A Centralized Energy-Efficient Wireless Sensor Network Routing Protocol for the Static Sensor Nodes

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Abstract

As the core technology of Internet of Things (IoT) and Big Data, Wireless Sensor Network sends the information to the high-level application through deploying large quantities of sensor nodes which collaboratively perceive, collect, process and transmit information of the perceived objects in the network coverage area. However, due to the selection of an inappropriate routing path, the energy consumption of the sensor nodes will be too high and thereby reduce the lifetime of the entire wireless sensor network. This paper proposes a Centralized Energy-Efficient Wireless Sensor Network Routing Protocol (CEERP) for the static sensor nodes in which the wireless sensor network is regarded as a weighted undirected graph model, combined with the residual energy of sensor nodes. The base station (or gateway) calculates its optimal energy consumption path to all sensor nodes, and these nodes will perform data transmission through the optimized path. Results of the simulation and experiment validate that the method we proposed saves about 30% energy consumption compared with the conventional WSN routing protocol, and will effectively extend the lifetime of WSN.

Keywords
multi-hop forward, centralized energy-efficient routing, static sensor node, wireless sensor network

1 Introduction

In the past few years, with the development of technologies such as sensor, wireless communication and distributed information processing, as an emerging technology, WSN [17] has achieved great success in applications of environment monitoring [16], smart cities [19], medical care [13, 18], target tracking [24] and behavior monitoring [9], and aroused widespread concerns in academia and industry.

Wireless sensor network is composed of large quantities of static or movable micro sensor nodes deployed in the monitoring area, the data monitored by these sensor nodes are transmitted along other sensor nodes hop by hop through wireless communication. During the transmission, the monitored data may be processed by different nodes and reached the base station (or gateway) through multi-hop route. These monitored data collaboratively perceive, collect, process and transmit information of perceived objects within the network coverage area and finally send these information to the network manager through internet or satellite [15, 11] as demonstrated in Figure 1. By seeking the optimal route between source node and destination node, the routing technologies in the wireless sensor network forward the data packets to the destination node through multi hop along the optimal route [25].

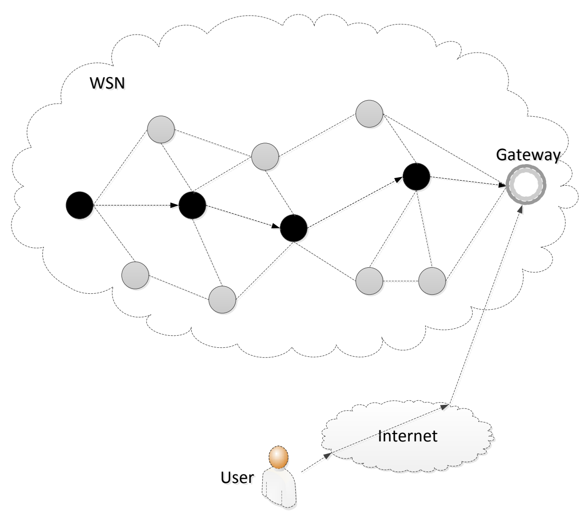

Figure 1. Structure of Wireless Sensor Network

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WSN generally has he characteristics of large-scale, self-organization, limited resource and complex environment [12]. As the key element of wireless sensor network, sensor node is composed of four parts [10], including sensor module, processing module, wireless communication module and power provision module (battery supply) as illustrated in Figure 2.

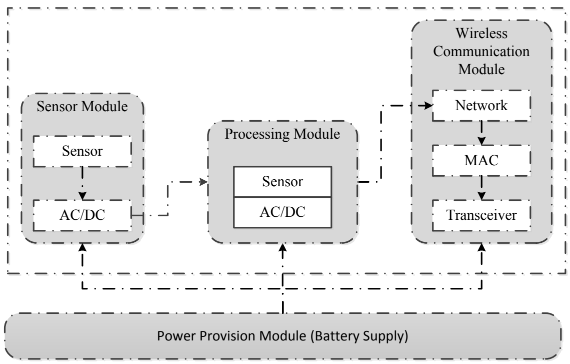


Figure 2. Structure of Wireless Sensor Network

In addition to local information collection and data processing, sensor node also fuses and forward the data sent from other nodes. Since the processing, storage and communication capabilities of these sensor nodes are relatively weak, and the battery supply is limited, thus, how to save energy and prolong the lifecycle of the whole network in the routing process is a crucial point of wireless sensor network.

Some existing routing protocol currently have the following problems:

1) Routing is distributed, and the nodes need to implement routing algorithm, this will increase the costs of calculation, storage and communication(LEACH[7])

2) The energy consumption and residual energy of the nodes aren't considered by routing calculation (MECN[20])

3) The nodes need to store large quantities of routing information (WRP[14])

For solving the above problems, this paper proposed a Centralized Energy-Efficient Wireless Sensor Network Routing Protocol (CEERP) for the static sensor nodes. This protocol is applicable to the scenario where the sensor nodes are fixed in the sensor network. First, the base station (or gateway) node acquires the topology information of the wireless sensor network; secondly, with guarantee of network connectivity, the base station (or gateway) calculates the optimal routing path of all sensor nodes to the base station (or gateway) in a centralized way; the base station (or gateway) node then notifies each sensor node of the optimal path. Finally, the perceived data is routed to the base station (or gateway) through multi-hop along the optimal route to achieve the purpose of saving energy, lowering node disturbance and prolonging lifecycle of the network.

This paper is organized as follows: The related work is described in Section II. The model related to the CEERP is discussed in Section III. Sections IV elaborates on the proposed protocol and its detailed analysis. Section V presents simulation and he experimental results of the proposed protocol compared to the RPL [27, 26]. Finally, conclude this study in Section VI.

2 Related Works

At present, research on wireless sensor network routing protocols has achieved certain results at home and abroad [21, 2, 6, 1]. The main routing methods are network structure-based routing, communication model-based routing, topology-based routing, and reliability routing.

The energy-efficient flooding with minimum latency plane routing algorithm proposed by Song HuaHua et al. [22] belongs to a network-based routing, and is constructed by constructing the shortest path tree with the smallest delay from the sink node to other nodes, and then establishing the minimum spanning tree with given time delay. However, this algorithm has the problems of information explosion and overlapping.

The LEACH algorithm proposed by Heinzelman et al. from MIT[7] divides the network into hierarchical cluster structures. They select the nodes as cluster head nodes based the cluster head selection algorithm, and the remaining non-cluster head nodes join corresponding clusters following certain rules. The non-cluster head nodes in the cluster transmit the perceived data to the respective cluster head nodes, and the fused data in the cluster head node are forwarded to the base station (or gateway), to reduce the energy consumption of the network. However, this algorithm cannot assure the uniform distribution of the cluster head nodes, and the energy consumption of the cluster head nodes farther away from the base station (or gateway) will be too high.

Directed Diffusion is a query routing mechanism based on communication model [8]. The whole process can be divided into five stages: data naming, interests spreading, gradients construction, data transmission, path reinforcement. The sink node sends the query tasks through the interest messages, and floods these interest messages to all sensor nodes in the whole area or partial areas. The interest message contains parameters such as task type, target area, data transmission rate, and timestamp. In the process of interest message transmission, the protocol establishes a reverse data transmission gradient from the data source to the sink node hop by hop on each sensor node. The sensor node transmits the collected data to the sink node along the gradient direction. However, the communication overhead of this method is large.

Y. Yu et al. proposed a topology-based GEAR routing protocol [28], which establishes an optimized path from a base station or a sink node to a time zone based on the address location of the time zone. GEAR is a location-based routing protocol that takes energy efficiency into consideration. It uses the query-driven data transfer mode as well as the geographic location information in the data packet to transmit the information spread throughout the network to the appropriate location area. Since the data table is exchanged during the period, the communication overhead is large.

QoS-based routing protocol is a reliable routing method. It achieves an equilibrium between energy consumption and quality of data transmission to meet some time delays and bandwidth requirements [5]. K Sohrabi et al. firstly proposed a SAR routing protocol by combining the service quality and routing selection [21]. This protocol determines the routing path based on the energy consumption, the requirements of service quality and packet priority. Their goal is to minimize the average weighting of QoS metrics throughout the whole lifecycle of the network.

3 Related Model of CEERP

3.1 Topological Model of Wireless Sensor Network

3.1.1 Definition of Topological Model

This paper abstracts the wireless sensor network into a weighted undirected graph model, i.e., $G=(V,E,W)$, where $V=\{v_1,v_2,\cdots,v_n\}$ is the set of nodes, $E\subseteq V\times V$ is the set of sides in the graph, and W is the weighted set of the side. For $\forall v\in V$, $v=(i,r_i)$ is a tuple, where i denotes the number of node, and r_i is the residual energy of the node i. For $\forall e\in E$, where $e=(v_i,v_j)$, which indicates the side formed by nodes v_i to v_j, is also a tuple. For $\forall w(e)\in W$, $w(e)=(d(e),c(e))$ is a tuple, where $d(e)$ represents the distance of the side formed by node v_i to v_j, and $c(e)$ is energy consumption when the perceived data is transmitted or received along side e. $i\in\{1,2,3,\cdots,n\}$, $j\in\{1,2,3,\cdots,n\}$.

3.1.2 Construction of Topological Model

In order to acquire the topology information of WSN, this paper uses the broadcast discovery mechanism to construct the network topology model. Figure 3 demonstrates the process of topological model construction taking a node as an example and the specific algorithm description is shown in Algorithm 1.

Algorithm 1: Topological Model Construction Algorithm

1: Set the length of time as L to broadcast message HELLO;
2: While (currentTime $\leq$ L) {
3: Each sensor node in WSN periodically broadcasts a datagram HELLO (id, HELLO);
4: The sensor node receiving the datagram HELLO feeds back a response datagram RESP (id,x,y);
5: }
6:Each sensor node generates its one-hop adjacency table$(neighbor_id, distance)$;
7: All sensor nodes transmit their own one-hop adjacency table and the residual energy r to the base station (or gateway);
8: The base station (or gateway) fuses all the one-hop adjacency tables received to obtain the topological information of the entire WSN.

Table 1 is the topological information generated after the base station fuses the adjacency tables of all nodes.

3.2 Energy Consumption Model

In this paper, the First Order Radio Model [4] is applied in calculation of energy consumption during data transmission as in Figure 4.

It can be known from the First Order Radio Model that the energy consumption is mainly composed of a transmitting module (Transmit Electronics), an amplifying module (Tx Amplifier) and a receiving module (Receive Electronics), where the energy consumption of Transmit Electronics and Receive Electronics is the same, that is $E_{Tx-elec}=E_{Rx-elec}=E_{elec}=50nJ/bit$, and the energy consumption of Tx Amplifier is $\varepsilon_{amp}=100pJ/bit/m^2$. The energy consumption when transmitting data is

$$E_{Tx}(k,d)=E_{elec}*k+\varepsilon_{amp}*k*d^2 \quad (1)$$

and the consumption when receiving data is

$$E_{Rx}(k)=E_{elec}*k \quad (2)$$

4 Description of CEERP Protocol

Since WSN is an application-oriented network, the fixed location of the sensor node is a wide application scenario in its application field. One of the most typical applications is the environmental monitoring. The routing protocol proposed in this paper is based on the following two assumptions: 1) Sensor node position is fixed; 2) Real-time requirement isn't high.

4.1 CEERP Process

The CEERP protocol is mainly divided into five steps: network initialization, topological model construction, calculation of optimal path, transmission of perceived data and updating topological model. The process flow for collection of a round data is shown in Figure 5.

The specific acquisition process is described as follows:

Step 1: Network initialization. Including specifying a unique ID for the sensor node, setting the initial energy of the sensor node as R and the maximum number of bits of data transmission as K;

Step 2: Constructing the topological structure information of WSN based on algorithm 1;

Step 3: Based on the constructed topological information, calculate the optimal path from the base station (or gateway) to all sensor nodes to form an optimal path set;

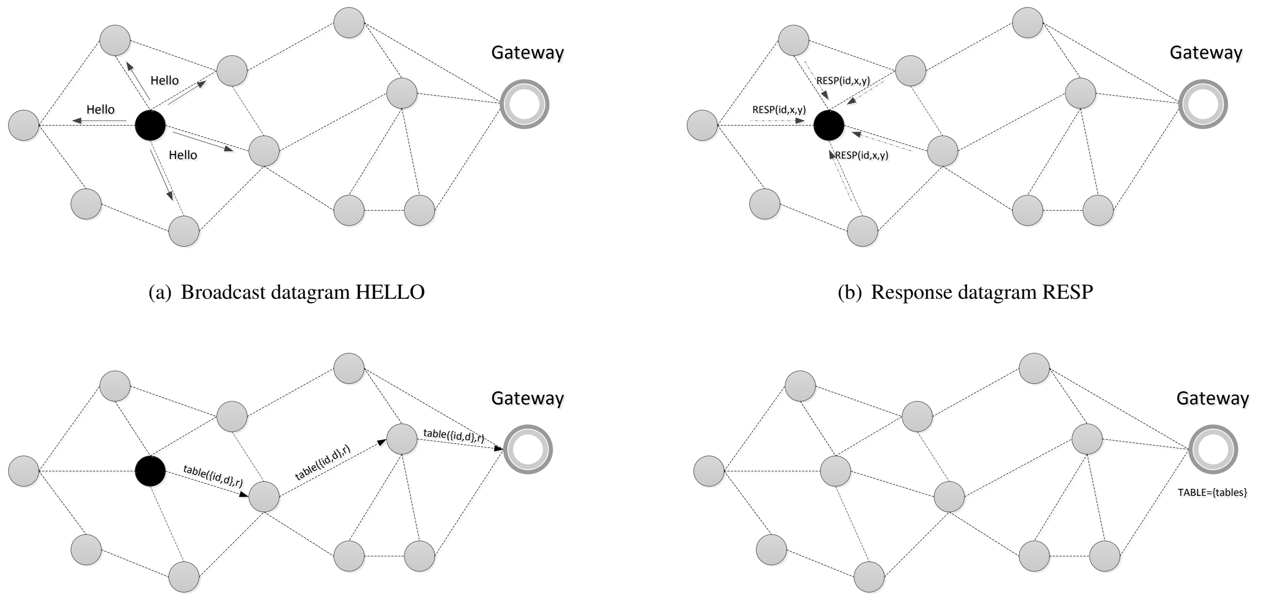
Step 4: According to the set screening rule, one of the optimal path sets is selected as the working path, and the information of the working path is sent to all sensor nodes on the working path and saved.

Step 5: The initial sensor node appeared on the working path forwards its own perceived data and residual energy to the next hop sensor node on the working path along the working path; the next hop sensor node fuses its own perceived data and residual energy, and then forwards it to the sensor node of next hop, and so on, until the base station (or gateway) receives all sensor node data on the working path;

Step 6: The base station (or gateway) receives the perceived data as well as the residual energy of all sensor nodes on the working path, and updates the residual energy of the corresponding sensor node in the topological information of the base station (or gateway);

Step 7: Based on the updated topological information, recalculate the optimal path from the sensor nodes whose data are uncollected to the base station (or gateway), then update the optimal path set;

Step 8: Repeat Step 4 to Step 7 until the perceived data and the residual energy of all sensor nodes are collected.



(a) Broadcast datagram HELLO (b) Response datagram RESP

(c) Passing one-hop adjacency table (d) Topology constructed by the base station

Figure 3. Illustration of Construction Process for Topological Model

Table 1. Topological Information Generated by the Base Station (or Gateway)

Node No./Residual Energy	$v_{(1)}/r_{(1)}$	$v_{(2)}/r_{(2)}$	$\cdots$	$v_{(n)}/r_{(n)}$
$v_{(1)}/r_{(1)}$	-	$d_{(12)}/c_{(12)}$	$\cdots$	$d_{(1n)}/c_{(1n)}$
$v_{(2)}/r_{(2)}$	$d_{(12)}/c_{(21)}$	-	$\cdots$	$d_{(2n)}/c_{(2n)}$
$\cdots$	$\cdots$	$\cdots$	-	$\cdots$
$v_{(n)}/r_{(n)}$	$d_{(12)}/c_{(n1)}$	$d_{(2n)}/c_{(n2)}$	$\cdots$	-

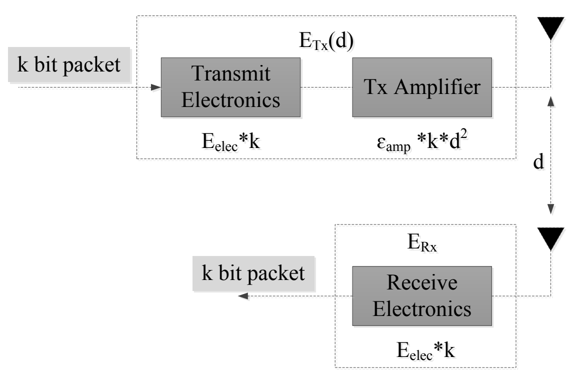


Figure 4. First Order Radio Model

4.2 Calculation of Energy Consumption

It can be known from the data collection process that the base station (or gateway) transmits the optimal path to each sensor node on the path, and then the node starts transmitting data to the base station (or gateway). Assume that $P = \{v_1 \to v_2 \to v_3 \to \cdots \to v_m \to base\}$ is a path from sensor node v_1 to the base station (or gateway), and the energy consumptions of data transmission are set as the weights on the sides, except that node v_1 only needs to receive and send data once, other nodes $v_2, v_3, \cdots, v_m$ need to receive and send data twice.

Therefore, the sides' weights of the network topological graph can be calculated by the following formula:

$$\begin{cases} E_{start} = E_{Rx}(k) + E_{Tx}(k,d) \\ E_{others} = 2\left[E_{Rx}(k) + E_{Tx}(k,d)\right] \end{cases} \tag{3}$$

where E_{start} is the energy consumption of the initial sensor node, E_{others} is the energy consumption of the sensor nodes other than the initial sensor node, $E_{Rx}(k)$ is the energy consumption of the received data, and $E_{Tx}(k,d)$ is the energy consumption of the transmitted data, which can be calculated by formulae (1) and (2).

4.3 Algorithm for Optimal Path

In order to minimize the energy consumption of each data transmission, the path with the least energy consumption is selected as the optimal path for data transmission, and the method for calculating the optimal path from the base station (or gateway) to all sensor nodes refers to algorithm 2.

Algorithm 2: Algorithm for Optimal Path

1: Initialization. Set the base station (or gateway) number as v_0, and let $S = \{v_0\}$, $T = \{V - S\}$ at initial;

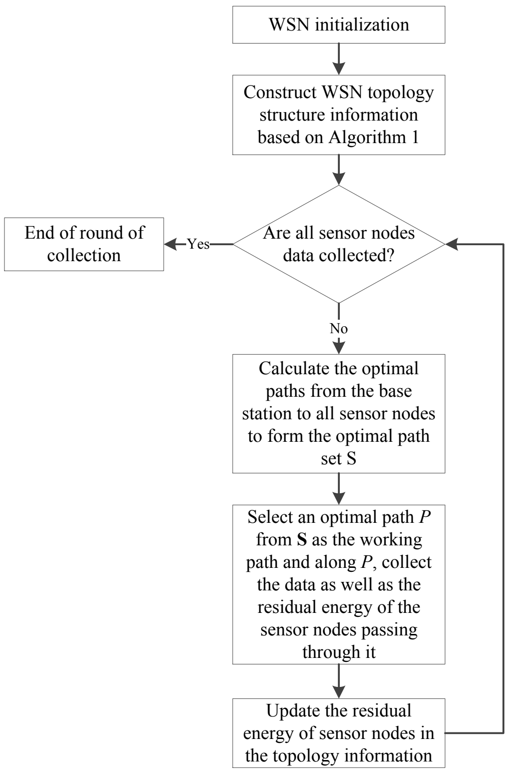


Figure 5. Flow chart of a round data collection

2: for each (node v_i) {
3: Set c_{0i} as the energy consumption value of data transmitted from the base station (or gateway) v_0 to the sensor node v_i, e_i is the residual energy of node v_i
4: if(v_0 is adjacent to v_i){
5: if $(c_{0i} > e_i)$ { $c_{0i} = \infty$; }
6: }
7: else{ $c_{0i} = \infty$; }
9: While ($V \neq S$) {
10: A sensor node with the smallest weight c is selected from T, denoted as v_{min} added to S, and the residual energy e of all forwarded sensor nodes is updated;
11: Update the weight values of the remaining sensor nodes in T:if the value of the side weight from v_0 to v_i is decreased after adding v_{min} as the intermediate node, then modify its value of the side weight;
12: }

5 Simulation and Analysis

In order to verify the effectiveness of the proposed method, the Contiki/Cooja [23, 3] platform was selected for simulation experiments, and the method was compared with the existing RPL protocol in terms of the network lifecycle and the energy consumption. Contiki is an open source and event-driven operating system that enables the interoperability of low-power, energy-constrained and memory-constrained micro devices.

5.1 Deployment of Experiment

We conducted a simulation experiment. We selected one base station node with 20 sensor nodes. The experiment was randomly deployed in the area of 100m*100m, and the upper limit of the transmission range of the sensor node was set to 20 meters. The basic simulation parameters are set as follows:

(1) The base station is at the coordinate (0,0);

(2) The energy consumption sent and received by the sensor node is $E_{Tx-elec} = E_{Rx-elec} = E_{elec} = 50nJ/bit$;

(3) The energy consumption of the sensor node amplification is $\varepsilon_{amp} = 100pJ/bit/m^2$;

(4) Initial energy of the sensor node is $100mJ$;

(5) The number of bits per packet transmission is 1000 bits.

The experiment is carried out in two stages. In the first stage, the topological model is constructed based on algorithm 1 and in the second stage, the perceived data are routed according to CEERP protocol. Also, the second stage is divided into several rounds, and it's counted as one round when data collection of all nodes is finished.

5.2 Simulation Results

Figure 6 is a WSN topological structure generated by the RPL protocol. Figure 7 is a topological structure of a WSN generated based on algorithm 1.

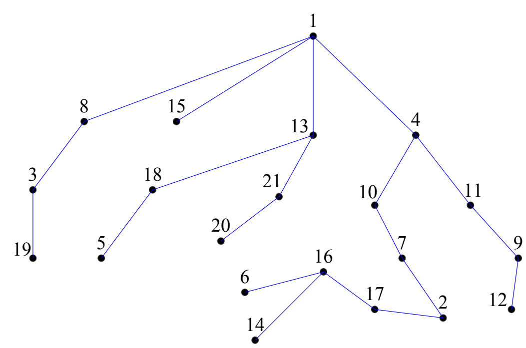


Figure 6. Topological Structure of Network Constructed by RPL

We can compare CEERP protocol proposed in this paper to the existed RPL protocol from two indexes: the whole network lifecycle and the energy consumption. The network lifecycle is measured by the number of rounds of data acquisition when the first sensor node dies and all sensor nodes die.

Figure 8 and 9 are the result diagrams of the network lifecycle. It can be seen from Figure 8 that the first sensor node of RPL protocol dies when rounds of data collection in the whole network reach 70th, while the first sensor node of CEERP protocol dies in 92nd round of data collection. Also, we can see from Figure 9 that all sensor nodes of RPL protocol die when rounds of data collection in the whole network reach 107th, while all sensor nodes of CEERP protocol

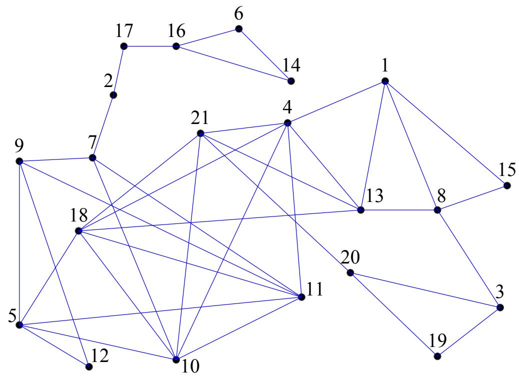


Figure 7. **Topological Structure of Network Constructed by CEERP**

die in 370th round of data collection. Therefore, the CEEPR protocol prolongs the lifecycle of WSN.

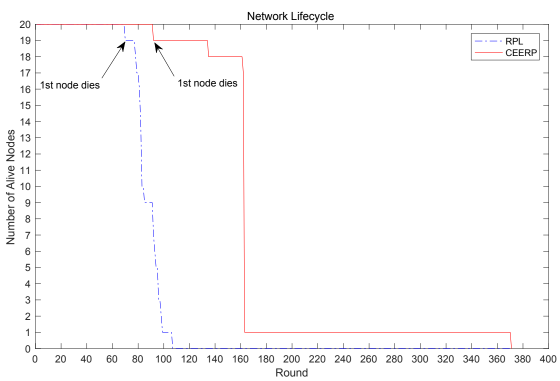


Figure 8. Rounds in Which the First Sensor Node Dies

Figure 10 demonstrates the energy consumption of the whole wireless network in each round of data collection. It can be clearly seen that the CEERP protocol consumes less energy during data collection than the RPL protocol, and the average energy consumption is reduced by about 30. In Figure 10, the RPL protocol line is shorter than the CEERP protocol line. This is because all sensor nodes in the RPL protocol die before the CEERP protocol, so there is no energy consumption data after that. This further validates that the CEERP protocol can prolong the lifecycle of the network.

6 Conclusions

This paper proposes a CEERP protocol, which is applicable to the scenario where the position of the sensor node is fixed. It is a centralized energy-efficient WSN routing protocol. The protocol consists of three parts: topology discovery, route calculation, and data transmission. Based on the weighted undirected graph model and combined with the residual energy of the sensor node, the base station (or gateway) calculates its optimal energy consumption path to

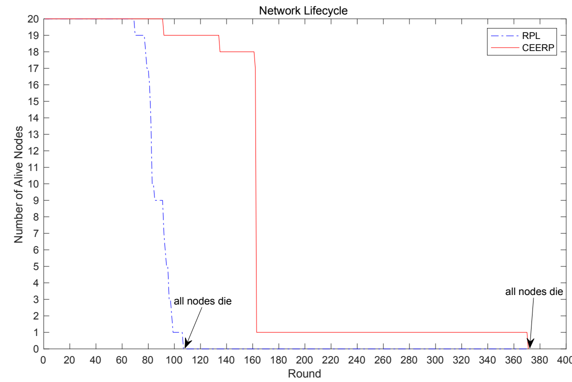


Figure 9. Rounds in Which All Sensor Nodes Die

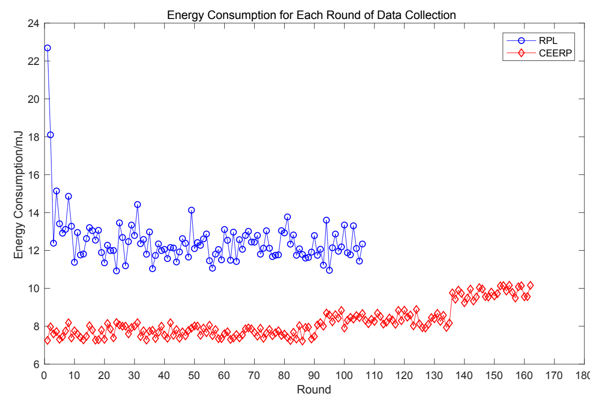


Figure 10. Energy Consumption for Data Collection

all sensor nodes, and the sensor node will perform data transmission according to the path. Finally, using the Contiki/Cooja platform, the CEERP protocol is verified and analyzed from the perspectives of network lifecycle and energy consumption. The experiments show that the CEERP protocol saves the energy consumption of around 30

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