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An Energy-Efficient Multi-Ring-Based Routing Scheme for WSNs

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ABSTRACT Data aggregation is an important solution to decrease energy consumption by reducing the transmitting data in the wireless sensor networks (WSNs). Although there have been many energy-efficient data routing algorithms devoted to data gathering, the highly correlation of sensed data in WSNs is not fully considered in many existing studies. A lot of redundant data is still transmitted to the sink, which increases the energy cost in the WSNs. In this paper, a novel scheme named Energy-efficient Routing Scheme based on Multi-Ring (ERSMR) is proposed to minimize the energy consumption. The core idea of the scheme is to aggregate data packets of nodes in the peripheral area as far as possible to achieve fully utilization of node energy far from the sink. The proposed scheme can not only minimize the size of receiving and sending data packets in hotspots, but also reduce the maximum energy consumption of nodes for prolonging the network lifetime. Furthermore, it could balance energy consumption in the network and increase energy efficiency of the nodes by exploiting the remaining energy of peripheral nodes. The correctness of the proposed scheme is proved by theory analysis. Simulations are implemented to evaluate the efficiency of the proposed scheme. The simulation results show that it could improve the network lifetime and the energy efficiency. Compared with the Data Aggregation scheme Centralized Sink (DACS), the lifetime can be increased by as much as 190%. The energy utilization efficiency can be increased by as much as 200%. In addition, the optimal transmission radius to maximize the network lifetime is described.

INDEX TERMS Correlated data gathering, energy-efficient, multi-ring routing.

I. INTRODUCTION

Sensors in wireless sensor networks (WSNs) are powered with limited batteries and often deployed in harsh, hostile or inaccessible environments. Therefore, it is a hard work or even impossible to replace or recharge batteries of sensors [1]–[3]. The deployed sensors usually sense the surrounding environment and send the sensed information periodically to the special node called sink. The sensed data may be huge and thus leads to excessive energy cost compared with the limited sensors power [4]–[6]. Therefore, energy saving for prolonging the lifetime of WSNs is still a key issue to be solved urgently.

Data aggregation is an important method to reduce energy consumption via reducing the transmitting data [7]–[10]. For the sensed data, there exists spatial and temporal correlation [11]–[15]. However, the correlation of sensed data in WSNs is not fully considered in many existing studies. For example, in clustering aggregation [4], [16], [17], nodes data are aggregated in their respective cluster areas. However, the sensing range of nodes located in the peripheral area of a cluster covers the other clusters. Therefore, there is still special correlation among the aggregated data of the cluster heads. In addition, the energy efficiency is low. As we know that the energy efficiency is defined as the ratio of the energy cost to initial energy when the network dies [18]. For WSNs with a single sink, there exists a particular "energy hole" phenomenon. Nodes located in the area close to the sink will die fast due to receiving and forwarding the data of the whole network. When nodes around the sink are died, the entire network loses its function. However, there is still as high as 90% of residual energy for nodes in the peripheral area

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when the network dies [6]. Therefore, the remaining energy is not fully utilized and the energy utilization efficiency is relatively low. Moreover, the node energy cost is unbalanced. Especially for the single sink-based network, the data load of the nodes located near the base station is very heavy. The energy is quickly exhausted. In many existing studies, network lifetime is defined as the time when the first node dies [18]. It does not mean that more node energy cost may reduce the network lifetime and the less node energy cost could improve the network lifetime because there is no linear relationship between network lifetime and node energy consumption. The network lifetime depends mainly on the node with the maximum energy cost. Thus, balancing the data load and energy consumption could prolong the network survival time.

To address the above issues, a multi-ring-based data aggregation routing scheme is proposed in the paper. In the proposed scheme, it consists of three components including constructing multiple ring routes in the network, aggregating data along the ring routing to one node, and transmitting the entire network aggregated data to the sink. The main contributions of the paper are as follows:

(1) A novel multi-ring-based data aggregation routing scheme is proposed. In the scheme, the sensors are divided into several ring regions according to the hops to the sink (nodes with the same hop in the same ring region). A selected ring acts as convergence ring and the final packet of each ring region are aggregated and routed along centripetal routing or centrifugal routing at ring-head node of convergence ring. The final aggregated data packet from convergence ring is sent to the sink by the shortest route. The proposed scheme can improve data aggregation through ring routing to reduce the transmitting data.

(2) The proposed scheme balances energy consumption in the network and improve network lifetime and energy utilization efficiency through dynamically selecting convergence ring. The proposed scheme can dynamically select nodes with more residual energy as ring-cluster nodes and ring-head nodes simultaneously. A ring is chosen as convergence ring according to the data load received by each ring-head node. Thus, the network energy consumption is balanced, and the energy utilization efficiency is improved by more than 2 times.

(3) The theory analysis and simulation results demonstrate that the proposed scheme can not only reduce the maximum node energy consumption but also balance energy consumption. Compared with the DACS, the lifetime can be improved by as much as 190%. The energy utilization efficiency can be increased by as much as 200%. Moreover, with bigger correlation coefficient, the energy cost is less and network lifetime can be further improved. In addition, the optimal transmission radius to maximize the network lifetime is described.

The structure of this paper is as follows: section 2 reviews the related works. Section 3 describes the system model and problem statement. Section 4 presents the energy-efficient multi-ring-based routing scheme. The performance is analyzed and discussed in section 5. Simulation results and performance evaluation are demonstrated in section 6. Finally, the conclusion is made in section 7.

II. RELATED WORK

Many exiting works devoted to improve the energy efficiency of WSNs through integrating routing technology and data aggregation.

Data aggregation is utilized by opportunistic way in [16]–[20]. They mainly focused on the design of routing scheme. Data is aggregated opportunistically when it is transmitted to the sink hop by hop along an established route. In the transmission process, the intermediate node aggregates the received packets with its own generated packet into one packet of the same size. In Power efficient Gathering in Sensor Information System (PEGASIS) [19] or Power Efficient Data gathering and Aggregation Protocol (PEDAP) [20], sensor nodes are organized into a chain structure or a minimum spanning tree. In Low-Energy Adaptive Clustering Hierarchy (LEACH) [16], nodes are aggregated into clusters. In Clustered Aggregation (CAG) [17], sensor nodes are aggregated into clusters. The transmitting packets are aggregated based on the similarity of the sensing data rather than the geographical proximity. Thus, the cluster head only needs to send a packet to the sink if sensed data in a cluster are similar. And, the amount of transmitted packet will be greatly reduced. Similarly, Gupta et al [21] have proposed an aggregation scheme. In the scheme, a small number of representative nodes are selected for transmission in each round of data gathering. The energy consumption is balanced through replacing these representative nodes in each round of transmission.

Reference [8], [22]–[25] focus on the data compression by coding technology. There are two different encoding schemes applied. They are distributed source coding (DSC) [22]–[24] and explicit side information aggregation [25], [8]. The DSC is based on Slepian Wolf coding theory. The main idea is that the correlated source data can be coded independently. The collaborative decoding is performed at the decoder. The coding efficiency is not less than that of the joint coding. Single input and multiple input aggregation models are typical explicit side information aggregation model. In the single input aggregation model, the context-sensitive of data aggregation is restricted [25]. In the multiple input aggregation models, data aggregation is performed only when the parent node receives all the child data [8]. The amount of aggregated data sent from a particular node to the next hop of the tree depends on the specific structure of the sub-tree of the node. Therefore, for the optimal tree structure, the data transmission rate is reduced by maximizing the aggregation rate of the intermediate nodes as much as possible.

Many existing works have focused on energy-saving issue by reducing the total amount of data delivered in the network, However, many studies found that only reducing the energy consumption of the network not necessarily improves the life of the network because of the energy consumption unbalance [9], [10]. In the paper, the proposed multi-ring-based data aggregation routing scheme can improve data aggregation through ring routing to reduce the transmitting data. Besides, it balances energy consumption in the network and improve network lifetime and energy utilization efficiency through dynamically selecting convergence ring.

III. THE SYSTEM MODEL AND PROBLEM STATEMENT

A. NETWORK MODEL

A circular wireless sensor network with the radius of R is considered. In the WSN, sensors are randomly deployed and the sensors density is ρ. Besides, there is one single sink located at the center of the network. It is assumed that all deployed nodes are not movable. They have the identical communication range r and the initial energy. Detecting their surrounding environment, the sensor nodes will generate packets and forward them to the sink periodically [26].

For data aggregation, it follows the aggregation model in [13]. It is as follows:

$$\phi(i,j) = max(\sigma_i, \sigma_j) + (1-c)min(\sigma_i, \sigma_j) \quad (1)$$

$$\phi(\phi_i, \varphi_j) = max(\phi_i, \varphi_j) + \varsigma(1-c)min(\phi_i, \varphi_j) \quad (2)$$

where, σ_i denotes the origin data packet length of node i, and $\varphi(i,j)$ denotes the intermediate aggregation result of node i with node j. In the formula φ_i denotes the current intermediate aggregation result of node i for simplification. φ_i denotes the final aggregation result of node i with all incoming nodes data. In Equation (1), c is the correlation coefficient, It is between 0 and 1. In Equation (2), ς is forgetting factor, and it is a decimal less than 1, e.g. $\varsigma = 0.8$, φ_i represent intermediate aggregation result , and ϕ_j represent final result of child nodes.

The energy consumption is calculated following the model in [27]. For sending or receiving one-bit data, it is as follows.

$$\begin{cases} E_t = E_\mu + \varepsilon_\epsilon d^\alpha \\ E_r = E_\mu \end{cases} \quad (3)$$

where, d represents the transmission distance. If it is less than the threshold, $\alpha = 2$. Otherwise, $\alpha = 4$. The meaning and values of other parameters could refer to [27].

B. PROBLEM STATEMENT

The goal of the paper is to propose an energy-efficient multi-ring routing scheme for data aggregation and energy consumption balance. In this paper, network lifetime is defined as the time when the first node dies and it is represented by data gathering rounds. Thus, the network lifetime is represented by using (4), where E_i represents the energy consumption of node$i$ in one round of data gathering, E_{ini} refers to the initial energy of each node. The lifetime of node i is $t_i = E_{ini}/E_i$.

$$T = \min_{0<i\leq n} (t_i) \quad (4)$$

The energy efficiency is defined as the ratio of the utilized energy to initial energy of the entire network when the network dies [18]. The energy efficiency is computed by using (5), where E^i_{cost} represents the energy consumption of node i. E^i_{init} denotes the initial energy of node i and η denotes the energy utilization efficiency.

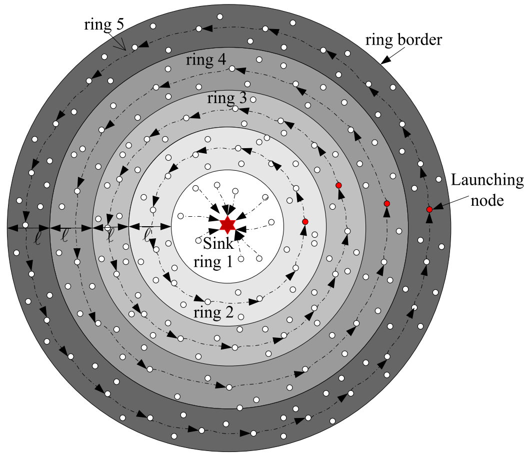


FIGURE 1. The structure of the ERSMR scheme.

$$\eta = \frac{\sum_{i\in n} E^i_{cost}}{\sum_{i\in n} E^i_{init}} \quad (5)$$

Data aggregation is implemented through ring routing to reduce the transmitted data in the network. The goal of this paper is to improve the network lifetime and the energy efficiency. It is expressed by using (6), where E^i_{left} represents the residual energy of node i.

$$\begin{cases} max\ (T) = max \min_{0<i\leq n} (t_i) = min \max_{0<i\leq n} (E_i) \\ max(\eta) = min \left(\frac{\sum_{i\in n} E^i_{left}}{\sum_{i\in n} E^i_{init}} \right) \end{cases} \quad (6)$$

IV. SCHEME DESIGN

A. OVERVIEW OF THE PROPOSED SCHEME

The overall structure of the proposed energy-efficient multi-ring-based routing scheme (ERSMR) scheme is illustrated in Fig. 1. As shown in Fig.1, the sensor nodes are divided into several ring regions according to hops from the sink (nodes with the same hop in the same ring region). Except the nodes in the first ring region, nodes in other ring regions are aggregated along the ring route at ring-head nodes respectively. After each ring-head node has aggregated all the data of the ring region, a ring is selected as the convergence ring if the ring-head node has the minimal aggregated data. Then, the final aggregated packet of each ring is routed along centripetal routing or centrifugal routing to ring-head node of convergence ring. So, ring-head node of convergence ring contains the entire network information. Finally, the final aggregated data packet is sent to the sink via the shortest route.

The goal of prolonging the network lifetime is realized by data aggregation and energy balancing. The receiving packets are aggregated with intermediate nodes packets in multi-ring route following the data aggregation model. The energy cost is balanced and energy efficiency is improved by dynamically selecting convergence ring.

B. THE DESIGN OF ERSMR

1) THE CONSTRUCTION OF RING REGION

A ring region is consisted by some nodes with the same number of hops to the sink. As depicted in Fig.1, network is divided into several ring regions, such as ring 1, ring 2, ring 3, ring4 and ring 5. The construction of the ring region consists of two steps:

(1) Calculating the hop count to the sink. The sink node floods a control message containing the node's ID and the hop count variable to all the sensors in the network [28]. Firstly, sink sets the hop count to itself as 0, other nodes set the hop count to sink as infinity. Then, sink starts broadcasting its control message to all nodes, and nodes set the hop message $+1$ after receiving it. The receiving nodes compare with the hop message $+1$. If the hop message $+1$ is smaller than current recorded hop count, they set current recorded hop count as hop message $+1$. The process goes on until all nodes with its hops to the sink.

(2) Constructing the ring region. Nodes with the same hop are in the same ring region. And all sensor nodes are grouped into ring regions based on their hop counts to the sink. Simultaneously, hop count is also node ring number. The ring number of the sink is 0.

All sensor nodes divided into several rings according to the perceptual radius of the node. The size of the ring changes as the perception radius of the node changes.

2) THE CONSTRUCTION OF RING ROUTING

In wireless multi-hop networks, only the nodes that lie within the maximum transmission range of the sink node can reach the sink node via single-hop transmissions, and this area is called as the Sink Connectivity Area (SCA). In this paper, SCA is composed of nodes with 1 hop count, such as ring region 1 in Fig. 1. Nodes that lie in the SCA also relay the received data from nodes that lie outside the SCA. Thus, SCA nodes have shorter lifetime compared to that of non-SCA nodes. In SCA, nodes transmit data to the sink directly such as nodes in the ring region 1 in Fig. 1. Non-SCA is composed of ring regions in which node hop count is more than 1, such as ring 2, ring 3, ring 4 and ring 5 in Fig. 1. The packets for nodes in the kth ($k > 1$) ring region are routed and aggregated hop by hop until to the ring head node. The construction of the kth ring route consists of the following steps:

(1) A ring route named $Route(k')$ is constructed. It consists some nodes (such as white nodes in Fig.2) in the kth ring region. In the kth ring region, a launching node (such as red nodes in Fig.2) is selected as ring head node to establish the ring route firstly. Then, the ring head node selects the farthest neighboring node which is k hops to the sink as the next hop by the right-hand rotation rule. The process is repeated until back to the launching node. Consequently, a ring route

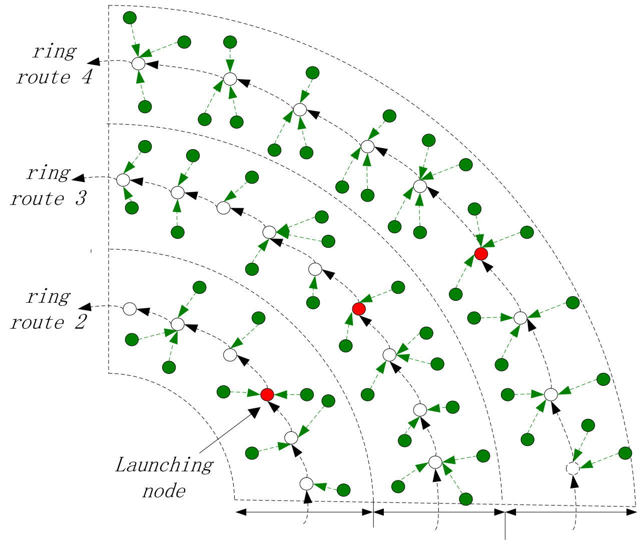


FIGURE 2. The kth ($k > 1$) ring route.

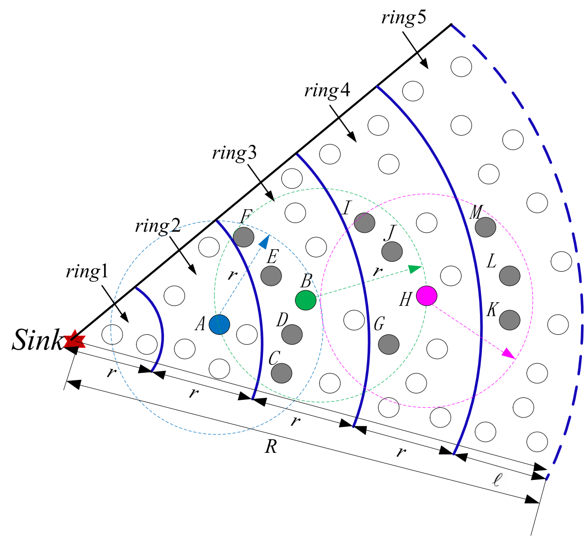


FIGURE 3. The selection of ring head node.

named $Route(k')$ is formed. Nodes in $Route(k')$ are called Ring-cluster node (RCN). Nodes without in $Route(k')$ are called Non-Ring-cluster node (NRCN).

Specifically, the ring head node is selected following the steps. Next Hop Node Set (NHNS) of node A refers to the nodes which lie in the transmission radius r of node A as well as their ring number are the same with node A. Heads Select Set (HSS) of node A refers to the nodes which lie in the transmission radius r of node A as well as their ring number equals to the ring number of node $A + 1$. In Fig. 3, HSS of node B (such as green nodes in Fig.3) contains node I, J, H, G, and HSS of node H (such as red nodes in Fig.3) contains node K, L, M. In each data collection round, the farthest node in HSS is selected as ring head node. In the first round, node with the smallest angles between itself and the X axis is the ring head node of the 2nd ring region. But in other rounds, node with the maximum residual energy is ring head node of the 2nd ring region. The ring head is selected following (7) ($3 \leq Top_j \leq K$), where V denotes the set of sensor node, $Dis(x, y)$ denotes the distance between x and$y$, r denotes the transmission radius r of node,Top_i denotes the hop count of node $i$from the sink, $leader\ (Top_i)$ denotes the head node in the Top_i ring and E^i_{left} represents the residual energy of node i.

$$\begin{cases} HSS\ (i) = \{j|Dis\ (j, i) \leq r, Top_j = Top_i + 1, i, j \in V\} \\ Dis_j = max\left(\bigcup_{j\in HSS(i)} Dis\ (j, i)\right), \quad 3 \leq Top_j \leq K \\ leader\ \left(Top_j\right) = j \end{cases} \tag{7}$$

And if $Top_j = 2$, the ring head is selected following (8).

$$\begin{cases} leader\ \left(Top_j\right) = \{j|min\ angle\ (j, X)\ , j \in V\}, \quad tim = 1 \\ leader\ \left(Top_j\right) = \{j|max(E^j_{left}), j \in V\}, \quad tim > 1 \end{cases} \tag{8}$$

(2) The rest of the nodes (such as green nodes in Fig.2) in the kth ring region are included into $Route(k')$. Thus, a new ring route $Route(k)$ is formed, which consists of the whole nodes of the kth ring region. Nodes in ring route $Route(k')$ start broadcasting packet to neighboring nodes, which are in the kth ring region and not in the $Route(k')$. The neighboring nodes dynamically select node in $Route(k')$ as its parent node according to energy consumption after receiving it. In this way, a ring route named $Route(k)$ is formed, such as ring route 2, ring route3, ring route 4 in Fig. 2.

Ring-cluster nodes in ring route select one launching node and the launching node starts in the counterclockwise direction routing along the ring, until to the launching node. In the end, data of all nodes in this ring region is aggregated into final packets. A ring-cluster node is routed along the ring to one ring-cluster node after it has received the original data of its child nodes. The routing in each ring is processed simultaneously without considering the interference among the rings.

The construction of the $Route(k')$ and $Route(k)$ is described in algorithm 1.

Algorithm 1 The Construction of the $Route(k')$ and $oute(k)$

$leader = A$ //node A is a launching node of the kth ring region.
$Dis = \emptyset$
Do
  For $i = 1$ **to** N_k //N_k denote the number of nodes in the kth ring region.
    calculate the distance $Dis(i)$ between $leader$ and each node in
    the kth **6** ring region.
    If $Dis\ (i) \leq r$
      node i is selected by the right-hand rotation rule.
      $Dis = Dis \cup Dis\ (i)$.
    End If
  End For
  $max(Dis)$ **a**nd select the node B with the farthest distance from $leader$ as
  ring-cluster node (RCS);
  $leader = B$.
While ($leader! = A$)
output $Route(k')$
$Dist = \emptyset$
For each node i which is in the kth ring region and not in $Route(k')$
  For each node j which is in $Route(k')$
    calculate the distance $Dis\ (i, j)$ between i and j;
    If $Dis\ (i, j) \leq r$
      $Dist = Dist \cup Dis\ (i, j)$.
    End If
  End For
  $min\ (Dist)$ and select node j as parent node of node i according to energy
  consumption.
End For
output $Route(k)$

3) RING-RING ROUTING AND THE SHORTEST PATH ROUTING

In data collection, the ring head node not only collects all information of its ring region, but also forwards packets containing information of other ring region. After each ring-head node has received all the data of itself ring region, the final packet of each ring region is routed along centripetal routing or centrifugal routing at ring-head node of convergence ring. The routing follows: in the nth round, if the xth ring acts as the convergence ring, for each ring head node between the 2nd ring and xth ring, data is gradually aggregated along centrifugal routing from the 2nd ring head node to the xth ring head node, which follows (9). For each ring head node between the Kth ring (K is the outermost ring) and xth ring, data is gradually aggregated along centripetal routing from the Kth ring head node to the xth ring head node, which follows (10).

$$\phi\ (\Psi_k, \Psi_{k+1}) = max(\Psi_k, \Psi_{k+1}) + \varsigma(1-c)min(\Psi_k, \Psi_{k+1}), \quad k \in [2, x) \tag{9}$$

$$\phi\ (\Psi_{k-1}, \Psi_k) = max(\Psi_{k-1}, \Psi_k) + \varsigma(1-c)min(\Psi_{k-1}, \Psi_k), \quad k \in [x+1, K] \tag{10}$$

where Ψ_k denotes data of all aggregated packets at ring-head node in the kth ring region. $\phi(i, j)$ denotes the aggregation result of node i with node j. So, ring-head node of convergence ring contains of the entire network data. The aggregated data which contain the entire network is routed to the sink following the shortest route. The construction of the Ring-Ring routing is described in algorithm 2.

Therefore, the detailed implementation of ERSMR is illustrated in Algorithm 3.

Algorithm 2 The Construction of the *Route*(*n*)

```
If tim = n // in the nth round and the xth ring acts as the convergence ring
    For each ring head node leader(i) between the 2nd ring and xth ring
        select leader(i + 1) as the father of leader(i).
    End For
    For each ring head node leader (i) between the Kth ring (K is the
        outermost ring) and xth ring,
        select leader(i − 1) as the father of leader(i).
    End For
End If
```

V. PERFORMANCE ANALYSIS

In the section, the performance of the proposed scheme is analyzed.

Theorem 1: In the ERSMR scheme, the average data packet load (ie. the amount of packet of non-ring-cluster nodes) of each ring cluster node with k hop from sink in ring route ($Route(k)$) is calculated by using (11),

$$\Phi(k) = (2 - c + (\frac{(2k-1)\pi r^2 \rho - \lceil 2\pi l/r \rceil}{\lceil 2\pi l/r \rceil} - 1)\varsigma(1-c))\lambda \quad k \geq 2 \tag{11}$$

Proof: if we assume λ is the size of the packet, N_k is the nodes number in the kth ring. The number of Ring-cluster nodes in $Route(k)$ is N_k^{RCS}, and the number of Non-Ring-cluster nodes in $Route(k)$ is $N_k - N_k^{RCS}$. For each Ring-cluster node in the kth $Route(k)$, it forwards the data from its neighbor Non-Ring-cluster nodes in the $Route(k)$. Therefore, the average size of packets received by each Ring-cluster node is:

$$\Omega_k^{RCS} = \frac{N_k - N_k^{RCS}}{N_k^{RCS}} \tag{12}$$

Each Ring-cluster node aggregate its current packet with packet received from its Non-Ring-cluster node. According to the Equation (1), the first data aggregation is obtained:

$$\varphi_k^{RCS} = \lambda + (1-c)\lambda \tag{13}$$

where, φ_k^{RCS} is a temporary data packet size of Ring-cluster node after data aggregation. Since the packets from Non-Ring-cluster nodes are the original data packets, and $\varphi_k^{RCS} > \lambda$, the second data aggregation is obtained according to the Equation (2):

$$\phi_k^{RCS} = \varphi_k^{RCS} + \varsigma(1-c)\lambda \tag{14}$$

Since $\phi_k^{RCS} > \lambda$, the third data aggregation is obtained $\Phi(k)_3 = \phi_k^{RCS} + \varsigma(1-c)\lambda$

$$= \varphi_k^{RCS} + \varsigma(1-c)\lambda + \varsigma(1-c)\lambda \tag{15}$$

Algorithm 3 ERSMR

```
[t]
Input: a given network graph G
Output: the energy cost of each node, network lifetime tim
For i = 1 to N// N denote the number of nodes in the sensor networks.
    calculate distance to the sink l (m) and Top_i (hop) //Top_i denote the hop
    of node i to the sink and nodes with the same hop are in the same ring.
End For
tim = 1 // tim denote the round
While each node's energy in sensor network is not exhaust.
    tim = tim + 1
    For k = 1 to K // k denote the k ring,K denote the outermost ring.
        If k = 1
            each node in the first ring sends packet directly to sink.
        Else
            The ring head is selected by Eq.7 and Eq.8.
            The construction of the kth ring route following algorithm 1.
            The construction of the ring-ring route following algorithm 2.
            The aggregated data which contain the entire network route to
            next hop by shortest path routing.
        End If
    End For
End While
```

The process is repeated. The final average packets load of each Ring-cluster node in the kth ring is obtained:

$$\begin{aligned}\Phi(k) &= \varphi_k^{RCS} + \varsigma(1-c)\lambda + (\Omega_k^{RCS} - 2)\varsigma(1-c)\lambda \\ &= \lambda + (1-c)\lambda + \varsigma(1-c)\lambda \\ &\quad + (\frac{N_k - N_k^{RCS}}{N_k^{RCS}} - 2)\varsigma(1-c)\lambda \\ &= (2 - c + (\frac{N_k - N_k^{RCS}}{N_k^{RCS}} - 1)\varsigma(1-c))\lambda\end{aligned} \tag{16}$$

As we know that r is the node communication range, the distance of nodes with k hop to the sink is l, $l \in ((k-1)r, kr]$, $k = 1, 2, 3, \ldots$. The length of k-hop ring route $Route(k')$ is $L_k = 2\pi l$, the number of Ring-cluster nodes in the $Route(k')$ is $N_k^{RCS} = \lceil 2\pi l/r \rceil$. The area of k-hop ring region is $W_k = \pi(kr)^2 - \pi((k-1)r)^2 = (2k-1)\pi r^2$, so the number of k-hop nodes is $N_k = (2k-1)\pi r^2 \rho$.

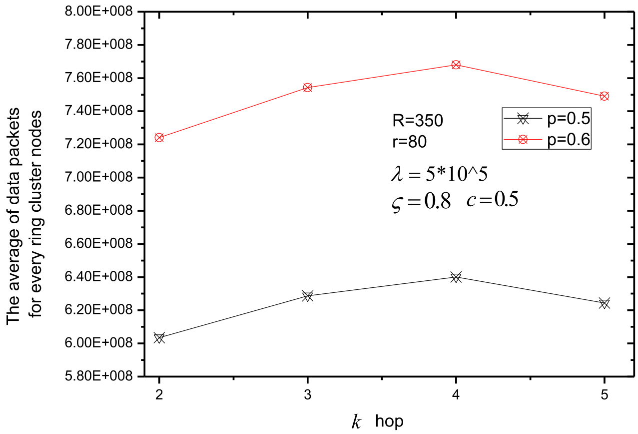


FIGURE 4. **The average data packet load of each ring cluster node.**

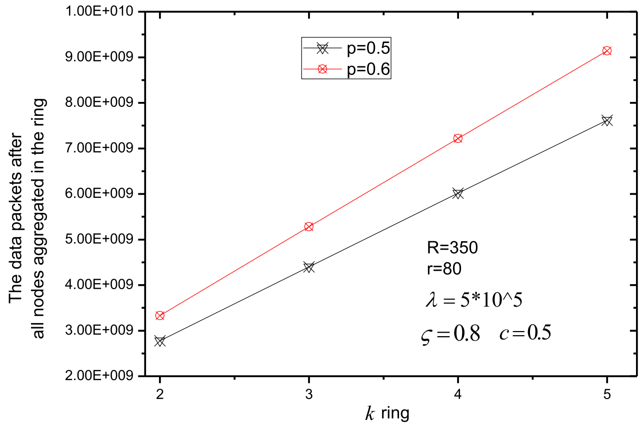


FIGURE 5. **The data of all aggregated packets at ring-head node in the *k*th ring region.**

Thus, $\Phi(k) = (2 - c + (\frac{N_k - N_k^{RCS}}{N_k^{RCS}} - 1)\varsigma(1-c))\lambda.$

$$= (2-c+(\frac{(2k-1)\pi r^2\rho - \lceil 2\pi l/r \rceil}{\lceil 2\pi l/r \rceil} - 1)\varsigma(1-c))\lambda \quad (17)$$

Fig.4 shows the average packet load of each ring cluster node with k hop from sink in ring route ($Route(k)$) in the ERSMR. It can be seen that the average packets of each Ring-cluster node are similar under $\rho = 0.5$ and $\rho = 0.6$. Each Non Ring-cluster nodes select the nearest neighbor Ring-cluster node as its father node. Because the energy consumption is proportional to packets load, the energy consumption of each Ring-cluster node is similar.

When a new data collection round begins, every new ring route $Route(k)$ is re-established by right hand rotation rule, so every node act as Ring-cluster node randomly. For example, node A is a Ring-cluster node in the 1st round and it need to receive data from other Non-Ring-cluster nodes, but in the next round, node A is selected as Non-Ring-cluster node and it needs to send its own original data to its parent. The method of acting as ring cluster nodes in turn disperse the energy consumption of nodes and make the energy consumption of nodes balanced.

To sum up, this scheme makes full use of the energy of nodes in different areas.

Theorem 2: In the ERSMR scheme, all aggregated packets size at ring-head node in the kth ring region is as shown in Equation (18),

$$\Psi_k = \Phi(k) + (N_k^{RCS} - 1)\varsigma(1-c)\Phi(k) \quad (18)$$

Proof: By theorem 1, the average data packets load of each ring cluster node in ring route ($Route(k)$) is $\Phi(k)$. A Ring-cluster node forwards the aggregated packet to another Ring-cluster node after it has received the original data of its child nodes. The receiving Ring-cluster node aggregate its current data with data from other Ring-cluster node until the launching node. The final aggregated data packet δ_k^{RCS} contains of all data in the k^{th} ring region. δ_k^{RCS} is calculated by Equation (19),

$$\delta_k^{RCS} = \Phi(k) + \varsigma(1-c)\Phi(k) \quad (19)$$

Since the number of Ring-cluster nodes in $Route(k)$ is N_k^{RCS}, the final aggregated data packets size at ring head node contains of all packets in the kth $Route(k)$ is obtained.

$$\Psi_k = \Phi(k) + (N_k^{RCS} - 1)\varsigma(1-c)\Phi(k) \quad (20)$$

Fig.5 shows all aggregated packets size at ring-head node in the kth ring region. As can be seen that the final aggregated packets size of each ring head node is changed from low to high according to the distance to the sink. For circular network, the number of nodes in each ring region is different, and the number of nodes in ring region far from the sink is much more than that in the region close to the sink.

Theorem 3: In the ERSMR scheme, if the xth ring acts as the convergence ring, for each ring head node, data is gradually aggregated following (9) and (10) from each ring head node to the xth ring head node. The data load in the xth ring head node is as the following:

$$\Gamma_x = \begin{cases} \Psi_K + \varsigma(1-c)\Psi_{K-1} + \varsigma(1-c)\sum_{i=2}^{K-2}\Psi_i, & x = 2 \\ \Psi_3 + \varsigma(1-c)\Psi_2 + \varsigma(1-c)\sum_{i=4}^{K}\Psi_i, & x = K \\ max(\Gamma'_x, \Gamma''_{x+1}) + \varsigma(1-c)min(\Gamma'_x, \Gamma''_{x+1}), & 2 < x < K \end{cases} \quad (21)$$

Proof: After a round of data collection of each node in ring region, the final aggregated data packet at each ring head node need to be aggregated following (9) and (10). According to the Theorem 2, the final aggregated data packet at ring head node is Ψ_k. In one related data collection, the ring head node not only collects all data of its ring region, but also forwards data of other ring region. If the xth ring acts as the convergence ring, the analysis is as follow:

(1) If $x = 2$, for each ring head node between the Kth ring (K is the outermost ring) and xth ring, data is gradually

aggregated along centripetal routing from the Kth ring head node to the xth ring head node. The process is as follows:

Data of the Kth ring Ψ_K aggregate with data of the $K-1$th ring Ψ_{K-1} at ring head node of the $(K-1)$th ring, and the aggregated data is Γ_{K-1},

$$\Gamma_{K-1} = max(\Psi_{K-1}, \Psi_K) + \varsigma(1-c)min(\Psi_{K-1}, \Psi_K) \quad (22)$$

The aggregated data of the $(K-1)$th ring Γ_{K-1} aggregates with data of the $(K-2)$th ring Ψ_{K-2} at ring head node. The aggregated data is represented by Γ_{K-2},

$$\begin{aligned}\Gamma_{K-2} &= \Gamma_{K-1} + \varsigma(1-c)\Psi_{K-2} \\ &= max(\Psi_{K-1}, \Psi_K) + \varsigma(1-c)min(\Psi_{K-1}, \Psi_K) \\ &\quad + \varsigma(1-c)\Psi_{K-2}\end{aligned} \quad (23)$$

The aggregated data of the $(K-2)$th ring Γ_{K-2} aggregate with data of the $(K-3)$th ring Ψ_{K-3} at ring head node and the aggregated data is Γ_{K-3},

$$\begin{aligned}\Gamma_{K-3} &= \Gamma_{K-2} + \varsigma(1-c)\Psi_{K-3} \\ &= max(\Psi_{K-1}, \Psi_K) + \varsigma(1-c)min(\Psi_{K-1}, \Psi_K) \\ &\quad + \varsigma(1-c)\Psi_{K-2} + \varsigma(1-c)\Psi_{K-3}\end{aligned} \quad (24)$$

The process is repeated until the aggregated data arriving at the 2nd ring. Therefore, the final aggregated data packets is Γ_2,

$$\begin{aligned}\Gamma_2 = max(\Psi_{K-1}, \Psi_K) + \varsigma(1-c)min(\Psi_{K-1}, \Psi_K) \\ + \varsigma(1-c)(\Psi_{K-2} + \Psi_{K-3} + \ldots \Psi_2)\end{aligned} \quad (25)$$

According to the Theorem 2, since $\Psi_{K-1} < \Psi_K$, so

$$\Gamma_2 = \Psi_K + \varsigma(1-c)\Psi_{K-1} + \varsigma(1-c)\sum_{i=2}^{K-2}\Psi_i \quad (x = 2, K >= 4) \quad (26)$$

(2) If $x = K$, for each ring head node between the 2nd ring and xth ring, data is gradually aggregated along centrifugal routing from the 2nd ring head node to the xth ring head node.

The process is as follows:

The aggregated data of the 2nd ring Ψ_2 aggregate with data of the 3th ring Ψ_3 at ring head node of the 3th ring, and the aggregated data is Γ_3,

$$\Gamma_3 = max(\Psi_2, \Psi_3) + \varsigma(1-c)min(\Psi_2, \Psi_3) \quad (27)$$

The aggregated data of the 3th ring Ψ_3 aggregate with data of the 4th ring Ψ_4 at ring head node of the 4th ring, and the aggregated data is Γ_4,

$$\begin{aligned}\Gamma_4 &= \Gamma_3 + \varsigma(1-c)\Psi_4 \\ &= max(\Psi_2, \Psi_3) + \varsigma(1-c)min(\Psi_2, \Psi_3) + \varsigma(1-c)\Psi_4\end{aligned} \quad (28)$$

The aggregated data of the 4th ring Ψ_4 aggregate with data of the 5th ring Ψ_5 at ring head node of the 5th ring, and the aggregated data is Γ_5

$$\begin{aligned}\Gamma_5 &= \Gamma_4 + \varsigma(1-c)\Psi_5 \\ &= max(\Psi_2, \Psi_3) + \varsigma(1-c)min(\Psi_2, \Psi_3) \\ &\quad + \varsigma(1-c)\Psi_4 + \varsigma(1-c)\Psi_5\end{aligned} \quad (29)$$

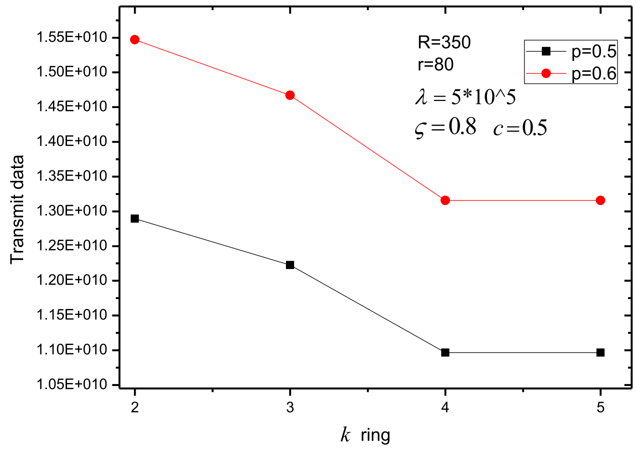


FIGURE 6. The data packet load of each ring head when the convergence ring is 2, 3 or 4 respectively.

Until the aggregated data at the Kth ring is Γ_k,

$$\begin{aligned}\Gamma_k = max(\Psi_2, \Psi_3) + \varsigma(1-c)min(\Psi_2, \Psi_3) \\ + \varsigma(1-c)(\Psi_4 + \Psi_5 + \ldots \Psi_K)\end{aligned} \quad (30)$$

According to the Theorem 2, since $\Psi_2 < \Psi_3$, so

$$\Gamma_K = \Psi_3 + \varsigma(1-c)\Psi_2 + \varsigma(1-c)\sum_{i=4}^{K}\Psi_i \quad (x = K, K >= 4) \quad (31)$$

(3) If $2 < x < K$, for each ring head node between the 2nd ring and xth ring, data is gradually aggregated along centrifugal routing from the 2nd ring head node to the xth ring head node. For each ring head node between the Kth ring (K is the outermost ring) and xth ring, data is gradually aggregated along centripetal routing from the Kth ring head node to the xth ring head node.

According to the (1), for each ring head node between the 2nd ring and xth ring, data is gradually aggregated along centrifugal routing from the 2nd ring head node to the xth ring head node, and the aggregated data at the xth ring head node is Γ'_x,

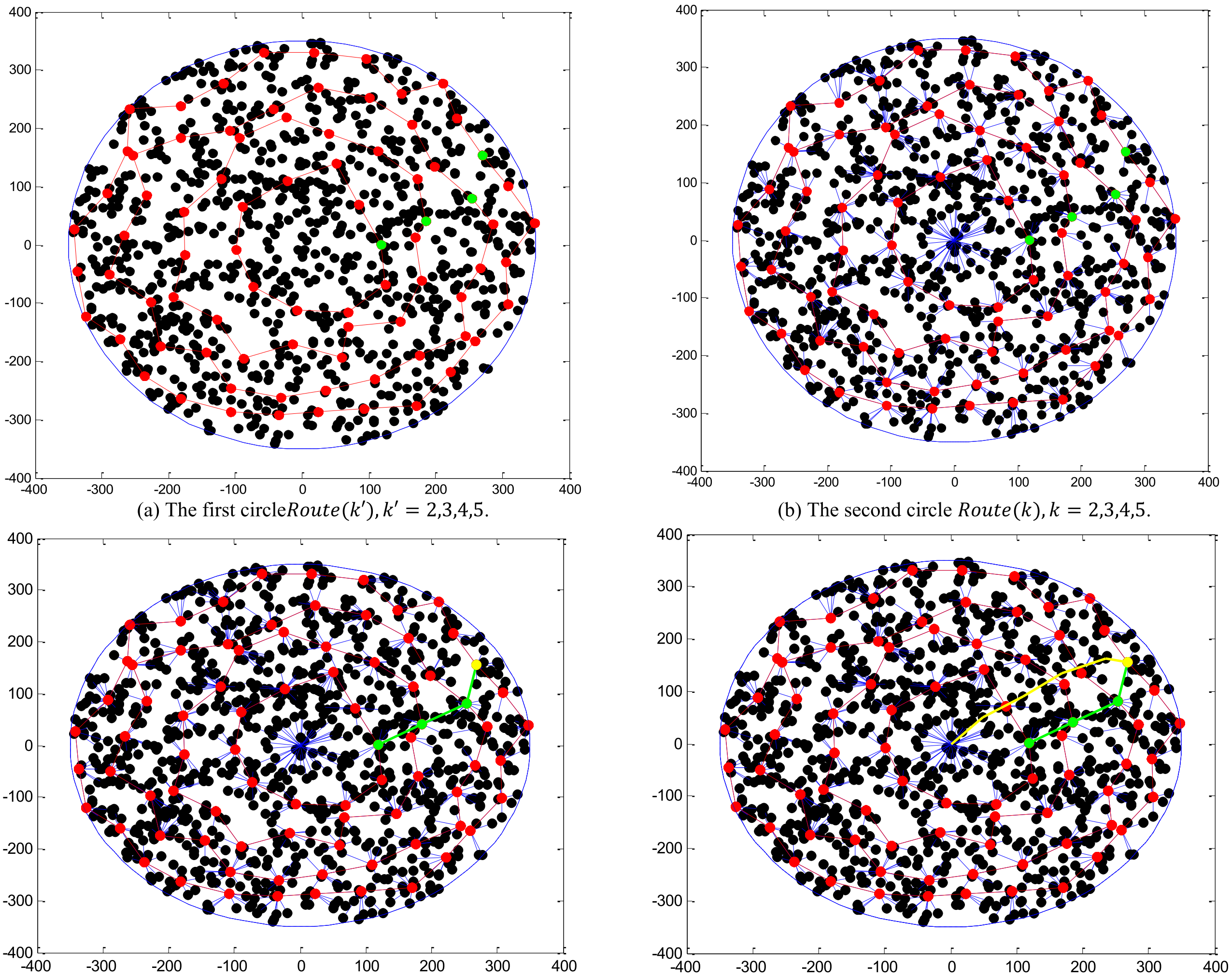
$$\begin{aligned}\Gamma'_x &= max(\Psi_2, \Psi_3) + \varsigma(1-c)min(\Psi_2, \Psi_3) \\ &\quad + \varsigma(1-c)(\Psi_4 + \ldots + \Psi_{x-1} + \Psi_x) \\ &= max(\Psi_2, \Psi_3) + \varsigma(1-c)min(\Psi_2, \Psi_3) \\ &\quad + \varsigma(1-c)\sum_{i=4}^{x}\Psi_i (x \geq 4)\end{aligned} \quad (32)$$

So,

$$\Gamma'_x = \begin{cases} \max(\Psi_2, \Psi_3) + \varsigma(1-c)\min(\Psi_2, \Psi_3)(x=3) \\ \max(\Psi_2, \Psi_3) + \varsigma(1-c)\min(\Psi_2, \Psi_3) \\ \quad + \varsigma(1-c)\sum_{i=4}^{x}\Psi_i(x \geq 4) \end{cases} \quad (33)$$

According to the Theorem 2, since $\Psi_2 < \Psi_3$, so

$$\Gamma'_x = \begin{cases} \Psi_3 + \varsigma(1-c)\Psi_2(x=3) \\ \Psi_3 + \varsigma(1-c)\Psi_2 + \varsigma(1-c)\sum_{i=4}^{x}\Psi_i(x \geq 4) \end{cases} \quad (34)$$



(a) The first circle$Route(k'), k' = 2,3,4,5$.

(b) The second circle $Route(k), k = 2,3,4,5$.

(c) Ring-ring route.

(d) The shortest route to the sink.

FIGURE 7. **The routing process in the 1st round.**

According to the (2), for each ring head node between the Kth ring (K is the outermost ring) and $(x+1)$th ring, data is gradually aggregated along centripetal routing from the Kth ring head node to the $(x+1)$th ring head node, and the aggregated data at the $(x+1)$th ring head node is Γ''_{x+1},

$$\begin{aligned}\Gamma''_{x+1} &= max(\Psi_{K-1}, \Psi_K) + \varsigma(1-c)min(\Psi_{K-1}, \Psi_K) \\ &\quad + \varsigma(1-c)(\Psi_{K-2} + \Psi_{K-3} + \ldots \Psi_{x+1}) \\ &= \Psi_K + \varsigma(1-c)\Psi_{K-1} + \varsigma(1-c)(\textstyle\sum_{i=K-2}^{x+1} \Psi_i)\end{aligned} \tag{35}$$

So,

$$\Gamma''_{x+1} = \begin{cases} \Psi_K, & x = K-1 \\ \Psi_K + \varsigma(1-c)\Psi_{K-1}, & x = K-2 \\ \Psi_K + \varsigma(1-c)\Psi_{K-1} & \\ \quad + \varsigma(1-c)(\sum_{i=K-2}^{x+1} \Psi_i), & x <= K-3 \end{cases} \tag{36}$$

Then, yields

$$\Gamma_x = max(\Gamma'_x, \Gamma''_{x+1}) + \varsigma(1-c)min(\Gamma'_x, \Gamma''_{x+1}) \tag{37}$$

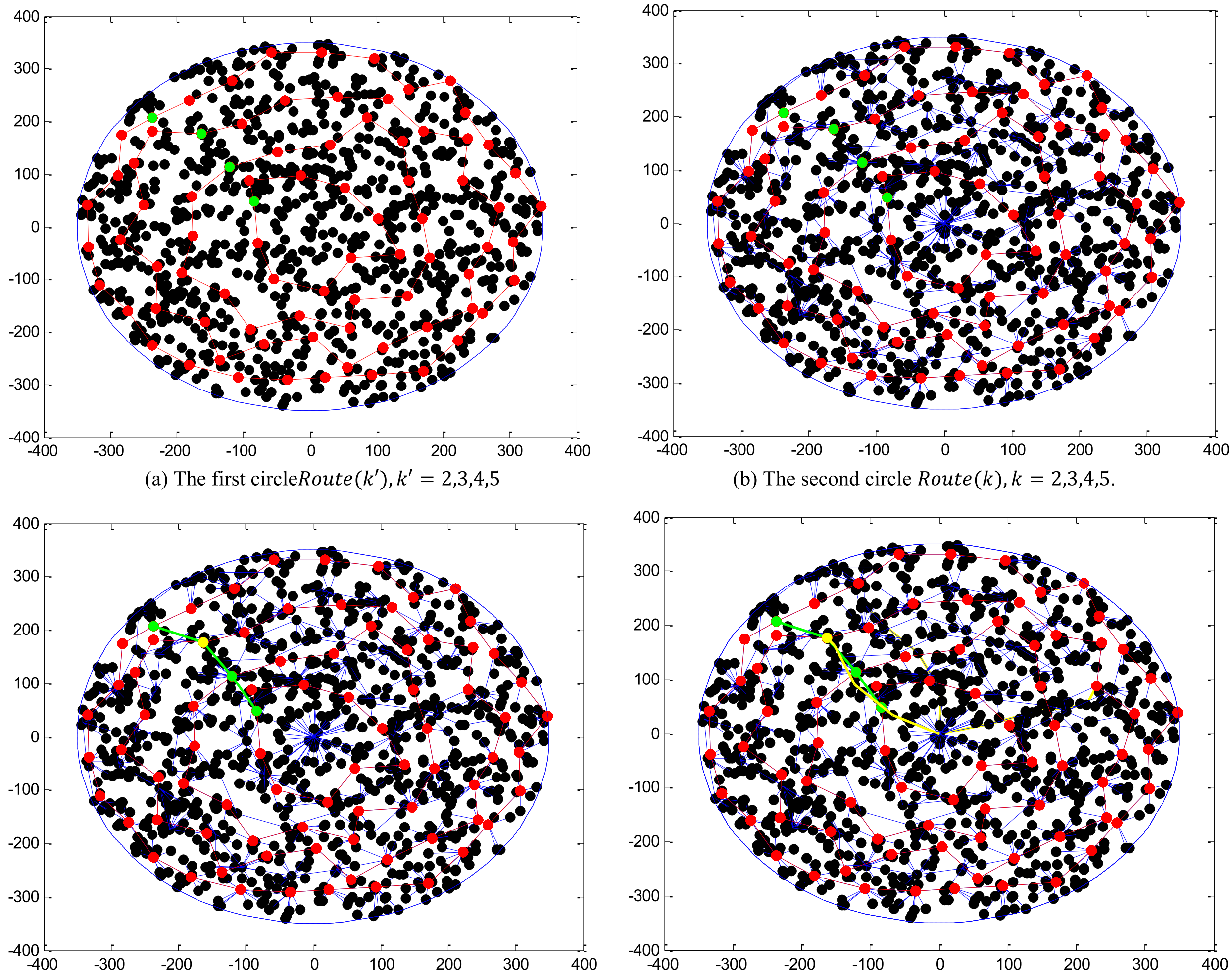
In conclusion, based on (1), (2) and (3), we can get data load in the xth ring head node. ■

The data packet load of each ring head is shown in Fig.6 when the convergence ring is 2, 3 or 4 respectively.

In Fig.6, the amount of packet carried by the ring which acts as the convergence ring near the sink is higher than that of the ring far from the sink. Therefore, for load balancing, we calculate the data packet load proportion of each ring as the convergence ring, and calculate time inverse proportion of each ring as the convergence ring, namely, the data collection round of each ring as the convergence ring.

VI. SIMULATION RESULTS

In this section, the performance of the proposed ERSMR scheme is evaluated by comparing with lossless data aggregation scheme and Data Aggregation scheme Centralized Sink named DACS. The simulation is conducted on MATLAB 7.0. The performance of the scheme is evaluated in a wireless sensor network with 1000 sensor nodes randomly deployed in



(a) The first circle$Route(k')$, $k' = 2,3,4,5$
(b) The second circle $Route(k)$, $k = 2,3,4,5$.
(c) Ring-ring route
(d) The shortest route to the sink

FIGURE 8. **The routing process in the 4st round.**

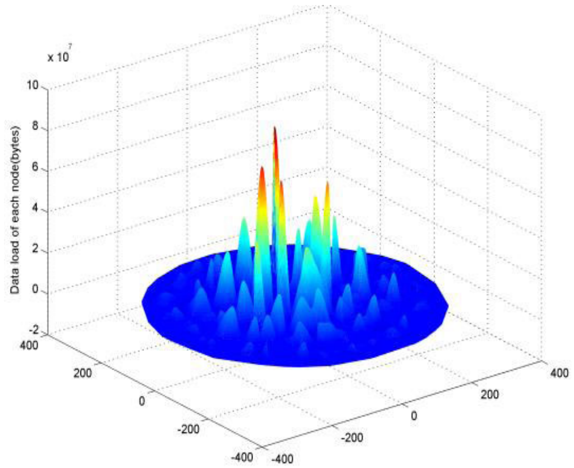
a circular region. And, the radius of the region is $\boldsymbol{R = 350m}$. The sink is located at the center. Set the same communication range $\boldsymbol{r = 80}$. Correlation coefficient and forgetting factor are respectively set $\boldsymbol{c = 0.5}$ and $\boldsymbol{\varsigma = 0.8}$. In one round of data gathering, each sensor will generate a packet and forward it to the sink following the proposed scheme. The size of an origin data packet is assumed 5*10^5 bits. The size of aggregated data packets is calculated by Equation (1) and Equation (2). Table 1 shows the parameters meaning and corresponding values in the paper. The energy of sink is assumed infinite and all the other nodes have the identical initial energy. The energy cost is calculated by Equation (3). The energy utilization efficiency is computed by Equation (5).

4) THE ROUTING PROCESSES

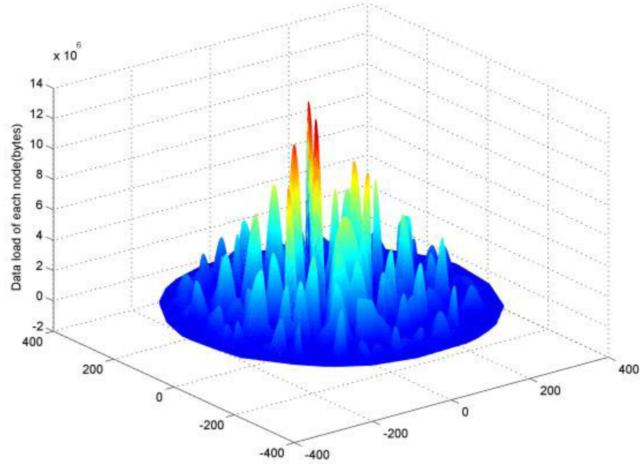
In the 1st data collection round, by algorithm 1, each ring route $\boldsymbol{Route(k')}$ consisting of some nodes including red nodes and green ring head nodes in Fig.7(a) in each ring region are constructed, such as red lines in Fig.7(a). Each ring route $\boldsymbol{Route(k)}$ consisting of all nodes in each ring region are formed, such as red lines and blue lines in Fig.7(b), and blue lines denote every non-ring-cluster node connected to their corresponding father nodes (ring-cluster nodes). The 1st hop

TABLE 1. **Network parameters.**

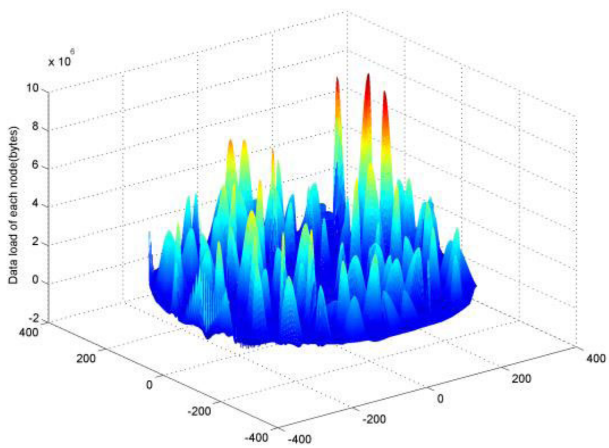
Symbol	Value
Initial energy E_{init}/J	20
Threshold distance d_0/m	87
Sensing range r_s/m	10
$E_{fusion}/nJ \cdot b^{-1}$	5
Packet size δ /bytes	5*10^5
$e_{fs}/pJ \cdot (b \cdot m^2)^{-1}$	10
$e_{amp}/pJ \cdot (b \cdot m^4)^{-1}$	0.0013
$E_{elec}/nJ \cdot b^{-1}$	50



(a) Lossless data aggregation scheme



(b) DACS scheme



(c) ERSMR scheme

FIGURE 9. **Data load in three-dimensional space under three different schemes after the 1st round data gathering.**

nodes transmits the data to the sink directly. By algorithm 2, ring-ring route is formed, such as green line in Fig.7(c), where yellow node is convergence node at convergence ring. As can be seen from Fig.7, each ring head node is gradually routed to the convergence node at the outermost ring in the first data collection round. The convergence node aggregates the entire network data and it transmits the data to the sink by the shortest route, as shown yellow line in Fig.7(d).

For a while, such as in the 4th data collection round, the routing process is shown in Fig.8.The ring-cluster nodes and ring head nodes are changed, such as shown in Fig.8(a) and Fig.8(b). The convergence ring is also changed, such as in Fig.8(c) and Fig.8(d).

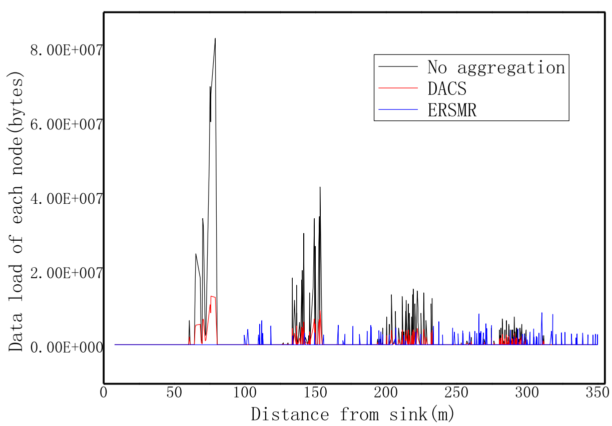
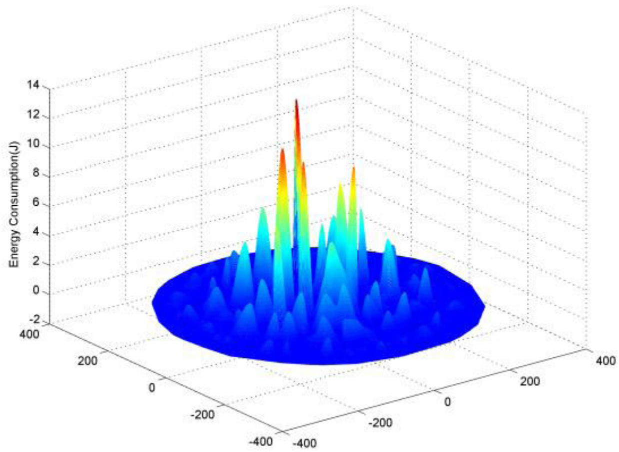


FIGURE 10. **Data load in different regions under three different schemes.**

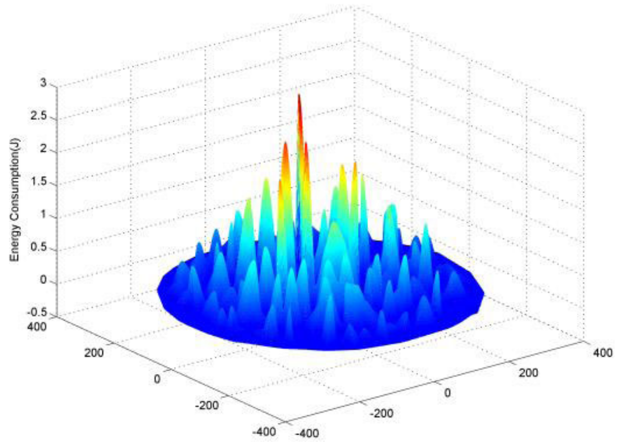
A. PERFORMANCE COMPARISON

1) DATA LOAD

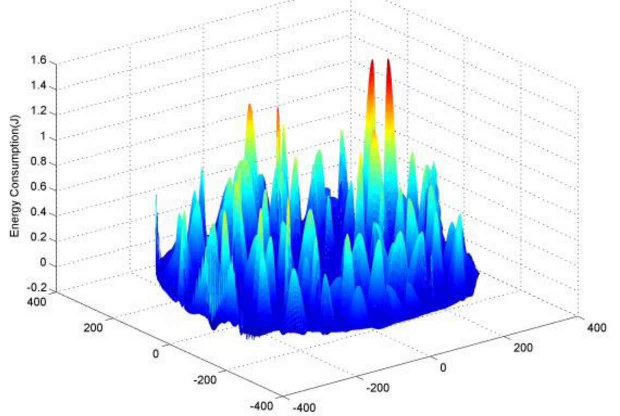
We compare the proposed ERSMR strategy with the DACS strategy and the non-aggregated strategy. The comparing results are presented by the data load in three-dimensional space and in different regions under three different schemes after the 1st round data gathering, such as shown



Lossless data aggregation scheme
(a)



DACS scheme
(b)



ERSMR scheme
(c)

FIGURE 11. Energy consumption in three-dimensional space under three different schemes after the 1st round data gathering.

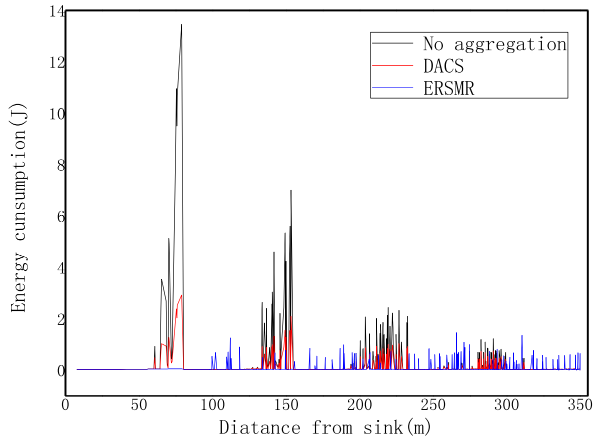


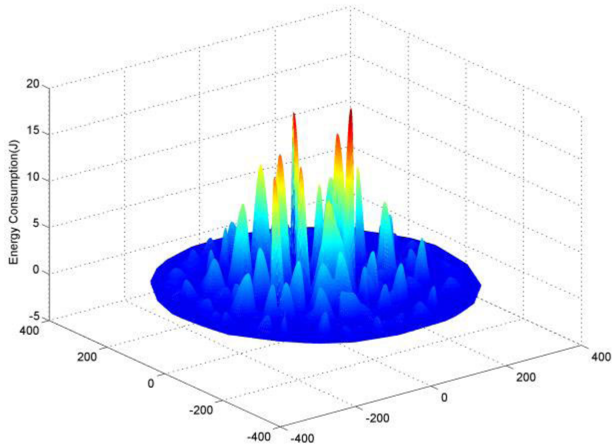
FIGURE 12. Energy consumption in different regions under three different schemes.

in Fig.9 and Fig.10 respectively. As can be seen from Fig.9, data load with lossless data aggregation scheme is far bigger than that with other two data aggregation scheme. Moreover, the data load of lossless data aggregation scheme and DACS scheme in regions close to the sink is bigger than that in other regions, which means the data load is unbalanced. But, data load of nodes in regions near the sink is greatly decreased in ERSMR.

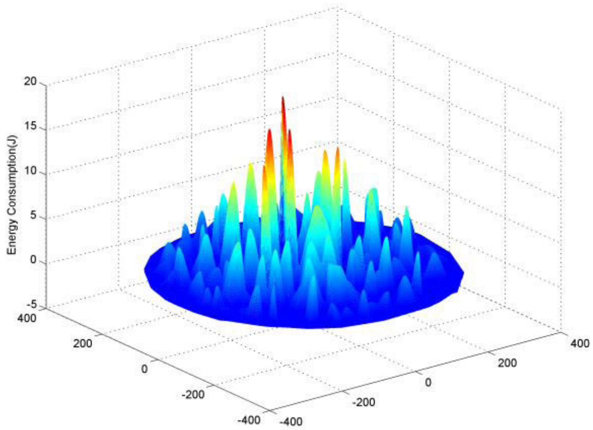
And in ERSMR, the data load of nodes in different regions is basically similar and the load is balanced. More importantly, for ERSMR scheme, the maximum data load of node is much less than that of DACS scheme and lossless data aggregation scheme, which means that the network lifetime is greatly increased.

2) ENERGY CONSUMPTION AND NETWORK LIFETIME

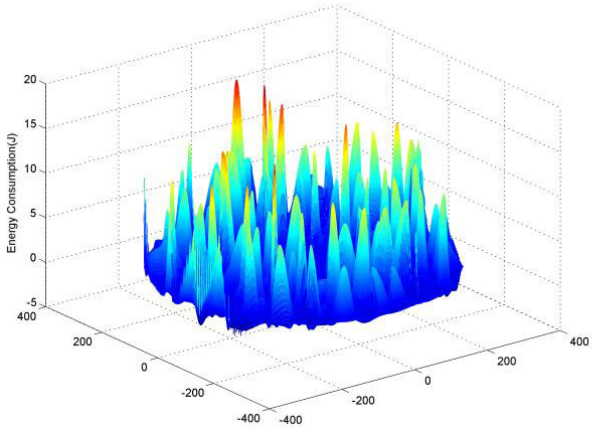
The proposed ERSMR strategy is compared with the DACS strategy and the non-aggregate strategy in energy consumption and network lifetime. The comparing results are presented by the energy consumption after the 1st round data gathering. Fig.11 and Fig.12 respectively show the results. As can be seen from Fig.11, in DACS and ERSMR, data load is much smaller than that in lossless data aggregation scheme and the energy consumption is thus greatly decreased. Moreover, in lossless data aggregation scheme and DACS scheme, the energy consumption in regions close to the sink is larger than that in other regions because data load of nodes in regions near the sink is larger than that in other regions. From the figures we can see that the ERSMR scheme can make energy consumption more balanced. This is because there exits data aggregation before s transmitting to the sink and the data load of nodes near the sink is minimized. Therefore, the energy consumption near the sink is decreased. For nodes far away from the sink, there is abundant remaining energy in this region. Moreover, the maximum node energy consumption of ERSMR is reduced dramatically and thus the network lifetime can be greatly improved. We can see from Fig.12 that there is an obvious fluctuation in lossless data aggregation scheme and DACS scheme. The nodes that consume more energy are away from sink 50-150 meters. While in ERSMR scheme, energy cost in different regions



Lossless data aggregation scheme
(a)



DACS scheme
(b)



ERSMR scheme
(c)

FIGURE 13. **Energy consumption in three-dimensional space under three different schemes when the network dies.**

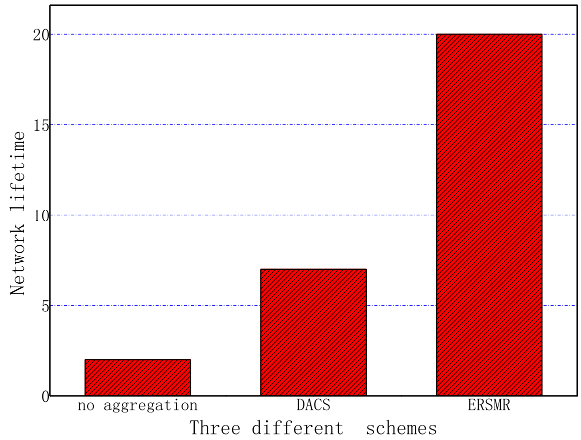


FIGURE 14. **Network lifetime under three different schemes.**

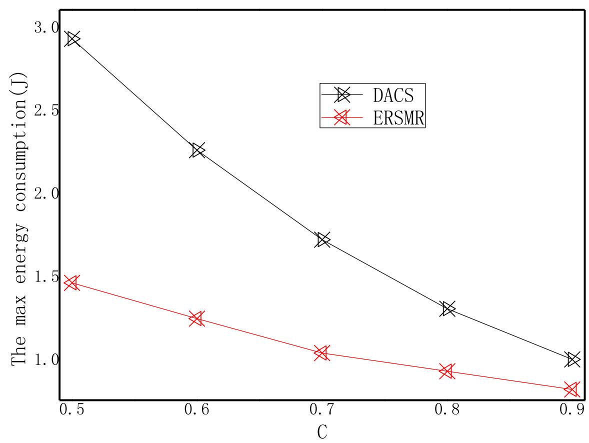


FIGURE 15. **Maximum energy cost of node in different schemes under different *c*.**

is basically the same. More importantly, in ERSMR scheme, the maximum energy consumption of node is much smaller than that in DACS scheme and lossless data aggregation scheme, which indicates that the network lifetime is greatly improved.

Fig.13 shows the energy consumption under three different schemes when the network dies. In ERSMR, we can see that the nodes in non- hotspot cost more energy when the network dies. Compared with lossless data aggregation scheme and DACS, ERSMR scheme has a better performance in energy consumption balance. Because ERSMR scheme select nodes with more residual energy as ring-cluster nodes and ring-head nodes dynamically, at the same time, choose a ring as convergence ring according to the data received by each ring-head node, and thus the data aggregation is carried out at the nodes with more residual energy, which can reduce the overall energy consumption and balance the energy utilization.

We compare the network lifetime of three different strategies and the results are shown in Fig.14. In from the figure we can see that, the network lifetime of DACS scheme is improved by $(7-2)/2=2.5$ times compared with the lossless data aggregation scheme under the same network parameter

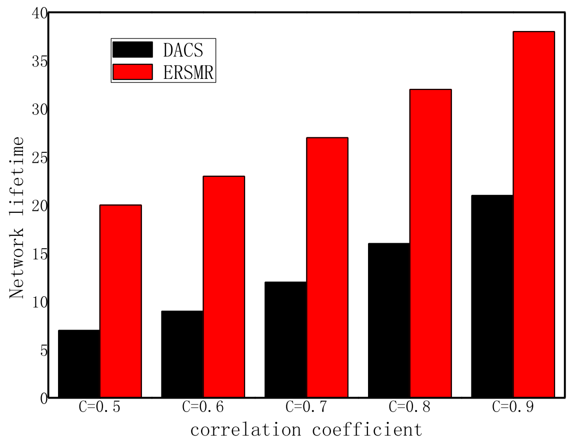


FIGURE 16. Network lifetime in different schemes under different *c*.

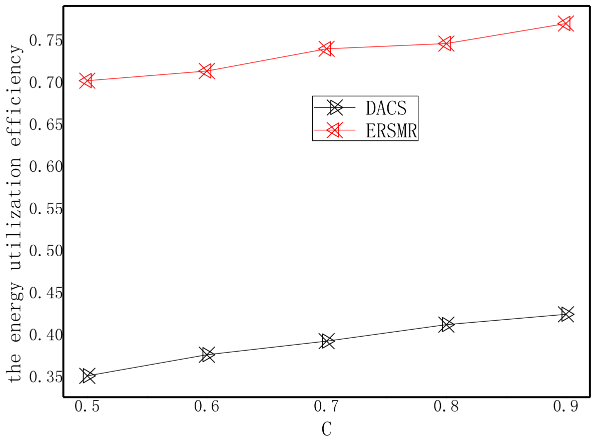


FIGURE 17. The energy utilization efficiency under different *c*.

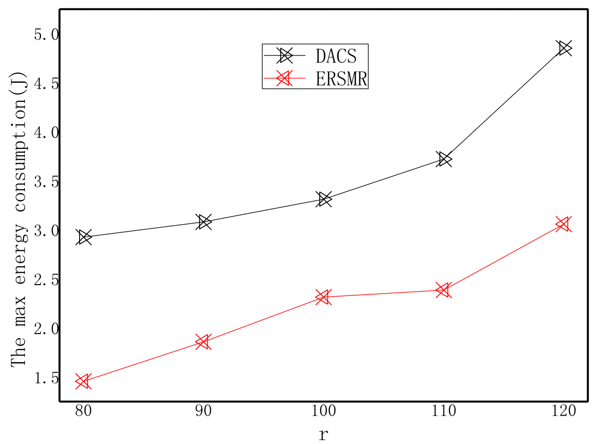


FIGURE 18. Maximum energy cost of node in different schemes under different *r*.

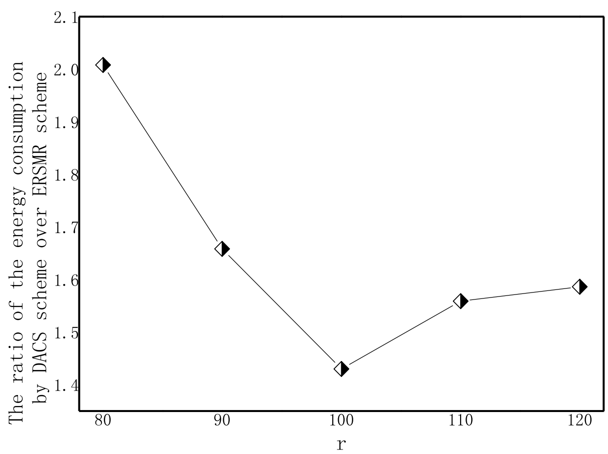


FIGURE 19. The ratio of the energy cost by DACS scheme over ERSMR scheme under different *r*.

settings. The network lifetime of the ERSMR scheme is improved by (20−7)/7=1.9 times compared with the DACS scheme. This is of great significance for WSN with limited energy.

3) PERFORMANCE COMPARISON UNDER DIFFERENT CORRELATION COEFFICIENTS *c*

We compare the maximum energy consumption in one data collection round. The comparison of network lifetime and energy utilization efficiency between the proposed ERSMR scheme and DACS scheme under different correlation coefficient are shown in Fig.15, Fig.16 and Fig.17 respectively. We can see from Fig.15, the maximum energy cost of ERSMR scheme is far less than that of DACS scheme no matter the value of the correlation coefficient. Furthermore, the bigger the correlation coefficient leads to the higher the degree of data aggregation and the smaller amount of data transmitted. Therefore, the energy consumption is reduced. It can be seen from Fig.16 that the network lifetime of ERSMR scheme is improved by (38-21)/21=0.8 times to (20-7)/7=1.9 times compared with the DACS scheme. It can be seen from Fig.17 that the energy utilization efficiency of the proposed ERSMR scheme outperforms that of DACS significantly. The energy utilization efficiency of ERSMR scheme is mostly about 70%, but that of DACS scheme is mostly about 35%. The energy utilization efficiency of ERSMR scheme is improved by 30% compared with the DACS scheme.

4) PERFORMANCE COMPARISON UNDER DIFFERENT COMMUNICATION RANGE *r*

We compare the maximum energy consumption and the maximum energy consumption ratio in one data collection round. The comparison of network lifetime and energy utilization efficiency between the proposed ERSMR scheme and DACS scheme under different communication range *r*, are shown in Fig.18, Fig.19, Fig.20 and Fig.21 respectively. From Fig.18, the maximum energy cost of ERSMR scheme is far less than that of DACS scheme no matter what the communication range *r*, which means the network lifetime is much

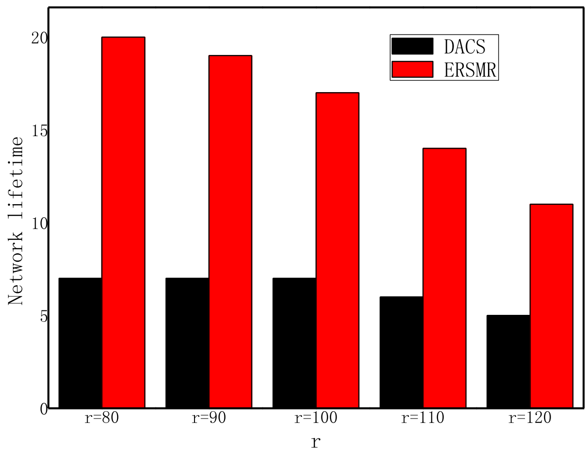


FIGURE 20. Network lifetime in different schemes under different *r*.

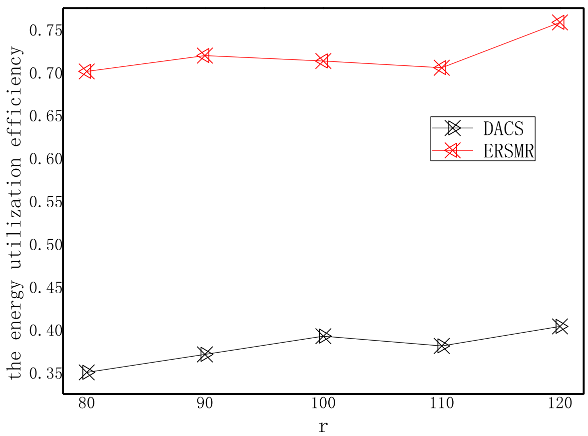


FIGURE 21. The energy utilization efficiency under different *r*.

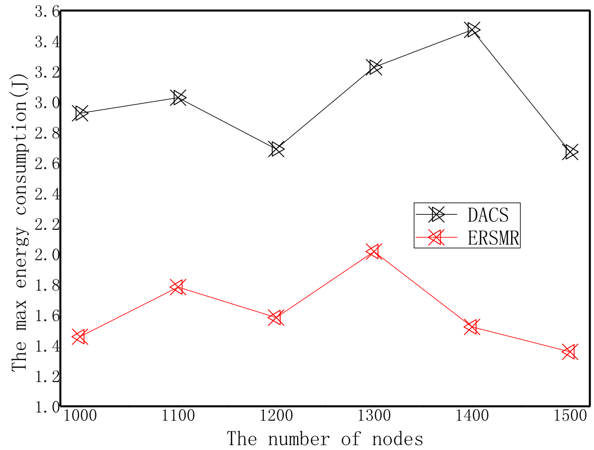


FIGURE 22. Maximum energy consumption of node in different schemes under different network scale.

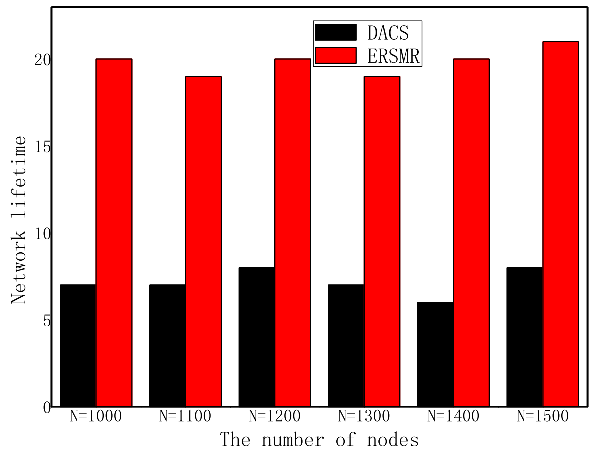


FIGURE 23. Network lifetime in different schemes under different network scale.

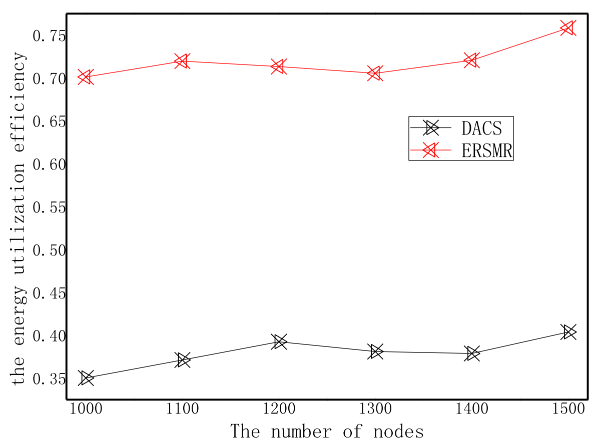


FIGURE 24. The energy utilization efficiency under different network scale.

higher than that of DACS scheme as shown in Fig.20. From Fig.19, we can see that the maximum energy consumption ratio of the two schemes is between 1.4 times-2 times and the network lifetime of ERSMR scheme is improved by (11−5)/5=1.2 times to (20−7)/7=1.9 times compared with the DACS scheme. Network lifetime will be different when selecting a different communication range. There is always an optimal radius r to maximize the network lifetime. The results of Fig.18, Fig.19 and Fig.20 show that when $r = 80$ the optimal value is obtained, which can minimize the energy consumption and maximize the network lifetime.

5) PERFORMANCE COMPARISON UNDER DIFFERENT NETWORK SCALE

The comparison of the maximum energy consumption, network lifetime and energy utilization efficiency of the ERSMR scheme with that of DACS is conducted under the different network scale in the same area including the nodes of 1000, 1100, 1200, 1300, 1400 and 1500 respectively. The results are shown in Fig.22, Fig.23, and Fig.24 respectively. It can be seen from the figures that ERSMR scheme can greatly decrease the maximum energy consumption and improve the network lifetime and energy utilization efficiency under the different network scale.

VII. CONCLUSION

This paper focuses on the design of routing algorithms for correlated data collecting in WSNs. We proposed an energy-efficient multi-ring-based routing scheme, which divide the networks into several ring regions. The proposed approach can not only minimize the number of receiving and sending data packets in hotspot but also make full use of energy far from the sink. Furthermore, energy utilization efficiency of the nodes is increased by exploiting the remaining energy of peripheral nodes. Our simulation results verify the effectiveness of the proposed ERSMR scheme. The dual goals of improving the network lifetime and increasing the energy utilization efficiency are simultaneously achieved.

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