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Research Article

Reliable Energy-Aware Routing Protocol in Delay-Tolerant Mobile Sensor Networks

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In the data transmission process of delay-tolerant mobile sensor networks, data is easily lost, and the network lifetime decreases due to energy depletion by the nodes. We propose a reliable energy-aware routing protocol, called RER. To ensure the reliability of message transmission, a hop-by-hop retransmission acknowledgement mechanism is introduced in the RER. Second, we design a metric called Reliable Energy Cost Based on Distance (RECBD) to aid RER, which is determined by analysing the distance between the current node and the relay node, the distance between the relay node and the sink node, the current residual energy of the current node, and the link quality. Finally, the message is routed based on the RECBD to improve reliability and reduce energy consumption. The simulation results show that the routing protocol can improve the energy utilization of the sensor nodes and prolong the network lifetime while guaranteeing the delivery ratio and reliability.

1. Introduction

In recent years, Internet of Things [1] (IoT) has been widely applied to production and daily life. As one of the supporting technologies of the IoT, Wireless Sensor Networks (WSNs) [2] have also become a topic of interest among scholars. Many applications collect data from moving vehicles, humans, or animals carrying sensor nodes, such as for air quality testing, flu virus tracking, and so on. There are many traditional routing protocols in WSNs, but these routing protocols are not suitable for this type of WSNs with mobile features. Because WSNs have a large monitoring area and nodes are sparse and mobile, the connection may be lost at any time, and a stable end-to-end communication path between the ordinary sensor nodes and the sink node will no longer exist. So, data transmission needs to rely on the opportunities brought by the nodes movement and transmission is possible only when nodes are within range of each other. Then, the Delay-Tolerant Mobile Sensor Network (DTMSN) was born, and quickly became a new research field in the wireless Network.

At present, most of the sensor nodes in the DTMSN are deployed in a challenge environment. The propagation of the wireless channel of the node is disturbed by noise and channel fading, which makes the stability of the wireless channel poor. This unreliable point-to-point links transmission mode causes the link between message transmissions to be frequently interrupted. The data of the DTMSN usually needs to be transmitted over a long distance from a common sensor node to a sink node. It is not desirable to use single-hop transmission. Generally, multihop transmission is adopted. However, in multihop transmission, there are phenomena such as loss of data packets and interruption of data transmission in a network due to environmental interference or failure of nodes due to energy exhaustion, which causes the link quality to deteriorate and the transmission to become unreliable. Moreover, the sensor nodes in the DTMSN are generally large in number, small in size, and low in cost, and the energy is powered by the node's own battery, which is difficult to replace or charge, and in an environment with delay-tolerant movement, the sensor node battery power consumption rate is fast, and the node will lose its function because it consumes the battery power and cannot continue to work. This makes it impossible for the sensor nodes to efficiently complete the task of collecting information. This is very disadvantageous to the application of DTMSN in the actual environment. At present, many scholars are seeking a compromise between energy efficiency and data transmission. Therefore, the research on the reliable energy-saving routing algorithm in DTMSN can improve the reliability of data transmission while reducing the energy consumption of nodes and the survival of the network of the case of harsh environment and unstable link quality. The increase in network survival time has theoretical significance, and it has practical significance of the wide application of DTMSN in the future, such as prolonging the survival time of sensor nodes in war and natural disaster environments.

According to the characteristics of DTMSN, nodes and links are prone to failure, which results at random packet loss during data transmission and affecting reliability. This kind of problems cannot be resolved by medium access control (MAC) protocol because MAC protocol can only guarantee the reliability of point-to-point transmission and cannot guarantee that messages can be sent to the destination node by Store-Carry-Forward method. In addition, the sensor nodes are usually powered by batteries, and their energy is very limited. Battery recharging is difficult to achieve, and nodes easily fail due to insufficient power. Therefore, reducing communication energy consumption and balancing energy in the entire DTMSN to prolong the network lifetime is an important problem to be solved while ensuring link reliability.

We propose a reliable energy-aware routing protocol in the DTMSN, called RER. Its basic idea is as follows. First, to ensure the reliability of message transmission, a hop-by-hop retransmission acknowledgement mechanism is introduced to the routing protocol. Second, we design a metric called RECBD (Reliable Energy Cost Based on Distance). The node's RECBD value is determined by analysing the distance between the current node and the relay node, the distance between the relay node and the sink node, the current residual energy of the current node, and the link quality. Finally, the message is routed according to the RECBD of the node.

The rest of the paper is organized as follows. Section 2 presents related work, and in Section 3, we describe the system model settings. Section 4 presents the detailed design of the RER. Section 5 shows the evaluation results from simulation. Section 6 outlines future works based on this paper.

2. Related Work

Routing algorithm is the primary problem that multihop network needs to solve. It is the basis of the correct delivery of packets of the network. At present, routing algorithms in DTN are generally applicable to DTMSN. The difference is that the destination node in DTN is not unique, while the sink node in DTMSN is the only destination node. In the DTMSN, because there are no stable end-to-end connections between the nodes, data transmission depends on "store-carry-forward", and thus DTMSN is a special type of DTN (Delay-Tolerant Network [3]). There are many routing algorithms for improving the energy efficiency, reliability, and network lifetime of sensor networks.

An energy-aware PRoPHET routing algorithm is proposed to [4]. It considers the energy of the node and the buffer available to the node to store the forwarded messages. In [5], a hybrid energy-efficient routing protocol is proposed that uses Epidemic to provide redundant messages with the shortest path length to ensure minimal delay, while PRoPHET can save network resources by relaying messages along the best path in the network. In [6], an energy-aware spray waiting protocol is proposed that calculates the utility function according to the velocity and residual energy of the nodes in the spraying phase and determines the number of forwarding replicas of the message based on the utility function. Reference [7] extends the utility function of [6] by considering the moving direction of nodes in the sensor network model of a single sink node with known location information. Reference [8] proposes a probabilistic routing protocol based on historical encounters and transport protocols in intermittently connected delay-tolerant WSNs. This protocol is an energy-aware routing protocol in which messages are transmitted based on the remaining energy of the node, the transmission predictability, and node types. In [9], a distance-based energy-aware routing protocol (DER) is proposed to save energy by reducing the transmission replicas based on the distance between the sensor node and the sink node and the remaining energy of the sensor node. In [10], to maximize the lifetime of WSNs, an optimal-distance-based transmission strategy is proposed by introducing two notions, the most energy-efficient distance and the most energy-balanced distance. It achieves not only high energy efficiency but also a good energy balanced with WSNs. However, these routing protocols only consider the energy factor and ignore the reliability of message transmission. In [11], a multipath routing protocol, DEERT, based on energy awareness is presented that uses a multipath transport protocol to achieve reliability and selects the best path according to the residual energy of neighbouring nodes and the distance to the sink node; however, the link quality is not considered. References [12] proposed the community-based forwarding algorithm Bubble Rap in the opportunity network, this algorithm is designed for a delay-tolerant network environment. The activity of the node was recorded according to the number of interactions between the nodes, reflecting the probability of the node as a potential relay node of message forwarding. This approach is suitable only for networks without considering the energy. However, for networks operating in highly dynamic environments and with energy considered, this model is not able to cope with the network faults and delays. To increase the probability of successful message delivery, [13] proposes SPRINT, an opportunistic routing algorithm that introduces an additional routing criterion: online social information about nodes. SPRINT delivers better results compared to traditional social-based routing approaches for different real-world and synthetic mobility scenarios. Reference [14] proposes a novel opportunistic routing approach ML-SOR (Multilayer Social Network based Routing) which extracts social network information to perform routing decisions. To select an effective forwarding node, ML-SOR measures the forwarding capability of a node when compared to an encountered node in terms of node centrality, tie strength, and link prediction. Multiple social network layers allow users to achieve good routing performance with low overhead cost. Reference [15] proposes TBGR to relay messages via a limited number of copies under homogeneous scenarios. Then TBHGR is proposed for heterogeneous scenarios where nodes have different visiting preference, which considers the message scheduling for transmission and storage. The results show that TBHGR has more reliable message delivery, while the routing overhead is low. In [16], the authors propose a new routing algorithm for energy-efficient transmission by finding the appropriate set of nodes for transmission through neighbourhood method, thus prolonging the network life cycle and solving the routing loop problem. Reference [17] introduces LEACH-SP, which is a new WSN protocol that combines submodule layout optimization technology with LEACH clustering protocol to achieve the goals of maximum coverage and minimum energy requirements.

In most traditional WSNs routing protocols, each node chooses the next-hop node based on a specific metric. References [18] described energy-aware routing protocol based on minimizing end-to-end hops, which effectively reduces end-to-end energy consumption. In [19–23], the routing path is chosen according to the residual energy of the nodes, and the availability of the sensor nodes is maintained with less energy by distributing the traffic load on nodes with higher residual energy to maximize the lifetime of the WSNs. Reference [24] proposes a joint design of asynchronous sleep-wake schedules and opportunistic routing called ASSORT to maximize the network lifetime. Meanwhile, a metric called Opportunistic Energy Cost with Sleep-wake schedules (OECS) is designed. Although ASSORT effectively prolongs network lifetime, it does not consider the reliability of message transmission.

This paper has some significant and originality ideas compare with existing studies, which can be summarized in the following three aspects.

(i) In the process of message transmission, we not only consider the energy consumed by the transmission nodes but also consider the energy consumed by the receiving node.

(ii) To ensure network reliability, we consider the impact of the number of transmission times and ACK (acknowledgement packets) on the energy consumption of the link.

(iii) Under guarantee of reliability, we explore the influence of transmission distance and link quality on the energy consumption of the nodes and the network lifetime.

3. System Model Design

3.1. Network Model. We assume that, in the initial state, there are N sensor nodes randomly and evenly deployed on a disk with radius R centred at the sink. The communication radius of the sensor nodes is r, and the network has the following properties.

(i) There are N ordinary sensor nodes equipped with GPS devices to obtain their own current position at any moment, and the nodes have the same initial energy ε_0 and the same communication radius r. The motion of these sensor nodes is in accordance with the Random Waypoint (RWP) [25].

(ii) There is only one sink node in the network that has enough energy and is deployed at a fixed position. Therefore, the ordinary sensor nodes know the location of the sink node.

(iii) The density of the nodes σ is the number of nodes in the unit area at any time. Since the nodes are randomly distributed and moving, the density of nodes can be expressed as

$$\sigma = \frac{N}{S} \tag{1}$$

where N is the number of nodes in the network and S is the network area.

(iv) Assuming that $i(x_i, y_i)$, $j(x_j, y_j)$, the distance between i and j can be calculated by

$$d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{2}$$

3.2. Energy Model. In this paper, the energy consumption model [26] adopts the free-space model and ignores the energy consumed by the sensor nodes, such as computation and storage. It only focuses on the energy consumed by communication between the nodes. When the sensor node sends l[bit] data onto a node with a distance from d, the energy consumed is $E_{Tx}(l, d)$.

$$\begin{aligned} E_{Tx}(l,d) &= E_{Tx-elec}(l) + E_{Tx-amp}(l,d) \\ &= \begin{cases} lE_{elec} + l\varepsilon_{amp}d^2, & d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, & d \geq d_0 \end{cases} \end{aligned} \tag{3}$$

The sensors node receiving l[bit] data consumes energy $E_{Rx}(l)$.

$$E_{Rx}(l) = E_{Rx-elec}(l) = lE_{elec} \tag{4}$$

in which $d_0 = \sqrt{\varepsilon_{amp}/\varepsilon_{mp}} = 87.7m$, which is a threshold. According to (3), when the distance between the sending node and the receiving node is less than d_0, the energy consumed by the sending node is directly proportional to the square of the distance. Otherwise, the energy consumed by the sending node is directly proportional to the fourth power of the distance. E_{elec} is a fixed energy value corresponding to the consumption of the sensor node sending l[bit] data. ε_{amp} is the energy consumption parameter of the power amplifier in free space, and ε_{mp} is the energy consumption parameter of the power amplifier in the multipath fading channel model. In this paper, we specify $r < d_0$.

3.3. Reliability Model. Because the wireless channel is unstable in DTMSN, it is easily interfered by noise, signal fading, and so on. Some packets are easily lost in the transmission process. To ensure that the packet can be received by the sink node, the lost packets must be detected and fed back for retransmission. In this paper, the hop-by-hop automatic retransmission mechanism is used to ensure the reliability of data packets. In the HBH system, in order to ensure link-level reliability, the sender retransmits the lost packets of each hop. When the receiver successfully receives the packet information, the receiver sends an acknowledgment (ACK) to the sender. If the sender does not receive an ACK (because the packet or its ACK is lost or corrupted), the sender resends the packet. This process is repeated until the sender receives an ACK or reaches the maximum number of allowed transmission attempts. If each link is reliable, the E2E path between the nodes is also reliable [27].

We assume that a node u can transmit a packet only Q_u times (including the first transmission). Thus, a packet might be retransmitted a random number of times not greater than $Q_u - 1$. Therefore, an ACK could be transmitted for the same data packet a random number of times not greater than Q_u. We assume $E[n_{u,v}(L_d)]$ is the expected number of times that u needs to transmit a packet of length L_d[bit] to deliver it to v (including the first transmission). Furthermore, we assume $E[m_{v,u}(L_h)]$ is the expected number of ACKs of length L_h[bit] sent by v for the data packet to u, where $L_h = \kappa L_d$. We denote the Packet Reception Ratio (PRR) of packets of length x[bit] transmitted by u to v by $p_{u,v}(x)$. In other words, $p_{u,v}(x)$ is the PRR of the packet of length x[bit] on the link (u, v). L_d indicates the size of the data packet to be transmitted, and L_h indicates the size of the ACK.

$$E\left[n_{u,v}\left(L_d\right)\right] = \frac{1-\left(1-p_{u,v}\left(L_d\right)p_{v,u}\left(L_h\right)\right)^{Q_u}}{p_{u,v}\left(L_d\right)p_{v,u}\left(L_h\right)} \tag{5}$$

$$E\left[m_{v,u}\left(L_h\right)\right] = \sum_{i=0}^{Q_u} i\Pr\left\{m_{v,u}\left(L_h\right)=i\right\} \tag{6}$$

where $\Pr\{m_{v,u}(L_h) = i\}$ denotes the probability that time i is required for v to send a packet of length L_h[bit] to u, as calculated in

$$\begin{aligned}
&\Pr\left\{m_{v,u}\left(L_h\right)=i\right\}\\
&=\begin{cases}
(1-p)^{Q_u}, & i=0\\
p^{Q_u}(1-p)^{Q_u-1}, & i=Q_u\\
\sum_{j=i}^{Q_u-1}\binom{j-1}{i-1}p^{i-1}(1-q)^{i-1}(1-p)^{j-i}pq+\binom{Q_u-1}{i-1}p^{i-1}(1-p)^{Q_u-i}(1-q)^{i-1}p+\binom{Q_u-1}{i}p^{i}(1-p)^{Q_u-1-i}(1-q)^{i}(1-p), & \forall i=1\ldots Q_u-1
\end{cases}
\end{aligned} \tag{7}$$

For convenience, we use p and q to denote the $p_{u,v}(x)$ and $p_{u,v}(x)$ in (7). Since the entire network is a homogeneous network, each sensor node has the same PRR. We consider a transmission path between two nodes $\mathscr{P}(n_1, n_{h+1}) = \{n_1, n_2, \ldots, n_h, n_{h+1}\}$. So, $\forall i$, the retransmission times of i allow $Q_i = Q_u$. The expected number of times that a packet transmits is denoted by $E[n_{n_i,n_{i+1}}(L_d)] = n$, the expected number of times that an ACK packet transmits is denoted by $E[m_{n_{i+1},n_i}(L_h)] = m$, and the link quality is denoted by $p_{n_i,n_{i+1}}(x) = p_{n_{i+1},n_i}(x)$.

4. The Reliable Energy-Aware Routing Protocol

4.1. Reliable Energy Cost Based on Distance. For nodes with different residual energies, the same energy consumption will affect them differently; that is, nodes with less residual energy should use their energy conservatively to avoid death due to exhaustion of energy, resulting in a decrease in network lifetime. Distance is another important factor affecting the energy consumption, which affects the network lifetime. Therefore, this paper defines energy cost as the RECBD metric, considering the residual energy of the nodes, the distance between the relay node and sink node, and the link quality. The goal is to minimize the energy cost of transmitting data at each time to balance the energy consumption in the network and prolong the network lifetime.

To calculate the end-to-end reliable energy cost from the source node to the sink node, each sensor node must consider the RECBD metrics of all its forwarding nodes when calculating its own RECBD metric. In this paper, each sensor node calculates the expected reliable energy cost of data forwarding from the source node to the sink node. For example, the RECBD metric for sensor node u is the expected reliable energy cost from node u to the sink node. RECBD metrics includes (i) the energy cost of transmitting messages from node u, (ii) the energy cost of the forwarding node receiving the message, (iii) the energy cost of the node transmitting the ACK, (iv) the energy cost of node receiving the ACK, (v) the expected RECBD metric of the forwarding set of node u to the sink node, and (vi) the ratio of the distance between the relay node and the sink node to the radius of the region. The calculation method is as follows:

$$\begin{aligned}
&RECBD_u\left(\mathscr{F}_u, \mathscr{P}_u\right)\\
&= \left[\min_{i\in\mathscr{F}_u}\left(\frac{C_{tx}+C_{rx}+C_{tACK}+C_{rACK}}{P_{TS}}\right)\right.\\
&\quad\left.+\frac{C_{fwd\longrightarrow sink}}{P_{TS}}\right]\times\left[\frac{d_{(j,sink)}}{R}\right]^2
\end{aligned} \tag{8}$$

where $\mathscr{F}_u$ denotes all forwarding node sets of the node u and $\mathscr{P}_u$ denotes the priority of the nodes in $\mathscr{F}_u$.

The following is a detailed description of (8), where r_u represents the residual energy of the node u.

(i) C_{tx} indicates the energy consumed by the current node to transmit the δ[bit] data to the forwarding node.

$$C_{tx} = \frac{\delta \bullet E_{Tx}(l,d)}{l \bullet r_u} \tag{9}$$

(ii) C_{rx} denotes the energy consumed by the relay node to receive the δ[bit] data from the sending node.

$$C_{rx} = \frac{\delta \bullet E_{Rx}(l)}{l \bullet r_i} \tag{10}$$

(iii) C_{tACK} is the energy consumed by the relay node to transmit an ACK.

$$C_{tACK} = \frac{\delta_{ACK} \bullet E_{Tx}(l,d)}{l \bullet r_i} \tag{11}$$

(iv) C_{rACK} represents the energy consumed by the current node in receiving an ACK.

$$C_{rACK} = \frac{\delta_{ACK} \bullet E_{Rx}(l)}{l \bullet r_u} \tag{12}$$

(v) $C_{fwd\longrightarrow sink}$ indicates the expected energy cost of the forwarding node; that is, the expected energy cost of the relaying data after the forwarding node receives the data sent by the sending node. For nodes with lower priority, data will not be relayed unless the nodes with a higher priority in the forwarding set cannot relay the data. That is, the forwarding node only needs to relay data when it correctly receives the data packet, and all nodes with higher priority in the forwarding set cannot receive the data. Therefore, the probability of the node relaying data is given by (13), in which $p_{u,i}$ denotes the reliability of the link (u, i) and p_i is the specified priority of node i.

$$\mathrm{P}[fwd = i] = p_{u,i} \bullet \prod_{p_j > p_i, j \in \mathcal{F}_u} \left(1 - p_{u,j}\right) \tag{13}$$

Thus, (14) shows $C_{fwd\longrightarrow sink}$, where $\mathcal{F}_i^*$ denotes the forwarding set of node i and $\mathcal{P}_i^*$ denotes the relay priority set of node i.

$$C_{fwd\longrightarrow sink} = \sum_{\forall i \in \mathcal{F}_u} RECBD_i\left(\mathcal{F}_i^*, \mathcal{P}_i^*\right) \bullet \mathrm{P}[fwd = i] \tag{14}$$

(vi) P_{TS} indicates the probability that at least one forwarding node successfully receives data, which is calculated according to

$$P_{TS} = 1 - \prod_{i \in \mathcal{F}_u} \left(1 - p_{u,i}\right) \tag{15}$$

In this paper, we consider both the energy consumed by the transmitting node and the energy consumed by the receiving nodes. The RECBD metric changes with the selection of different nodes in the forwarding set during the computation. In addition, priority determines the sequence of forwarding nodes to forward the data, and thus the setting of priority will affect the value of $C_{fwd\longrightarrow sink}$ in RECBD. Therefore, to prolong the network lifetime, each sensor node can minimize the RECBD value by determining the appropriate forwarding set and priority to minimize the energy cost to the sink node.

4.2. Routing Protocol. During message transmission, when two nodes meet each other, they first exchange the network information by querying and responding. Second, the priority is allocated according to the RECBD value of the node, the forwarding node is selected, and the data is transmitted. In the process of message transmission, the initial calculation of the RECBD value starts from the sink node. This paper assumes that the RECBD value of the sink node is zero and that the initial RECBD value of the ordinary sensor node is infinity. The computational process of this method is similar to the distance vector routing algorithm [28], because they all need the warmup stage to get the proper parameters. Once the sensor node receives information from its neighbour nodes, it calculates the RECBD value. Through the propagation of metric computing, each sensor node in the network can obtain the RECBD value. The process of the initial RECBD metric calculation will continue until the measure of each node converges. When the sensor node determines its forwarding set, the RECBD value of the neighbour nodes is given, and the greedy selection algorithm is applied. First, sensor node u sets its forwarding set $\mathcal{F}_u$ to be empty; second, node u adds neighbour nodes with a minimum RECBD value to $\mathcal{F}_u$ and relay order $\mathcal{P}_u$, and the forwarding node's priority of forwarding data is allocated according to the RECBD value of the forwarding node in ascending order. In addition, the RECBD value of the sensor node depends on the RECBD value of the forwarding set; thus, to add a set of forwarding neighbours in $\mathcal{F}_u$, the $RECBD_u(\mathcal{F}_u, \mathcal{P}_u)$ must be recalculated. The process is repeated until the neighbour node to add forwarding set $\mathcal{F}_u$ cannot improve $RECBD_u(\mathcal{F}_u, \mathcal{P}_u)$.

The RECBD metric for a sensor node depends on the node's remaining energy and the RECBD metric for its forwarding set, and thus the RECBD metrics for each node change over time and interact with each other. To effectively recalculate the RECBD metric, each sensor node appends its latest RECBD metric to the ACK.

This process is carried out in turn until the message is successfully transferred to the sink node. The specific routing protocol is shown in Pseudocode 1. When selecting forwarding nodes, the protocol only needs to consider the RECBD values of neighbour nodes and does not need to obtain the RECBD values of all nodes in the network. Therefore, if the network exceeds the warmup time, the protocol is convergent at any time. In addition, because the routing protocol needs to obtain RECBD of neighbour nodes, the time and space complexity of this protocol is only related to the number of neighbour nodes $|\Phi|$, whose values are both O(n). The overheads of this protocol depend on the forwarding times of a packet and its ACK packet as analysed in Section 3.3, so the overheads of transmitting a packet are $\mathrm{E}[n_{n_i,n_{i+1}}(L_d)] \cdot L_d + \mathrm{E}[m_{n_{i+1},n_i}(L_h)] \cdot L_h$.

5. Performance Evaluation

We compare RER with the following routing schemes via ONE simulator: (1) RER-D is a reliable energy-aware routing protocol without considering distance; (2) DER [9] is a distance-based energy-aware routing protocol. We measured the following aspects of performance.

```
Φ                                        // Φ represents the neighbor nodes set
j = 0
minRECBD=Infinite
for n=1;n≤|Φ|; n++ do                    // |Φ| represents the number of nodes in Φ
    if Φn.RECBD<minRECBD then
        minRECBD = Φn.RECBD              // Φn represents the n-th node in set Φ
        j = n
    end if
end for
if j>0 then
    forwardmessage(Φj)
end if
```

Pseudocode 1: Pseudocode of the routing protocol.

Table 1: Simulation parameter settings.

Parameter	Value
Network radius (R)	400 m
Simulation time (t)	21600 s
Number of sensor nodes (N)	100
Speed of sensor nodes (m/s)	0.5 - 3.5
Initial battery energy of each node (ε_0)	3 [J]
Maximum times of transmissions in hop-by-hop systems (Q_u)	3
Data packet size (L_d)	400 [kbit]
ACK packet size (L_h)	0.1 [kbit]
Message generation rate (ϕ)	16 [kbit/s]
ε_{amp}	10 $pJ/bit/m^2$
ε_{mp}	0.0013 $pJ/bit/m^2$
p	0.8
q	0.8

(1) We compare the routing protocol proposed in the paper with the other two routing protocols in terms of average delivery ratio, average overhead ratio, average latency, average hop count, and network lifetime. We define the network lifetime as the interval time from the start of work on the network to the appearance of the first node death.

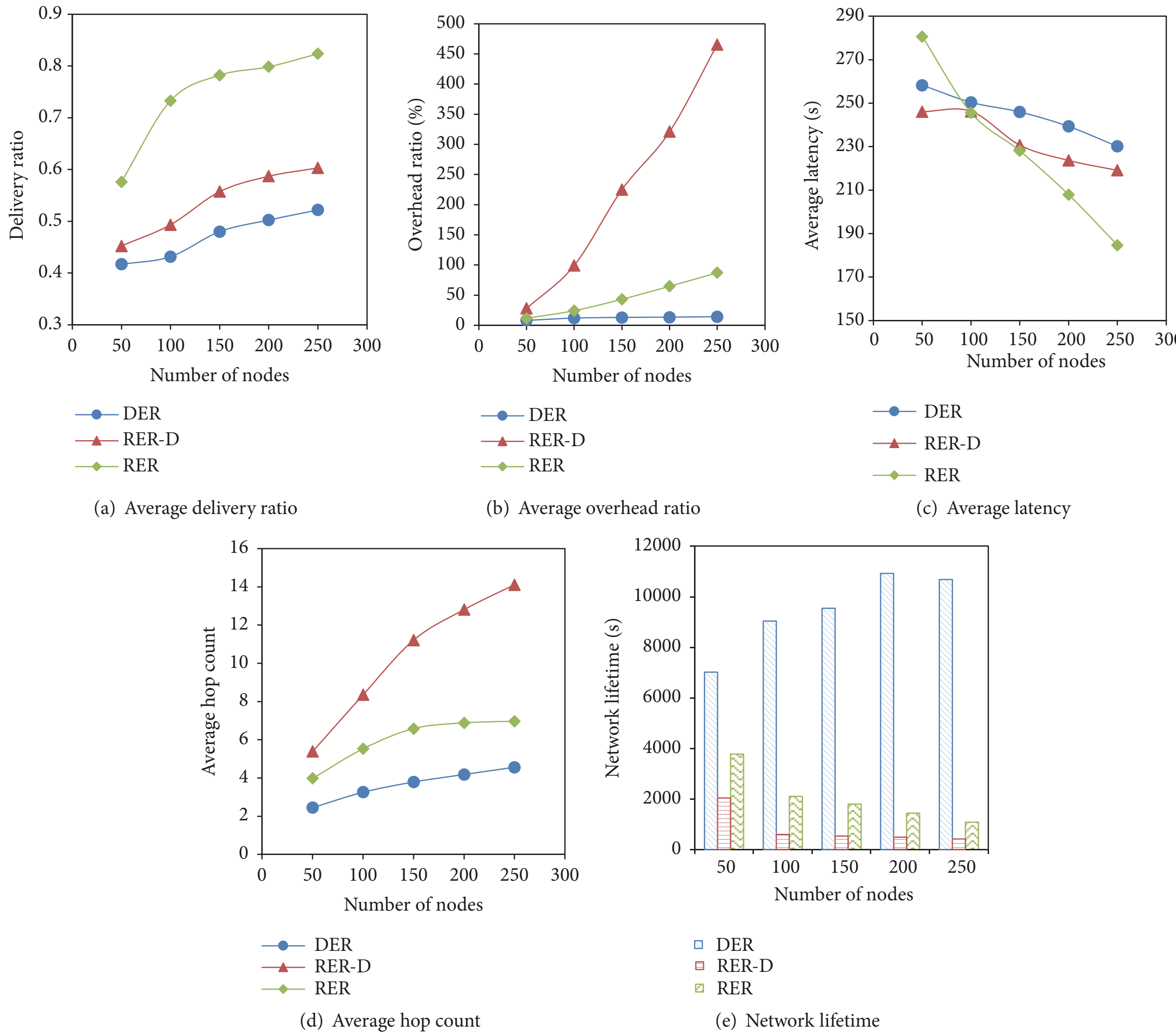
(2) The effects of the number of nodes, the different communication radius, and the link quality on the three routing protocols of RER, RER-D, and DER are studied.

In the experiment, the entire motion region of the nodes is defined as a circle with a radius of 400 m as proposed in [10], and the sink node is located at the centre of the circle. Other network parameters and the corresponding default values are shown in Table 1. The experimental results in this paper are the mean of 100 independent experiments

5.1. Impact of Node Density. In DTMSN, the topology of the network is closely related to the density of the nodes. In our experiment, the impact of the node density on the performance of the routing protocols is mainly studied. In the default parameter settings [22], the number of nodes in the network is set to 50, 100, 150, 200, and 250, and the transmission scheme can achieve the average delivery ratio, average overhead ratio, average latency, average hop count, and network lifetime. They are calculated as the following formulas:

$$\begin{aligned} &\textit{message delivery ratio} = \frac{\textit{delivered message}}{\textit{total created messages}} \\ &\textit{overhead ratio} \\ &\quad = \frac{\textit{relayed messages} - \textit{delivered messages}}{\textit{delivered messages}} \\ &\textit{average latency} = \frac{\sum_{i=1}^{i=\textit{all delivere messages}} \textit{latency}(i)}{\textit{all delivered messages}} \\ &\textit{average hop count} \\ &\quad = \frac{\sum_{\textit{all delivered messages}} \textit{total hops of each message}}{\textit{total created messages}} \end{aligned} \tag{16}$$

As shown in Figure 1(a), as the number of nodes increases, the density of network nodes increases, the probability of meeting between nodes increases, and the message delivery ratio increases. The DER has the lowest message delivery ratio, which is only 51% at maximum. The RER-D messages delivery ratio is slightly higher than that of DER, whereas



(a) Average delivery ratio
(b) Average overhead ratio
(c) Average latency
(d) Average hop count
(e) Network lifetime

FIGURE 1: Impact of node density.

the RER delivery ratio is the highest, with a maximum value of 83%. The message delivery ratio of DER depends on multiple replica guarantees, whereas RER-D and RER are single-replica routing protocols in which the message delivery ratio is guaranteed by the reconfirmation mechanism. The experimental results show that it is better to confirm retransmission than use multiple copies. As the density of the network nodes increases, the probability of meeting between nodes increases, and the message delivery ratio increases. The values of the network overhead ratio and average hop count, as shown in Figures 1(b) and 1(d), increase for the three routing protocols as the number of nodes increases. As the number of nodes increases, the network overhead ratio and the average hop count increase sharply in the RER-D. The network overhead ratio and average hop count of RER are slightly higher than those of DER.

Figure 1(c) shows that the average latency decreases with increasing network density. The key factor is that when the node density is high, the network connectivity is enhanced, meeting between nodes becomes easier, the message transmission latency is reduced, and the latency of RER is minimal. Figure 1(e) shows that the network lifetime of DER is the longest and first increases and then decreases as the number of nodes increases. The network lifetimes of RER-D and RER decrease with increasing node density, and the network lifetime of RER is higher than that of RER-D. This is because the number of nodes increases, the number of packets in the network increases, the probability of collision between packets increases, and the energy consumed by sensor nodes increases. Because DER is multireplica transmission, as the density of nodes in the network increases, the number of copies required for transmission decreases, and the corresponding energy consumed also decreases. DER also consumes more buffer space than the other two routing protocols; it takes space for time, so the network lifetime is longer. In addition, DER delivery ratio is the lowest, and thus its energy efficiency is also lower.

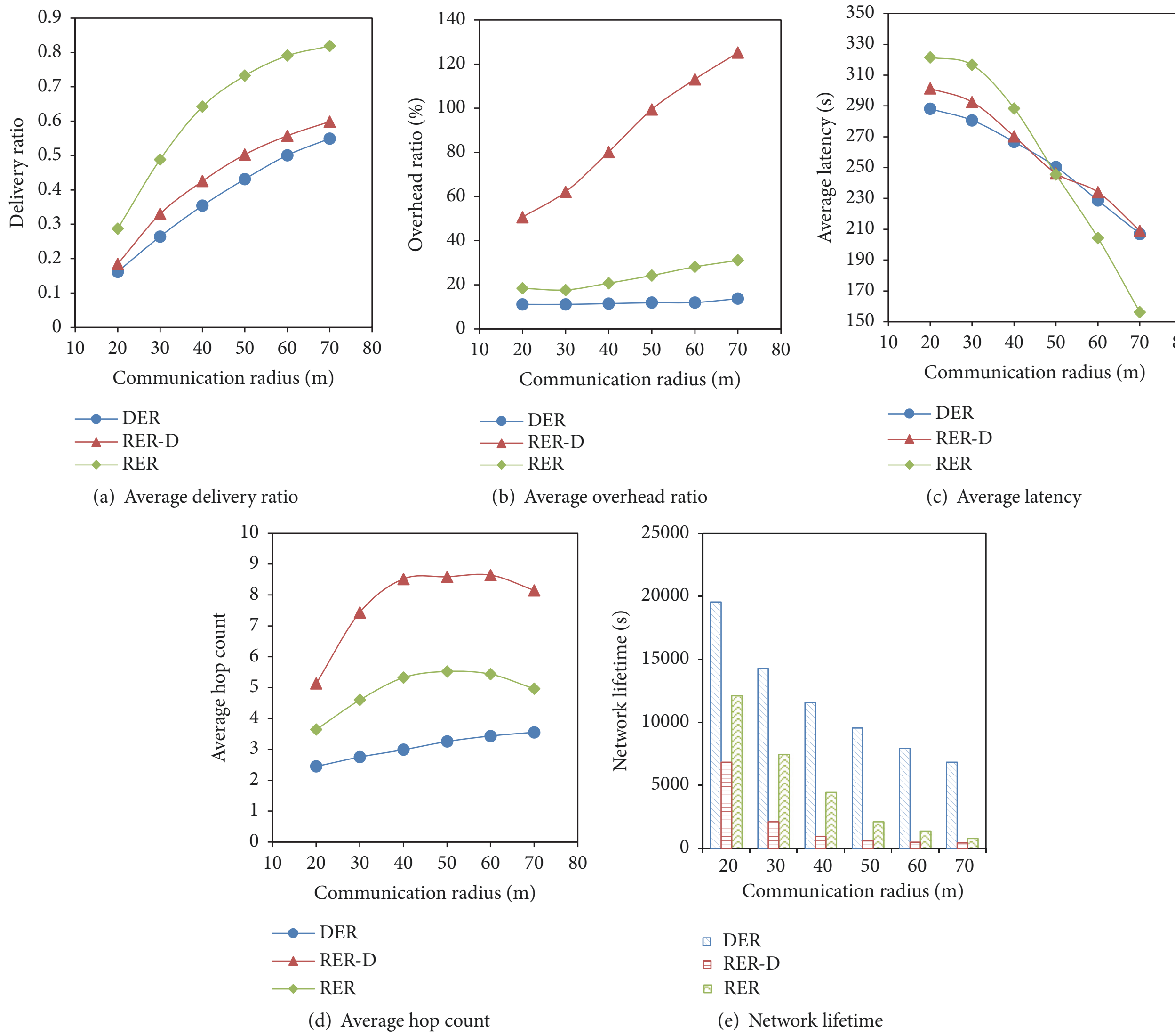


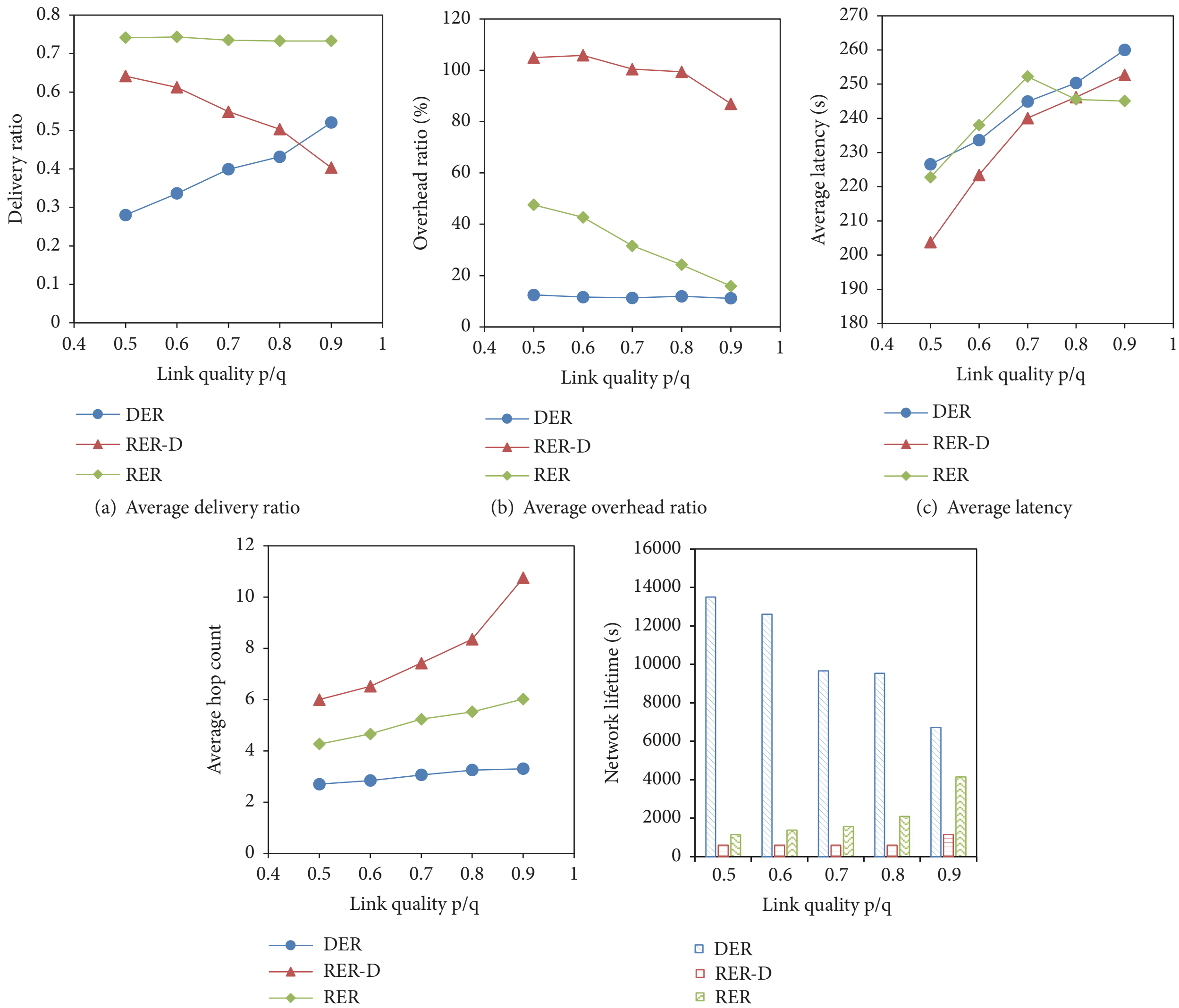
FIGURE 2: Impact of communication radius.

5.2. Impact of Communication Radius. This experiment mainly studies the average delivery ratio, average overhead ratio, average latency, average hop count, and network lifetime in different routing protocols under the default parameter settings. The simulation results are shown in Figure 2.

As shown in Figure 2(a), as the communication radius increases, the message delivery ratios of the three types of routing protocols increase gradually. The message delivery ratio is the lowest in DER, slightly higher in RER-D, and far higher in RER than in DER and RER-D. In DER, confirmation by the retransmission mechanism ensures the reliability of message delivery. When the communication radius is low, due to the poor connectivity of the network and the longer meeting time interval of the nodes, the message delivery ratio is lower. As the communication radius increases, encounters between nodes gradually become more frequent, and the ratio of message delivery increases.

As shown in Figures 2(b) and 2(d), the network overhead ratio and average hop count of the three routing protocols increase with increasing node communication radius. As the communication radius increases, the network overhead ratio and average hop count increase sharply in the RER-D. The network overhead ratio and average hop count are slightly higher in RER than in DER.

Figure 2(c) shows that the average latency decreases as the communication radius increases. As the communication radius increases, then the probability of encountering nodes increases, so that packets can be forwarded between nodes more quickly. Figure 2(e) shows that DER has the longest network lifetime, and the network lifetime of the three routing protocols decreases with increasing communication radius. This is because as the radius of communication increases, the frequent encounters between nodes increase, and the probability of collisions between data packets and the energy consumed by the sensor nodes increase. Although the network lifetime is longer, DER delivery ratio is lowest. This is not in line with actual application needs.



(a) Average delivery ratio

(b) Average overhead ratio

(c) Average latency

(d) Average hop count

(e) Network lifetime

Figure 3: Impact of link quality.

5.3. Impact of Link Quality. In this paper, we use the PRR to measure the link quality of the WSNs. We assume that the link quality is the same for data transmission and ACK transmission, namely, $p = q$. As shown in Figure 3, the link quality of the network has different impacts on the different routing protocols.

As shown in Figure 3(a), the message delivery ratio of RER is the highest among the three routing protocols. As the link quality improves, the message delivery ratio of RER remains stable and is hardly affected by the link quality. This result proves that the reconfirmation mechanism not only ensures the reliability of the link but also the accuracy of message delivery. However, the message delivery ratio of DER increases, because when the link quality improves, the probability of packet dropping in the transmission process decreases, and the message delivery ratio increases. Conversely, the RER-D messages delivery ratio decreases gradually. Although the probability of packet dropping decreases with increasing link quality, the number of network messages increases significantly, which increases the probability of collision between packets and thus reduces the message delivery ratio.

Figure 3(b) shows that as the link quality improves, the average overhead ratio of the three routing protocols decreases. Furthermore, the average overhead ratio of RER decreases almost linearly. As the link quality improves, the number of packets that need to be delivered decreases significantly, and the network overhead ratio is reduced.

As shown in Figures 3(c) and 3(d), as the link quality improves, the average hop count and average latency increase continuously, expect for the average latency of RER. The reason for this phenomenon is that as the link quality improves, the probability of packet dropping is reduced, the number of data packets is aggregated, the time of packets queuing waiting for transmission is prolonged, and the hop count of data packets to the destination node is increased. In RER, when the link quality is improved to a certain extent, the data packets that require retransmission in the network are reduced, and the latency is reduced.

Figure 3(e) shows that the network lifetimes of RER and RER-D also increase with increasing link quality, whereas the network lifetime of DER gradually decreases. This is because, in RER and RER-D, as the link quality improves, the dropping rate of messages decreases, the number of messages that need to be retransmitted is reduced, the energy consumption of the nodes is reduced, and the lifetime of network is improved. For DER, with the increase in link quality, the ratio of message delivery increases, the energy consumption of nodes is increased, and the network lifetime is reduced.

Overall, when the link quality is 0.9, the network lifetimes of RER and DER are nearly identical, but their message delivery ratios are nearly 20% different, indicating that the energy efficiency of DER is too low.

6. Conclusion

In view of the limited energy and unreliable link quality in DTMSN, we propose a reliable energy-aware routing protocol. In this routing protocol, the forwarding of the message is determined based on the node's RECBD value and the RECBD values of other nodes in its communication range. According to the transmission characteristics of the DTMSN, the node's RECBD value is calculated by the distance between the current node and the relay node, the distance between the relay node and the sink node, the current residual energy of the nodes, and the link quality. The aim is to ensure that the node can obtain the message with the highest possible delivery ratio and smallest energy consumption to send to the sink node.

Our simulation experiments explored RER, RER-D, and DER by comparing the average delivery ratio, average overhead ratio, average latency, average hop count, and network lifetime. The results showed that RER can greatly improve the average message delivery ratio and reduce the average latency. Although the network lifetime is lower in RER than in DER, the energy utilization ratio is higher, which ensures the reliability of message transmission in a single copy transmission.

In our subsequent research, we will consider how to further reduce energy consumption and prolong network lifetime while guaranteeing reliability, the message delivery ratio, and the network overhead ratio. In addition, this work is implemented in the simulation environment, and there is a big gap with the real environment. Therefore, in the future work, we will deploy RER in the real environment and make the research more practical.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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