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Coverage Area Optimization Algorithm for Directed Sensing Network Based on Energy Aware

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Abstract

Target area coverage is the most fundamental goal of WSN (Wireless Sensor Network) application, so the design of energy aware based algorithm for coverage time maximization becomes a core problem of a large network. For this reason, a DECAR (Distributed-energy and Coverage Aware Routing) protocol is proposed in this paper to realize the goal of network coverage maximization. Specifically, the rest energy and the coverage overlapping degree of the nodes are considered during CH (cluster head) selection process so as to provide more opportunities for the nodes with more rest energy or higher coverage overlapping degree to become CH; like this, the nodes with less rest energy will not be selected as CH, thus to avoid shortening the network lifetime due to early failure of these nodes and balance the network energy consumption. Meanwhile, the main data transmission line composed of CHs is constructed in the data transmission stage in order to improve data transmission efficiency. The simulation result shows: compared with CPCP-ea and EEUC protocols, the proposed DECAR protocol can obtain longer network lifetime and better data coverage ratio.

Keywords*: Cluster; Distributed energy; Coverage ratio; Wireless sensor network; Network lifetime*

1. Introduction

Along with the development of modern electronic technology, WSN is widely applied in various fields, such as rehabilitation therapy, battlefield and field environment monitoring [1]. In these application scenes, sensor nodes are required to be deployed in the target area through a random or specific way, and then these sensor nodes are adopted to sense the environmental data and directly or indirectly transmit these data to CH. In order to timely monitor the environment, the target area must be completely covered by the sensor nodes. Therefore, for completely covering the target area, a lot of sensor nodes are deployed redundantly to avoid coverage holes [2]. However, due to limited or insufficient sensor node energy, some sensor nodes gradually become ineffective along with the energy consumption, thus causing coverage holes. As a result, how to improve node energy utilization and solve coverage hole problem becomes the research hotspot in WSN.

At present, researchers have proposed many energy conservation technologies. The fundamental objective of these technologies is to reduce the energy consumption of sensor nodes so as to prolong the network lifetime and accordingly maintain the complete coverage of the target area. Due to the advantages in energy utilization improvement, the cluster-based technologies are well known by people. In the cluster-based technologies, all sensor nodes are divided into different clusters,

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wherein each cluster includes a CH and other sensor nodes are CMs (cluster members). Specifically, CHs are responsible for collecting and integrating the sensing data of CMs and then forwarding these data to the Sink through multi-hop communication mode.

In allusion to WSN, researchers have proposed many cluster algorithms [4-7]. However, due to the failure of some sensor nodes, these algorithms cannot ensure the complete coverage of the target area. Therefore, the cluster-based algorithms shall be able to sense the coverage area so as to maintain the coverage lifetime of the sensor network. In other words, even though some sensor nodes become ineffective, WSN shall still be able to maintain the maximum coverage area. The coverage aware cluster algorithms are also proposed in literature [8], but the overlapping problem of the coverage area of the sensor nodes is ignored in these algorithms.

Additionally, the cluster-based multi-hop routing protocol is proposed in literatures [9~11] as the effective technology for prolonging network lifetime. In multi-hop communication, one CH usually transmits data to the Sink through other CHs as the intermediate forwarding nodes. However, this protocol mainly has the following problem: CHs near the Sink undertake more data forwarding tasks, thus accelerating the energy consumption thereof and easily causing energy hole problem.

Therefore, a DECAR (Distributed-energy and Coverage Aware Routing) protocol is proposed in this paper to improve network coverage lifetime. In DECAR protocol, firstly, differently sized clusters are formed to solve the fast energy consumption problem of CHs near the Sink during the data transmission process; then, one CH is selected in each cluster according to the rest energy of the nodes and the coverage overlapping degree; finally, the main data transmission path composed of CHs is established. The simulation result shows that the proposed DECAR protocol can effectively prolong network lifetime and coverage lifetime and reduce energy consumption.

2. Network Model

In this paper, WSN nodes are considered as the isomorphic nodes with the same initial energy. These nodes are statically deployed in the target area, namely: such WSN is a static network. Additionally, the sensor nodes can obtain their own position information through positioning technology [12].

2.1. Network Time Sequence

The network time sequence is divided into multiple periods in this paper, and each period is called as a round, and each round includes a clustering stage and a data transmission stage, as shown in Figure 1. Specifically, the clustering stage is responsible for selecting CHs and forming clusters, and the data transmissions stage is responsible for data transmission. Additionally, the nodes in each cluster send the data sensed thereby to CH; after data collection and fusion, CH sends the data to the base station. In order to avoid the mutual interference of the data transmission among the nodes, each node is allocated with one time slot for the data transmission therein during the data transmission process.

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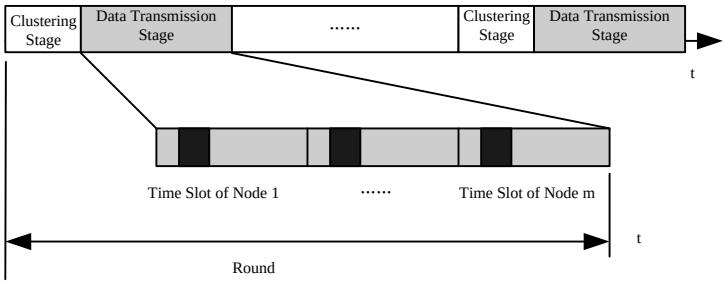

Figure 1. Network Time Sequence

2.2. Energy Model

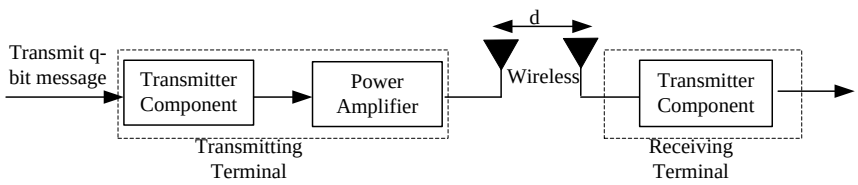

Figure 2. Wireless Energy Consumption Model

For the energy consumption model as shown in Figure 2, the transmitting terminal is composed of transmitter components and power amplifiers, and the receiving terminal is composed of transmitter components, and the distance between the transmitting terminal and the receiving terminal is d m. In case of short d, the free space transmission model is adopted. In case of long d, multipath fading channel model is adopted. Specifically, when the transmission distance is d, the energy consumption for the transmitting terminal to transmit q-bit message to the receiving terminal is as follows:

$$E_{TX}(q,d)=\begin{cases} q*E_{elec}+q*E_{fris}d^2, if\ d<d_o \\ q*E_{elec}+q*E_{tworay}d^4, if\ d\geq d_o \end{cases} \tag{1}$$

Wherein E_{elec} represents the energy consumption for the transmitter components to transmit each bit of message; E_{fris} and E_{tworay} respectively represent the energy consumption of unit power amplifier under free space transmission model and two ray ground model, and d_o is calculated as follows:

$$d_o=\sqrt{\frac{(4*\pi)^2*l*h_t^2*h_r^2}{\lambda^2}}=\sqrt{\frac{E_{fris}}{E_{tworay}}} \tag{2}$$

Correspondingly, the energy consumption for receiving q-bit message is as follows:

$$E_{RX}(k)=q*E_{elec} \tag{3}$$

3. DECAR Protocol

DECAR protocol will be described in details mainly from the following three aspects: information updating, clustering and data transmission.

3.1. Information Updating

In the initial stage, each node broadcasts its control information to the neighbor nodes, including node ID and position information. If a node receives this message, then this node will update its neighbor table N. Afterwards, each sensor node calculates the coverage overlapping degree with the neighbor nodes. For a node i, the coverage overlapping degree $\tau(i)$ with the neighbor nodes is calculated as follows:

$$\tau(i)=\frac{1}{A(i)}\bigcup_{j\in N(i)}A(i)\cap A(j) \tag{4}$$

Wherein $N(i)$ represents the neighbor node set of node i and $A(i)$ represents the size of the coverage area of node i. According to Formula (4), $\tau(i)$ is in the range of 0~1. If $\tau(i)$=1 is true, then it is indicated that the coverage area of this node is completely overlapped with that of the neighbor node thereof. The size of the overlapping area can be calculated according to the algorithm proposed in literature [13].

3.2. Clustering Stage

T_{CH} is assumed as the maximum time slot of CH and can be divided into two stages T_1 and T_2 ($T_1<T_2\le T_{CH}$) . The timer is enabled before each node competes for CH. Timer $t(i)$ of node i is assumed as follows:

$$t(i)=\begin{cases}\dfrac{E_m(i)-E_r(i)}{E_m(i)}\times T_1,\ if\ \tau(i)=1\\ \dfrac{E_m(i)-E_r(i)}{E_m(i)}\times T_2, if\ if\ \tau(i)<1\end{cases} \tag{5}$$

According to Formula (5), the timer of the node with $\tau(i)$=1expires before that of the node with $\tau(i)<1$, thus indicating that the node with $\tau(i)$=1is more advantageous for competing for CH. Therein, $E_m(i)$ and $E_r(i)$ respectively represent the initial energy (maximum energy) and the rest energy of node i. According to Formula (5), the node with more rest energy is preferably selected as CH.

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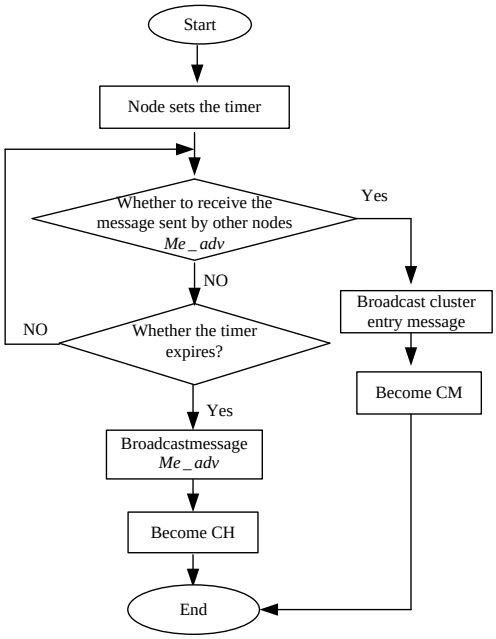

Figure 3. Clustering Process

Once the timer expires, the node will announce it as CH and broadcast one CH messages Mes_adv within its communication radius $C_r(i)$. Communication radius of node i is defined as shown in Formula (6):

$$C_r(i)=\left(1-e\frac{D_{\max}-D_{i-sink}}{D_{\max}-D_{\min}}\right)R_c \tag{6}$$

Wherein $D_{\max}$ and $D_{\min}$ respectively represent the maximum distance and the minimum distance between the nodes in the network and the Sink; D_{i-sink} represents the distance between node i and the Sink; R_c represents the allowable maximum communication radius of CH; e is a constant between 0 and 1.

Once receiving Mes_adv message broadcasted by other nodes, the node concerned will give up the competition for CH, cancel the timer and become CM. Meanwhile, this node will send the cluster entry message to the nearest cluster. The specific clustering process is as shown in Figure 3.

3.3. Main Data Transmission Line

Simple formula is adopted in this section to find the levels of CHs in the network. The whole wireless network is assumed to be divided into several levels, and the level $L(u)$ of cluster u is defined as shown in Formula (7):

$$L(u)=\left\lceil \frac{D_{(u,sink)}}{R_c} \right\rceil \tag{7}$$

Wherein $D_{(u,sink)}$ represents the distance between CH and the Sink.

The Sink is assumed at level 0, namely the maximum level, as shown in Figure 4. Each CH broadcasts the control message thereof in the range of kR_c and finds one CH as the next-hop node for the data transmission to the Sink. k is initially assumed as $k=2$. Once CH receives the message, it will immediately reply ACK confirmation message. If ACK confirmation message is not received within the specified period, then it is indicated that no CH receives the control message within the range of $k=2$, so the node will expand the broadcasting range, namely: k is increased by 1 as $k=3$, and then broadcast the control message again. The above process is repeated till the

confirmation message is received from a higher level, thus to form the main data transmission path.

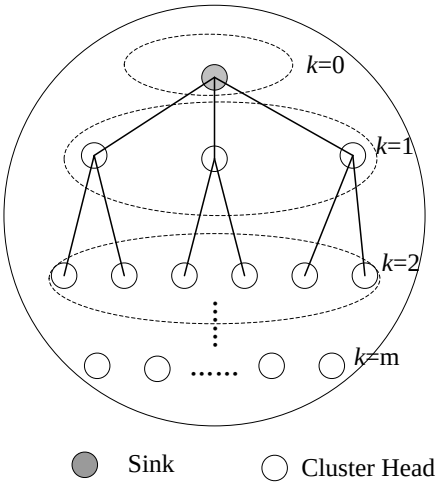

Figure 4. Cluster Level Diagram

3.4. Data Transmission

When receiving the confirmation message from the CH at a higher level, CH will select the CH at a higher level as the next-hop node. The level of CH u is assumed as $L(u)$, and the confirmation message received by CH u is from CH set $V=\{\vartheta_1,\vartheta_2,\cdots,\vartheta_p\}$. The cost function for β-bit data transmission from node i to node j is as follows:

$$CF(i,j)=\frac{E_r(j)}{E_{tx}(i,j)} \tag{8}$$

Wherein $E_{tx}(i,j)$ represents the energy consumption for β-bit data transmission from node i to node j.

According to the cost calculation for the data transmission from CH u to various nodes in CH set V, CH u selects the CH with maximum cost as the next-hop node. The rest energy of the node and the transmission path loss are respectively the numerator and the denominator of Formula (8), namely: the higher the cost, the more the rest energy of the node or the smaller the transmission path loss. The selection of the node with more rest energy is favorable for prolonging the working time of CH and improving the coverage ratio; but the selection of the node with small transmission path loss as the next-hop node is favorable for reducing energy consumption and prolonging network lifetime.

4. Performance Simulation

4.1. Simulation Parameters and Performance Indexes

MATLAB is adopted to establish the simulation platform for evaluating the performance of DECAR algorithm, wherein 100 nodes are randomly distributed in the area with the size of $40m\times40m$. The specific simulation parameters are as shown in Table 1.

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Table 1. Simulation Parameters

Parameter Type	Value
Experiment Area	$40m \times 40m$
Sink Position	$(20,0)$
Number of Nodes	100
CH Communication Radius	$10m$
Initial Energy of Node	$0.5J$
Data Packet Length	500 bit
Control Packet Length	100 bit
Free Space Transmission Model E_{frris}	10pJ/m^2/bit
Two Ray Ground Model E_{tworay}	0.0013pJ/m^4/bit

Additionally, the corresponding simulation data are adopted to compare DECAR protocol with CPCP-ea protocol [8] and EEUC protocol [14] in the aspects of network lifetime, coverage lifetime and other performances. Specifically, the coverage lifetime is expressed by number of rounds, which is equal to the number of the continuous rounds for the complete coverage of the target area. For example, if the target area is completely covered at round *M* but is not completely covered at round *M+1*, then the coverage lifetime is calculated as *M* rounds. Similarly, the network lifetime is also expressed by number of rounds, which is equal to the number of the rounds for the first node failure in the network.

4.2. Network Lifetime and Energy Consumption

The energy consumption and the number of the disabled CHs of DECAR scheme are firstly analyzed, and the analysis results are as shown in Figure 5. Under the same number of rounds, the energy consumption of the proposed DECAR scheme is less than that of CPCP-ea and EEUC schemes. Since CH failure is not considered in CPCP-ea protocol, namely: data are also transmitted to the disabled CH, thus the energy utilization thereof is relatively low. Instead, CH failure is considered in EEUC protocol, so EEUC protocol is superior to CPCP-ea protocol.

Additionally, the number of disabled CH of these protocols is as shown in Figure 5. According to relevant data, the number of disabled CHs is obviously less than that of CPCP-ea and EEUC protocols.

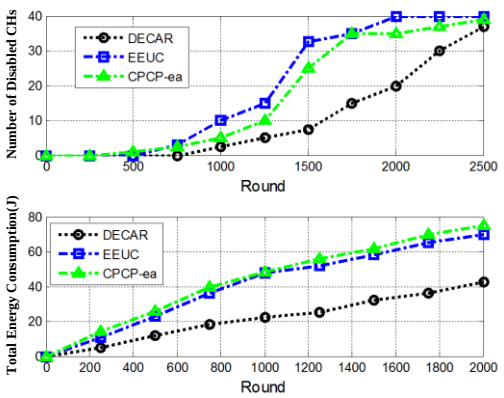

Figure 5. Energy Consumption

Table 2. Relation between Energy Consumption and Number of Rounds

Test	Energy Consumption 50%			For 1,000 Rounds		
	CPCP-ea	EEUC	DECAR	CPCP-ea	EEUC	DECAR
1	475	476	1038	48.89	47.35	23.49
2	477	474	1088	48.43	46.95	21.87
3	475	476	1109	48.48	47.76	21.23
4	479	484	1092	48.60	47.76	21.23
5	475	484	1123	48.99	47.01	20.24
6	478	480	1058	48.69	47.30	22.89
7	474	473	1076	48.94	47.48	22.71
8	482	472	1060	48.66	47.83	22.61
9	469	483	1097	48.81	47.30	21.48
10	475	478	1116	48.60	47.38	21.03

Some experiment data are as shown in Table 2. According to Table 2, when 50% of the energy is consumed, the proposed DECAR protocol has been operated for 1,082 rounds while CPCP-ea and EEUC protocols have been operated respectively for 477 rounds and 478 rounds. According to the energy consumption data, compared with CPCP-ea and EEUC protocols, the energy utilization of DECAR protocol is increased respectively by 127.0% and 126.6%. For example, when the protocols are operated for 1,000 rounds, the proposed DECAR protocol only consumes 22.0J energy while CPCP-ea and EEUC protocols respectively consume 48.6J energy and 47.5J energy.

Table 3. Number of active Nodes and Number of rounds for the First Node Failure

Test	Number of Active Nodes (For 2,000 Rounds)			Network Lifetime		
	CPCP-ea	EEUC	DECAR	CPCP-ea	EEUC	DECAR
1	1	9	25	754	736	1274
2	1	6	15	755	716	1228
3	1	9	19	754	739	1265
4	1	5	18	775	758	1303
5	2	6	21	783	676	1231
6	1	10	21	761	731	1328
7	1	5	16	782	696	1148
8	1	8	25	760	759	1329
9	1	4	22	764	723	1320
10	1	9	21	772	769	856

The data for two items are listed in Table 3: 1) the number of active nodes after operating the protocols for 2,000 rounds; 2) the total number of rounds for the first node failure, namely network lifetime. According to Table 3, compared with CPCP-ea and EEUC protocols, the time for the proposed DECAR protocol to have the first disabled node is respectively prolonged by 66.9% and 71.9%. The reason for such performance improvement is that CH is selected in DECAR protocol according to the rest energy of the nodes and the coverage overlapping ratio.

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4.3. Coverage Ratio

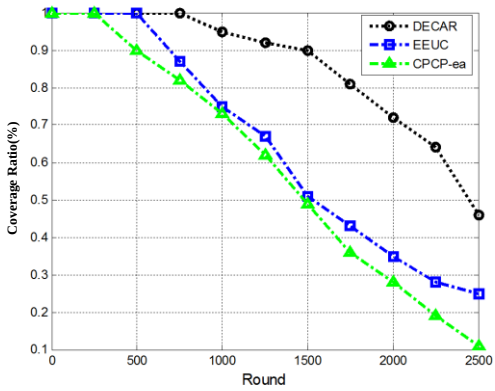

Figure 6. Coverage Ratio

The coverage ratio change of the three protocols is as shown in Figure 6. According to Figure 6, the coverage ratio of the proposed DECAR protocol is superior to that of EEUC and CPCP-ea protocols, because DECAR protocol can improve the energy utilization and reduce the energy consumption of the nodes as well as optimize the data transmission path.

5. Conclusion

In allusion to the data transmission problem in WSN, a DEACR protocol is proposed in this paper, wherein the cluster technology is introduced in DEACR protocol. Firstly, sensor nodes are divided into different clusters, CH is selected for each cluster according to the rest energy of the nodes and the coverage overlapping degree and other nodes are taken as CMs; secondly, the main data transmission line composed of CHs is established, and the data carrying CH is adopted to calculate the costs for the data transmission to neighbor CHs in order to select the node with high cost as the next-hop data forwarding node. The cost function contains the information regarding the rest energy of the nodes and the path loss, and the higher cost indicates more rest energy and smaller path loss which are all favorable for energy conservation and network lifetime prolonging. Additionally, the protocol is simulated to analyze the performance thereof in the aspects of network lifetime, coverage ratio and energy consumption. The simulation result shows that the proposed DEACR protocol can reduce energy consumption, prolong network lifetime and improve coverage ratio.

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