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A Reliable Hybrid Routing Strategy for Durability Monitoring of Concrete Structures in Wireless Sensor Networks

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ABSTRACT Routing is of great significance for durability monitoring of concrete structures in wireless sensor networks. However, current solutions cannot satisfy the requirement of comprehensive network performance, including reliable communication, low data delay, and high energy efficiency. In this paper, we study the multi-objective data transmission problem and propose a hybrid routing strategy named HRRS based on packet retransmission and packet reproduction. The goal is to achieve the tradeoff of low energy consumption, low delay and high reliability. This strategy combines the reproduction mechanism and retransmission mechanism to ensure high reliable communication, and reduces the number of reproduction paths to reduce the number of packet copies in the network, and accordingly reduce the energy consumption of the network. Meanwhile, the average transmission delay of the network is guaranteed by the reproduction mechanism. Furthermore, the data load, network reliability and delay of the nodes are analyzed, and the multi-objective constraint model is established. Simulations are implemented to evaluate the HRRS scheme that proposed in this paper greatly improves the reliability of transmission while ensuring the average transmission delay of the network, and is superior to the PR scheme in energy efficiency performance. The energy cost of HRRS is reduced by 10%-20% compared to the PR.

INDEX TERMS Packet retransmission, package reproduction, reliability, concrete durability, wireless sensor network.

I. INTRODUCTION

Wireless sensor network is an important communication guarantee in the durability monitoring system of concrete structure. The basic process of concrete structure durability monitoring network is to monitor the service status of concrete in various external environments through sensors. The collected durability data such as temperature, humidity, CO_2, pH value, structural stress and structural crack are transmitted to the big data platform via wireless sensor network for the purpose of monitoring the durability of concrete structure [1], [2].

However, there are still some problems in the durability monitoring of concrete structures in wireless sensor networks. Firstly, wireless sensor networks in durability monitoring of concrete structures usually require higher communication reliability than ordinary wireless sensor network. Structural durability monitoring involves parameters of various structures and materials, which directly represents the safety of the structure, and the safety of the structure is related to personal safety [3]. Secondly, wireless sensor networks in durability monitoring of concrete structures usually requires long network lifetime. The durability monitoring of concrete structure is a long-term and continuous process for several decades. By reducing the energy consumption of sensor network nodes, we can avoid the premature death of sensor due to excessive use of its battery energy, which leads to the failure of wireless network [4].

Many exiting works on data transmission take into account delay and reliability [5]–[8], or delay and network lifetime [9]–[11], or network lifetime and reliability [12]–[14]. Traditional performance optimization is based on the loss of

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other performance indicators. As far as we know, few studies have considered the overall performance optimization of the network. At present, in order to ensure the high reliability of transmission, the typical solutions of packet loss avoidance and packet loss recovery are often to set up multiple routes to simultaneously transmit data or to retransmit the lost packets multiple times. This method is at the expense of energy consumption and delay, which affects the network lifetime and increases the transmission delay.

Therefore, how to extend the network lifetime becomes a great challenge with the guarantee of high transmission reliability and low latency. In recent years, some researches focus on the application of modern artificial intelligence algorithm for achieving multi-objective optimization. However, these algorithms are complex to require high-performance hardware, and it is difficult to implement on terminal sensor nodes with limited resources.

In this paper, we propose a routing strategy named Hybrid green and Reliable Routing Scheme(HRRS) based on packet retransmission and packet reproduction. Based on the fault tolerance of the routing mechanism in the network layer, a data transmission strategy with low energy consumption, low delay and high reliability is realized to improve the overall performance of the network. The main contributions are as follows:

1) This strategy combines the reproduction mechanism and retransmission mechanism to achieve multiple objectives, including ensuring high reliable communication, reducing energy depletion, and guaranteeing low average transmission delay.
2) We analyze and calculate the maximum number of reproduced packets, the data load, energy consumption and delay of each node. Also, the number of automatic retransmission packets of the source node is analyzed to achieve reliability.
3) Simulations are implemented to evaluate the HRRS scheme, and show that this strategy greatly improves the reliability of transmission while ensuring the average transmission delay of the network, and is superior to other strategies in energy efficiency performance.

The rest of this paper is organized as follows: In Section 2, the related work is reviewed. In Section 3, the system model is established. In Section 4, the HRRS scheme is designed. In Section 5, The performance is analyzed and discussed. Simulation results and performance evaluation are demonstrated in Section 6. Finally, the conclusion is made in Section 7.

II. RELATED WORK

It is critical to provide reliable transmission services for a concrete wireless sensor network [15], [16]. There are two typical categories of avoiding and recovering lost packets to ensure reliable transmission in the existing works. Avoiding packet-loss strategies are usually costly, so they are not widely applied in practice. Reliable transmission by recovering lost packets is widely used in concrete structure monitoring, such as Automatic Repeat Request (ARQ) protocol [17], [18]. This is a typical packet loss recovery strategy and the network reliability is guaranteed by retransmitting the lost packet one or more times. There are two main applications:

1) End-to-End retransmission [19]: After sending packets to the sink, the source node needs to wait for the ACK message returned by sink. If the source node receives ACK, it is believed that the data has been successfully transmitted to the sink, otherwise, the source node will automatically retransmit the wrong or lost packet after waiting for some time.
2) Hop-by-Hop retransmission [20]: After transmitting packet, the sending node will listen to the channel to confirm whether the receiving node has sent the received packet. If not, the packet is retransmitted by the sending node.

For a node that 5 hops from the sink, when the error rate of each hop is 20% and the transmission success rate between adjacent nodes is 80%, the success rate of packet transmission of this node to the sink is only $(80\%)^5 = 32.7\%$. If retransmission times is 3, the success rate can be increased to $1-(1-32.7\%)^3 = 69.5\%$ with End-to-End retransmission. However, the success rate of one hop can be increased to $1 - (20\%)^3 = 99.2\%$, and the success rate of packet transmission to the sink can be increased to $(99.2\%)^5 = 96.1\%$ with hop-by-hop retransmission. Obviously, hop-by-hop retransmission greatly improves data reliability compared to end-to-end retransmission. While ARQ solutions can improve the reliability of transmissions, retransmission of lost packets can lead to high latency, which is unacceptable for the field of building structure with real-time requirements.

In order to improve transmission reliability and reduce transmission latency, packet reproduction (PR) [21] protocol is proposed. And the PR scheme is also a typical packet loss recovery strategy. In the PR, the source node has multiple copies of packets and sends them simultaneously through multiple routes. Packets lost in the routing path are reproduced at the appropriate time and forwarded through a multipath route, the process is repeated until it reaches sink. Although PR scheme can guarantee the reliability of network with multi transmission routing of data, there are a large number of copies of packets transmitted in the network, which will lead to a large amount of extra energy consumption and reduce the network life.

Both of these recovering lost packets strategies improve the reliability of network transmission by increasing the redundancy of packet. The PR protocol establishes multiple routing paths between the source node and the sink to ensure the transmission reliability. Retransmission is to transmit wrong or lost packets repeatedly on a single link to ensure reliability. During the transmission of the PR, a large number of packet copies are generated and forwarded, it consumes more energy than retransmission. Retransmission is bound to increase data transmission delays because of ACK message

FIGURE 1. The concrete structure durability monitoring network.

confirmation and retransmission of lost data. Thus, extending network life is a challenging issue while ensuring high transmission reliability and low latency.

In recent years, some studies have focused on the application of modern artificial intelligence for multi-objective optimization [22]. For example, the application of group intelligence in large-scale wireless sensor networks is studied to improve the reliability and energy efficiency of data transmission in [23]. The path planning of the artificial bee population algorithm is simulated in the data acquisition application of wireless sensor network in [24]. Also, artificial ant colony optimization [25]–[28] is used to achieve energy depletion balance and extend the system longevity. There is no denying that these algorithms are effective.

In addition, some strategies focus on other aspects to improve multiple performances of such networks. For example, mobile sinks in [29]–[32] are performed to collect data throughout the network, balancing energy expenditure and extending the network lifespan. In another instance, in [33]–[36], mobile relays are used to deliver data from a isolated segment to another one. This contributes to reducing the energy dissipation and enhancing the network reliability.

However, these algorithms often require high performance hardware and are difficult to implement on end sensor nodes with limited resources.

III. THE SYSTEM MODEL AND PROBLEM STATEMENT

A. SYSTEM MODEL

1) NETWORK MODEL

We consider a wireless sensor network where sensor nodes are randomly deployed in a flat circular area with a radius of R, and the sensors density of ρ. All deployed sensor nodes are not movable. They have the identical communication range r and the same initial energy. In order to detect events, the sensor nodes collect packets and periodically forward them to the Sink, which is located in the center of the network.

2) ENERGY CONSUMPTION MODEL

Similar to that in [37], the energy consumption is calculated according to the following two equations:

$$E_t(\gamma) = \begin{cases} \gamma\left(E_{elec} + \varepsilon_{fs} d^2\right), & d < d_0 \\ \gamma\left(E_{elec} + \varepsilon_{amp} d^4\right), & d \geq d_0 \end{cases} \tag{1}$$

$$E_r(\gamma) = \gamma E_{elec} \tag{2}$$

where $E_t(\gamma)$ represents energy consumption of sending one-bit data, and $E_t(\gamma)$ represents energy consumption of receiving one-bit data.

In Equation (1) and Equation (2), γ represents the number of bits in a packet, and d represents the transmission distance. If d is less than the $d_0, \alpha = 2$. Otherwise, $\alpha = 4$. The meaning and values of other parameters are mentioned in [37].

B. PROBLEM STATEMENT

The goal of this paper is to design a green data transmission routing scheme to optimize the whole performance optimization of reliable communication, delay and energy efficiency.

Packets may be lost in the transmission because of the unreliable wireless communication links. δ represents network reliability, and it is used to express the success rate of packet delivered to sink from all source nodes. If there are more than one packet copies from the same source node transported to the sink through multiple routes successfully, only one packet copy will be recorded. In each round of data collection, each sensor node has only one chance to become a source node. We assume that the length of the routing path from the source node i to the sink is h hops. Let $P_i = \{V_h^i, V_{h-1}^i, \ldots, V_1^i\}$ represent the nodes contained in the path, and $[\varepsilon_h^i, \varepsilon_{h-1}^i, \ldots, \varepsilon_1^i]$ represent the reliability of the node i route to the next-hop node. $\emptyset_i$ indicates the success rate of packet delivered to sink from one source node i, and $\emptyset_i = \prod_{k=1}^{h} \varepsilon_k^i$. $\emptyset_i \geq \delta$ means that $\emptyset_i$ is not less than the network reliability δ.

Network lifetime T depends largely on the node with the largest energy consumption of the network. We use the first exhausted node time to approximately represent network lifetime. We assume that node i has an initial energy E_{ini} and energy consumption E_i in each round of data collection. Data collection rounds of node i is $t_i = \lfloor E_{ini}/E_i \rfloor$, and network lifetime is $T = (t_i)\,(0 < i \leq n)$.

Delay denotes the transmission time took in transferring procedure. Transmission delay or E2E delay represents the earliest time for a packet from a source node to finish its successful transmission to the sink. Let ϑ_i represents the delay of node i via the retransmission path, and $\omega_i\,(k)$ indicates the delay of node i via the reproduction path. Transmission delay D_i of node i is the minimum of ϑ_i and $\omega_i(k)$. The average transmission delay Ω of network is defined as the average of E2E delay for all source nodes, and $\Omega = ave \sum_{i=1}^{n} D_i$. In the transmission, the packet needs time to finish one hop route, packet reproduction and ACK message of packet retransmission. The total time needed for transmission, reproduction, and ACK message confirmation is formed to DELAY statistics.

In summary, the optimization goal of this paper is to minimize the energy consumption of the node with the largest energy consumption while ensuring network reliability without increasing the node transmission delay. it needs to ensure the Equation (3).

$$\begin{cases} \underset{0<i\leq n}{\emptyset_{\mathrm{i}}} = \prod_{k=1}^{h} \varepsilon_k^i \geq \delta \\ max(T) = max \underset{0<i\leq n}{min} (t_i) = min \underset{0<i\leq n}{max} (E_i) \\ D_i = min\,(\vartheta_i, \underset{1<k\leq \lambda-1}{\min} (\omega_{\mathrm{i}}(k)) \end{cases} \tag{3}$$

IV. SCHEME DESIGN

A. RESEARCH MOTIVES

In the PR protocol [21], each original data packet carries ID, TTL, and DELAY. ID describes the information of the packet. TTL (Time To Live) describes the routing length of the data packet, namely, the number of hops before the data packet is reproduced. DELAY represents the transmission delay of the node and records the time required for a data packet to be successfully transferred to sink.

Provided that the lifetime of the data packet is TTL $= h$, and one-hop transmission reliability between each adjacent node is ε, the reliability of the data packet transmitted to the sink after h hop is $\emptyset = \varepsilon^h$. For example, if $\varepsilon = 0.9$, $h = 10$, the reliability of the data packet to the sink is reduced to $\emptyset = 0.9^{10} = 35\%$, and the loss rate is as high as 65%. In order to increase the reliability of the data packet transmitted to the sink and reduce the loss rate, the data packet can be reproduced λ copies and forwarded via λ reproduction paths after h hops. Now, the transmission reliability of the data packet transmitted to the sink is as shown in Equation (4).

$$\emptyset = 1 - (1 - \varepsilon^h)^\lambda \tag{4}$$

Therefore, the number of reproduced data packet is shown in Equation (5).

$$\begin{aligned} \lambda &= log_{(1-\varepsilon^h)}(1-\emptyset) \\ \lambda &= \frac{log_{10}\,(1-\emptyset)}{log_{10}(1-\varepsilon^h)} \\ log_{10}(1-\varepsilon^h) &= \frac{log_{10}\,(1-\emptyset)}{\lambda} \\ \varepsilon^h &= 1 - 10^{\frac{log_{10}(1-\emptyset)}{\lambda}} \\ h &= log_\varepsilon \left(1 - \left(10^{log_{10}(1-\emptyset)}\right)^{\frac{1}{\lambda}}\right) \end{aligned} \tag{5}$$

So, h is shown by Equation (6).

$$h = log_\varepsilon \left(1 - (1-\emptyset)^{\frac{1}{\lambda}}\right) \tag{6}$$

According to Equation (6), Figure 2 illustrates the relationship between the data copies λ and the packet TTL h. From the Figure 1, we can see that when h increases, the corresponding λ generated by source or relay nodes should be increased to ensure the transmission reliability. Furthermore, it can be seen that the reliability of node $\emptyset$ is decreased with the increase of the h when the reproduced packets λ is fixed. What's more, it can also be seen from Figure 2 that the more data copies λ are, the more the packet TTL h is, and the fewer the number of reproduction is. During transmission, data packets take time to finish one-hop routing and reproduction. The packet reproduction time is longer than the transmission time, and reducing packet reproduction times means reducing the delay of node. Therefore, the number of packet reproduction times is reduced in the transmission path from the source node to the sink. At the same time, a large amount of packet copy transmission in the network will increase the energy consumption of nodes, resulting in a large energy consumption in the network.

In order to ensure the reliability of communication transmission and reduce the energy consumption in the network, a hybrid routing scheme based on packet retransmission and

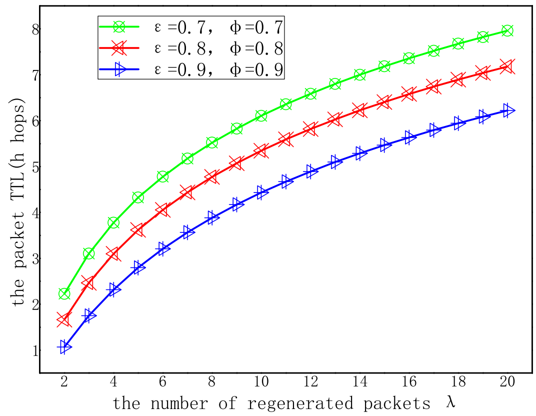


FIGURE 2. The relationship between the parameters λ and *h*.

packet reproduction is considered. A random routing path is selected among λ paths for retransmission instead of reproduction, which can reduce the number of data packet copies in the network and reduce the energy consumption in the network. Retransmission paths in hybrid routes ensure high transmission reliability.

As mentioned above, the E2E delay from a source node is equal to the earliest time required for all packets transmitted to the sink successfully. If the data packets arrive successfully through the reproduction path in the hybrid route, the E2E delay of the node is guaranteed.

B. OVERVIEW OF THE PROPOSED SCHEME

In this section, A novel Hybrid green and Reliable Routing Scheme based on packet retransmit and packet reproduction (HRRS) is suggested.

In order to achieve effective data collection and optimize the overall performance of the network, a scheme that combines data packet retransmission and reproduction with reliable communication, latency, and energy efficiency is proposed in this section.

Combined with the retransmission mechanism, a route path is randomly selected in λ paths for retransmission. As long as a data packet is lost or fails to be transmitted, it will be retransmitted repeatedly, the rest λ-1 paths will be reproduced, and the path will be terminated if the packet is lost. This method reduces the amount of data packet copies in the network by reducing a reproduction path, so as to reduce energy consumption in the network and improve network life. At the same time, the scheme guarantees the survival of a path, and all nodes on this path that failed to transmit are retransmitted, which makes the packets of the source node arrive at the sink with high reliability, though the arrival time will be delayed. Although retransmission waiting results in slower transmission speeds and delay, data packets can arrive at the sink early if there is no loss of data on any of the remaining λ-1 reproduction paths. Since the E2E delay of a node records the earliest time required for a packet to be successfully transmitted to the sink, this scheme has little effect on the average transmission delay of the network. The overall approach is shown in Figure 3.

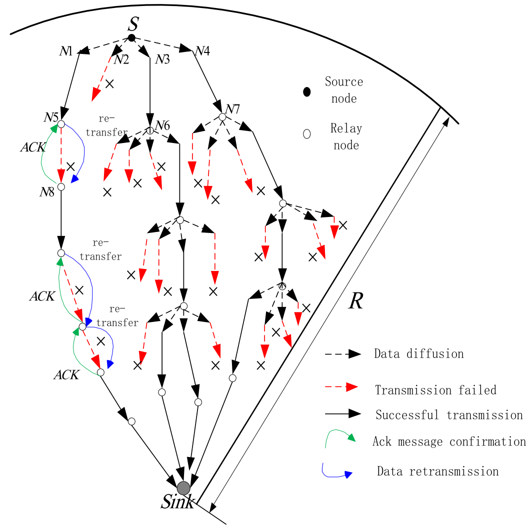


FIGURE 3. The HRRS Structure.

Figure 3 presents the process of packets are transmitted from the source node S to the sink with HRRS scheme. Firstly, several data copies carrying their TTL are initiated by the source node S. Secondly, the packets are retransmitted by choosing a path randomly on the basis of ensuring the transmission reliability. For example, N1 performs retransmission of the lost packet, and as long as the data packet is lost or error, retransmission is performed until the packet reach the sink. The rest of the data packet is distributed in the network through several routing paths, such as N2, N3, and N4, and the TTL is completed through the shortest path route. If the transmission fails, the path is terminated, such as N2. Otherwise the reproduced node is successfully reached. For example, the data packet will be reproduced at the reproduction nodes N6 and N7, and the process continues until the sink is reached. Otherwise, if the packet reaches the reproduction node successfully, such as N6 and N7, the packet will reproduce at N6 and N7, and the process continues until it reaches the sink.

Definition 1 (Source Node): The sensor node that generates and senses data is called source node., They generate λ data copies in the data reproduction.

Definition 2 (Reproduction Node): When the TTL of the data packet received by the intermediate node is less than 1, namely, after the data packet routing is completed, it is necessary to generate λ data copies again at the intermediate node to ensure the success rate of the transmission and these intermediate nodes are called reproduction nodes.

The HRRS scheme proposed in this paper integrates data packet generation or reproduction, data packet retransmission, data packet dispersing and shortest path routing. The whole transmission process of a packet from a source node to the sink consists of many rounds of these four parts.

TABLE 1. Variables and their meanings used in Algorithm 1 - Algorithm 6.

Variable	Meaning	Variable	Meaning
N	Total number of network nodes	M	Number of packets arriving at node j
Top_i	The number of hops of node i from Sink	h	Packet lifetime TTL
ε	Node single-hop reliability	μ	Number of retransmissions
θ	An angle randomly selected in directional distribution	$Q(x, y)$	Node location reached in directed distribution
R_i	Nodes that are selected for retransmission in the set of nodes that the node i is directed to distribute	λ	Number of packets reproduced on the source or reproduction node

1) Data generation or reproduction. To ensure transmission delay, M packets of copies are generated on the source node. During the transmission process, some packets may be lost due to some unreliable factors. Therefore, after several hops, M packets will be reduced to M' ($M' < M$) packets. To compensate for the lost data packets, several new packets are reproduced again on the reproduction node. For example, the number of new data packets is Q. Then, $Q + M'$ data packets will be continuously forwarded to the destination.

2) Data packet retransmission. In order to ensure the reliability and energy efficiency, a path is randomly selected for retransmission. The node on the path selected for retransmission will wait for the ACK confirmation information of the receiving node after sending the data packet. If the waiting time is up, the data packet is considered to be lost or errored during the transmission and the retransmission mechanism will be started to retransmit the last packet. The nodes on the retransmission path do not need to reproduce. There is always only one path to the sink.

3) Data packet dispersing and shortest path routing. The purpose of dispersity is to transmit the reproduced packets randomly to different nodes around the source node or the reproduction node and enable the data packets to be transmitted to destinations by multiple paths. When the data copies are dispersed by direction dispersity to the intermediate nodes, they will finish their TTL following the traditional shortest path routing schemes.

C. THE DESIGN OF HRRS

This section illustrates the proposed HRRS scheme, including data packet reproduction, data packet retransmission, data packet dispersing, and shortest path routing algorithms. Some variables of this paper are listed in Table 1.

1) PACKET REPRODUCTION

In the HRRS, the same number of data packet copies is generated on all source nodes or reproduction nodes. According to Equation (6), when the number of data copies λ is large, the packet carries a correspondingly longer TTL, which means that the packet has a longer path route before the next reproduction. Otherwise, λ is small and the packet TTL is short.

In reality, $h = \left\lfloor log_{\varepsilon}\left(1 - (1 - \emptyset)^{\frac{1}{\lambda}}\right)\right\rfloor$. For example, if data packet copies is $\lambda = 2$, the TTL is $h = 3$. If data packet copies is $\lambda = 3$, the TTL is $h = 4$. If data packet copies is $\lambda = 4$, the TTL is $h = 5$. If data packet copies is $\lambda = 5$, the TTL is $h = 7$. A special case is that if the source or reproducing node has one or less than one hop distance to the sink, the packet is transmitted directly to the sink.

Algorithm 1 Reproduction of Source Node

```
for i = 1 to N // N denote the number of nodes in the sensor networks. do
    if Top_i > 1 // //Top_i denote the hop_count of this node from the sink. then
        reproduce the λ packets.;
        calculate data packet TTL h following Equation(6).
    else
        λ = 1 and trans packet directly to the sink.
    end
end
```

Algorithm 1 is for the reproduction of the source node. All the sensor nodes in the network are calculated as the hops h to the sink. A special case is that if the source or reproducing node has one or less than one hop distance to the sink, the packet is transmitted directly to the sink. Otherwise, λ data copies are generated at the source or reproducing node, and the TTL h of each packet is calculated by Equation (6).

Algorithm 2 is used for reproduction of the reproduced node. The TTL h carried by each packet arriving at node j is calculated. If $h \geq 1$, the algorithm 5 (shortest path routing algorithm) rather than the algorithm 2 is executed, and the data packet continues to route to the next node. If $h < 1$ and the packet is not lost, it is necessary to reproduce λ data copies for the data packet arriving at node j by algorithm 2.

Algorithm 2 Reproduction of Reproduction Node

for *$i = 1$ to M // M denote the number of the transmitted packet* **do**
  arriving at one node j.;
  if *the packet's $h < 1$ && the packet is not lost* **then**
    else
      $Top_j > 1$ // //Top_j denote the hop_count of this node from the sink.
    end
    reproduce λ packets.;
    calculate data packet TTL h following Equation(6). $\lambda = 1$ and trans packet directly to the sink.
  end
end

2) PACKET RETRANSMISSION

In order to ensure the reliability and energy efficiency, a path is randomly selected for retransmission. The node on the path selected for retransmission will wait for the ACK confirmation information of the receiving node after sending the data packet. If the waiting time is up, the data packet is considered to be lost or errored during the transmission and the retransmission mechanism will be started to retransmit the last packet. The nodes on the retransmission path do not need to reproduce. There is always only one path to the sink. Implementation is shown in Algorithm 3.

Algorithm 3 Packet Retransmission

$\mu = 0$. // μ denote the number of retransmission.
// R_i denote the node selected to be retransmitted in the set of
nodes that node i disperse.
R_i trans the packet to the next node j and waite for ACK .
if *node R_i is not receive ACK and considers packet is lost* **then**
  if *$\mu = num$ // num denote the max number of retransmission.* **then**
    retransmit has reached the upper limit, the path is failed. **else**
      $\mu = \mu+1$.
    end
    R_i retransmit the packet to the next node j and waite for ACK.;
    goto 3.
  end
  $R_i \leftarrow j$. // packet is not lost and routing to the next node.
end

3) DIRECTIONAL DISPERSITY

The purpose of dispersity is to transmit the reproduced packets randomly to different nodes around the source node or the reproduction node and enable the data packets to be transmitted to destinations by multiple paths.

The specific dispersity process is that taking the source node or the reproduction node as the axis, λ angles are randomly selected around them to represent λ dispersity directions respectively. In the process of implementing the packets dispersity, the packets are dispersed along the X direction and Y direction simultaneously. We assume one selected angle dispersing is β, it means that the packet is transmitted $\tan\theta_1$ hops along the Y direction whenever it is transmitted by one hop along X direction, which is illustrated in Figure 4. The paper assumes that the dispersing distance is one hop along the X direction. As shown in Figure 4, the dispersing direction is different according to the randomly β. There are four data packets dispersed to four intermediate nodes, which are of $S_1(x = 1, y = tan\beta)$, $S_2(x = -1, y = -tan\beta)$, $S_3(x = -1, y = -tan\beta)$ and $S_4(x = 1, y = tan\beta)$. A implementation of packet dispersity is given in Algorithm 4.

Algorithm 4 Directional Dispersity of the Packet

for *each packet in initiated or reproduced packets* **do**
  call a random function. // select λ angles from 2π randomly.;
  the distribution direction of each angle θ follows Figure 4.;
  return $Q(x, y)$. // Q denote the node which the directed distribution;
  arrives.
end

4) SHORTEST PATH ROUTING

After being dispersed to the intermediate nodes, the data copies are forwarded to the next-hop node or the sink through the shortest path route. The rule for selecting the next-hop node is: C1. The next-hop node is closer to the sink; C2. The forwarding distance between nodes is gradually shortened. The shortest path route is shown in Algorithm 5.

The presented HRRS scheme is shown in Algorithm 6.

V. PERFORMANCE ANALYSIS

The key operation of HRRS is to combine the reproduction mechanism and the retransmission mechanism, to reduce the number of reproduction paths and data packet copies in the network. Therefore, under the premise of ensuring transmission reliability, the energy consumption in the network is reduced and the network lifetime is prolonged without affecting the average transmission delay of the network. In this section, the parameters and performance of the HRRS scheme are discussed.

A. MAXIMUM NUMBER OF COPIES OF REPRODUCED PACKETS

Theorem 1: Suppose R represents the radius of the network, r represents the transmission distance of the node,

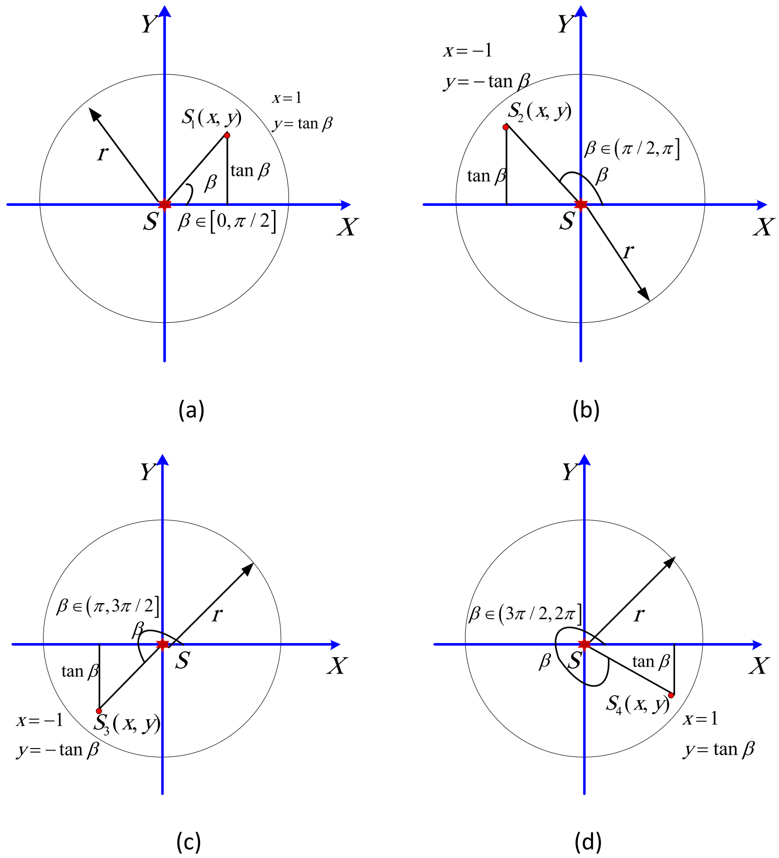


FIGURE 4. **Directional dispersity of the packet.**

Algorithm 5 Shortest Path Routing

for *each packet arriving at node j* **do**
  if *the packet is not lost* **then**
    $h = h - 1.$;
    if $Top_j <= 1$ // *Top_j denote the hop_count of this node from the sink* **then**
      trans packet directly to the sink.;
      else
        If $h > 1$
      end
      select one node as the next node of *j* by C1, C2.
    end
  end
end

the total length of the network radius is κ hop, τ represents the total number of reproductions of the initial packet sensed by a source node during the transmission to the base station, h_k indicates the TTL (hop count) of the packet at the kth reproduction, then the maximum number λ_{max} of reproduced packets can be expressed as follows.

$$\lambda = log_{(1-\varepsilon^h)}(1-\emptyset)$$
$$\lambda_{max} \le log_a(1-\emptyset)/log_a(1-\varepsilon^h) \quad (7)$$

Proof: Because $R = \kappa r$, $\sum_{k=1}^{\tau} h_k \le \kappa$, $h_{max} \le \kappa$, by the Equation(6), there is $h = log_\varepsilon\left(1-(1-\emptyset)^{\frac{1}{\lambda}}\right)$, get $h_{max} = log_\varepsilon\left(1-(1-\emptyset)^{1/\lambda_{max}}\right) \le \kappa$. Because of $0 < \varepsilon < 1$, there is $\left(1-(1-\emptyset)^{1/\lambda_{max}}\right) \ge \varepsilon^\kappa$, $1-\varepsilon^\kappa \ge (1-\emptyset)^{1/\lambda_{max}}$. And because of $1-\varepsilon^\kappa \in (0, 1)$, $(1-\emptyset)^{1/\lambda_{max}} \in (0, 1)$, there is $log_a(1-\varepsilon^k) \le log_a(1-\emptyset)^{1/\lambda_{max}}$. Therefore, $\lambda_{max} \le log_a(1-\emptyset)/log_a(1-\varepsilon^k)$.

It can be seen from Theorem 1 that the number of reproduced packets has a maximum value. If the maximum value is exceeded, the hop count in packet routing will exceed that of the network radius, and the relay node cannot reproduce the packet.

B. MINIMUM NUMBER OF RETRANSMISSIONS

Theorem 2: It is assumed that the perceptual transmission radius of each source node in the network is r, the hop count from each source node to the sink is h, and The probability of single hop successful transmission between adjacent nodes is ε. To satisfy the network reliability δ, the number of retransmissions of the source node is shown in Equation (8):

$$N = \left\lceil log(1-\delta)/log(1-\varepsilon^h)\right\rceil \quad (8)$$

Proof: After the route h hop, the success probability of data packets transmitted to the base station is reduced to ε^h.

Algorithm 6 HRRS

input : a given network graph G, the node reliability ε, the number of data copies λ, the number of retransmission μ

output: the network reliability δ, the average transmission delay, the max energy cost

1 **for** $i = 1$ ***to*** N *// N denote the number of nodes in the sensor networks.* **do**

2 reproduce following algorithm 1. // N nodes reproduce the initated λ packets.

3 disperse following algorithm 4.

4 call a random function // select a path to retransmit and the rest of

5 the path to reproduce.

6 **else**

7 random number is equivalent to retransmit path

8 **end**

9 retransmitting following algorithm 3. the other λ-1 paths route to the next hop following algorithm 5.

10 **if** *the packet's* $h < 1$ *&& the packet is not lost* **then**

11 reproduce following algorithm 2. // reproduced nodes reproduce;

12 λ data copies.;

13 goto 3.

14 **end**

15 **end**

To increase the success rate of packets to the base station, the packet was sent N times. According to the Bernoulli test, the random number of successful transmissions is $\varsigma \sim (N, \varepsilon^h)$, and the result was subject to secondary distribution. The probability of all failures of N transmissions is $(1-\varepsilon^h)^N$, and the probability of success at least once is $1-(1-\varepsilon^h)^N$.

As mentioned above, δ represents network reliability, φ_i represents the success rate of packets transmitted from source node i to base station.$\varphi_i \geq \delta$ means that the packets of each node are transmitted to the base station at a success rate not less than the network reliability δ. So there is:

$$\begin{aligned} 1-(1-\varepsilon^h)^N &\geq \delta \\ 1-\delta &\geq (1-\varepsilon^h)^N \\ log(1-\delta) &\geq log(1-\varepsilon^h)^N \\ N &\geq log(1-\delta)/log(1-\varepsilon^h) \\ N &= \left\lceil log(1-\delta)/log(1-\varepsilon^h) \right\rceil \end{aligned}$$

C. ENERGY CONSUMPTION

We discuss the number of packets transmitted on each node after a round of data collection.

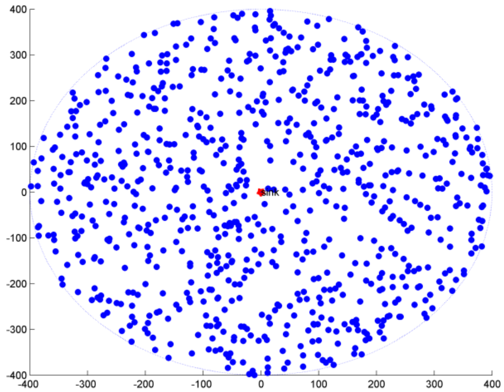


FIGURE 5. A network consisting of 800 sensor nodes.

Theorem 3: The network density is ρ, the emission radius of the sensor node is r, the distance from the sink is l, and the data load β_k of the node with hop count $k = \lceil l/r \rceil$ is calculated as follows:

$$\beta_k = \frac{\left(2\left\lceil \frac{1}{2} \right\rceil - 1\right)\pi r^2 \rho \cdot \lambda + \sum_{m=1}^{h} \left(2\left\lceil \frac{l+mr}{r} \right\rceil - 1\right)\pi r^2 \rho \cdot \lambda}{\left(2\left\lceil \frac{1}{2} \right\rceil - 1\right)\pi r^2 \rho} \tag{9}$$

Proof: Let the node's emission radius be r, and the distance of the k-hop node from the sink is l, $l \in ((k-1)\,r, kr], k = 1, 2, 3, \ldots k$. The area of the kth hop area is $\pi(kr)^2 - \pi((k-1)r)^2 = (2k-1)\pi r^2 \rho$, so the number of nodes at the kth hop in the network is $(2k-1)\pi r^2 \rho$.

Based on the shortest path route, each node looks for its next-hop neighbor node. If the number of reproduced packets on the source or reproduction node is fixed to λ, each k-hop node assumes the transmission of its own λ packets, and undertakes packet forwarding from the $k+1$ hop to the h hop node. The total length of the radius is h hop. The average amount of data that each k-hop node assumes is:

$$\begin{aligned} \beta_k &= \frac{(2k-1)\pi r^2 \rho \cdot \lambda + \sum\limits_{k'=k+1}^{h} (2k'-1)\pi r^2 \rho \cdot \lambda}{(2k-1)\pi r^2 \rho} \\ &= \frac{\left(2\left\lceil \frac{1}{2} \right\rceil - 1\right)\pi r^2 \rho \cdot \lambda + \sum_{m=1}^{h} \left(2\left\lceil \frac{l+mr}{r} \right\rceil - 1\right)\pi r^2 \rho \cdot \lambda}{\left(2\left\lceil \frac{1}{2} \right\rceil - 1\right)\pi r^2 \rho} \end{aligned}$$

The loss of the packet is not considered here. If a certain packet is lost, the actual value is less than this value. In the HRRS policy, a routing path is randomly selected from the λ routing paths for retransmission without spreading, which can reduce the number of packet copies reproduced by relay nodes in a route path. Thus, the average amount of data that each k-hop node assumes is less than the value of Equation (9). Since energy consumption varies with the data load assumed by each node, the HRRS strategy will have an advantage over the PR strategy in terms of energy consumption savings.

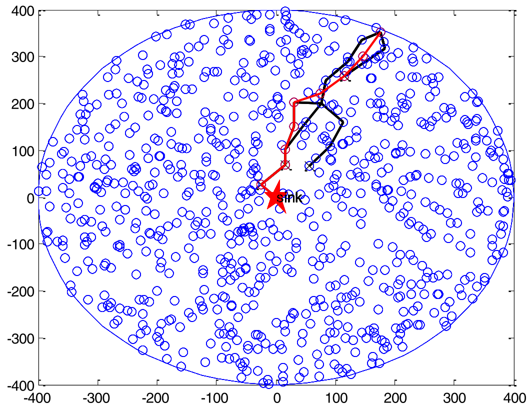


FIGURE 6. The transmission route to the sink from one source node.

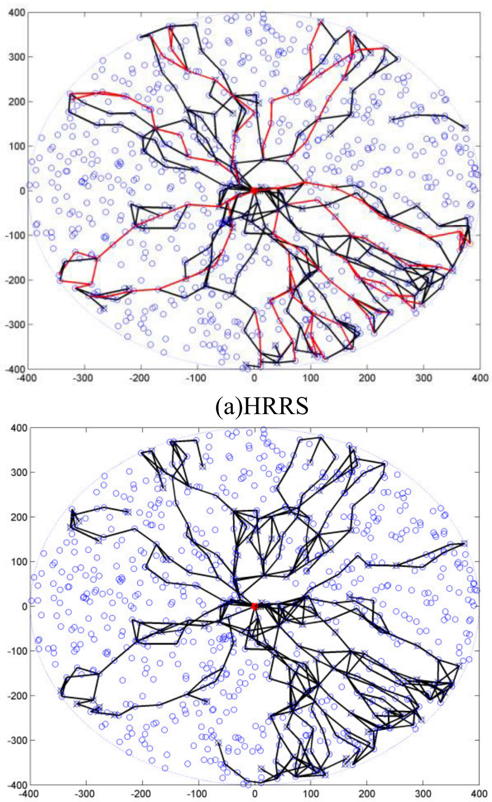


FIGURE 7. The transmission route to the sink from all source nodes located in the outermost ring.

D. NETWORK AVERAGE TRANSMISSION DELAY

The total length of the network radius is κ hop, ie $R = \kappa r$. In the transmission process from the source node to the base station, it is assumed that the number of reproduction on the diffusion path is τ. It is known from Theorem 1 that the number of the reproduced packet has a maximum value. According to the characteristics of Figure 2, a longer TTL is required for transmission. According to $h = \log_a \left[1-(1-\emptyset)^{1/\lambda}\right] / \log_a \varepsilon$, the maximum TTL of the reproduced packet is $h_{max} = \log_a \left[1-(1-\emptyset)^{1/\lambda_{max}}\right] / \log_a \varepsilon$, so $\sum_{k=1}^{\tau} h_k \leq \kappa$.

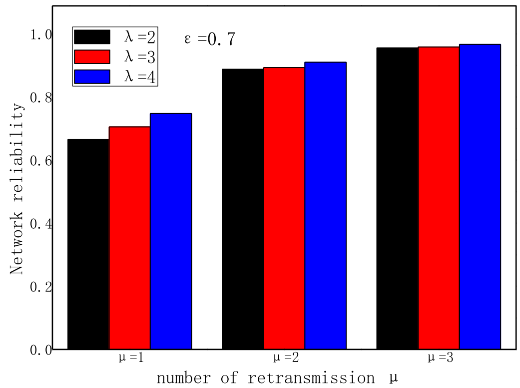


FIGURE 8. The network reliability comparison under different λ in HRRS.

Assuming that ν represents the time required for one-hop transmission, at least a κ hop is required from the source node to the base station, υ represents one packet reproduction time, then the node transmission delay ω on the diffusion path is calculated as shown in Equation (10):

$$\omega = \tau \cdot \upsilon + \nu \cdot \kappa \tag{10}$$

Because the time of one data reproduction is much longer than the transmission time of a data packet, that is $\upsilon \gg \nu$, the node transmission delay ω on the diffusion path mainly depends on the number of reproduction.

The node transmission delay ϑ on the retransmission path is determined by the retransmission waiting ACK time w, the one-hop transmission time ν, and the number μ of retransmissions. The node E2E delay ϑ on the retransmission path is calculated as shown in Equation (11):

$$\vartheta = (\mathrm{w} + \nu) \cdot \kappa \cdot \mu \tag{11}$$

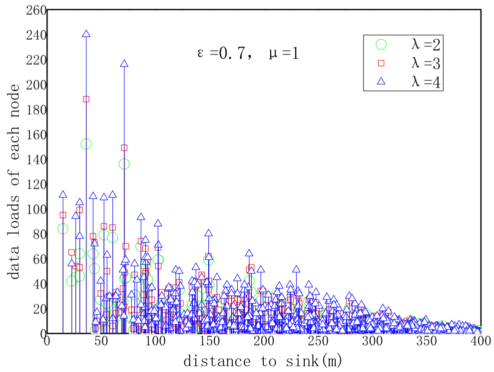
It can be seen from Equation(10) and Equation(11) that ϑ arrives earlier when the number τ of reproductions is large, the number μ of retransmissions is small, and the number λ of reproductions is small. When the number of reproductions λ is large, the number of reproductions τ is small, and the number of retransmissions μ is large, ω arrives earlier.

According to the definition, the E2E delay D_i from one source node i to the base station is equal to the earliest time required for all packets generated during transmission to be successfully transmitted to the base station. ϑ_i is the transmission delay of packets from the i node to base station through retransmission path, $\omega_{\mathrm{i}}(k)$ represents the transmission delay of packets from the i node to base station through the reproduction path, and the transmission delay D_i of the i node is the minimum value of that of λ successful paths. As shown in Equation (12):

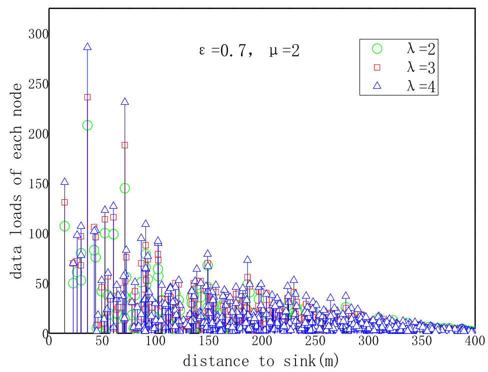
$$D_i = min(\vartheta_i, \min_{1<k\leq\lambda-1} (\omega_{\mathrm{i}}(k))) \tag{12}$$

The network average transmission delay Ω is defined as the average time of E2E delay of all source nodes successfully arriving at the sink, as shown in Equation (13):

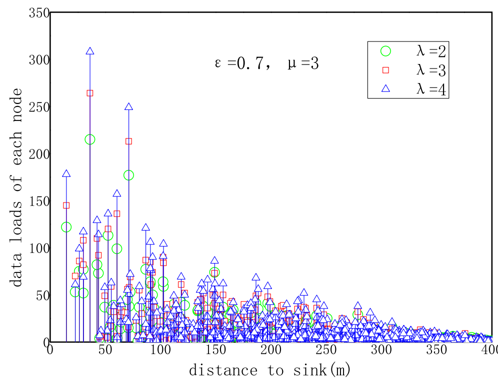
$$\Omega = ave \sum\nolimits_{i=1}^{n} D_i \tag{13}$$



(a) ε = 0.7 , μ = 1



(b) ε = 0.7 , μ = 2



(c) ε = 0.7 , μ = 3

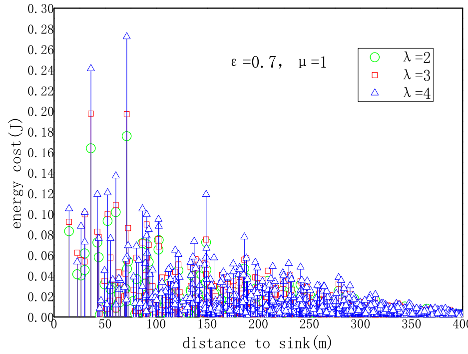
FIGURE 9. The data load comparison under different λ in HRRS.

In summary, the E2E delay of the node and the average transmission delay of the network are little affected in the HRRS scheme.

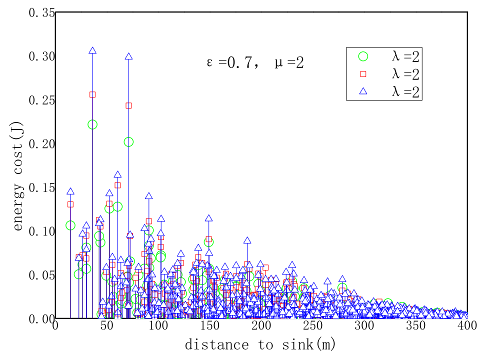
VI. SIMULATION RESULTS

In this section, the proposed HRRS scheme is evaluated and compared with the existing PR routing mechanism in terms of three performance indicators, including 1) network reliability; 2) the maximum energy consumption; and 3) the average transmission delay after one round of data collection.

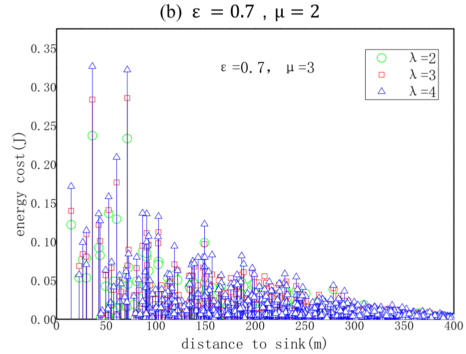
As shown in Figure 5, the simulation scenario is a network consisting of 800 sensor nodes that are uniformly deployed in a circular area with the radius of $R = 400m$. The sink is located at the center of the area. The transmission range r of each sensor node is 60 (m). The packet size of each



(a) ε = 0.7 , μ = 1



(b) ε = 0.7 , μ = 2



(c) ε = 0.7 , μ = 3

FIGURE 10. The energy consumption comparison under different λ in HRRS.

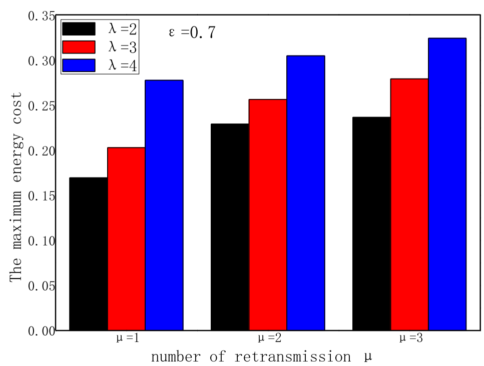
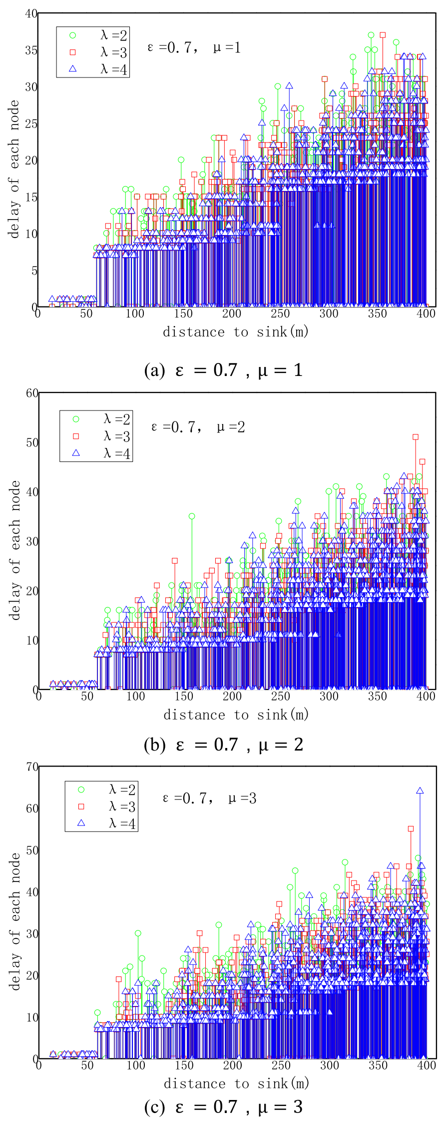


FIGURE 11. The maximum energy consumption Comparison of nodes under different λ in HRRS.

TABLE 2. The comparison results under different λ.

ε=0.7	λ	Network Reliability	The Maximum Energy Consumption (J)	Average Transmission Delay (ms)
	2	66.47%	0.1695	18.6533
μ=1	3	70.56%	0.2030	17.4767
	4	74.78%	0.2778	16.4854
	2	88.75%	0.2292	21.3038
μ=2	3	89.31%	0.2567	19.6292
	4	91%	0.3051	18.8848
	2	95.53%	0.2367	22.1887
μ=3	3	95.85%	0.2795	20.6341
	4	96.63%	0.3246	19.5668



(a) ε = 0.7 , μ = 1
(b) ε = 0.7 , μ = 2
(c) ε = 0.7 , μ = 3

FIGURE 12. The node delay comparison under different λ in HRRS.

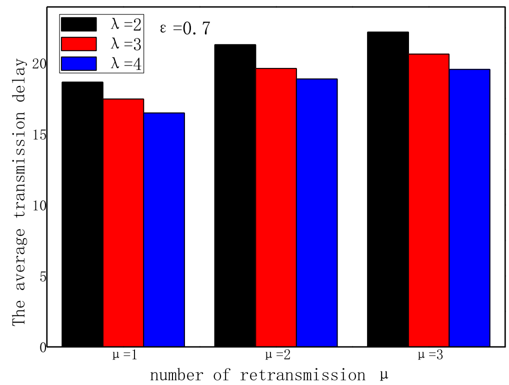


FIGURE 13. The average transmission delay comparison under different λ in HRRS.

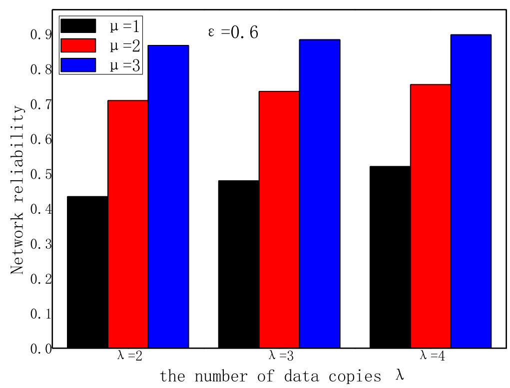


FIGURE 14. Network reliability comparison under different μ in HRRS.

round is fixed 10000 bits. One hop transmission time is 1 (ms) and the packet reproduction time is 5 (ms). All the nodes except the sink have the identical initial energy of 2(J). The energy consumption of each node is calculated based on the data loads by Equation (1) and Equation (2). The data loads of each node includes the number of packets received and sent.

The simulation is conducted on MATLAB 7.0. Each simulation runs 1000 times, and the average value is reported as the final result.

A. HRRS ROUTE

We assumed that the one-hop transmission reliability of the node is $\varepsilon = 0.85$, the number of retransmissions is $\mu = 1$, and the number of diffusion fractions is $\lambda = 3$.

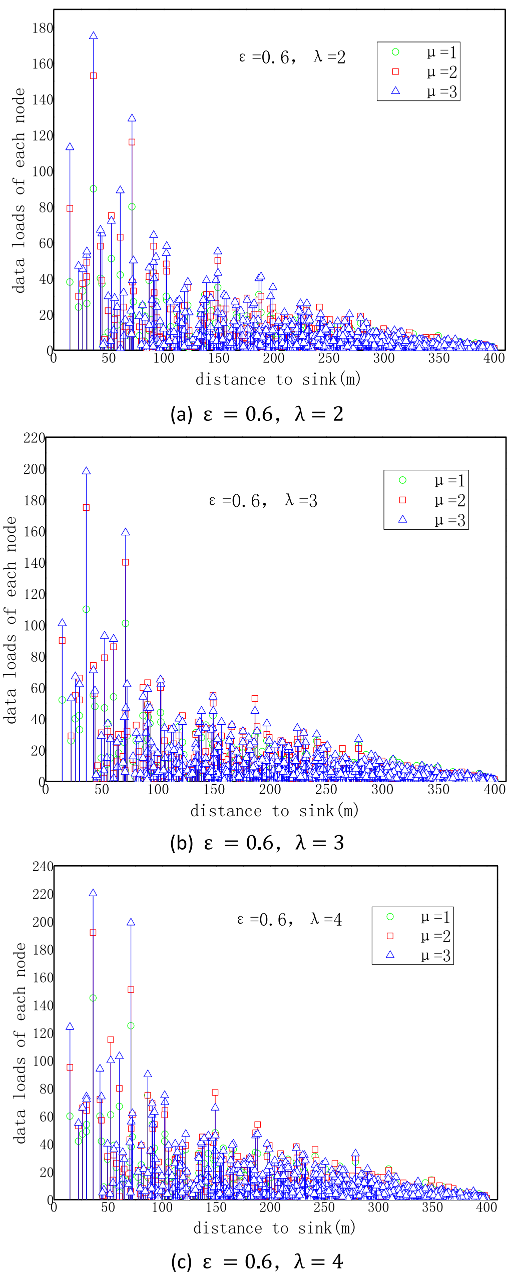


FIGURE 15. The data load comparison under different μ in HRRS.

The transmission route to the sink from one source node located in the outermost ring is shown in Figure 6. As can be seen from the figure, the red mark is a retransmission path of the HRRS, the black mark is reproduction path of the HRRS. The symbol "x" indicates the transmission failure between the nodes. For the retransmission path, there is an opportunity to retransmit between the nodes although the "x" is marked, and it may be successfully transmitted to the sink finally, but for the reproduction path, "x" indicates that termination of the transmission. The transmission route to the sink from all source nodes located in the outermost ring is shown in Figure 7. HRRS ($\mu = 1$, $\lambda = 3$) scheme and PR ($\lambda = 3$) scheme are used respectively in Figure 7 (a) and Figure 7 (b). There are many routing paths and high failure rates in the PR scheme.

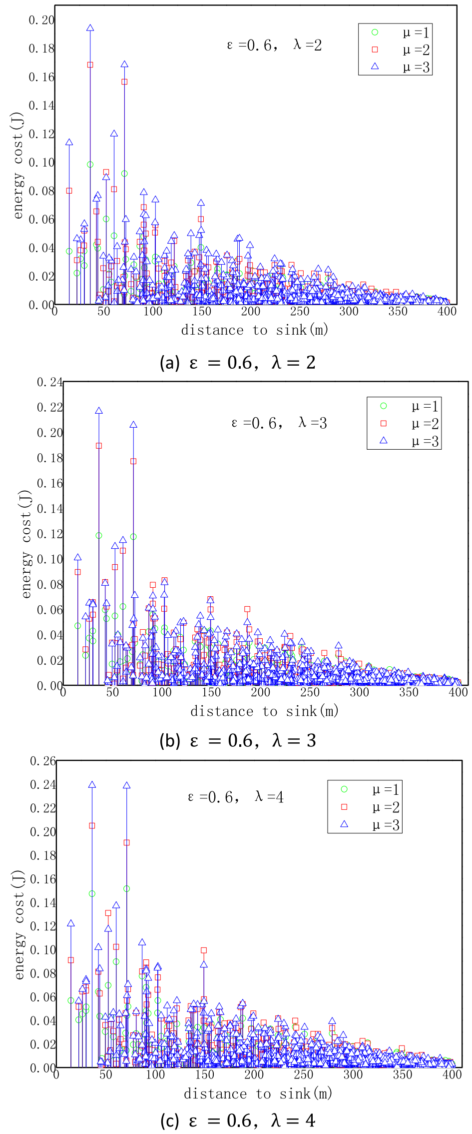


FIGURE 16. The energy consumption comparison under different μ in HRRS.

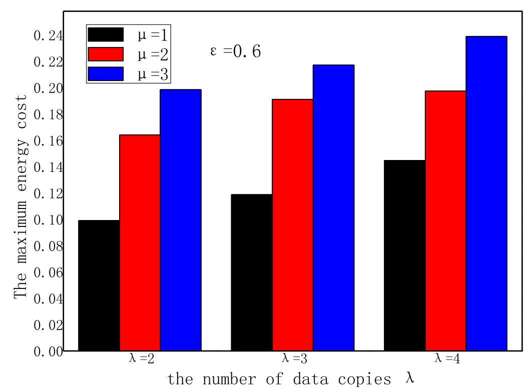
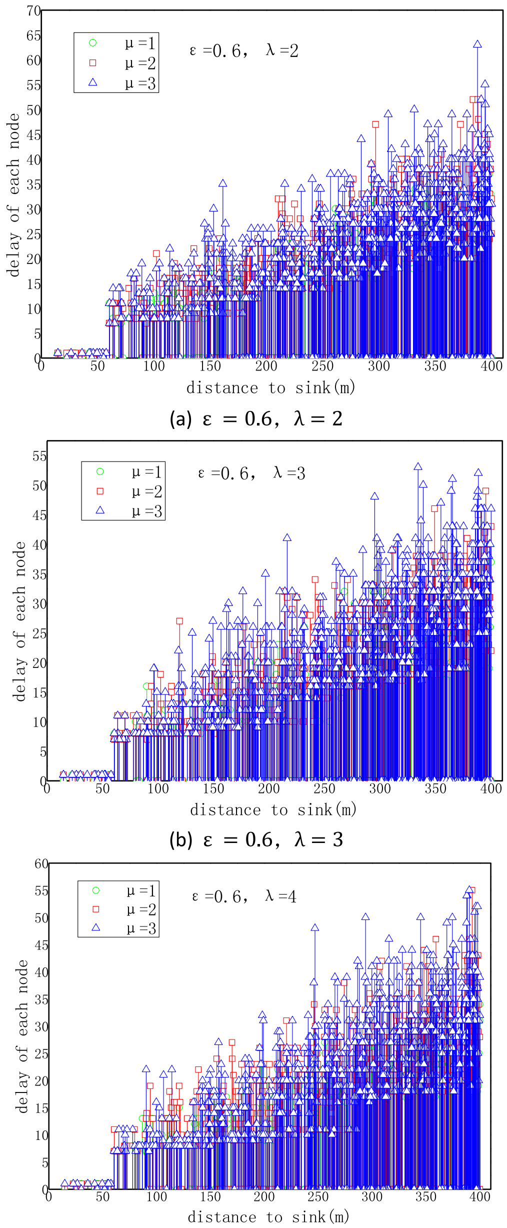


FIGURE 17. The maximum energy consumption comparison under different μ in HRRS.



(a) ε = 0.6， λ = 2

(b) ε = 0.6， λ = 3

(c) ε = 0.6， λ = 4

FIGURE 18. The node delay comparison under different μ in HRRS.

B. PERFORMANCE COMPARISON UNDER DIFFERENT λ

In this section, we evaluate the impact of λ on the performance of HRRS. We respectively conduct simulation on performance indexes of reliability, energy consumption and average transmission delay. One-hop node reliability is assumed with $\varepsilon = 0.7$, and the number of retransmissions is fixed to $\mu = 1$, $\mu = 2$ or $\mu = 3$. According to Theorem 2, there is a maximum number of packet copy of source node or reproduction node, and the $\lambda_{max} = 5$ is the maximum copies in our experiment. Thus, the performance is evaluated under the $\lambda = \{2, 3, 4\}$. Under the three different cases, our simulation are shown in Figure 8-Figure 13, where multiple metrics are reflected, including reliability, node load, energy cost, the maximum energy cost, and delay. Also, the comparison result of these metrics is shown in Table 2.

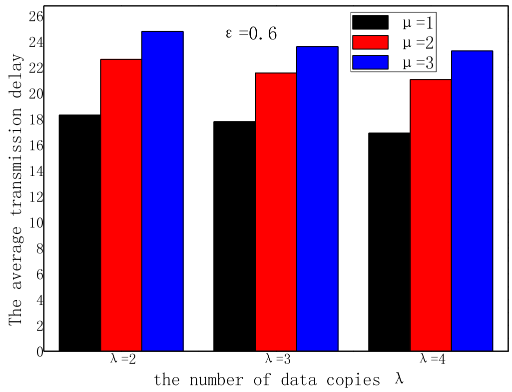


FIGURE 19. The average transmission delay comparison under different μ in HRRS.

It is illustrated in Figure 8 that the bigger value of λ leads to the higher network reliability in various of ε and μ. This means that the more copies of reproduction packet transported in the network provides the higher reliable transmission.

As shown in Figure 9, it can be seen that there are more data packets to be forwarded for nodes in the area closer to the sink as a whole. And a larger value of λ leads to a larger amount of transmitted data, which is caused by more copies of the packet in the network. For example, $\lambda = 2$ has less packets transmitted on each node compared to $\lambda = 3$. And when $\lambda = 4$, it has the largest amount of transmitting data compared with $\lambda = 2$ and $\lambda = 3$.

Figure 10 illustrates the energy consumption of each node after one round of data gathering. In the simulation, it is only necessary to calculate the energy consumed in transmitting and receiving data packets, and the energy consumed by the data packet reproduction is negligible. Therefore, the energy consumption presents a similarly changing trend with the data loads carried by each node. The maximum energy consumption comparison after one round of data gathering is demonstrated in Figure 11. It can be clearly seen from the figure that the maximum energy consumption is larger with the bigger λ.

The E2E delay of each node is shown in Figure 12. In addition, the average transmission delay comparison is shown in Figure 13. As can be seen from Figure 12, the delay is longer when the distance to the sink becomes much farther. Moreover, we can see that the delay is reduced when the λ is becoming larger. As can be seen from Figure 13, the average transmission delay is reduced when the λ is becoming larger.

This is because that a larger λ leads to less reproducing times. Therefore, the number of packet reproduction times is reduced in the transmission path from the source node to the sink. The packet reproduction time is longer than the transmission time, and reducing packet reproduction times means reducing the delay of node. In this way, the delay through the reproduction routing path in HRRS is reduced.

TABLE 3. The comparison results under different μ.

ε=0.6	μ	Network Reliability	The Maximum Energy Consumption (J)	Average Transmission Delay (ms)
	1	43.41%	0.0990	18.2988
λ=2	2	70.91%	0.164	22.6174
	3	86.69%	0.1984	24.7876
	1	47.94%	0.1187	17.7881
λ=3	2	73.53%	0.1910	21.5696
	3	88.32%	0.2170	23.6194
	1	52%	0.1446	16.9087
λ=4	2	75.47%	0.1973	21.0597
	3	89.75%	0.2388	23.2827

And, it means that the average transmission delay is reduced. For example, a source node is located at 400 meters, according to the Equation (5), the TTL time of the data packet is 3 hops when $\lambda = 2$. At this time, the data packet needs to be reproduced at least 4 times when it reaches the sink through the reproduction routing path in HRRS. The TTL time of the data packet is 5 hops when $\lambda = 4$, and the reproduction time is required twice. Therefore, the transmission delay of the node is larger than the that of the node when $\lambda = 4$.

C. PERFORMANCE COMPARISON UNDER DIFFERENT μ

In this section, we evaluate the impact of μ on the performance of the proposed HRRS. We respectively conduct simulation on performance indexes of reliability, energy consumption and average transmission delay. One-hop node reliability is assumed with $\varepsilon = 0.6$, and the number of reproduction packet is fixed to $\lambda = 2$, $\lambda = 3$ or $\lambda = 4$. The performance is evaluated under the $\mu = \{1, 2, 3\}$.

Under the three different cases, our simulation results on metrics of reliability, node load, energy cost, the maximum energy cost, delay and the average transmission delay are shown in Figure 14-Figure 20. The comparison result is shown in Table 3.

As observed from Figure 14 that the bigger value of μ leads to the higher network reliability. This means that the more packets arrived to the sink successfully provides the higher reliable transmission because of more retransmission times. Network reliability is mainly guaranteed by the retransmission times in HRRS. When the retransmission times is 3, the network reliability δ can reach 90% even if ε is 0.6.

Figure 15 illustrates the number of packets transmitted by each node in different areas of the network. As shown in the Figure 15, it can be seen that there are more data packets to be forwarded for nodes in the area closer to the sink as a whole. Data load of each node includes data packets received and transmitted, and a larger value of μ leads to a larger amount of transmitted data. For example, $\mu = 3$ has the largest amount of transmitted data compared with $\mu = 1$ and $\mu = 2$.

As shown in Figure 16, the energy consumption presents a similarly changing trend with the data loads carried by each node.

The maximum energy consumption comparison after one round of data gathering is demonstrated in Figure 17. It can be clearly seen from the figure that the maximum energy consumption is larger with the bigger μ. The energy consumption of the node mainly comes from the energy consumed when transmitting data packets. Some nodes consume more energy because of repeated retransmissions, which results in the increase of the maximum energy consumption.

The E2E delay of each node is shown in Figure 18. In addition, the average transmission delay comparison is shown in Figure 19. As can be seen from Figure 18, the delay is longer when the distance to the sink becomes much farther. Moreover, we can see that the retransmission waiting time is increased correspondingly when μ is becoming larger, and the delay is increased too.

As observed from Figure 19, the average transmission delay is increased when the μ is becoming larger. The delay of the retransmission path will increase because of the retransmission waiting time if all the reproduction paths fail, thus increasing the average transmission delay of the network.

D. COMPARISON OF HRRS AND PR

In this section, the proposed HRRS scheme is compared with the existing PR routing mechanism from three performance indicators including network reliability, the maximum energy consumption and average transmission delay after one round of data collection.

Firstly, assuming that ε and μ are the same, the network reliability of HRRS is compared with PR under $\lambda = 2$, $\lambda = 3$ and $\lambda = 4$. The specific comparison results are shown in Table 4.

As observed from Table 4 that the network reliability of HRRS is far greater than that of PR no matter what the value of parameter λ is. When the one hop node reliability is relatively low, such as $\varepsilon = 0.6$, the network reliability of the PR scheme is only 26.87% even if $\lambda = 4$, while the HRRS scheme can reach 89.75%. When the one hop node reliability is relatively high, such as $\varepsilon = 0.85$, the network reliability of the HRRS scheme is close to 100% even if $\lambda = 2$. In contrast, the reliability of the PR scheme is only 76.47%.

TABLE 4. Comparison of reliability between HRRS and PR.

parameters/reliability		HRRS(μ=1)	HRRS(μ=2)	HRRS(μ=3)	PR
ε=0.6	λ=2	43.41%	70.91%	86.69%	18%
	λ=3	47.94%	73.53%	88.32%	20.75%
	λ=4	52%	75.47%	89.75%	26.87%
ε=0.7	λ=2	66.47%	88.75%	95.53%	32.12%
	λ=3	70.56%	89.31%	95.85%	41.38%
	λ=4	74.78%	91%	96.63%	50.66%
ε=0.85	λ=2	92.94%	98.35%	99.38%	76.47%
	λ=3	95.50%	99.07%	99.47%	86.41%
	λ=4	97.44%	99.22%	99.62%	90%

TABLE 5. THE maximum energy consumption Comparison between HRRS and PR.

parameters/ Maximum energy cost (J)	HRRS(μ = 1)	PR
λ=2	0.3157	0.3895
λ=3	0.4771	0.5427
λ=4	0.6748	0.7542

Figure 20 shows the network reliability comparison between HRRS scheme and PR scheme after a round of data collection. As can be seen from Figure 20(a), the network reliability of the HRRS scheme is much greater than the network reliability of the PR scheme. For example, if $\varepsilon = 0.6$, the transmission success rate in HRRS can be nearly 90% when $\mu = 3$, while the PR is only below 30%. The same is true for Figure 20(b) and Figure 20(c).

When one hop node reliability $\varepsilon = 0.85$, the data load comparison after the round of data collection of the HRRS and the PR is shown in Figure 21, and the energy consumption of each node is compared as shown in Figure 22. Table 5 shows the detailed comparison results of the maximum energy consumption, and Figure 23 shows the comparison of the maximum energy consumption. As can be seen from Table 5 and Figure 23, the energy cost of HRRS is lower than that of PR, and the maximum energy cost is reduced by 19%, 12% and 11% respectivel.

Figure 24 desplays the comparison of the E2E delay at each node between the proposed HRRS scheme and the PR scheme after a round of data collection. Table 6 illustrates the detailed comparison results of the average transmission delay. Figure 25 shows the comparison of average transmission delay.

As reflected from Figure 24, the delay is longer when the distance to the sink becomes much farther. Moreover, the E2E delay of the HRRS scheme seems to be higher than that of the PR scheme, and this phenomenon is normal. Because the E2E delay represents the earliest time for a packet from a source node to finish its successful transmission to the sink. So the E2E delay of the node is based on the earliest time to arrive at the sink no matter what the packets of the node are transmitted in the retransmission path or the reproduction

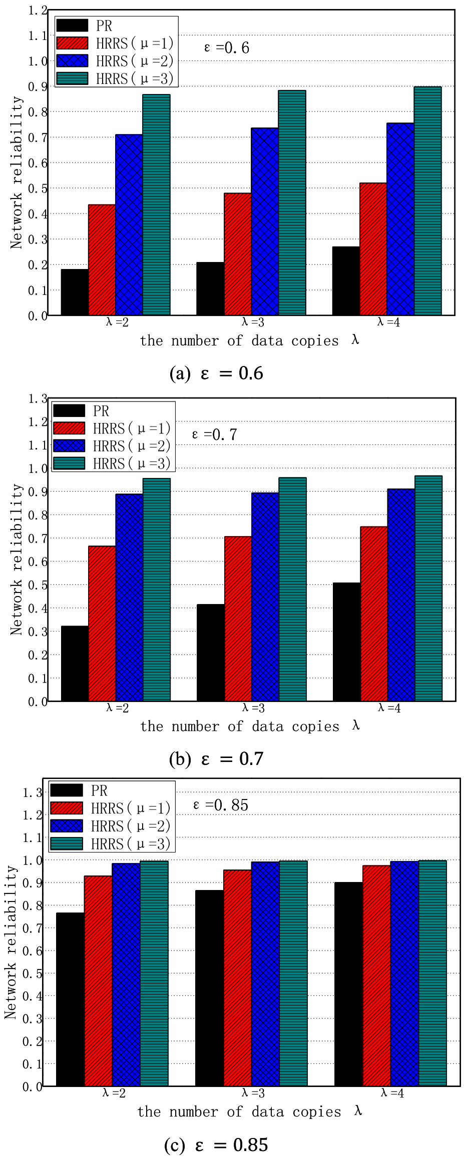
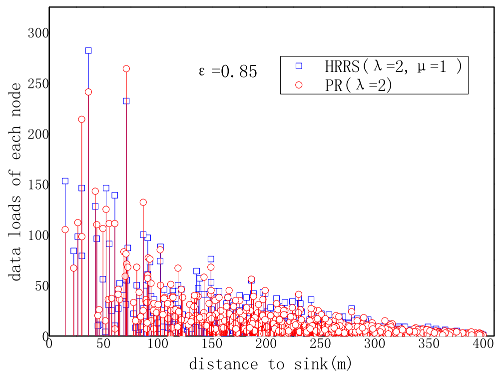


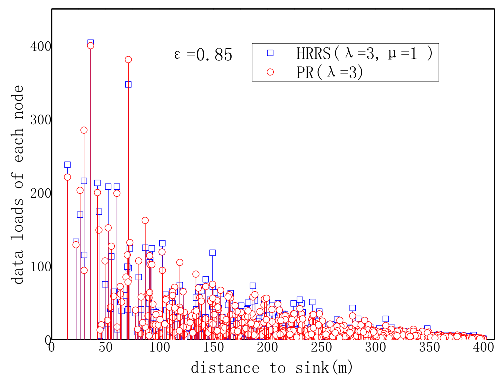
FIGURE 20. Comparison of network reliability between HRRS and PR.

path in the HRRS. Therefore the E2E delay of the node in the HRRS scheme is not greater than that in the PR scheme.

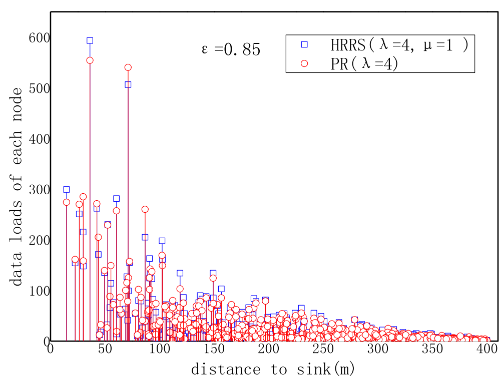
In HRRS, the successful transmission rate between nodes is higher than PR,and the retransmission waiting time is



(a) ε = 0.85, λ = 2

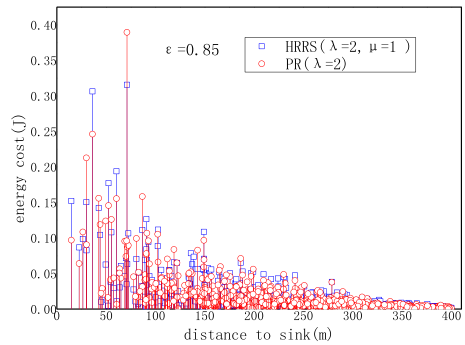


(b) ε = 0.85, λ = 3

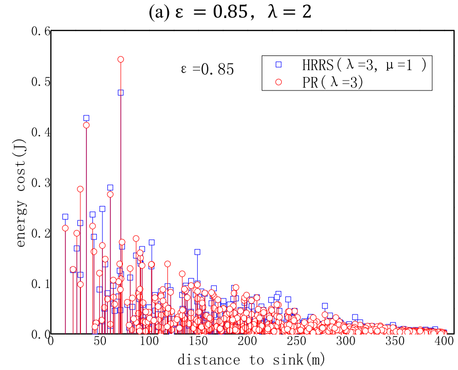


(c) ε = 0.85, λ = 4

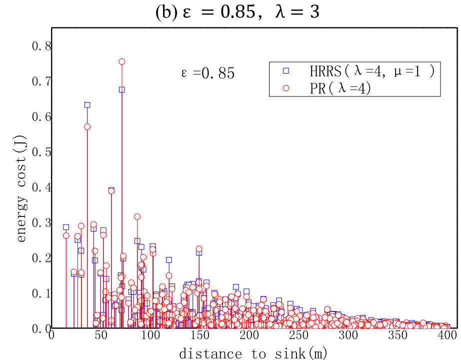
FIGURE 21. **Comparison of data load between HRRS and PR.**



(a) ε = 0.85, λ = 2



(b) ε = 0.85, λ = 3



(c) ε = 0.85, λ = 4

FIGURE 22. **Comparison of energy consumption between HRRS and PR.**

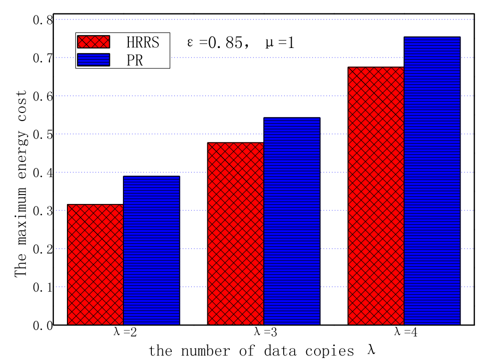


FIGURE 23. **Comparison of maximum energy consumption between HRRS and PR schemes.**

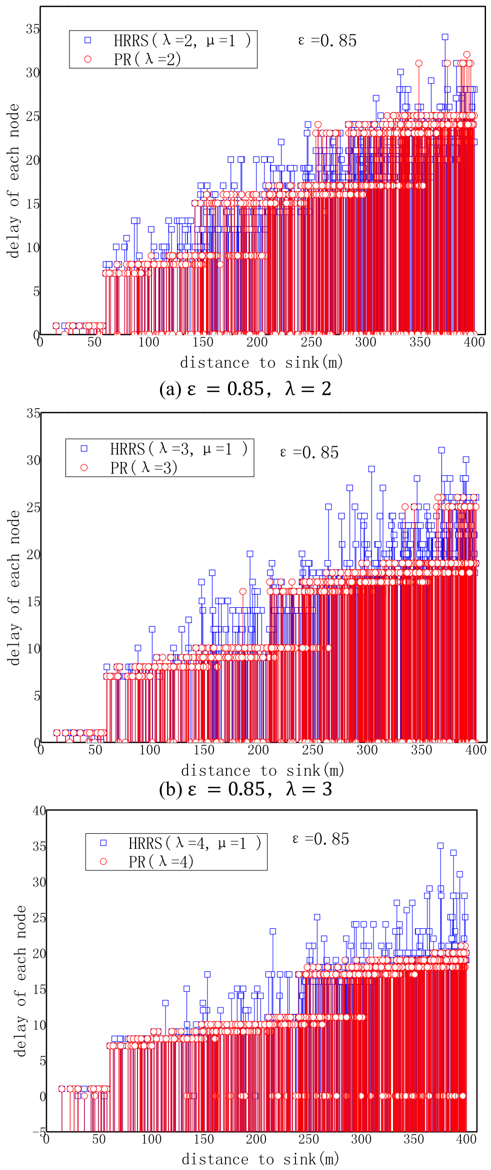
also considered. Therfore, the E2E delay of some nodes in HRRS seems to be higher than that in PR scheme. However, the average transmission delay of network is defined as the average of E2E delay for all source nodes, so the average transmission delay of the two schemes is almost the same, as shown in Table 6 and Figure 25.

The above analysis is implemented to evaluate the HRRS scheme that proposed in this paper greatly improves the reliability of transmission while ensuring the average transmission delay of the network, and is superior to the PR scheme in energy efficiency performance.

In the field of building structures that pay great attention to reliability and energy consumption, we have made a comparison between the proposed HRRS scheme and PR scheme on the premise of the same network reliability. The results

TABLE 7. Comparison between HRRS and PR schemes while ensuring network reliability.

ε	scheme	reliability	Maximum energy cost (J)
0.85	HRRS(λ = 2, μ = 1)	92.25%	0.3157
	PR(λ = 4)	91%	0.7542
0.7	HRRS(**λ** = 2, **μ** = 1)	65.25%	0.1586
	PR(**λ** = 5)	61.38%	0.2597
0.6	HRRS(**λ** = 2, **μ** = 1)	42.38%	0.089
	PR(**λ** = 6)	32%	0.1158



(a) ε = 0.85, λ = 2

(b) ε = 0.85, λ = 3

(c) ε = 0.85, λ = 4

FIGURE 24. Comparison of node E2E delay between HRRS and PR.

are shown in Table 7. The energy consumption of each node is compared as shown in Figure 26. The maximum energy consumption of a node is shown in Figure 27.

TABLE 6. Comparison of average transmission delay between HRRS and PR.

parameters/ The average E2E delay (ms)	HRRS(**μ** = 1)	PR
λ=2	17.7965	17.6458
λ=3	16.0831	15.0441
λ=4	14.9502	14.0412

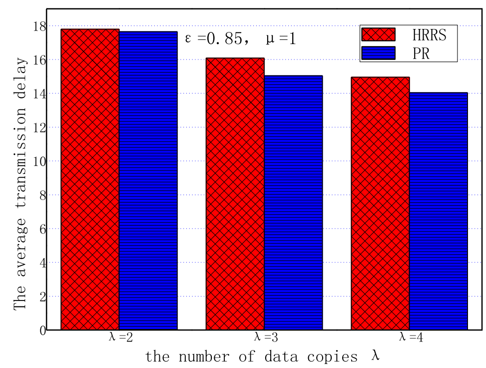
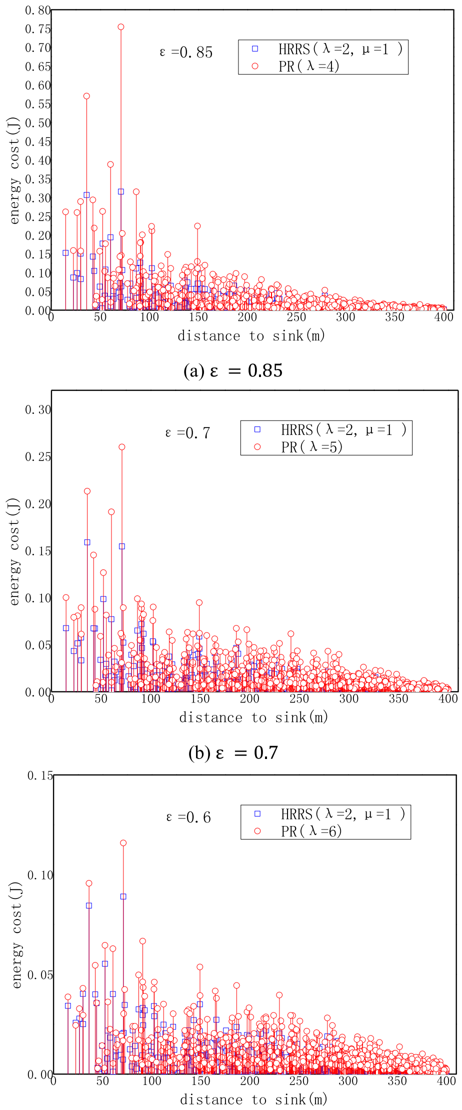


FIGURE 25. Comparison of average transmission delay between HRRS and PR.

In HRRS, the successful transmission rate between nodes is higher than PR,and the retransmission waiting time is also considered. Therfore, the E2E delay of some nodes in HRRS seems to be higher than that in PR scheme. However, the average transmission delay of network is defined as the average of E2E delay for all source nodes, so the average transmission delay of the two schemes is almost the same, as shown in Table 6 and Figure 25.

Table 7 and Figure 26 show that, when the node reliability $\varepsilon = 0.6$, one retransmission and two reproduction are only required in HRRS, and the network reliability $\delta = 42.38\%$, while in the PR scheme, 6 packet copies need to be reproduced, and the network reliability can only reach $\delta = 32\%$, and the maximum energy consumption of the node increases by 30.1%.

When the node reliability $\varepsilon = 0.7$, 5 packet copies need to be reproduced in the PR scheme, and the network reliability $\delta = 61.38\%$. In the HRRS scheme, only one retransmission and two reproduction are required, and the network reliability



(a) ε = 0.85

(b) ε = 0.7

(c) ε = 0.6

FIGURE 26. Comparison of energy consumption of each node in the HRRS and PR schemes while ensuring network reliability.

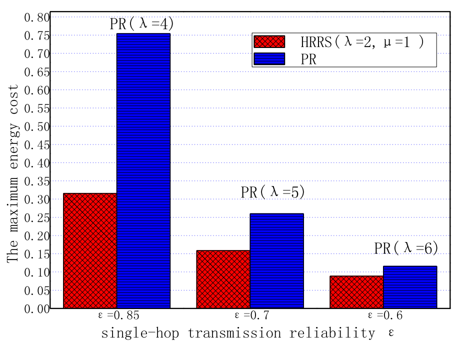


FIGURE 27. Comparison of maximum energy consumption of nodes in HRRS and PR schemes while ensuring network reliability.

is $\delta = 62.25\%$. The maximum energy consumption of the node is reduced by 40%. When the node reliability $\varepsilon = 0.85$, 4 packet copies need to be reproduced in the PR scheme, and the network reliability is $\delta = 90\%$. When the HRRS scheme is selected, only one retransmission and two reproduction are required, and the network reliability can reach $\delta = 92.25\%$. Not only the reliability is high, but also the maximum energy consumption of nodes is reduced by 58.1%. It is very important to improve the lifetime of wireless sensor networks with limited energy.

VII. CONCLUSION

This paper proposed a data transmission strategy with the goal of high energy efficiency, low data delay and high reliability for concrete monitoring in wireless sensor networks. In our strategy, the packet retransmission and packet reproduction mechanism are designed to achieve such objectives.

In order to ensure the reliability of communication transmission and reduce the energy consumption in the network, a routing path is randomly selected in multiple routing paths for retransmission without reproducing, then the number of data packet copies in the network can be reduced, energy consumption in the network is reduced accordingly. The retransmission path in the hybrid route ensures high reliability of the transmission. Theoretical analysis and simulation results show that the HRRS scheme is superior to the PR scheme in energy consumption and network reliability. Meanwhile, the average transmission delay of the network is guaranteed.

However, the number of reproduced packets unchanged in the HRRS, and it cannot be adjusted adaptively according to the remaining energy of the node and the distance to the sink. In order to prolong the use of battery, the sensor node must automatically adapt to changes of available power and adopt an intelligent forwarding scheme based on the current network. The adaptability and intelligence of routing scheme deserve further study.

REFERENCES

[1] J. M. Juez, R. Artoni, and B. Cazacliu, "Monitoring of concrete mixing evolution using image analysis," *Powder Technol.*, vol. 305, no. 1, pp. 477–487, 2017.

[2] T. M. Kim, D. H. Kim, and M. K. Kim, "Fiber Bragg grating-based long-gauge fiber optic sensor for monitoring of a 60 m full-scale prestressed concrete girder during lifting and loading," *Sens. Actuators A, Phys.*, vol. 252, no. 12, pp. 134–145, 2016.

[3] M. Jose Gandia-Romero, R. Bataller, P. Monzon, I. Campos, E. Garcia-Breijo, M. Valcuende, and J. Soto, "Characterization of embeddable potentiometric thick-film sensors for monitoring chloride penetration in concrete," *Sens. Actuators B, Chem.*, vol. 222, no. 1, pp. 407–418, 2016.

[4] P. Kar, A. Roy, and S. Misra, "Connectivity reestablishment in self-organizing sensor networks with dumb nodes," *ACM Trans. Auton. Adapt. Syst.*, vol. 10, no. 4, pp. 28–29, 2016.

[5] M. S. Hossain and G. Muhammad, "Cloud-assisted industrial Internet of Things (IIoT)—Enabled framework for health monitoring," *Comput. Netw.*, vol. 101, no. 1, pp. 192–202, 2016, doi: 10.1016/j.comnet.2016.01.009.

[6] C. Joo and N. B. Shroff, "On the delay performance of in-network aggregation in lossy wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 22, no. 2, pp. 662–673, Apr. 2014, doi: 10.1109/TNET.2013.2256795.

[7] J. H. Zhang, J. Long, G. Zhao, and H. Zhang, "Minimized delay with reliability guaranteed by using variable width tiered structure routing in WSNs," *Int. J. Distrib. Sensor Netw.*, vol. 3, no. 4, pp. 4–18, 2015, doi: 10.1155/2015/689504.

[8] J. H. Zhang, J. Long, C. Y. Zhang, and G. H. Zhao, "A delay-aware and reliable data aggregation for cyber-physical sensing," *Sensors*, vol. 17, no. 2, pp. 395–418, 2017, doi: 10.3390/s17020395.

[9] Q. Li, A. Liu, T. Wang, M. Xie, and N. Xiong, "Pipeline slot based fast rerouting scheme for delay optimization in duty cycle based M2M communications," *Peer-Peer Netw. Appl.*, vol. 12, no. 6, pp. 1673–1704, 2019, doi: 10.1007/s12083-019-00753-z.

[10] X. Xiang, W. Liu, T. Wang, M. Xie, X. Li, H. Song, A. Liu, and G. Zhang, "Delay and energy efficient data collection scheme based matrix filling theory for dynamic traffic IoT," *EURASIP J. Wireless Commun. Netw.*, vol. 21, no. 12, pp. 168–180, 2019, doi: 10.1186/s13638-019-1490-5.

[11] X. Liu, "A novel transmission range adjustment strategy for energy hole avoiding in wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 67, no. 5, pp. 43–52, 2016.

[12] S. Boulfekhar and M. Benmohammed, "A novel energy efficient and lifetime maximization routing protocol in wireless sensor networks," *Wireless Pers. Commun.*, vol. 72, no. 2, pp. 1333–1349, 2013, doi: 10.1007/s11277-013-1081-4.

[13] J. Tang, A. Liu, M. Zhao, and T. Wang, "An aggregate signature based trust routing for data gathering in sensor networks," *Secur. Commun. Netw.*, vol. 2018, no. 1, pp. 1–30, 2018, doi: 10.1155/2018/6328504.

[14] X. Sun, W. Liu, T. Wang, Q. Deng, A. Liu, N. Xiong, and S. Zhang, "Two-hop neighborhood information joint double broadcast radius for effective code dissemination in WSNs," *IEEE Access*, vol. 7, pp. 88547–88569, 2019.

[15] X. Liu, M. Zhao, A. Liu, and K. Wong, "Adjusting forwarder nodes and duty cycle using packet aggregation routing for body sensor networks," *Inf. Fusion*, vol. 53, no. 6, pp. 183–195, 2020.

[16] T. Shu, W. Liu, T. Wang, M. Zhao, N. Xiong, M. Ma, X. Li, and A. Liu, "Broadcast based code dissemination scheme for duty cycle based wireless sensor networks," *IEEE Access*, vol. 7, pp. 105258–105286, 2019.

[17] Z. Li and Y.-K. Kwok, "A new multipath routing approach to enhancing TCP security in ad hoc wireless networks," in *Proc. 34th Int. Conf. Parallel Process. (ICPP)*, Jun. 2005, pp. 372–375.

[18] Y. Liu, A. Liu, Y. Li, Z. Li, Y.-J. Choi, H. Sekiya, and J. Li, "APMD: A fast data transmission protocol with reliability guarantee for pervasive sensing data communication," *Pervasive Mobile Comput.*, vol. 41, pp. 413–435, Oct. 2017.

[19] Y. G. Iyer and S. V. S. Gandham, "STCP: A generic transport layer protocol for wireless sensor networks," in *Proc. Comput. Commun. Netw.*, 2005, pp. 114–120.

[20] T. Le, W. Hu, and P. Corke, "ERTP: Energy-efficient and reliable transport protocol for data streaming in wireless sensor networks," *Comput. Commun.*, vol. 32, no. 7, pp. 1154–1171, 2009.

[21] Y. Liu, Y. Zhu, L. Ni, and G. Xue, "A reliability-oriented transmission service in wireless sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 12, pp. 2100–2107, Dec. 2011.

[22] M. Wu, Y. Wu, X. Liu, M. Ma, A. Liu, and M. Zhao, "Learning based synchronous approach from forwarding nodes to reduce the delay for industrial Internet of Things," *EURASIP J. Wireless Commun. Netw.*, vol. 2018, no. 10, pp. 1–22, 2018, doi: 10.1186/s13638-017-1015-z.

[23] V. Rosset, M. A. Paulo, J. G. Cespedes, and M. C. V. Nascimento, "Enhancing the reliability on data delivery and energy effciency by combining swarm intelligence and community detection in large-scale WSNs," *Expert Syst. Appl.*, vol. 78, no. 2, pp. 89–102, 2017, doi: 10.1016/j.eswa.2017.02.008.

[24] W. L. Chang, D. Z. Zeng, R. Chen, and S. Guo, "An artificial bee colony algorithm for data collection path planning in sparse wireless sensor networks," *Int. J. Mach. Learn.*, vol. 6, no. 3, pp. 375–383, 2015, doi: 10.1007/s13042-013-0195-z.

[25] T. Camilo, C. Carreto, J. S. Silva, and F. Boavida, "An energy-efficient ant-based routing algorithm for wireless sensor networks," in *Proc. 5th Int. Workshop Ant Colony Optim. Swarm Intell. (ANTS)*, (Lecture Notes in Computer Science), vol. 4150. Berlin, Germany: Springer, 2006, pp. 49–59.

[26] O. Selcuk and K. Dervis, "Routing in wireless sensor networks using an ant colony optimization (ACO) router chip," *Sensors*, vol. 2009, no. 9, pp. 909–921, Sep. 2009.

[27] S. Gajjar, M. Sarkar, and K. Dasgupta, "FAMACROW: Fuzzy and ant colony optimization based combined MAC, routing, and unequal clustering cross-layer protocol for wireless sensor networks," *Appl. Soft Comput.*, vol. 43, no. 6, pp. 235–247, 2016.

[28] X. Liu, T. Qiu, and T. Wang, "Load-balanced data dissemination for wireless sensor networks: A nature-Inspired approach," *IEEE Internet Things J.*, vol. 6, no. 6, pp. 9256–9265, Dec. 2019, doi: 10.1109/JIOT.2019.2900763.

[29] J. Y. Chang and T. H. Shen, "An efficient tree-based power saving scheme for wireless sensor networks with mobile sink," *IEEE Sensors J.*, vol. 16, no. 20, pp. 7545–7557, Oct. 2016.

[30] X. Liu, T. Qiu, X. Zhou, T. Wang, L. Yang, and V. Chang, "Latency-aware anchor-point deployment for disconnected sensor networks with mobile sinks," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2019.2916300.

[31] H. Salarian, K.-W. Chin, and F. Naghdy, "An energy-efficient mobile-sink path selection strategy for wireless sensor networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, pp. 2407–2419, May 2014.

[32] X. Liu, T. Wang, W. Jia, A. Liu, and K. Chi, "Quick convex hull-based rendezvous planning for delay-harsh mobile data gathering in disjoint sensor networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, to be published, doi: 10.1109/TSMC.2019.2938790.

[33] A. Abbas and M. Younis, "Establishing connectivity among disjoint terminals using a mix of stationary and mobile relays," *Comput. Commun.*, vol. 36, no. 13, pp. 1411–1421, Jul. 2013.

[34] X. Liu, A. Liu, T. Qiu, B. Dai, T. Wang, and L. Yang, "Restoring connectivity of damaged sensor networks for long-term survival in hostile environments," *IEEE Internet Things J.*, to be published, doi: 10.1109/JIOT.2019.2953476.

[35] X. Liu, "Survivability-aware connectivity restoration for partitioned wireless sensor networks," *IEEE Commun. Lett.*, vol. 21, no. 11, pp. 2444–2447, Nov. 2017.

[36] Y. K. Joshi and M. Younis, "Restoring connectivity in a resource constrained WSN," *J. Netw. Comput. Appl.*, vol. 66, pp. 151–165, May 2016.

[37] X. Liu and P. Zhang, "Data drainage: A novel load balancing strategy for wireless sensor networks," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 125–128, Jan. 2018.

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