed space-time encoding and the cooperative node is selected through the dynamic election in the process of data transmission. Single-node cooperation mechanism is easy to realize and the control overhead is less. However, the study work in [8] mainly adopts the power control technology to analyze the method of choosing the cooperative node and the application in the large-scale multihop WSNs is not considered.

3. Network Mode

As shown in Figure 1, the nodes of the large-scale WSNs are randomly placed in a square area $L \times L$ according to Poisson process with intensity ρ. The sink node is deployed at a fixed position (x, y) on one side, closing to the users. The characteristic properties of the network nodes are as follows.

(1) After deployment, the nodes are not mobile. In addition to the sink node, the capacity of any network node is similar and the status is equal.

(2) Every network node stores the location information of the sink node. It can determine its position according to the position service module.

(3) Any network node has two wireless communication modules. One is used to transfer data and control

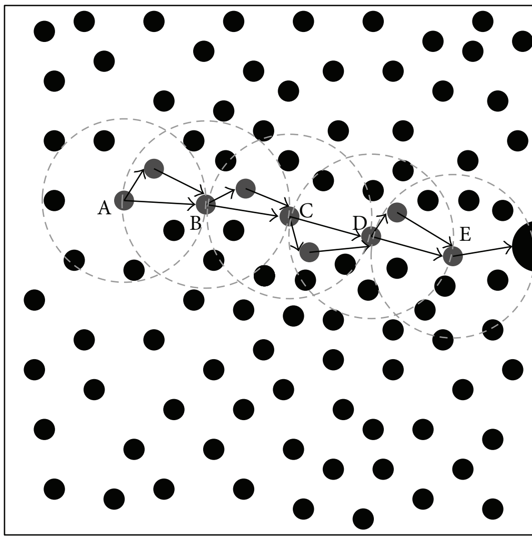

FIGURE 1: Node distribution model of WSNs.

information. The transmit power is adjustable in [0, P_{max}]. It is called the main module and the relative wireless communication channel is called the main channel. The other only sends and listens to busy signal. The transmit power is fixed P_{max}. This module is called wake-up module and the relative wireless channel is called wake-up channel. The maximum communication coverage is far less than the equivalent radius of network coverage area. Therefore, the node sends data information to the sink node through multihop mode.

(4) The channel of nodes obeys the quasistatic flat Rayleigh fading and it remains unchanged in a burst data transmission period. The channel is independent in every transmission. The channel gain between any two nodes is a Gaussian random variable in which mean value is zero and variance value is Ω_{ij}. The noise of channel is an additive white Gaussian noise whose mean value is zero and unilateral power spectral density value is N_0.

The first attribute of WSNs is the typical settings of general networks. The second attribute shows the position information of nodes used by the proposed ESCDD protocol. The third attribute is mainly considered for the network application and energy saving. The fourth attribute is mainly considered for the harsh environment in which the network is usually used. Figure 1 shows the basic process of data transmission from the source node A to the sink node using ESCDD protocol.

4. Energy-Saving Measure Based on Topology Control

Because of the high redundancy and the burstiness of large-scale WSNs, the idle listening and crosstalk of mass network nodes are generated. The network energy is greatly wasted. In

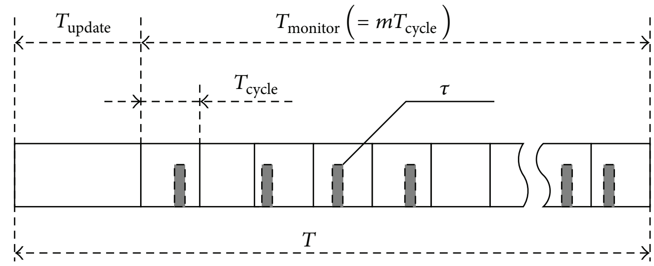

FIGURE 2: Time allocation of one period.

ESCDD protocol, a distributed energy-saving strategy is used to keep the network connectivity and reduce idle listening of nodes. The implementation process is as follows. The time is divided into a number of periods, and a period is denoted by T. Each period consists of two phases. The node synchronization and the neighbor information can be achieved in the first phase denoted by T_{update}. The node monitoring work is implemented in the second phase denoted by $T_{monitor}$. Then, $T_{monitor}$ is further divided into a number of time slots T_{cycle}; namely, $T_{monitor} = mT_{cycle}$, wherein m is a positive integer which is much greater than 1. One T_{cycle} is a listening/sleeping cycle. The time allocation is shown in Figure 2. In a T_{cycle}, the nodes actively listen for time τ according to a probability p_i $(0 < p_i \leq 1)$ on wake-up channel. The calculation formula of p_i can be expressed as (1). Consider

$$p_i = \left(\frac{CD_E}{CD_i}\right)(1 + \alpha + \beta), \quad (0 < p_i \leq 1), \tag{1}$$

where CD_i is the connectivity of node i, namely, the number of neighbor nodes. CD_E is the desired node connectivity. It can be determined according to the application requirements. α is the adjustment coefficient to balance the distance between nodes. β is the adjustment coefficient to balance the energy consumption of nodes. α and β can be, respectively, calculated in (2) as follows:

$$\begin{aligned} \alpha &= \frac{\left(\sum_{j=1}^{CD_i} d_{ij}/CD_i - d_0\right)}{\left(\sum_{j=1}^{CD_i} d_{ij}/CD_i\right)}, \\ \beta &= \frac{\left(E_i - \sum_{j=1}^{CD_i} E_j/CD_i\right)}{\left(\sum_{j=1}^{CD_i} E_j/CD_i\right)}, \end{aligned} \tag{2}$$

where d_{ij} is the length of distance between node i and node j. d_0 is the average distance between a node and its neighbor nodes. In the case of the uniform distribution of network nodes, d_0 is $2R/3$. Therefore, here d_0 is configured as $2R/3$. R is the radius of the maximum communication region covered by nodes at the maximum transmission power P_{max}. E_i is the residual energy of node i. The wake-up probability p_i of local node i is mainly determined by the number CD_i of neighbor nodes. The larger CD_i is the fewer nodes are waked up. Thence, the energy consumption is reduced.

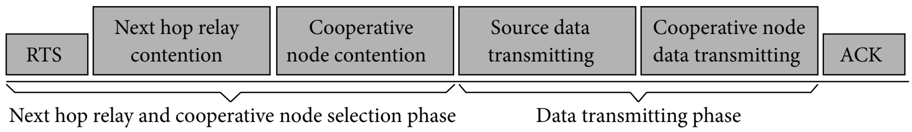

Figure 3: The transfer process of burst communication for one-hop data in ESCDD protocol.

5. ESCDD Protocol

For the purpose of later research, we give some descriptions beforehand, shown as follows.

Definition 1 (neighbor node). For an arbitrary node i, its neighbor nodes are defined as follows:

$$N(i) = \{j \in N \mid d(i, j) \leq R,\ j \neq i\}, \tag{3}$$

where N is all of nodes in the network, $d(i, j)$ is the distance between the node i and node j, and R is the communication range when nodes transmit information with the maximum transmit power $P_{\max}$.

Definition 2 (forwarding candidate node). For an arbitrary node i, if the Euclidean distance between sink node and node i is d_i, the forwarding candidate nodes are expressed as follows:

$$\mathrm{FC}(i) = \{j \in N(i) \mid d_i - d_j \geq 0,\ j \neq i\}. \tag{4}$$

Definition 3 (cooperative candidate node). For an arbitrary node i, if its forwarding node is j, the cooperative candidate nodes from that a cooperative node will be chosen to help node i accomplishing the cooperative communication is expressed as follows:

$$\mathrm{CoC}(i, j) = N(i) \cap N(j) + \{i\}. \tag{5}$$

5.1. The Overview of ESCDD Protocol. Different from the GeRaF protocol, ESCDD adopts the above energy-saving measure based on topology control to keep the local connectivity of nodes stable. In addition, combined with the power control of the physical layer, a cross-layer design based on the physical layer, MAC layer, and routing layer is proposed in ESCDD protocol. At each hop of data transmission, the single-node cooperation mechanism is used to reduce the energy consumption of data transmission. The process of the communication for one-hop in ESCDD protocol is shown in Figure 3.

The ESCDD protocol includes two stages in the data transmission of each hop, next hop forwarding node and cooperative node selection phase and the data transmitting phase. If the event information is monitored by the source node and the data need to be sent to the sink node, the two wireless modules of the node will be activated and will keep the listening state. If the channel is idle during the listening time $\Delta\tau$, the node will begin to send a busy-tone signal on the wake-up channel to awake the main channel of neighbor nodes. Then, the node starts to send a RTS message. All nodes receiving the RTS information decide whether to become forwarding candidate nodes according to the information included in RTS, their position information, and the position information of sink node. One of the forwarding candidate nodes which has the highest priority and the minimum back-off time firstly sends CTS response message and becomes the forwarding node of the next hop. In order to reduce the energy consumption of the sending nodes during data transmission, all neighbor nodes hearing the RTS and CTS will become cooperative candidate nodes. These cooperative candidate nodes compete to send a control frame CoTS firstly according to energy consumption and become the only cooperative node of the source node. When the source node listens to the CoTS message, the data transmitting phase starts. The source node and its cooperative node will send their data using decode forwarding (DF). The received data will be recovered by the forwarding node using maximal ratio combining (MRC). There is a special situation in the cooperative node selection which can change the way of data transmission. Because the source node is one of its cooperative candidate nodes according to Definition 3, it may be chosen as its own cooperative node. The details are discussed later.

5.2. The Selection of Forwarding Node. RTS/CTS, similar to the mechanism in IEEE802.11MAC protocol, is used in the selection of the forwarding node in the ESCDD protocol. The wake-up channel of any idle node is awaked for time τ based on probability p_i in every listening/sleeping cycle T_{cycle}. Once the busy-tone signal is listened, the node will activate the main channel to keep listening and starts to compete for becoming the forwarding node through RTS/CTS mechanism. In order to estimate the channel gain, RTS/CTS contains the pilot sequence coding by CRC (cyclic redundancy check). Moreover, RTS does not contain the address of the next hop receiving node. The concrete realization process of selecting forwarding node in ESCDD protocol is as follows.

5.2.1. The Source Node Sends a RTS Frame. Firstly, the source node of data transmission activates wireless modules of the main channel and the wake-up channel for listening time $\Delta\tau$. According to the different results of interception, three kinds of treatment methods are introduced in detail. If the busy-tone is only heard by the wake-up channel, the node delays sending data and the main channel continues to listen. If the main channel is busy, the node immediately enters the sleep state for a monitoring cycle regardless of whether wake-up channel is busy. If the two channels are in the idle state, the node immediately sends a busy-tone signal and then sends the RTS frame.

5.2.2. Determining the Forwarding Candidate Nodes. When the source node continuously sends busy-tone signal for a listening/sleeping cycle, its neighbor nodes wake up according to the wake-up probability and listen to the busy-tone signal, thereby activating its main channel and entering into the listening state. According to the different results of interception, two kinds of treatment methods are proposed in detail. If the node does not listen to any news in a monitoring period, it immediately enters the sleep state. If the node listens to RTS frame, it utilizes the data of RTS frame to send the location information of the source node, the node itself, and the sink node. Then, according to (4), the forwarding candidate nodes are determined. Moreover, each of the forwarding candidate nodes uses the received RTS frame to estimate the channel gain h_{sr} between the source node and itself. Every forwarding candidate node uses the geographic information to determine its priority RP (relative priority) and calculates back-off time t_r before sending CTS according to (6) and (7), respectively, as follows:

$$\mathrm{RP} = \left(R - l_{sr}\cos\theta\right)\left(\frac{NP}{R}\right), \tag{6}$$

$$t_r = \left[1 - \frac{(l_{sD} - R)}{l_{rD}}\right]\left(\frac{\mathrm{RP}}{NP}\right)T_{1-\max}. \tag{7}$$

In (6), I_{sr} is the Euclidean distance between the source node and the forwarding candidate node and θ is the angle of position interconnection wires from the source node to the sink node and the forwarding candidate node. NP represents the maximal priority of the forwarding candidate nodes, which can be user-defined according to the application. In (7), l_{rD} is the Euclidean distance between the forwarding candidate node and sink node. $T_{1-\max}$ is the maximum time window.

5.2.3. Competing to Become Forwarding Node. The forwarding candidate nodes will compete to send the CTS frame firstly according to the back-off time. Then, only one becomes the forwarding node and waits for the data from the source node. Note that the channel gain is included in the CTS frame in order to select the forwarding node. In addition, due to the transmission delay and the smaller difference between back-off times t_r of forwarding candidate nodes, forwarding candidate nodes may simultaneously send the CTS frame to cause the collision. If this situation happens, the source node will resend a RTS to the forwarding candidate nodes and then a new competition to become forwarding node will begin. Due to the dynamics of back-off times t_r for forwarding candidate nodes to send CTS, this collision avoidance mechanism is guaranteed to have a single winner [3].

5.3. The Selection of Cooperative Node. The main purpose of adopting cooperative node in ESCDD protocol is to reduce the energy consumption of each hop. For selecting the cooperative node which can help the source node to transmit the data with minimum energy consumption, the control frame, CoTS (cooperative to send), is adopted. Although CoTS is similar to CTS frame, they also have some differences which will be illustrated in the selecting process of cooperative node.

5.3.1. Determining the Cooperative Candidate Nodes. During the selection of forwarding node, the source node sends a RTS and the forwarding node sends a CTS as a response. The common neighbor nodes of the source node and the forwarding node may hear the RTS and the CTS. According to Definition 3, the neighbor nodes hearing the RTS and CTS frame can be identified as the cooperative candidate nodes when the source node selects the forwarding node. In addition, the source node always is one of its cooperative candidate nodes.

5.3.2. Estimating the Channel Gains. On the basis of the RTS and CTS frame successively received from the source node and the forwarding node, each of the cooperative candidate nodes, respectively, estimates its own channel gain $h_{s-\mathrm{coc}}$ from the source node to itself and channel gain $h_{\mathrm{coc}-r}$ from itself to the forwarding node. Additionally, the channel gain h_{sr} from the source node of data transmission to the forwarding node is extracted from the CTS.

5.3.3. Estimating the Transmit Power. The transmit power P_s of the source node and the transmit power P_{coc} of the cooperative node are determined by solving the optimization problem at the cooperative candidate nodes. According to the information of the estimated channel gain, the cooperative candidate node minimizes the energy consumption of cooperative transmission to its objective. The transmit power P_s of the data transmission source node and the transmit power P_{coc} of the cooperative node can be obtained by solving the following types:

$$\min_{P_s, P_{\mathrm{coc}}} f_s\left(P_s, P_{\mathrm{coc}}\right) = N_b\left(P_s T_b + P_{\mathrm{coc}} T_b\right) + N_c P_{\mathrm{oth}} T_b, \tag{8}$$

$$C_r \le \frac{1}{2}\log_2\left[1 + \frac{P_s\left|h_{sr}\right|^2}{(N_0 W)} + \frac{P_{\mathrm{coc}}\left|h_{\mathrm{coc}-r}\right|^2}{(N_0 W)}\right], \tag{9}$$

$$C_r \le \frac{1}{2}\log_2\left(1 + \frac{P_s\left|h_{s-\mathrm{coc}}\right|^2}{(N_0 W)}\right), \tag{10}$$

where the objective function is directly proportional to the total energy consumption of one-hop data transmitting from the cooperative node. P_{oth} is equal to $P_{\max}$. N_b is the number of bits from the transmitted data packets, N_c is the total number of bits from the transmitted control packets, and T_b is the duration for a bit. Equations (9) and (10) are got from the Shannon formula of information theory. Here, assuming C_r (bit/s/Hz) is the one-hop data transmission rate in the minimum energy consumption, (9) shows that the data sent to the forwarding node can be correctly recovered with maximal ratio combining. Equation (10) shows that the data message sent by the source node can be correctly received by the cooperative candidate node. W is the channel bandwidth.

In order to simplify the analysis, $N_0 \cdot W = 1$. Therefore, the above optimization problem can be simplified as follows:

$$\min_{P_s, P_{\mathrm{coc}}} f_s\left(P_s, P_{\mathrm{coc}}\right) = \frac{\left(P_s + P_{\mathrm{coc}}\right) N_b}{\left(C_r W\right)}, \quad (11)$$

$$P_s \left|h_{sr}\right|^2 + P_{\mathrm{coc}} \left|h_{\mathrm{coc}-r}\right|^2 \geq 2^{2C_r} - 1, \quad (12)$$

$$\frac{\left(2^{2C_r} - 1\right)}{\left|h_{s-\mathrm{coc}}\right|^2} \leq P_s \leq P_{\max}, \quad 0 \leq P_{\mathrm{coc}} \leq P_{\max}. \quad (13)$$

To solve the above optimization problem by using the method of linear programming, the solution can be easily obtained. However, according to the different channels, there are several different forms.

If $h_{sr} < h_{s-\mathrm{coc}}$ and $h_{sr} < h_{\mathrm{coc}-r}$, the following two different solutions (a) and (b) are got by using the linear programming.

(a) If $(2^{2C_r} - 1)/|h_{s-\mathrm{coc}}|^2 \leq P_{\max}$ and $((2^{2C_r} - 1)/|h_{\mathrm{coc}-r}|^2)(1 - |h_{s-r}|^2/|h_{s-\mathrm{coc}}|^2) \leq P_{\max}$,

$$P_s = \frac{2^{2C_r} - 1}{\left|h_{s-\mathrm{coc}}\right|^2}, \qquad P_{\mathrm{coc}} = \frac{2^{2C_r} - 1}{\left|h_{\mathrm{coc}-r}\right|^2}\left(1 - \frac{\left|h_{s-r}\right|^2}{\left|h_{s-\mathrm{coc}}\right|^2}\right). \quad (14)$$

(b) If $(2^{2C_r} - 1)/|h_{s-\mathrm{coc}}|^2 \leq P_{\max}$, $((2^{2C_r} - 1)/|h_{\mathrm{coc}-r}|^2)(1 - |h_{s-r}|^2/|h_{s-\mathrm{coc}}|^2) > P_{\max}$, and $(2^{2C_r} - 1 - |h_{\mathrm{coc}-r}|^2 P_{\max})/|h_{s-r}|^2 \leq P_{\max}$,

$$P_s = \frac{\left(2^{2C_r} - 1 - \left|h_{\mathrm{coc}-r}\right|^2 P_{\max}\right)}{\left|h_{s-r}\right|^2}, \qquad P_{\mathrm{coc}} = P_{\max}. \quad (15)$$

If $h_{sr} > h_{s-\mathrm{coc}}$ or $h_{sr} > h_{\mathrm{coc}-r}$, only the source node competes to become the cooperative node. Other cooperative candidate nodes do not participate in the competition. The two solutions (a) and (b) that solved the optimization problem are as follows.

(a) If $(2^{2C_r} - 1)/|h_{s-r}|^2 \leq P_{\max}$,

$$P_s = \frac{\left(2^{2C_r} - 1\right)}{\left|h_{s-r}\right|^2}, \qquad P_{\mathrm{coc}} = 0. \quad (16)$$

(b) If $P_{\max} \leq (2^{2C_r} - 1)/|h_{s-r}|^2 \leq 2P_{\max}$,

$$P_s = P_{\max}, \qquad P_{\mathrm{coc}} = \frac{\left(2^{2C_r} - 1\right)}{\left|h_{s-r}\right|^2} - P_{\max}. \quad (17)$$

If certain cooperative candidate nodes cannot meet the above conditions, their effective solutions of the optimization problem will not be got. Then, these cooperative candidate nodes will not participate in the competition of becoming the cooperative node.

5.3.4. Determining the Back-Off Time t_{coc}. For the cooperative candidate nodes getting the effective solutions, the waiting time t_{coc} from receiving CTS frame to sending CoTS frame is calculated as follows:

$$t_{\mathrm{coc}} = \left[\frac{f_s\left(P_s, P_{\mathrm{coc}}\right)}{f_s\left(P_{\max}, P_{\max}\right)}\right] T_{\Delta}, \quad (18)$$

where T_{Δ} is the maximum delay time of the cooperative candidate nodes competing to become the cooperative node. It can be defined by the user. Obviously, the smaller $f_s(P_s, P_{\mathrm{coc}})$ is, the shorter the waiting time t_{coc} is. Therefore, the cooperative candidate node with minimum waiting time t_{coc} will firstly send the CoTS frame. Then, it will win the competition and become the cooperative node of the source node. If there is a tie, it is resolved on the basis of node ID. When other cooperative candidate nodes hear the CoTS frame, they will give up the competition and enter into the sleep state.

5.4. Data Transmission and Recovery. In this section, we introduce the process of data transmission and recovery in detail. The special situation that the source becomes its own cooperative node is discussed in detail.

5.4.1. The Data Transmission of the Source Node. The source node will transmit its data in the following two kinds of circumstances, hearing CoTS from the cooperative node or sending the first CoTS.

The source node hears CoTS. Once the source node hears CoTS messages, it represents that the cooperative node has been selected from the cooperative candidate nodes except the source node. The source node immediately transmits data information according to the transmit power P_s extracted from the CoTS. Then, the forwarding node and the cooperative node will receive the data signal from the data source node. The received signals are treated as follows. The cooperative node will decode the received signals and restore the decoded information. The forwarding node will temporarily store the received signals without decoding.

The source node firstly sends CoTS messages. Namely, the source node becomes its own cooperative node as mentioned before. When the waiting time t_{coc} is ended, the CoTS message is immediately sent. Then, the data information is sent to the forwarding node according to the calculation of transmit power P_s calculated by itself. The forwarding node will temporarily store the received data signal without decoding.

5.4.2. The Data Transmission of the Cooperative Node. Based on whether the cooperative node is the source node, the data transmission is implemented as follows. If the cooperative node is not the source node, it will send the data in the same way as the source node to the forwarding node with the transmit power P_{coc} calculated by itself after it receives and decodes the data information from the source node. If the cooperative node is the source node as well, it will send again the data information to the forwarding node with the transmit power P_{coc} calculated by itself after finishing the first data transmission.

5.4.3. The Data Recovery at Forwarding Node. The forwarding node has received both signals from the source node and the cooperative node, and then it processes the two signals using the maximal ratio combining (MRC) algorithm. After that, the original data information can be recovered.

6. Simulation Evaluation

In order to evaluate the performance of ESCDD protocol, the simulation platform is established. The proposed ESCDD is compared with the existing GeRaF, REEGF, and EERNFS in four performance indicators: the delivery ratio of data packet, the average delay of multihop transmission, the average energy consumption of nodes, and the energy consumption distribution in the WSNs. GeRaF is an efficient data collection protocol of WSNs mentioned in [4]. REEGF and EERNFS are two data collection protocols without cooperative MIMO proposed by the authors of this paper [9, 10].

6.1. Simulation Scene and Parameter Setting. The simulation experiment still adopts the most common many-to-one data collection model applied in wireless sensor networks. The nodes are randomly placed in a $1000 \times 1000\,\text{m}^2$ area. The sink node locates at any side of the area. We assume the communication range is 100 m. At the same time, the energy consumption model of the two wireless modules on every node is the same. The initial energy of network nodes is 10J. The other parameter settings can be referred to [8].

6.2. Result Analysis. The simulation results are shown from Figure 4 to Figure 7.

Figure 4 shows the packet delivery rate when the neighbor nodes increase from 5 to 80. The packet delivery rate of ESCDD is significantly higher than the other three protocols. The packet delivery rate of GeRaF is the smallest. The packet delivery rates of EERNFS and REEFG are between ESCDD and GeRaF. When the number of the neighbor nodes increases to 40, the packet delivery rates of ESCDD, EERNFS, and REEFG reach the maximum and start to remain stable. The packet delivery rates of GeRaF reached the maximum when the number of average neighbor nodes increased to 60. Then, the packet delivery rate begins to decrease. The main reasons why these situations appear are introduced below. The periodic listening/sleeping of GeRaF is mutually independent and random. But the periodic listening/sleeping of the other three protocols is synchronized with the probability. In the low density of the network, the momentary interruption of the network connectivity is easily caused in GeRaF. Compared to this, neighbor nodes must be fully aroused for a given time in every listening/sleeping cycle in ESCDD, EERNFS, and REEFG. Therefore, the network connectivity of ESCDD, EERNFS, and REEFG is significantly higher than GeRaF, which makes the higher packet delivery rates. Meanwhile, ESCDD uses the single-node cooperation to further resist fading, which makes it have the highest packet delivery rate. ESCDD, EERNFS, and REEFG rely on local neighbor information to control the transient connectivity of nodes so that the transient connectivity begins to remain stable when the number of neighbor nodes is up to 40. However, GeRaF does not control the wake-up frequency, which makes the frequency of every node constant. With the increasing density of network, the instantaneous connectivity also increases. The competition for becoming forwarding nodes gets intense. Then, the time of data transmission is prolonged. As a result, the packet delivery rate of GeRaF slightly decreases.

Figure 5 shows the change of the average multihop delay of the four protocols. ESCDD has less data collection delay compared with GeRaF, EERNFS, and REEFG. The delay performance of EERNFS and REEFG is close. GeRaF is the last. Along with the increasing of network density, the average multihop delays of the four protocols decrease gradually. The average multihop delays of ESCDD, EERNFS, and

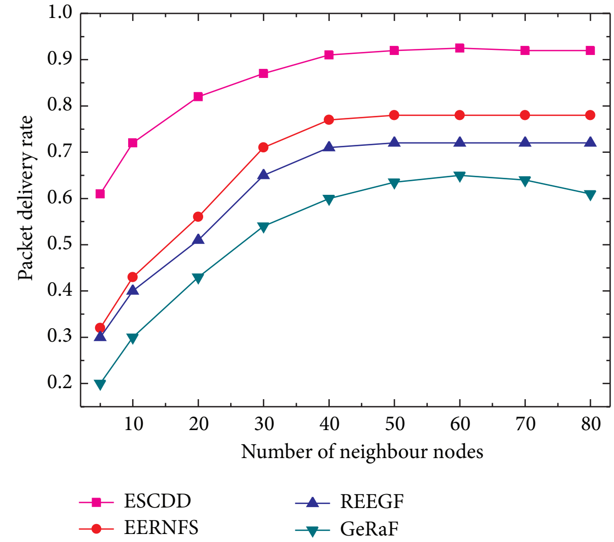

Figure 4: The change of packet delivery rate with the node deployment density.

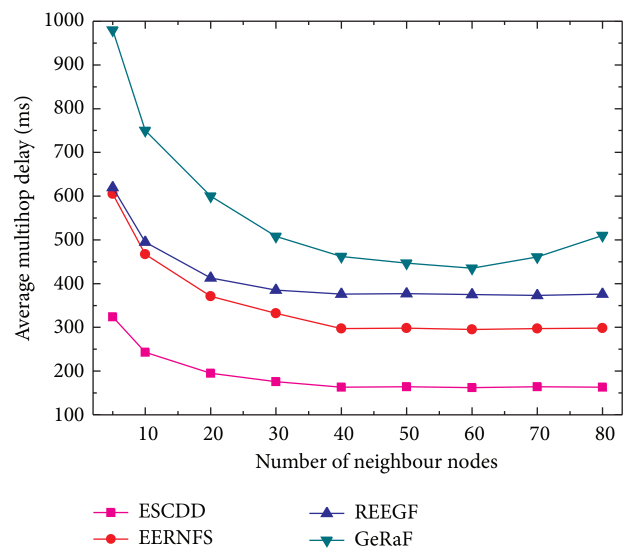

Figure 5: The change of the average multihop delay with the node deployment density.

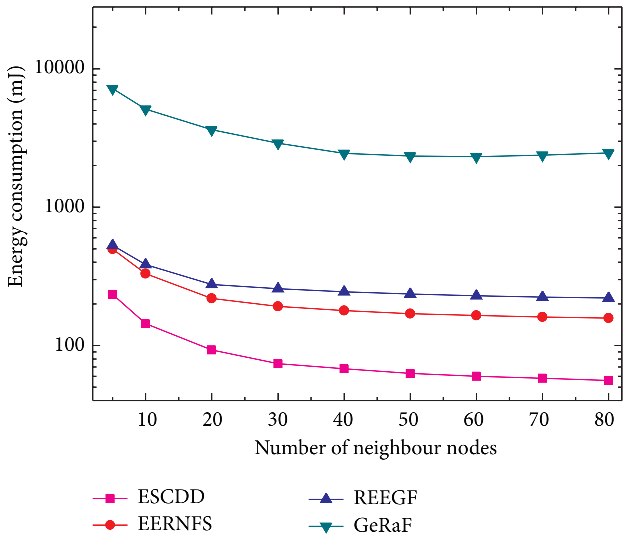

Figure 6: The change of the average energy consumption with the node deployment density.

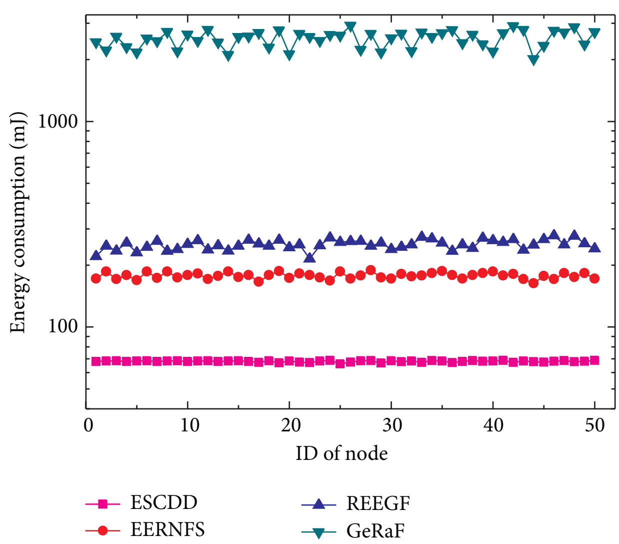

Figure 7: The energy consumption distribution of nodes.

REEFG tend to be stable when the number of neighbor nodes increases to 40. The average multihop delay of GeRaF reaches the minimum when the number of neighbor nodes increases to 60. Then, the average multihop delay begins to increase. The main reasons resulting in these above outcomes are as follows. In the low density network, all neighbor nodes are activated in every listening/sleeping cycle in ESCDD, EERNFS, and REEFG. But the number of activated neighbor nodes is proportional to the network density in GeRaF. The adopting of the polling mechanism in GeRaF based on RTS/CTS makes the empty probability much larger than the other three protocols in selecting forwarding nodes. With the gradual increasing of network density, ESCDD, EERNFS, and REEFG relying on the stability of local network connectivity can control the competition for being forwarding nodes and the average multihop delays tend to be stable. Meanwhile, the using of single-node cooperation makes ESCDD have the lowest multihop delay. With the increasing of network density, the local network connectivity of GeRaF also increases. Then, the numbers of forwarding candidate nodes also increase, which results in an intense competition.

Figure 6 gives the change of the average energy consumption of the four protocols. The average energy consumption of ESCDD is significantly less than the other three protocols. In the low density network, the average energy consumption of the four protocols is relatively large. With the increasing of network deployment density, the average energy consumption of four protocols is gradually decreased. The average energy consumption of GeRaF reaches the minimum value when the number of the neighbor nodes increases to 60. Afterwards, the average energy consumption increases a little when the number of neighbor nodes increases from 60 to 80. The main reasons resulting in these above outcomes are as follows. ESCDD, EERNFS, and REEFG awake the nodes with probability in every listening/sleeping cycle. At the same time, the nodes listen to the busy-tone signal and the listening time is very short. Based on the local information, ESCDD, EERNFS, and REEFG control the instantaneous connectivity. However, GeRaF randomly awakes the main channel to listen to the control message in every listening/sleeping cycle. Therefore, GeRaF needs a much longer listening time than the other three protocols. With the increasing density of the network, ESCDD keeps the local connectivity of nodes stable to make the establishment time of data link stable. The total energy consumption of data transmission is shared by more network nodes resulting in the average energy consumption of network nodes being less and less. Because the wake-up neighbor nodes in every listening/sleeping cycle are not controlled in GeRaF, the local network connectivity increases with the increasing density of network. Therefore, every one-hop competition for becoming forwarding node gets very intense. The energy consumption also increases. Meanwhile, ESCDD uses the greedy algorithm to select the forwarding nodes and reduce the number of hops for the data collection. It uses the power control technology of physical layer to select the single cooperative node for minimizing energy consumption. The cooperative data transmission at each hop is performed. Then, the data transmission consumption at each hop is effectively reduced, and the fading is resisted.

Figure 7 shows the energy consumption distribution of network nodes. When the deployment density of network nodes is 40 and the sink node receives 1000 data packets, the simulation obtained from the randomly selected 50 nodes is shown in Figure 7 based on the experimental result of Figure 6.

As shown in Figure 7, compared with the other three protocols, ESCDD can significantly reduce the energy consumption of every node. Meanwhile, the energy consumption is more balanced. But the change of the energy consumption in GeRaF is dramatic. ESCDD not only controls the wake-up frequency in every listening/sleeping cycle by using the channel information and the energy information of nodes but also uses the cooperative nodes to execute the cooperative transmission in every hop. Therefore, the total energy consumption of data transmission is shared by more nodes, so the energy consumption of the network nodes is balanced, which can extend network lifetime.

7. Conclusions

According to the topology control and energy information of nodes, ESCDD controls the wake-up probability of each node in every listening/sleeping cycle to maintain the connectivity of network consistent and stable. ESCDD uses the greedy strategy and the control information based on RTS/CTS to interactively select forwarding nodes, which can reduce the hops in the multihop data transmission and save energy. Based on the power control in physical layer and the control frame CoTS, ESCDD chooses a single cooperative node to perform cooperative transmission and recover the data through maximal ratio combining. Then, the implementation complexity of cooperative MIMO adopted in ESCDD protocol is reduced. The energy consumption per hop in data transmission and the number of retransmission are reduced. Furthermore, the total energy consumption in data collection process is shared by more nodes, which can make the energy consumption more balanced and extend network lifetime. The simulation result shows that ESCDD can effectively reduce the average delay of multihop data transmission, improve the successful delivery rate of data packets, save the energy consumption of network nodes, and make the energy consumption more balanced. Compared with other protocols, ESCDD has a better scalability and adaptability to adapt to changing network environment.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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