

Article

E-ReInForMIF Routing Algorithm Based on Energy Selection and Erasure Code Tolerance Machine

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Abstract: Aiming at the problems of data loss and uneven energy consumption in wireless sensor networks during data transmission, this paper proposes a ReInForM transmission fault-tolerant routing algorithm based on energy selection and erasure code fault-tolerant machines (E-ReInForMIF). The E-ReInForMIF algorithm improves the multi-path routing algorithm by combining an erasure coding fault-tolerant machine and node residual energy sorting selection. First, the erasure coding fault-tolerant machine is used to encode the signal, determine the number of transmission paths through multi-path routing, and then select the specific node of the next hop by sorting the residual energy of the node. The E-ReInForMIF routing algorithm effectively solves the problems of uneven energy consumption and data loss in data transmission, improving network lifespan and transmission reliability. Finally, the signal is decoded. The simulation results show that the E-ReInForMIF routing algorithm is superior to the ReInForM routing algorithm in improving the reliability of data transmission.

Keywords: ReInForM routing protocol; energy selection; erasure correcting coding fault-tolerant machine; node residual energy ranking



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1. Introduction

In recent years, with the extensive use of WSN, the requirements for data transmission reliability have been gradually improved, especially, in the fields of national defense and the military [1], environmental monitoring [2], space exploration [3], etc. When transmitting data, the wireless link is unreliable causing severe packet loss and low transmission reliability. In addition, each node consumes different amounts of energy, and cluster head nodes consume higher energy, making them more likely to fail due to insufficient energy, resulting in network paralysis. Therefore, it is important to address the issues of high energy consumption and low reliability in transmission. The reliability of transmission is mainly reflected in packet acceptance rate and packet accuracy rate. At present, aiming at the low reliability of wireless sensor networks, the packet loss rate of inter-node links is reduced by retransmission [4] and the packet acceptance rate and accuracy [5]. The main solutions to the problems of high energy consumption among nodes, uneven energy consumption among nodes [6], and easier failure of cluster head nodes are through energy balance [7].

Xu Jiuqiang et al. introduced the energy balancing method EBETX [8], which uses the ETX value as a routing metric while taking into account the energy consumption of the nodes in the network. This ensures balanced energy consumption among nodes in the network, improving node lifetime, extending network lifetime, and effectively solving the problem of node energy constraints. However, data are easily lost during transmission and the reliability is not high. The scientific literature [9] introduces ReInForM routing into wireless sensor networks. The ReInForM routing algorithm establishes a corresponding path based on the number of observation matrices required for reconstructing the signal.

Experimental results show that this algorithm has high reliability and ensures the effective operation of the network. Wang Dengdi combined the energy balancing method with ReInForM routing and proposed a ReInForM routing algorithm based on energy selection [10]. This algorithm ranks the nodes to be selected in the neighbor node set according to their energy consumption, preferentially selecting nodes that consume less energy and have more residual energy, which effectively solves the energy balancing problem in data transmission. In addition, the adoption of retransmission improves reliability to a certain extent. However, the ReInForMIF algorithm still suffers from data loss and its improved reliability is not high. Adding FEC code to the ReInForM routing algorithm improves the receiving rate of packets but the accuracy of packets is not high. The advantages and disadvantages of the algorithm are summarized in Table 1.

Table 1. Advantages and disadvantages of the method.

Method	Advantage	Disadvantage
Energy balancing method	To balance the energy loss of nodes and extend the network life.	Data are easy to lose; reliability is not high.
ReInForM routing algorithm	High reliability to ensure the effective work of the network.	Uneven energy consumption of each node easily causes network breakdown.
ReInForM routing algorithm based on energy selection	Low energy loss and reliability.	The problem of data loss; the packet acceptance rate is low.
ReInForM Routing Algorithm with FEC Encoding	Improved packet reception rate and reduced energy consumption.	The accuracy of data packets is not high.

To solve the problem with the above algorithm, this paper proposes a new routing algorithm: a ReInForM transmission fault-tolerant routing algorithm based on energy selection. The E-ReInForMIF algorithm evaluates the energy consumption of nodes in the path and adds an erasure coding fault-tolerant mechanism [11]. Before sending the data, the node-processing packet is made into a data slice using the erasure coding fault-tolerant mechanism. At the same time, when the sending node selects the next hop node, it sorts the energy of neighbor nodes and determines the next hop node according to the node's residual energy [12] and prioritizes selecting nodes with less energy consumption and more residual energy. After reaching the node, the data slice is decoded and restored it to the original data packet. During the whole transmission process, a certain number of data packets are allowed to be lost. The next hop is selected by the method of node residual energy ranking, which effectively reduces energy consumption and prolongs the working life of the network. The addition of erasure coding fault-tolerant machines reduces the packet loss rate in data transmission and improves the accuracy of data transmission. The E-ReInForMIF algorithm ensures the accuracy of data transmission, balances the energy of nodes in the network, and improves the reliability of data transmission.

2. E-ReInForMIF Algorithm Principle

Nodes on the ReInForM routing protocol's default data packet transmission path know the error rate e of each path. While the receiving node completes data collection, it analyzes the energy cost required to transmit data, estimates the transmission reliability rate r based on the path energy consumption, and puts r into the data packet being transmitted. If the source node jumps at least h times to reach the sink node, the probability of successful data transmission using a single path is $(1 - e)^h$. If $(1 - e)^h < r$, the whole transmission does not reach the expected reliability.

In the ReInForM algorithm, the source node makes multiple copies of the data packets that need to be transmitted and transmits these data packets over randomly selected paths. Djukic et al. proposed forward error correction technology [13] (forward error correction, FEC). Based on the load balancing principle, the FEC copies source data packets into multiple copies and creates multiple disjoint paths. The use of FEC technology can reduce the data loss rate and ensure the integrity of the data received by the destination node. S. Kim et al. combined multiple transmission fault-tolerant methods such as retransmission [14] and erasure coding (EC) to improve the reliability of data transmission. However, the overall energy consumption is high, whereas the data accuracy is not high. This paper improves the ReInForM algorithm, quantifies the energy consumption of nodes in the path, and adds an EC fault-tolerance mechanism. The ReInForM transmission fault-tolerant routing algorithm based on energy selection is proposed to ensure accurate transmission of data packets and reduce energy consumption.

The EC fault-tolerant mechanism is adopted at the source node before data transmission. EC can obtain higher data reliability with smaller data redundancy and improve the fault tolerance of data transmission. In the process of data transmission, multi-path transmission [15] is combined with a fault-tolerant mechanism and node energy consumption evaluation mechanism to improve the reliability of data transmission and improve the data transmission rate.

2.1. EC Fault-Tolerant Machine Based on the Quantitative Evaluation Mechanism of Node Energy Consumption

In practical applications, data can be lost during transmission due to various network problems. An EC fault-tolerant mechanism effectively avoids the problem of data packet loss. The specific process is as follows: the data is first encoded during transmission to form multiple data slices, and then these data slices are sent through multiple paths. When the destination node is reached, the data piece is decoded at the destination node, and the data is sorted into source data packets [16]. In the whole mechanism, the accuracy of data transmission is guaranteed within the scope of allowing data packet loss. An EC fault-tolerant machine is shown in Figure 1.

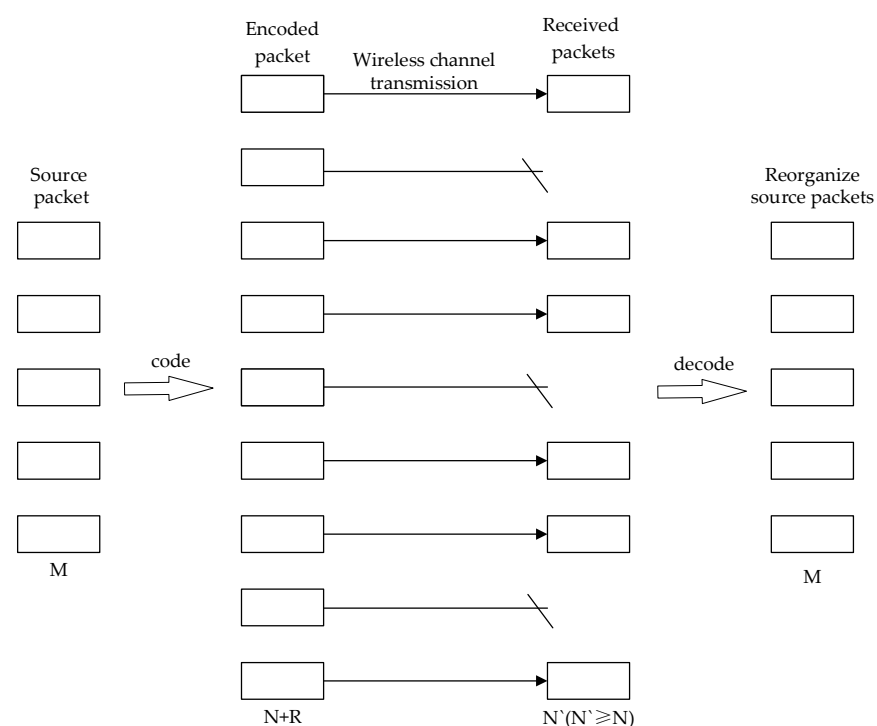


Figure 1. Erasure coding fault-tolerant machine.

In the EC fault-tolerant mechanism, the sending node decomposes the data packet of bM bytes into M data slices of b bytes and encodes them into $N + R$ data slices, where R is the redundancy of data coding. In WSN, the encoded data slice is transmitted through the source node and sent through n paths x_1 to x_n , where the path and encoded data slice need to meet $\sum_{i=1}^n x_i = N + R$. The destination node will receive N' ($N \leq N' \leq N + R$) encoded data slices. In the transmission process, it should be noted that EC allows the loss of data slices not greater than R . When R is greater than the data transmission loss rate, the destination node can use the redundant transmission to recover the source data packets [17]. The destination node needs to receive no less than N encoded data slices to decode and recover M source data. If Z_i random data pieces are received on path x_i , it needs to meet $\sum_{i=1}^n Z_i \geq N$.

The EC fault-tolerant machine will consume node energy while ensuring the accuracy of data transmission. Therefore, a quantitative evaluation mechanism for node energy consumption is introduced to balance the energy consumption of the entire network nodes.

By estimating the distance between the surrounding nodes and the sink node, as well as the amount of energy required in the data transmission process and sorting adjacent nodes, the sending node selects the most suitable next-hop node among the neighbor nodes to ensure the reliability of data transmission, balance the network energy consumption, and improve the quality of data transmission [17]. The parameters required for node energy consumption are defined as follows:

- (1) $EC(N_j)$ is the energy consumption from node N_j to the sink node. The path from N_j to the sink node is estimated according to the minimum number of jumps.

First, node A sends the data packet to B, and node B continues to forward the data packet to C. At this time, the two transmissions consume the same energy, that is, $e_{AB} \approx e_{BC}$. The energy consumption of nodes is only related to the transmission of data. When transmitting the same data packet, the energy consumption is approximately equal. Secondly, there are many transmission paths for node A to reach the sink node through node B. Therefore, the energy required in the node A to sink node path is equal to the product of e_{AB} and the minimum number of hops h of the node in the transmission data path is $e_{AB} \times h$. At this time, the energy consumption of node A to the sink node can be calculated. The path that requires the least energy consumption is selected for each jump. In the process of data transmission, ensure that each step of transmission consumes the least energy, so that the network can be fully utilized and the service life of the network can also be extended.

Estimating the minimum hop times of a node can improve the sensitivity of the network to path changes, so $EC(N_j) \approx e_{jx} \times h_j$ (node x is the next hop neighbor node of node j and h_j is the minimum number of hops from node j to the sink node. Because the energy consumption of the set node is only related to the transmission of data, node x is any neighbor node of node j).

- (2) $EM(N_i, N_j)$ is the transmission of energy consumption from the node N_i to the neighbor node N_j .

$$EM(N_i, N_j) = e_{ij}^\alpha \left(1 - \frac{(R_i^\beta - R_{ij}^\alpha)}{R} \right) = e_{ij} \lambda \quad (1)$$

The energy consumption of data transmission N_i through N_j and the remaining energy of the forwarding node are comprehensively analyzed. Where e_{ij}^α is the energy consumption value of the node N_i transmitting data directly to N_j , $e_{ij}^\alpha = v_t \times \mu$ (v_t is the number of data packets sent per unit time, and μ is the energy consumption value of forwarding unit data packet). R is the initial energy of the node, R_i^β is the residual energy of the node N_i , and λ is the energy consumption impact factor. The greater the λ , the greater the node energy consumption and the smaller the residual energy. α and β are the adjustment coefficients, set to 1.

- (3) $C_{N_i N_j}$ is the overall energy consumption of the node N_i sending data to the sink node through N_j .

$$C_{N_i N_j} = EC(N_j) + EM(N_i, N_j) \quad (2)$$

$C_{N_i N_j}$ consists of $EC(N_j)$ and $EM(N_i, N_j)$. Consider the energy consumption of data transmission as a whole and avoid only considering the minimum energy consumption of one hop, resulting in ignoring the overall energy consumption of jumping to the sink node.

The energy consumption of each neighbor node for transmitting data packets is compared with the energy consumption of hops from the source node to the sink node. They are classified according to the comparison between the former and the latter; they are classified into three categories: less 1, the same, and more 1, and the corresponding combination is H^- , H^0 , and H^+ . Apply $C_{N_i N_j}$ to each neighbor node set H^- , H^0 , H^+ . Each node in its own set is sorted incrementally according to $C_{N_i N_j}$, as shown in Figure 2.

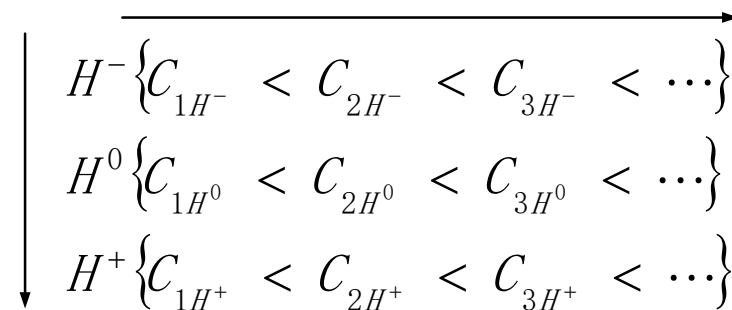


Figure 2. Energy ranking of nodes in each neighbor set.

2.2. Residual Energy of Nodes

Select the next hop node according to the energy order of the node. First, in the H^- node set, select from the smallest to the largest according to the node energy consumption ranking, then select from the H^0 node set, and finally select from the H^+ node set until all nodes on the path have been selected. If there are vacant locations, start with the H^- node set collection and continue the above operations until the nodes on the determined path are fully deployed. The selection of residual energy nodes is shown in Figure 3. The points on the set belong to the set represented by the circle.

After arranging the residual energy of each node set in the path from high to low, and according to the rule of preferentially selecting nodes with high residual energy, we complete the collection of the next hop node and additional nodes. The residual energy sets H^- , H^0 , and H^+ of a node comply with this rule. After selecting the node with the highest residual energy, these nodes are placed in the set of next-hop nodes until the number of next-hop nodes is satisfied. If the total number of next-hop node sets for sending node S is 4, there are 3 neighbor nodes and then the number of neighbor nodes for node S is 12 $V_1, V_2, \dots, V_{12}$. According to this principle, continue to select two node sets, as well as a set of nodes that are not within the selected range. As shown in Figure 3, $\{V_1, V_2, V_3\}$ is the H^- set, $\{V_4, V_5, V_6\}$ is the H^0 set, $\{V_7, V_8, V_9, V_{10}\}$ is the H^+ set, and $\{V_{11}, V_{12}\}$ is outside the selected range. Compare the residual energy of the set $\{V_1, V_2, V_3\}$; if the node V_1 has the highest residual energy, consider the node V_1 as the next hop node. The residual nodes $\{V_2, V_3\}$ in the set H^- continue to be selected according to this rule. Finally, select V_2, V_3 , and V_4 to join the next hop node set. If the data does not reach the sink node and the node cannot find the next-hop node of the next-hop node, the path is rebuilt at the next-hop node, and the residual energy of the nodes is ordered. The residual energy of the node is sorted. Repeat the above operation until the data is transmitted to the sink node.

In this process, the node selects the node set with the highest residual energy during each hop, ensuring the user's expected reliable value for data transmission. Therefore, while improving the reliability of data transmission, the improved algorithm balances the use of energy and the residual amount in the network, prolonging the usage time of the network.

The traditional ReInForM routing algorithm does not analyze and compare the residual energy of the next hop node, resulting in poor overall transmission reliability and unbalanced network energy consumption. The improved algorithm not only improves the data coding and ensures the integrity of data transmission but also analyzes and compares the energy consumption of nodes in the path and the next hop, reducing the number of failed nodes and extending the life cycle of the network.

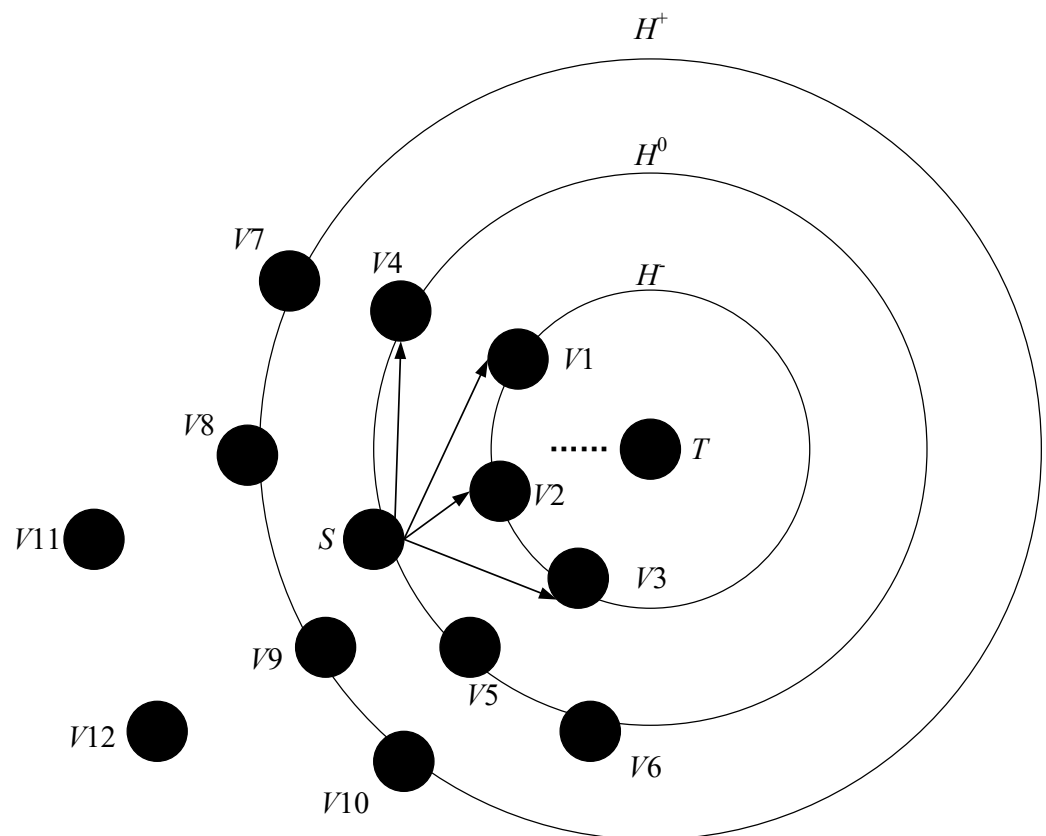


Figure 3. Selection of remaining energy nodes.

3. E-ReInForMIF Algorithm Steps

3.1. E-ReInForMIF Algorithm Flow

This research combines an EC fault-tolerant machine with node residual energy sorting and selection to propose a new routing algorithm, namely the E-ReInForMIF algorithm. The overall process for the E-ReInForMIF algorithm is shown in Figure 4.

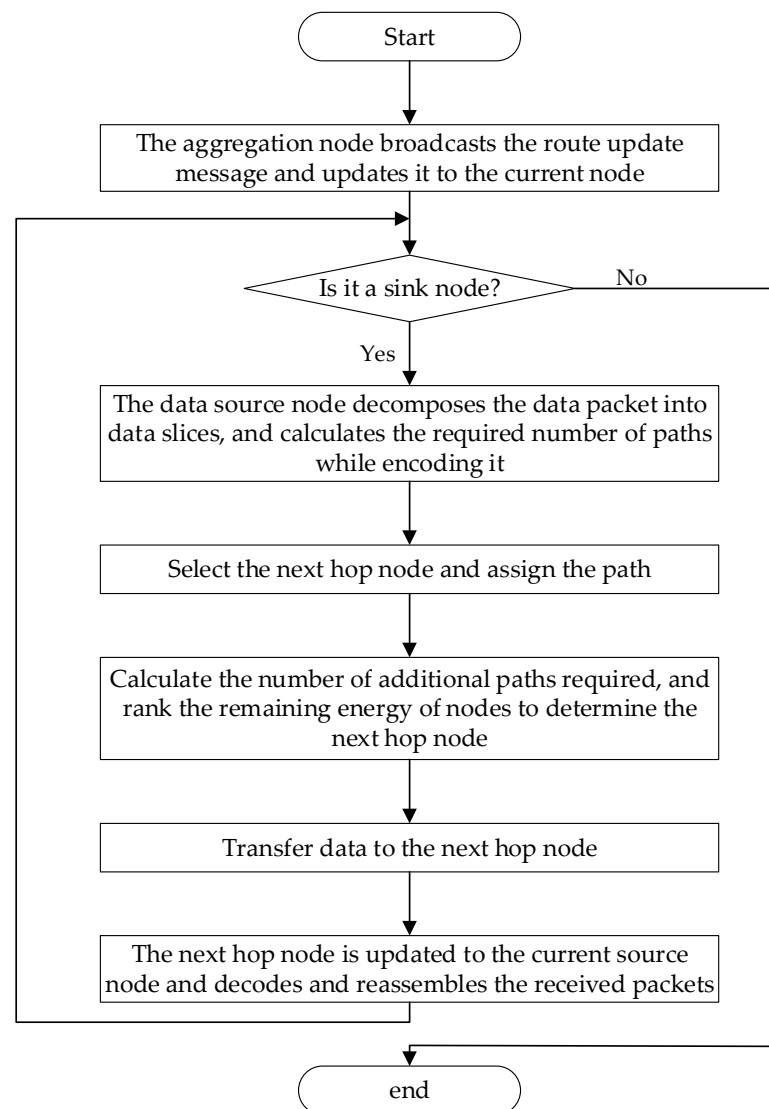


Figure 4. E-ReInForMIF algorithm flow.

3.2. Specific Steps of the E-ReInForMIF Algorithm

- (1) The sink node broadcasts the updated content selected by the entire path node to each other node periodically. Each node adjusts its hop count based on the received message and broadcasts the message to other neighboring nodes. In the path, each node knows the jump to the sink node by itself and its surrounding nodes;
- (2) The sending node processes the bM byte data packets, arranges them into M data slices of b bytes, and encodes them;
- (3) Calculate the transmission path: according to the source node data reliability parameter r_s , channel error rate e_s , and hop count h_s , use the following formula:

$$P(r_s, e_s, h_s) = \frac{\log(1 - r_s)}{\log[1 - (1 - e_s)^{h_s}]} \quad (3)$$

prepare for reliable data transmission through calculation and analysis;

- (4) Compare the energy consumption of each neighbor node transmitting data packets with the energy consumption of the source node to the sink node hop. According to the comparison between the former and the latter, they are classified into three categories: less 1, the same, and more 1. The corresponding combinations are H^- ,

H^0 , and H^+ . The incremental ordering of each aggregation node is determined by the calculation $C_{N_i N_j}$ of each node in the transmission path;

- (5) Select the next hop node from three sets according to the data transmission energy consumption requirements. The source node first selects the next hop node at H^- . If $1 - e_s$ is smaller than the calculated number of paths, additional paths need to be added when the source node transmits data. The additional number of paths is:

$$P = \frac{\log(1 - r_s)}{\log[1 - (1 - e_s)^{h_s}]} - (1 - e_s) \quad (4)$$

After the number of redundant paths is determined, select nodes in the order of H^- , H^0 , and H^+ according to the three node sets sorted out previously. When P is greater than the number of nodes included in H^- , select nodes from H^0 and H^+ in turn until the selected number of paths meets the calculated probability value. If the required number cannot be reached, select again from the node set H^- and continue to cycle this operation until the selected number of paths meets the probability requirements. Each selected node continues to create its path number and is added to the additional path value. The calculated total external path number is the total external path number created by all selected nodes. Finally, the node transmits the created path to each array, and then transmits the residual energy value of the node, as well as the encoded data slice, to all neighboring nodes through the created path;

- (6) After receiving the data slice, the neighbor node decodes the data; the entire encoding and decoding process is performed using a system encoding method;
- (7) At this point, consider the neighbor node as the source node, calculate the number of new transmission paths again, and cycle through the previous operations until the data is transmitted to the sink node.

In the E-ReInForMIF algorithm, the nodes provide the number of data packets lost during transmission. Considering the reliability of the number of paths created, energy surplus and transmission energy consumption of the next hop nodes are analyzed to improve the overall reliability of network data transmission.

4. Experimental Simulation Result

The E-ReInForMIF algorithm takes the number of data packets received by the destination node and the integrity of the received data packets as measurement results, namely, the packet reception rate and accuracy. The higher the reception rate, the smaller the data packet loss rate in transmission. The greater the accuracy, the more complete the data received. The higher the data packet reception rate and accuracy, the higher the reliability of data transmission. This article compares the improved algorithm with three algorithms, which are:

Method 1: Based on the ReInForM algorithm, the data is directly allocated to the transmission path without considering the energy balance of the path nodes;

Method 2: Based on the ReInForM algorithm, distribute source data packets evenly into the transmission path without considering packet coding;

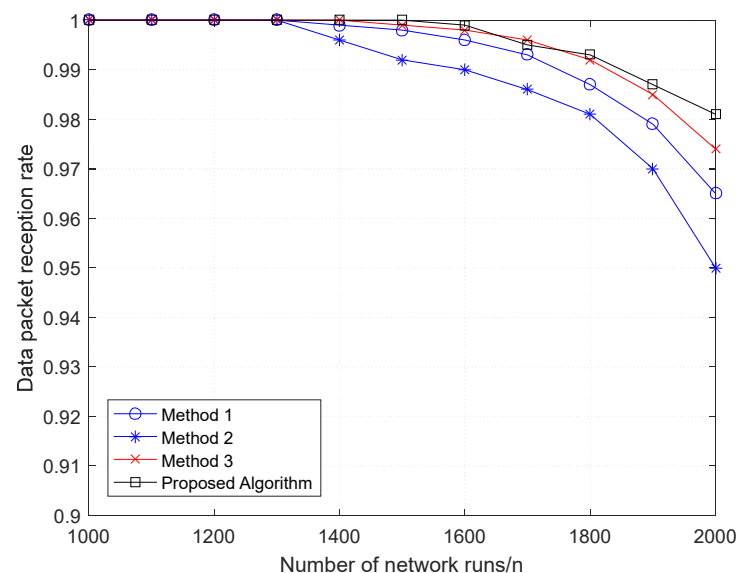
Method 3: Based on the ReInForM algorithm, add FEC coding to provide a certain fault tolerance rate.

The experiment was conducted on matlab2016 b; the network structure of this experiment adopts a multi-path structure, with a network coverage area of $600 \text{ m} \times 600 \text{ m}$ that is monitored in real-time. During the entire simulation run of 1000–2000 times, the data packet reception rate and accuracy rate of the above three algorithms were compared with those of the proposed algorithm in this article. It is proved that the proposed algorithm is the best of the four algorithms. The relevant parameters of the wireless sensor network and the performance indicators of the nodes are shown in Table 2.

Table 2. WSNs-related parameter settings.

Parameter Type	Parameter Value
Number of network nodes	100
Node initial energy	9900 J
Node residual energy	9700 J
Transmitter amplifier energy consumption (E_{amp})	500 pJ/bit/m ²
Destination node energy consumption (E_{fuse})	8J
Radio energy consumption (E_{elec})	250 J/bit
Forwarding each data packet energy consumption	2 J
Node maximum transmission distance	100 m
Data packet length	128 B
Control packet length	64 bit
Expected reliability	0.9
Channel error rate	0.4

When the network runs from 1000 to 1300 times, the data packet reception rate of the four algorithms is 1. For 1300–2000 runs, the packet reception rate of Method 3 and the proposed algorithm are still above 0.97, which has obvious advantages. For 1600–1800 runs, the data packet reception rate of the proposed algorithm in this article is slightly lower than that of Method 3 but still higher than Method 1 and Method 2. For 1800–2000 runs, the proposed algorithm is again higher than the other algorithms and remains above 0.98, as shown in Figure 5.

**Figure 5.** Packet reception rate (energy consumption parameters: E_{fuse} , E_{elec} , E_{amp}).

As can be seen from Figure 5, the greater the number of network operations, the clearer the difference in data packet reception rates among various algorithms. The Figure 6 simulation increases the network operation energy consumption by five times. Method 1 and Method 2 decrease rapidly and the overall data packet reception rate is not high. The difference between Method 3 and the proposed algorithm is not significant, and both have high data packet reception rates. When the network runs 1200–1600 times, the data packet reception rate of Method 3 and the proposed algorithm is almost the same. It can be seen that when the network runs 2000 times, the packet reception rates of Method 3 and the

proposed algorithm remain above 0.97. In other runs, the data packet reception rate of the algorithm proposed in this article is higher than that of the other three algorithms, as shown in Figure 6.

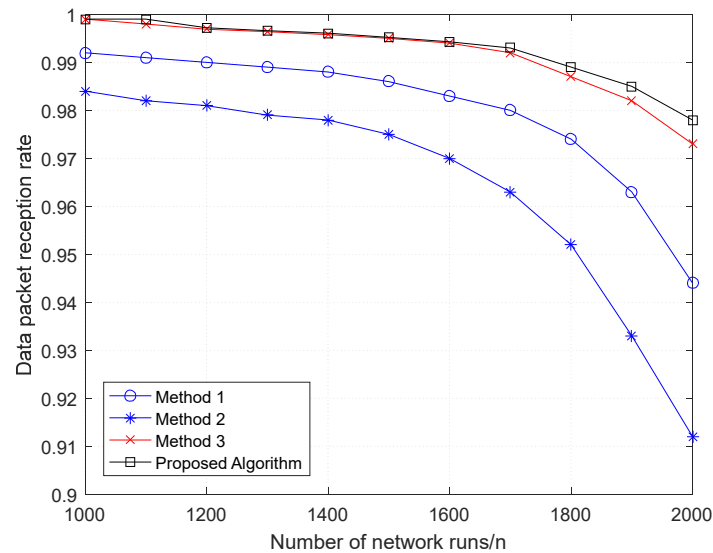


Figure 6. Packet reception rate (energy consumption parameters: $5E_{fuse}$, $5E_{elec}$, $5E_{amp}$).

In the case of low energy consumption parameters, the data packet accuracy of all four methods remains at 1 when the network runs 1000 to 1400 times. When the network runs 1400–2000 times, the data packet accuracy of all four methods has decreased, but the data acceptance rate of the proposed algorithm is always the highest, being maintained above 0.99. When the network runs 1400–1700 times, there is not much difference between the proposed algorithm and Method 3 in this article; however, it is still higher than Method 1 and Method 2. When the network runs 1800–2000 times, the data packet accuracy of the proposed algorithm is significantly higher than that of Method 3 and there is a significant difference between the two. From the simulation results, it can be seen that the data packet accuracy of all four methods remains above 0.97, as shown in Figure 7.

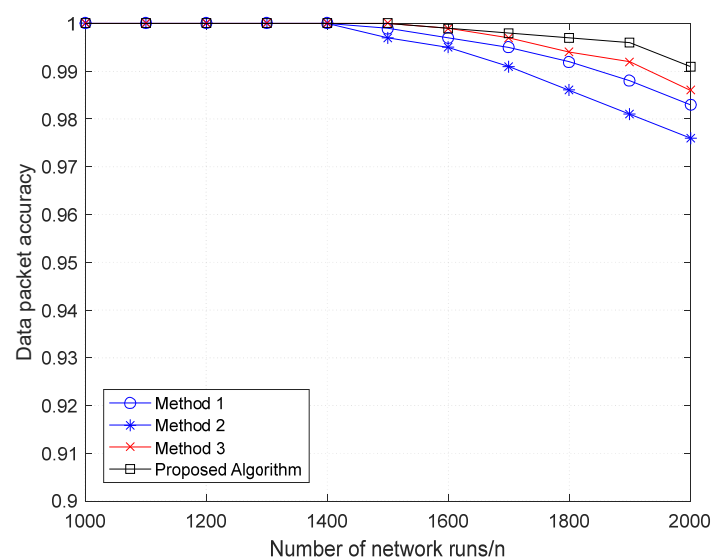


Figure 7. Data accuracy (energy consumption parameters: E_{fuse} , E_{elec} , E_{amp}).

Increasing the energy consumption parameter by five times is different from the simulation results of the data packet acceptance rate, and the difference in data packet accuracy among different algorithms is not significant. Due to the use of an EC encoding

fault-tolerant mechanism, the data accuracy of the proposed algorithm is the highest and the decrease is relatively smooth, with an accuracy rate consistently maintained above 0.985. For Method 3, the addition of FEC encoding has achieved a certain fault tolerance rate, but the fault tolerance rate is lower than the proposed algorithm. Therefore, the data packet accuracy of Method 3 is lower than that of the proposed algorithm but significantly higher than Methods 1 and 2. As shown in Figure 8.

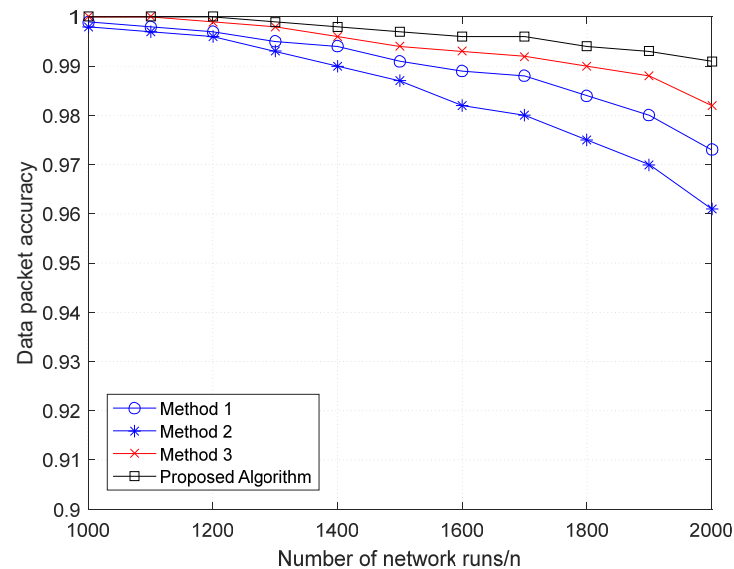


Figure 8. Data accuracy (energy consumption parameters: $5E_{fuse}$, $5E_{elec}$, $5E_{amp}$).

The energy efficiency of the path is calculated by analyzing the energy value required by the destination node to receive data and the energy value of the original node to send data. Method 2 has the lowest energy efficiency. The difference between the proposed algorithm and Method 3 in this paper is not significant when the number of runs on the network is 1000–1700 times. When the network runs 1700 times, the proposed algorithm in this article is slightly lower than Method 3. After running the network 1700–2000 times, it can be seen that the proposed algorithm has the highest energy efficiency. It is kept above 350, as shown in Figure 9.

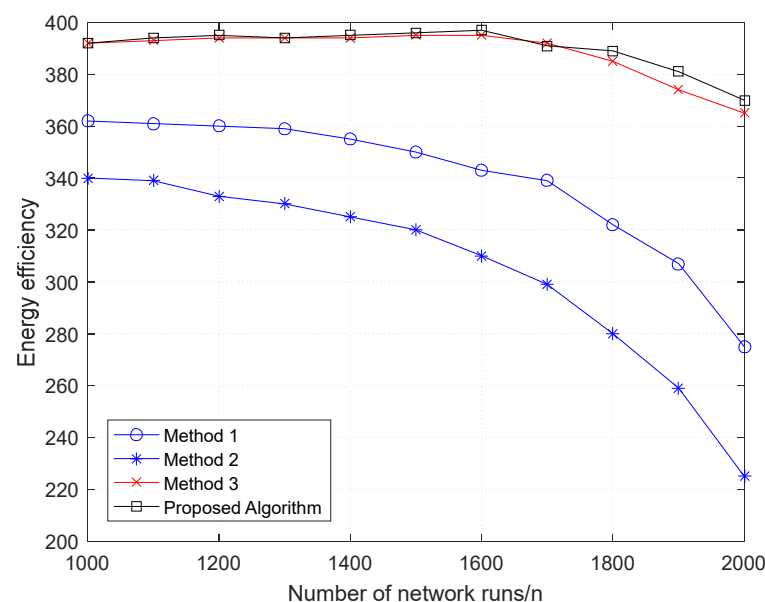


Figure 9. Energy efficiency analysis.

From the above simulation results, it can be seen that the proposed algorithm is significantly superior to Method 1 and Method 2 in terms of data packet reception rate, accuracy, and energy efficiency. Compared with the three-phase method, the algorithm proposed in this paper does not have significant advantages in packet reception rate and energy efficiency. However, with the addition of an EC encoding fault-tolerant mechanism, the proposed method significantly outperforms Method 3 in terms of data packet accuracy. Overall, the proposed algorithm is the best of the four algorithms and is a highly reliable and low-energy-consuming routing algorithm.

5. Conclusions

By analyzing the reliability of data transmission in wireless sensor networks, the performance of wireless sensor networks can be measured. This paper proposes the E-ReInForMIF algorithm, which improves the multipath routing algorithm by combining the EC fault-tolerant machine and node residual energy sorting selection. The encoded data is transmitted through the calculated path. During transmission, the energy consumption and residual energy of the nodes in the transmission path are always considered and a certain amount of data packet loss is provided to ensure the accuracy of data transmission. After transmitting to the destination node, the destination node decodes the encoded data. In the whole transmission process, the method of node residual energy ranking is used to quantitatively evaluate the energy consumption of nodes, so that the whole algorithm can improve the efficiency of data transmission, reduce energy consumption, and improve the reliability of data transmission. This article compares and analyzes the improved algorithm with traditional methods. From the simulation results, it can be seen that the algorithm proposed in this article has higher data packet acceptance and accuracy rates than the other three methods and also has higher energy efficiency than the other three methods. Therefore, the E-ReInForMIF algorithm in this article is better. Due to its excellent reliability advantage, it can be applied to the detection of all toxic gas parameters in public places such as schools and factories. Detection of temperature and pressure in pipelines such as water supply, heating, and oil supply is essential to prevent the occurrence of disasters. In the future, with the deepening of research on wireless sensor networks, they can also be applied to the healthcare industry. Remote detection of patients' conditions will enable them to receive timely treatment even at a distance from the hospital, achieving remote medical control.

Author Contributions: Conceptualization, Q.W.; methodology, Q.W.; software, H.H.; validation, J.Q., Q.W. and J.G.; writing—original draft preparation, X.L. and C.Y.; writing—review and editing, C.Y.; project administration, Q.W.; funding acquisition, X.L. and Q.W. All authors have read and agreed to the published version of the manuscript.

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