An Energy-Optimization Method for Multipath Wireless Sensor Networks

Haofei Xie, Yushuang Wu, Rui Li, Daixiong Liu, Wanglin Zhang, Zhejian Jia

***Abstract*—This paper proposes an energy-optimization modified method for multipath Wireless Sensor Networks (WSNs). This method involves an optimized cluster head selection mechanism. We select the cluster head in the first round to obtain a fixed cluster; then compare the residual energy clusters between the fixed cluster and the reselected cluster; finally, extract the new cluster head by the comparison results. In this case, according to the energy of cluster, we design an optimal path search strategy and plan the path of data collection, so that arrange the converged paths from nodes to main path. The simulation results show that, compared with SC-MAC, the average energy utilization rate and the network life cycle are respectively increased by 8.40 times and 4.53 times; and they are respectively increased by 1.32 times and 0.95 times compared with the RMER algorithm.**

***Index Terms*—Clustering methods, Energy optimization, Multipath routing algorithm, Wireless sensor networks (WSNs)**

I. Introduction

WIRELESS Sensor Networks (WSNs), composed of many microsensor nodes deployed in the monitoring area, are multihop self-organizing wireless communication networks. To achieve network-to-area detection of specific information or events, sensor nodes collaborate with each other to collect and transmit data. With the rapid development of technologies such as sensors, microelectronics, wireless communication, and low power embedded technologies. WSNs have been widely used in industry producing, environment monitor, military applications and smart life [1]. The traditional energy-efficient routing algorithm only optimizes the data collection method and path, so it remains a challenge to design energy-saving and reliable sensor communication protocols. A typical WSN involve the sensor nodes and multihop wireless transmission, which collects monitor data and send them to the nodes. The node receive data and transmit the test results to the users through Internet, in order to realize the function of the entire network [2]. Most of the sensor nodes are powered by batteries and generally deployed in harsh or unattended monitoring areas. It means that it is significantly difficult to charge or replace the node batteries. Energy saving is a great challenge for WSNs in this case, so the lifetime and energy utilization are the key performance indicators for WSNs [3], [4].

Related research mainly reduces the energy consumption of sensor nodes to extend the network life cycle. In fact, spatially related sensor nodes close to each other usually collect a lot of redundant information. However, not all space-related nodes have to send the same monitoring data, as long as a few active sensor nodes perform tasks. It can effectively reduce network energy consumption and significantly extend network life. However, it may affect the reliability of network transmission. The distortion of event detection can measure the reliability of network detection and refers to the accuracy of the sink node of event detection. And the monitoring data can be received according to the processing of the sink node, the specific information in the network can be obtained, and the event detection can be completed.

Since sensor nodes of WSNs have large-scale and high-density distribution characteristics, multiple sensor nodes monitoring the same event may have spatial correlation, and their sizes are proportional to the distance between the different nodes. Because the fact of redundant information of numerous nodes, it is difficult for the receiving node to realize event detection, which greatly reduces detection distortion and reliability [5], [6]. At present, there have been reports on the energy research of efficient routing algorithms in WSNs. The typical LEACH algorithm mainly focuses on extending the life of the network, however, lacks indepth research on reliability. RMER takes energy efficiency and reliability into account, but does not consider the path energy consumption of nodes [7]. Therefore, based on the LEACH and RMER, this paper proposed an energy-optimized multipath routing (EOMR) algorithm with the following characteristics:

1) The algorithm is divided into multiple rounds, and each round includes initial settings and cluster head update. In the initial setup phase, sensor nodes are deployed in the network and subdivided into clusters responsible for cluster heads. These cluster heads collect data from sensor nodes, and combine data by removing all redundant bits so as to reduce capacity. The actual data which CH forwards the collected data to BS.

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2) The main experimental method is to make use of the residual energy of nodes, energy consumption of paths and hops as performance indexes to design an optimal path search strategy based on forwarding candidate set (FCS), which plan the optimal main path of data collection and the optimal converged paths from ARNs to main path. Monitoring data is firstly sent to an aggregation node through convergence paths, then sent aggregated data to the sink through main path. The optimal path search strategy based on FCS will further balance energy consumption and effectively prolong network lifetime.

II. RELATED WORKS

In WSNs, factors such as energy efficiency and network lifetime limit sensor nodes. Based on this concept, the researchers proposed a space-based MAC protocol for the energy efficient problem. The MAC layer protocol is at the bottom of the WSNs communication protocol, which would enhance the network by reasonably allocating limited wireless communication resources between sensor nodes performance.

LEACH can be considered as a classical WSNs protocol, and most of the LEACH variant papers propose a different cluster head selection process for increasing the network lifetime [8]. According to the reported work in [9], an optimal cluster head selection process without the requirement of sensor node location information is developed. According to the energy reserve of each sensor node in [10], which proposed a cluster head election process. In this case, researchers recommend using a constant number of clusters [11], [12]. ModLEACH is an effective cluster head replacement scheme, which selects a new cluster head for the corresponding cluster and determines the new cluster members [13]. RMER is another cluster protocol in which nodes with higher residual energy are more likely to be selected as cluster heads. HEED is an energy-saving distributed cluster protocol [14]. it considers the choice of CH in two stages, but it leads to an imbalance in energy consumption and generates redundant clusters. EEUC adopts a distributed and competitive operation mechanism [15]. Each node has a specified competition radius. It means that the closer to the base station, the smaller the competition radius. Although the link cost is increased, the network lifetime is significantly improved. However, most aggregation algorithms emphasize CH selection and do not consider how to transfer aggregated data to relay nodes. The extended network lifetime and improved stability in aggregation problems have also been the focus of future research.

The S-MAC protocol is one of the typical MAC protocols, which divides a node into multiple virtual clusters through a dormancy coordination mechanism [5]. By sleeping on the virtual cluster, the nodes stay the dormant model as much as possible to reduce power consumption. The activity/sleep period of the node can be dynamically adjusted according to network traffic to further reduce energy consumption. Vuran and Akyildiz proposed the CC-MAC protocol, which divides the event area into different subnets by using the relevant radius and selects only one node in each subnet as an active reporting node (ARN) [4]. Other nodes are in sleep mode, which reduces channel competition and power consumption. They also proposed a MAC protocol to guarantee the network QoS for large-scale densely distributed WSNs. This protocol controls only one monitoring node in the neighborhoods to send messages with the purpose of redundant data suppression. By minimizing the amount of data transmission below the distortion threshold, the network effectively reduces the transmission delay and power consumption.

The routing protocol can find the optimal path from the source node to the destination node and correctly transmit the data packet along the designed path. Therefore, efficient routing protocols can effectively reduce node energy consumption and extend network lifetime. Classic routing algorithms include planar routing algorithms and hierarchical routing algorithms [16]. Energy efficient plane routing algorithms include Mini-Hops routing algorithm, DD routing algorithm, SPIN routing algorithm, and SAR routing algorithm Typical hierarchical routing algorithms include LEACH, TEEN and PEGASIS [17]-[23]. To optimize the energy usage, a lot of research on network QoS, especially in detection area has been reported. Network detection reliability refers to the accuracy of sink node detection of events, which can be measured by the degree of distortion of event detection. The closer the distance between nodes is, the stronger the spatial correlation is. The monitoring data of these nodes includes much redundant information. The sink node needs a certain amount of monitoring data to complete the event detection. In the case of a certain amount of data, the increasement of redundant information in the monitoring data will lead to the greater detection distortion of sink node and the lower reliability of the event detection [4]. Zhang et al. proposed a spatial correlation model of WSNs [24]. The model is used to investigate the influence of sensor node position on the detection distortion of sink nodes. The degree of distortion measures the reliability of detection, so that they designed an iterative node selection algorithm. ISN algorithm gives the monitoring node a better position distribution and acquires the minimized detection distortion. Liu et al. proposed a circular space correlation model [7]. The priority of the access channel is assigned to the node according to the distance between the node and the event source. The closer the event source is, the higher the node priority is, so that the sink node receives the distance as much as possible. High quality monitoring data with near event sources will reduce detection distortion. Bouabdallah, Bouabdallah and Boutaba proposed a reliability evaluation model based on spatial correlation, and the influences of the number of monitoring nodes, location and the number of monitoring packets on the reliability of sink node detection are evaluated [5]. Based on these considerations, they designed SC-MAC based on spatial correlation. The routing algorithm uses an active-reporting-node selection mechanism based on the correlation radius to eliminate redundant nodes and suppress the transmission of redundant data. The collection scheme of existing data is difficult to provide high detection reliability as well as the high energy efficiency. To solve this problem, a reliable and multipath encounter routing algorithm is proposed [7]. In general, the hotspot area (the area within the one-hop range of sink node) has the fastest energy consumption, which will accelerate the exhaustion of energy in the hotspot area and result in the death of the network. Nodes in nonhotspot areas typically have much unused energy.

The multipath encounter routing algorithm satisfies the detection reliability and energy efficiency requirements to a certain extent. However, there are two main defects:

1) This algorithm does not consider whether the energy of the cluster head node will affect the data transmission, because the cluster head selection will determine the initial energy of the sink node.
2) The algorithm selects the ARNs based on the remaining energy of the node. However, the algorithm estimates the residual energy based on the distance from the node to the sink node, regardless of the influence of node density on energy consumption in different regions. In the case of uneven distribution of network nodes, RMER cannot use network energy completely uniformly.

The algorithm proposed in this article can solve the above problems.

III. ALGORITHM MODEL

The network scenario is a large circular network with a radius of R, where the network nodes are randomly and nonuniformly distributed, and the node density varies in different areas, as shown in Fig. 1. The sensing range of nodes is r_s, and transmission range is r_c. The sink node locates in the center of the network, collecting information from all the nodes. And the network model has the following characteristics:

1) All sensor nodes are homogeneous, including the same structure and initial energy, the perception of energy and location information, the certain storage and computing capabilities and the unique identifiers.
2) The sensor node MAC layer uses the improved IEEE 802.11 DCF-based protocol mentioned in [25] to compete for channels through the RTS/CTS mechanism.
3) The sensor node has a perceived radius r_s, and a transmission radius r_c, where $r_c \geq 2r_s$.

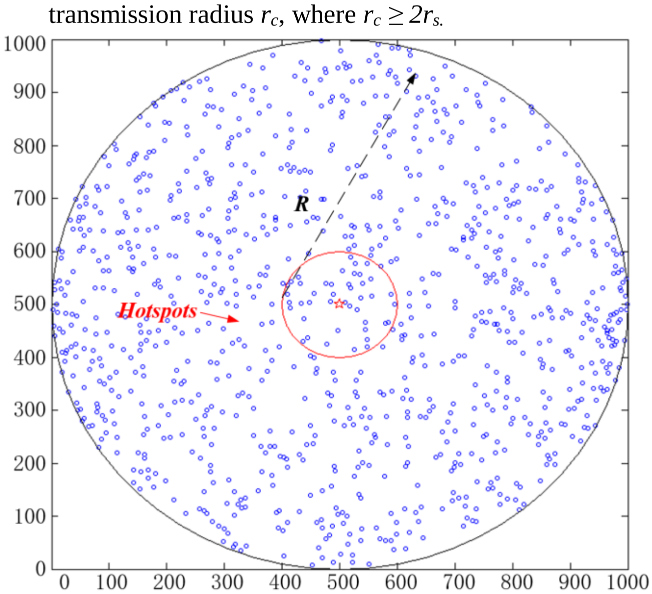

Fig. 1. Network model

The network is event-driven, and specific events trigger communication. Once an event occurs, m nodes are selected as ARNs in the event areas (circular area with the center of the event source S and radius r_s), and continuously send n packets to the sink node. Network reporting frequency is f, which means the number of monitoring packets sent by the ARNs in the unit time when network monitors events occur. Nodes adopt the periodic sleep/active work mode. We divide the main energy consumption of the node into two parts:

Energy consumption is in active mode, which adopts w_a to denote the energy consumption rate; Energy consumption occurs when nodes send and receive data. The typical WSN energy consumption model is adopted to calculate the energy consumption of sending and receiving data, which is given by (1) and (2) respectively.

$$E_T(l) = \begin{cases} lE_{elec} + l\varepsilon_{fs} d^2, d < d_0 \\ lE_{elec} + l\varepsilon_{mp} d^4, d \geq d_0 \end{cases} \tag{1}$$

$$E_R(l) = lE_{elec} \tag{2}$$

where E_{elec} is the transmission circuit energy consumption, d_0 and l respectively represent the distance threshold and the data length. The power amplifier follows the free space model when the transmission distance is less than d_0 and follows the multipath fading model on the contrary. ε_{fs} and ε_{amp} represent the necessary energy consumption of the power amplifier corresponding to the two models, respectively.

We adopt the lossless step-by-step multihop aggregation model [7]. In this model, the convergence nodes aggregate the continuous arrival data.

$$\varphi(N_i, N_j) = \max(\theta_i, \theta_j) + (1-c)\min(\theta_i, \theta_j) \tag{3}$$

where c denotes the correlation coefficient. If the aggregated data packets are not both origin data, the aggregation results is given by:

$$\varphi(N_i, N_j) = \max(\theta_i, \theta_j) + \varsigma(1-c)\min(\theta_i, \theta_j) \tag{4}$$

where ζ is the forgetting factor which is a decimal in the range of 0-1. According to communication theory, the observation noise N_i is modeled as Gaussian random variable of zero mean and variance σ_m^2. The event source information S_i is modeled as a joint Gaussian random variable (JGRV) as follows:

$$E(S_i) = 0, \operatorname{var}\{S_i\} = \sigma_s^2, i = 1, \ldots, m$$
$$\rho(i, j) = K_\vartheta(\mathrm{d(i,j)}) = \frac{E(S_i S_j)}{\sigma_s^2} \tag{5}$$

where $d(i,j)$ denotes the distance between nodes i and j [26].

EOMR is executed in the stable operation phase of the network. Before the network runs stably, it performs initialization operation. This process generally occurs after the completion of network deployment. During the network initialization phase, the network performs the following initialization processes:

1) Through the minimum hop routing algorithm, each sensor node finds its minimum hop path and stores it in the route [19].
2) Sink node calculates and generates a sensor information table of the entire network based on the location information.

3) Sink node uses the calculation method of SC-MAC to find the multigroup of the network $(N,R(N),r_{corr})$, as shown in Fig. 2.

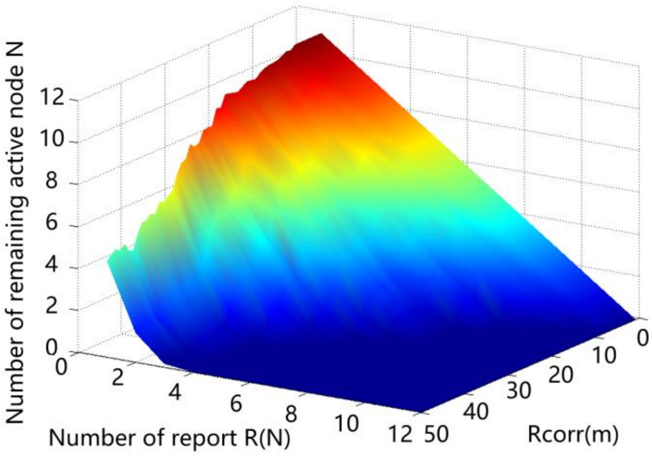

Fig. 2. Network $(N,R(N),r_{corr})$ group

IV. ALGORITHM DESIGN

A. Cluster Head Selection Algorithm

This paper proposes an improved cluster head selection method, which is divided into three stages: estimation of node energy consumption rate, number allocation of ARNs, and cluster head update.

Estimation of Node Energy Consumption Rate

Munadi et al. proposed an energy consumption estimation model based on the distance between nodes and sink nodes [18]. The energy consumption of a node consists of three parts:

1) The energy consumption from data transmitting for the node.
2) The noncommunication energy consumption of the node in the active state.
3) The energy consumption of the node is in the sleep state.

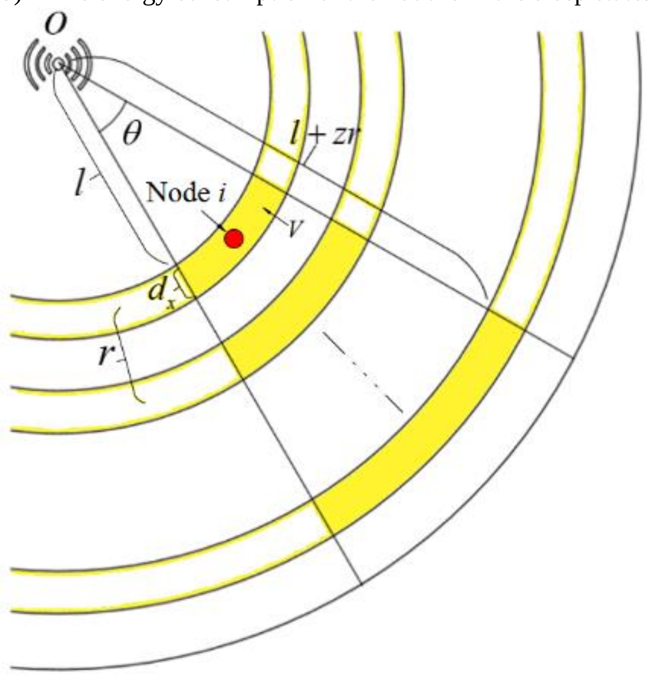

Fig. 3. Network packets transmission model

However, the model did not evaluate the effect of node density in different areas on energy consumption. Therefore, introducing the node density in the estimation is essential. It is considered that a network radius of R, where events occur in the network randomly. In a period, the event occurrence probability per unit area is recorded as μ, and the total packets generated by each event is defined as n. Monitored data is aggregated in the aggregate node whose distance from the event source S is b hops. The transmission radius of the node is expressed as r.

As shown in Fig.3, a small sector area V is selected in the network. The width of V is $dx \to 0$ and the angle range is $\theta \to 0$. Node i is allocated in this area, and its distance from the sink node is marked as l, where $l=hr+x$. The area V receives the data sent by the node in the sector area $V', V'' \cdots$, which is $l+kr(k \in \{1, \ldots, z\}$ away from V.

The packets received by area V can be divided into two parts: one is the unaggregated packets sent by the area that is within b hops from area V and the other is the aggregated packets sent by the area that is not within b hops from area V. The number of unaggregated packets is firstly calculated. The area of the V is $\theta l d_x$ and the number of packets generated by V is n $\theta l d_x \mu$. The number of packets generated by V' is denoted $n \theta (1+r) d_x \mu$, and so on. Therefore, the total number of unaggregated packets for area V transmission is represented by:

$$P_l^1 = n\theta \mathrm{d_x} \mu \{l + (l+r) + \ldots + (l+br)\} \tag{6}$$

Assuming that data is aggregated in convergence node j, according to the data aggregation model in section II, the number aggregation of the first two packets can be calculated.

$$\varphi(i) = len(p) + (1-c) len(p) = len(p)(2-c) \tag{7}$$

After the first two packages are aggregated, the aggregated packet continues to be aggregated with the subsequent n-2 packets.

$$\begin{aligned}\varphi(i) &= len(p)(2-\mathrm{c}) + (\mathrm{n}-2)\varsigma(1-\mathrm{c})\mathrm{len}(\mathrm{p}) \\ &= \mathrm{len}(\mathrm{p})\{(2-\mathrm{c}) + (\mathrm{n}-\mathrm{c})\varsigma(1-\mathrm{c})\}\end{aligned} \tag{8}$$

Thus, the number of aggregated packets is obtained, which can be expressed as:

$$\begin{aligned}\mathrm{p}_l^2 &= n\theta d_x \mu\{(l+(b+1)r) + (l+(b+2)r) + \\ &\ldots + (l+(b+z)r)\}\{(2-c) + (n-2)\varsigma(1-c)\}\end{aligned} \tag{9}$$

The node density of the area V is defined ρ_l, thereby the total number of packets transmitted by the node i is calculated as:

$$\begin{aligned}p_l^i &= \frac{(p_l^1 + p_l^2)}{\rho_l \theta l d_x} \\ &= \left\{\begin{aligned}&\left(b+1+\frac{(1+b)br}{2l}\right)n\mu \\ &+\left(z-b+1+\frac{(b+z)(z-b+1)r}{2l}\right) \\ &\times\mu\left((2-c)+(n-2)\varsigma(1-c)\right)\end{aligned}\right\} / \rho_l\end{aligned} \tag{10}$$

Assume that an event occurring in the area with a distance *l* from sink is allocated with m_l ARNs, thus the probability of each node being selected as ARNs in the event area can be obtained.

$$\lambda_l^a = \frac{m_l}{\rho_l \pi r_s^2} \times \pi r_s^2 \mu = \frac{\mu m_l}{\rho_l} \tag{11}$$

The energy consumption of nodes to transmit *a* packet is defined *e*, and the energy consumption rate of the active mode is ω_a. Therefore, the energy consumption of the node in the event area of each period is expressed as follows:

$$E_l = P_l^i e + \left(\frac{n}{f}\right)\omega_a \lambda_l^a \tag{12}$$

Number Allocation of ARNs

This paper assigns the corresponding number of ARNs to the event area based on the energy consumption rate. The allocation principle of the number of ARNs selects more ARNs in slow energy consumption area and fewer ARNs in the fast energy consumption area. And the area with the lowest node density in hotspot is the fastest energy consuming area. Generally, in the whole network, the highest energy consumption rate occurs in the lowest node density area, as shown in Fig. 4, where the H means the hotspot area, and the P express the energy peak area.

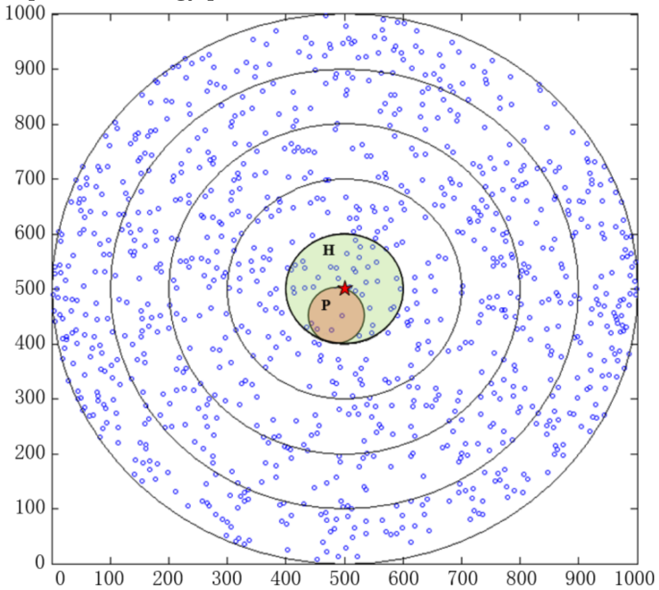

Fig. 4. Network energy peak area

In order to ensure the detection reliability threshold, the minimum ARNs number m_{hot} in the energy peak area is allocated to reduce the energy consumption. In other areas of the network, the energy consumption rate is close to the peak energy by adjusting the number of nodes, so that we can improve energy efficiency and detection reliability. In the ideal case it can be expressed as:

$$E_l = E_{hot} \tag{13}$$

Thus, the number of ARNs in the event area with a distance *l* from sink node can be calculated:

$$m_l = \frac{\rho_l}{\rho_{hot}} m_{hot} + \frac{\left(P_{hot} - P_l\right) e \rho_l}{\left(\frac{n}{f}\right)\omega_a \mu} \tag{14}$$

where ρ_{hot} denotes the node density of the energy peak area, ρ_l denotes the number of packets transmitted by the node in the energy peak area.

Cluster Head Update

After the first round of randomly selecting cluster heads, the cluster heads in the current network broadcast information to the cluster member nodes, then request to check the signal strength of the message and confirm the added cluster heads. The method of consumption influence function is taken:

$$M_l = \min\left\{\frac{E_{res}^{n_1}}{E_{CH}^{n_1}}, \frac{E_{res}^{n_2}}{E_{CH}^{n_2}}, \dots, \frac{E_{res}^{n_{L-1}}}{E_{CH}^{n_{L-1}}}\right\} \tag{15}$$

$E_{res}^{n_{L-1}}$ and $E_{CH}^{n_{L-1}}$ respectively represents the remaining energy of candidate nodes and the energy consumed when becoming cluster head, and L represents the number of surviving nodes.

The next cluster head should be represented as:

$$CH_{selected} = \max \frac{E_{res}^{CH} \times f_L}{d\left(CH, BS\right)} \tag{16}$$

B. ARNs Selection Algorithm Based on Dynamic Correlation Radius

In the process of ARNs allocation in the event area, the nodes in the event area continuously select the first ARN through the RTS/CTS mechanism. If the number of ARNs allocated in the event area, the algorithm step of ARNs selection based on the dynamic correlation radius can be described as follows:

Step1: Number of initial ARNs *atc=0*.

Step2: *N=0*， *R(N)=m*, Initial correlation radius r_c=r_{corr}.

Step3: According to the event area node information received in the process of ARNs number calculation, the sink node respectively generates the ARNs node set *N(ARNs)* and the event area node set *N(Alts)*, where *N(ARNs)* contain only one ARN， but *N(Alts)* contain all nodes except the first ARN in the event area.

Step4: *atc=atc+1*, if *atc=m*, then the algorithm is ended, otherwise ***Step5*** is executed.

Step5: Each node in *N(Alts)* is determined if the distance between the node and any one of *N(ARNs)* is less than or equal to r_c, and the node is deleted from *N(Alts)*.

Step6: If node set *N(Alts)* is not an empty set, ***Step7*** is executed; if node set *N(Alts)* is an empty set, ***Step8*** is executed.

Step7: In node set A, one node with the highest remaining energy is selected as the ARN, and the node from A to B is moved, and then ***Step4*** is executed.

Step8: r_c=r_c-r_{step}, *atc=1*, node sets *N(ARNs)* and *N(Alts)* to the generation state is reset and ***Step5*** is re-executed, where r_{step} expresses the length of each shortened by r_c.

The detailed algorithm is as shown:

TABLE I
ARNs SELECTION ALGORITHM BASED ON DYNAMIC CORRELATION RADIUS

INPUT: EventAreaNodes, FirstARN, *m*
OUTPUT: ARNs
N = 0; R(N) = m; r_{corr} *= (N,R(N),*r_{corr}*);*
ARNs = zeros(1,m);
ARNs(1,1) = FirstARN;
Alts = EventAreaNodes;
Remove(FirstARN,Alts);
Atc = 1;
FOR r_c = r_{corr}:-r_{step}:*1*
  FOR atc = 1:1:m

```
    FOR NumAlts = 1:1:length(Alts)
      FOR NumARNs = 1:1:length(ARNs)
        IF (distance(Alts(1,NumAlts),ARNs(1,NumARNs))<= rc)
          Delete(Alts(1,NumAlts),Alts);
        END
      END
    END
    MaxResidualEnergyNode = 1; MaxRE = ResidualEnergy Alts(1,1);
    FOR NumAlts = 2:1:length(Alts)
        IF (MaxResidualEnergyNode(Alts(1,NumAlts)) >= MaxRE);
          MaxResidualEnergyNode=NumAlts;
          MaxRE = axResidualEnergyNode(Alts(1,NumAlts));
        END
    END
     Rmove(ARNs,Alts(1,MaxResidualEnergyNode))
     IF (length(Alts) == 0)
       break;
    END
  END
  IF (length(ARNs) == m
    break;
  END
END
```

After the execution of the algorithm, the nodes in the obtained node set *N(ARNs)* are the event areas which are ARNs. Then the selection of the event area ARNs, the path of data transmission for each ARN needs to be planned for the EOMR algorithm. The following points should be considered for ARNs node path planning:

1) The transmission path should avoid the "hot spot" node with less residual energy so that the energy consumption of network data transmission is balanced as much as possible, which can effectively extend the network life cycle.
2) While avoiding energy "hot spots", the total energy consumption of the data transmission path should be as small as possible.
3) The delay of data transmission is related to the number of path hops. Therefore, the path hop factor should be considered when planning the path. The path hop count should be close to the minimum hop count and can not increase too much.

Based on the above analysis, this paper develops an optimal path search algorithm through forward forwarding node set.

C. The Optimal Path Search Strategy Based on FCS

The EOMR algorithm plans the energy-balanced multipath encounter routing by optimal path search strategy based on FCS, the main steps of the strategy are as follows [27]:

Suppose that A and B respectively express the source node and the destination node.

The detailed algorithm is as shown:

TABLE II

THE OPTIMAL PATH SEARCH STRATEGY BASED ON FCS

```
INPUT: Coordinates A(x,y) and B(x,y)
OUTPUT: The optimal path from A to B
Function [Paths(A,B) = Get_optimal_path_set(A,B)]
RelayNode = A;
WHILE (Distance(Neighbor(RelayNode),B)>Rc)
      OptionalNode(RelayNode)
      FOR Node = 1: length(Neighbor(RelayNode))
            IF Distance(Node,B) < Distance(NextRelayNode,B)
                  NextRelayNode = Node;
            END
      END
      FOR Node = 1: length(Neighbor(RelayNode))
            IF Distance(Node,NextRelayNode) < Ro
                  Remove(OptionalNode(RelayNode),Node);
            END
      END
       Paths(A,B)=Routing(Paths(A,B),RelayNode,OptionalNode(Rel
  ayNode));
      Get_optimal_path_set(OptionalNode(RelayNode),B);
END
      OptimalPath = MAX(QualityEvaluation(Paths(A,B)));
END
```

Step1: Select the nearest neighbor node from a to b as the master node. Then the primary node is taken as the center and r_0 is taken as the radius, so as to form a circular screening area. The neighbor nodes of A in the circular screening area constitute the FCS of A. A form the first hop path with the nodes in the FCS, as shown in Fig. 5.

Step2: The nodes in the FCS of A seek their FCS by the method of step1 and form the new hop with the nodes in their FCS. As shown in Fig. 5, the nodes b_4, b_5 are sought as the FCS of a_3 and form the second hop with a_3.

Step3: The nodes of every new FCS repeat step 1 and step 2 until the nodes in their FCS are all the neighbor node of node B. All the formed paths constitute the optimal path alternative set *V(A,B)*.

Step4: Evaluate path quality *P(n)* by performance index function and select optimal path from *V(A,B)*. The performance index function synthetically considers four factors: 1) $E_{ave}(n)$: Average residual energy of nodes on the path. 2) E_{min}: Minimum residual energy of nodes on the path. 3) $E_{con}(n)$: Energy consumption of the path. 4) $H_{hop}(n)$: Hopping number of the path. Use the minimum and maximum standardization method to transform the data, and then use the linear-weighted-sum method to obtain the performance index function, which is the formula (17).

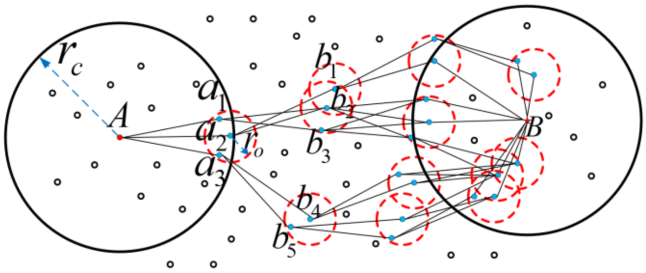

Fig. 5. The optimal routing path selection strategy based on FCS

$$
\begin{aligned}
P(n) &= \lambda \frac{(E_{ave})\max - E_{ave}(n)}{(E_{ave})\max - (E_{ave})\min} + \\
&\mu \frac{(E_{\min})\max - E_{\min}(n)}{(E_{\min})\max - (E_{\min})\min} + \beta \frac{(E_{con})\max - E_{con}(n)}{(E_{con})\max - (E_{con})\min} \\
&+ \delta \frac{(E_{hop})\max - E_{hop}(n)}{(E_{hop})\max - (E_{hop})\min}
\end{aligned} \tag{17}
$$

where $\lambda+\mu+\beta+\delta=1$.

D. Steps of The EOMR Routing Algorithm

The main stages of EOMR are as follows:

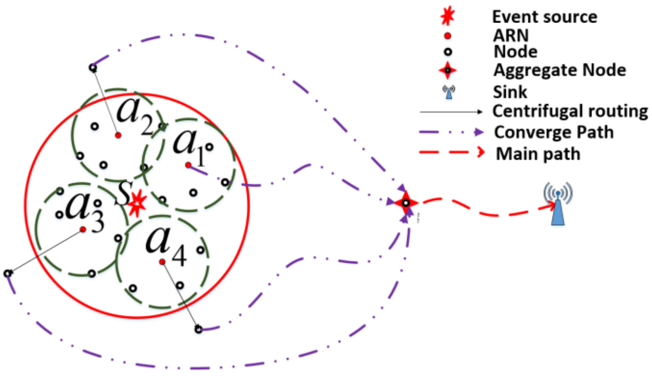

Fig. 6. The main stages of EOMR

The flow chart of the EOMR routing algorithm is as follows:

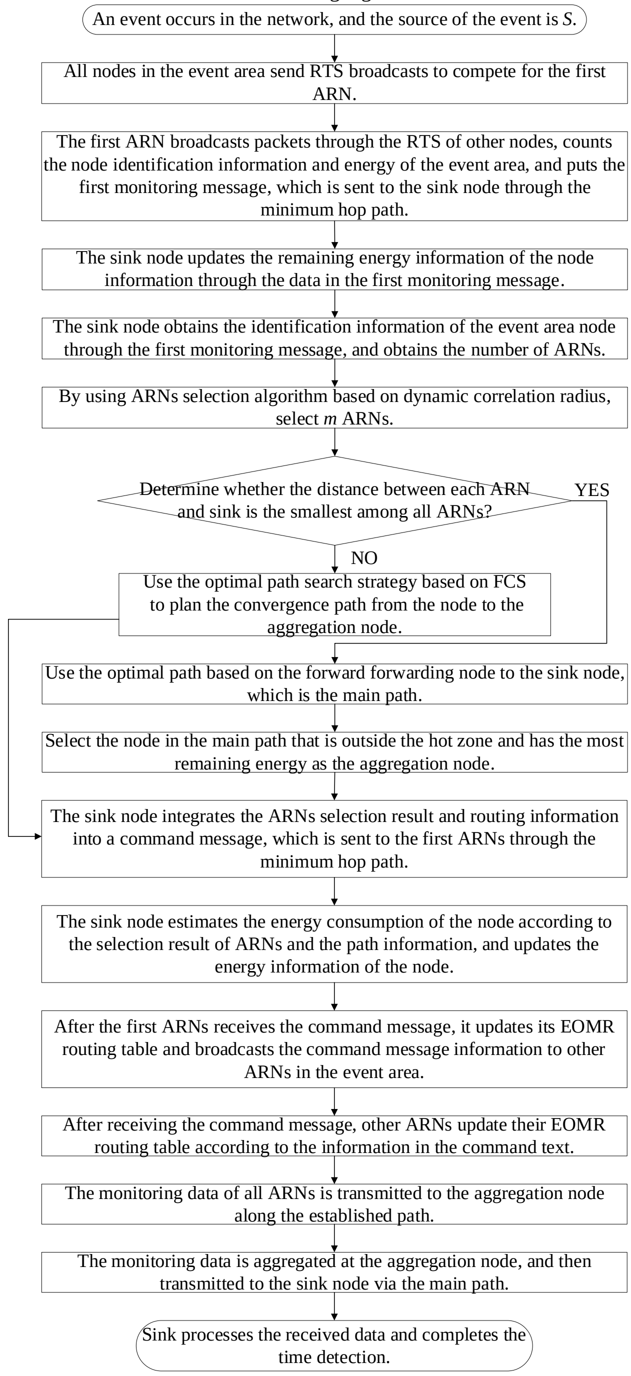

Fig. 7. EOMR routing algorithm flowchart

Stage1. Selection of ARNs: Once an event occurs, the algorithm allocates the number of ARNs *m* for the event area by the number allocation mechanism of ARNs based on energy balance. Then use the node selection algorithm based on the relative radius to select the *m* ARN. ARNs are turned to active model from sleep model, continuously monitoring events, while other nodes in the event area remain sleep model. As shown in Fig. 6, a_1, a_2, a_3, and a_4 are selected as ARNs.

Stage2. Formation of Main Routing: After the ARNs selection phase, the algorithm selects the ARN a_1 with the shortest distance to the sink node as the starting node of the main path. The main path is planned from a_1 to the sink node by the optimal path search strategy based on FCS, and the node is selected with the most residual energy on main path as the aggregation node.

Stage3. Centrifugal Routing and Encounter Routing: Other ARNs firstly do centrifugal routing out of the event area by selecting the neighbor node with the farthest distance to the event source *S* as the next hop, thereby we can reduce collision and event detection delays in the event area. After the centrifugal routing, the converging paths from ARNs to the convergence node is planned by the optimal path search strategy based on FCS. All monitoring data of ARNs reach the aggregation node through the centrifugal path and converging path.

Stage4. Data Aggregation and main path transmission: All data are aggregated at the aggregation node and then are transmitted to the sink node through the main path.

V. SIMULATION RESULTS

To evaluate the performance of EOMR, we use MATLAB for simulation and comparison. According to the optimization goal of the algorithm, this paper selects three performance indicators to test and analyzes the algorithm as follows:

1) θ expresses detection reliability.
2) T expresses network life cycle, which is the time when the first dead node in the network appears. The network energy utilization in this paper refers to the ratio of the energy used by the network to the initial total energy when the network dies. For the nodes in the network, the initial energy of each node is defined as *e*, and the residual energy of each node is expressed q_i when the network dies.

The detailed parameter of simulation is shown in Table III.

TABLE III
SIMULATION PARAMETERS

Network radius *R*	400m
Number of nodes *n*	800
Node transmission range r_c	80m
Node sensing range r_s	40m
Packet length *l*	1024 bi
Event occurrence frequency	30
Threshold distance d_0	85m
E_{elec}	40nJ/bit
e_{fs}	15pJ/bit/m^2
e_{mp}	0.0014pJ/bit/m^4
Initial energy	0.5J
Event detection threshold Φ	8

A. Event Detection Distortion

The detection distortion for different distance as shown in Fig. 8.

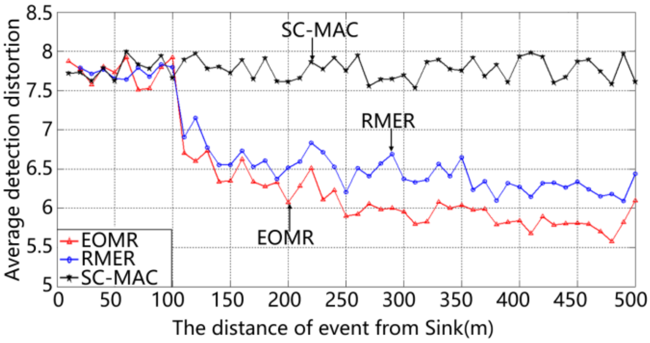

Fig. 8. The detection distortion for different distance

Since the SC-MAC protocol selects the same number of ARNs regardless of where the event occurs, the detection distortion almost remains invariant. As the distance between the event area and the sink node increases, RMER selects more ARNs, which reduces the detection distortion of nonhotspot event. EOMR selects ARNs by number allocation mechanism of ARNs based on energy balance, which makes the energy consumption rate of different network area to approach to the energy peak, thereby fully using the network energy and further reducing the detection distortion.

The abscissa demonstrated in Fig. 9 indicates the distance between the event and the sink node, and the ordinate indicates the detected distortion of the event. The simulation results show that, compared with SC-MAC, RMER, and EOMR greatly reduce the detection distortion outside the hotspot area, and the distortion decreases as the distance between the event area and the sink node increases. Furthermore, the algorithm selects more ARNs in the low-energy region outside the hotspot area, which increases the information amount of the sink node detection event and the accuracy of the information, thereby improving the detection reliability.

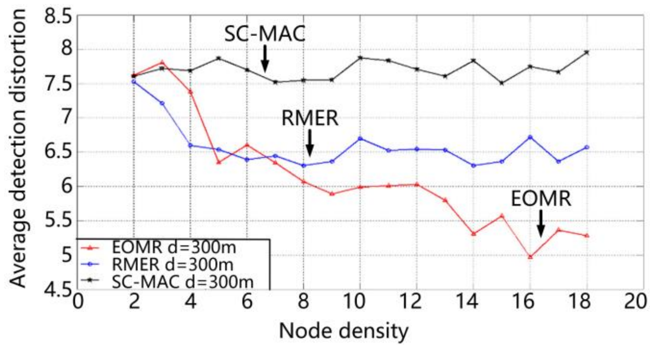

Fig. 9. Detection distortion of different node density areas at a distance of 300m from the sink node

Fig. 10 illustrates the distribution of ARNs in different regions of the network by three algorithms. The abscissa is the distance between the event and the sink node, and the ordinate is the theoretical value of the number of ARNs in the event region.

1) The number of ARNs allocated by SC-MAC in all event areas of the network is constant, and the minimum number of network detection reliability that satisfies the reliability threshold is maintained.
2) RMER allocates different numbers of ARNs in different areas of the network based on the remaining energy.
3) EOMR introduces node density and residual energy allocation.

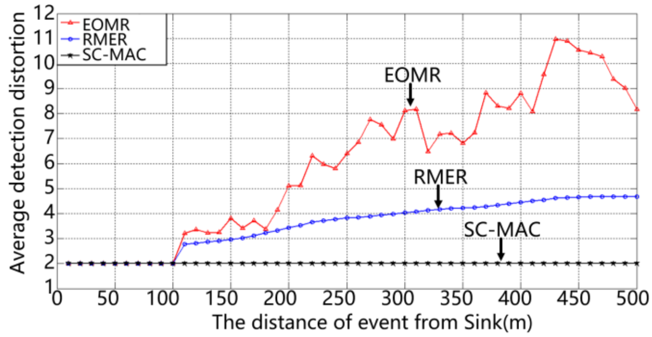

Fig. 10. Distribution of ARNs in different regions of the network

B. Energy Efficiency and Network Lifetime

Network energy consumption reflects the energy consumption of the three algorithms when the network dies. In the Fig. 11, the X and Y axes are network coordinates, and the Z axis is the energy consumption of nodes in different regions when the network dies. As shown in Fig. 11, it reflects the energy consumption of SC-MAC.

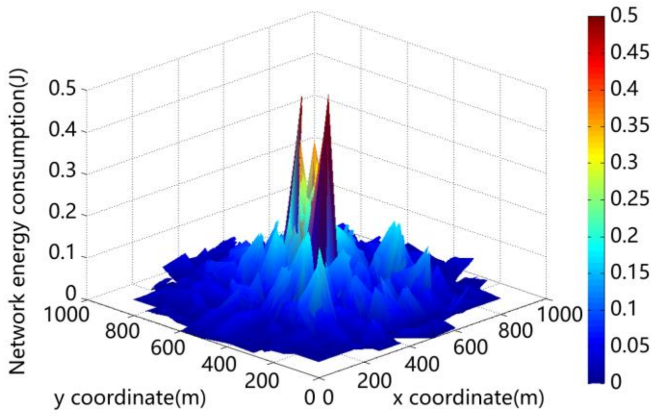

Fig. 11. Network energy consumption of SC-MAC

The energy consumption of SC-MAC in the hotspot area is much larger than that of other areas of the network. The key nodes passing through multiple paths in the hotspot area are significantly fast, which forms an obvious energy hole, seriously affecting the network life and the network energy consumption.

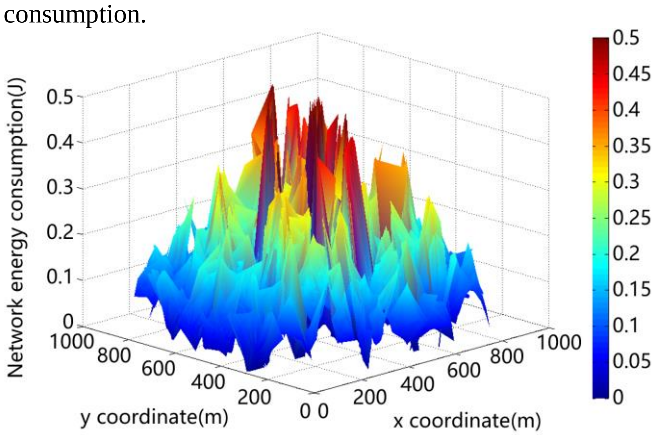

Fig. 12. Network energy consumption of RMER

RMER improves the energy utilization outside the hotspot area by selecting more ARNs in the non-hotspot area and reduces the energy consumption of the hotspot area through data aggregation. From Fig. 12, the energy balance of RMER is improved when compared with SC-MAC. However, RMER does not consider the influence of node density on regional energy consumption when assigning the number of ARNs. There are many ARNs in the low node density area and a smaller number of high-density ARNs in the network. However, since the algorithm data transmission adopts the minimum hop path transmission method, the network still generates energy holes in the hot spot area and the network energy consumption is still unbalanced.

The EOMR algorithm allocates the number of ARNs to the event area according to the energy consumption rate and reduces the energy consumption of the hotspot area through data aggregation. Compared with RMER, EOMR considers the influence of node density on the regional energy consumption when assigning the number of ARNs. In the event area with the same distance from the sink node, the number of ARNs with larger node density is larger, and vice versa. EOMR selects the nodes with more residual energy as the ARNs and equalizes the energy consumption of the event area node. Meanwhile, the algorithm adopts the set based on the forwarding node. Therefore, the optimal path search algorithm plans the main path and the aggregation path of data collection while avoids nodes and paths whose energy consumption is significantly fast, balances the energy consumption of network data transmission. As depicted in Fig. 13, when the network dies, EOMR could achieve a relatively balanced energy consumption in different areas of the network.

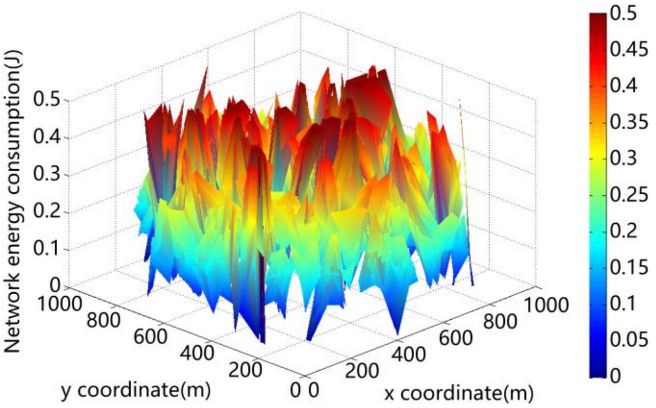

Fig. 13. Network energy consumption of EOMR

Compared with SC-MAC and RMER, EOMR can avoid the energy hole and significantly balance the energy consumption.

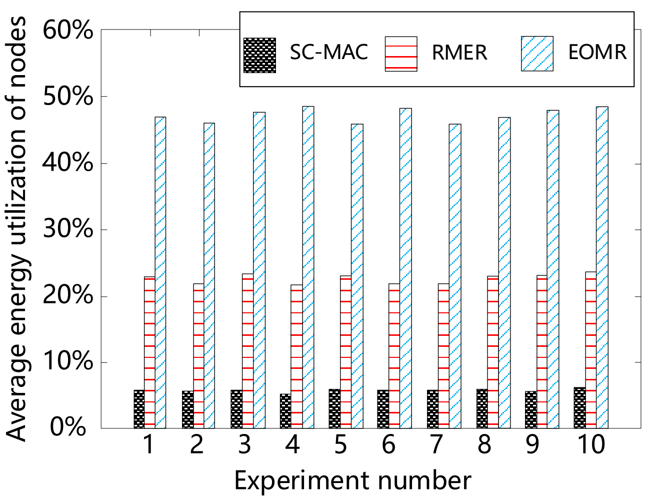

Fig. 14. Average energy utilization of the three algorithms

Fig. 14 shows the comparison of the average energy utilization and network lifetime of the three schemes. The results show that the average node utilization of SC-MAC and RMER were 5.57% and 22.56% respectively, and the average node utilization of EOMR reached 52.34%. In addition, compared with SC-MAC and RMER, EOMR has increased the energy utilization rate by about 8.40 times and 1.32 times, respectively.

Fig. 15 shows the network life cycle of the three algorithms after repeated tests. The simulation results show that SC-MAC and RMER died after an average of 349 events and 990 events on the network, respectively, while RMER died after an average of about 1930 events on the network. Compared with SC-MAC, the RMER's network lifespan has increased by an average of 4.53 times; compared with RMER, the EOMR's network lifespan has increased by an average of 0.95 times.

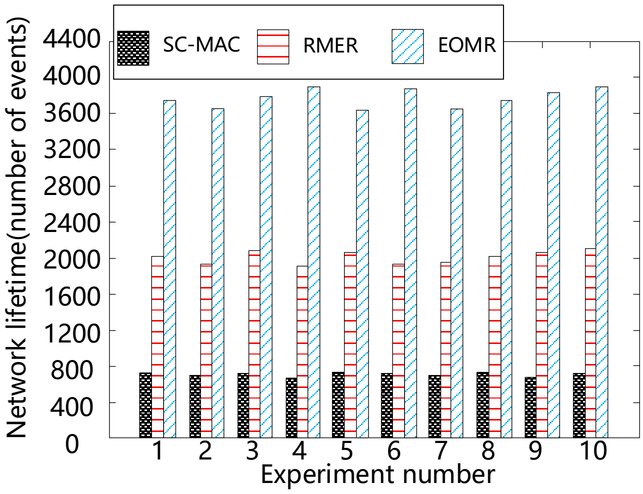

Fig. 15. The network life cycle of the three algorithms

The simulation results show that compared with SC-MAC, the average energy utilization rate was increased by 8.40 times, and the network life cycle was increased by 4.53 times. In addition, compared with RMER, the average energy utilization rate was increased by 1.32 times, and the network life cycle was increased by 95%.

VI. CONCLUSION

Aiming at the problem that it is difficult to balance the energy efficiency and detection reliability of wireless sensor networks, this paper proposes an EOMR routing algorithm, and simulates and compares SCMR, RMER and EOMR on MATLAB. The results show that EOMR effectively extends the network life and improves the average energy utilization. However, in the design and verification of the algorithm, this article assumes that the data transmission of the network is stable and reliable, and does not consider the impact of packet loss and delay on the network performance. The delay analysis of the algorithm is the next step.

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