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Low-Delay and Energy-Efficient Opportunistic Routing for Maritime Search and Rescue Wireless Sensor Networks

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Abstract: After the occurrence of a maritime disaster, to save human life and search for important property equipment in the first time, it is indispensable to efficiently transmit search and rescue sea area data to the maritime search and rescue command center (MSRCC) in real-time, so that the MSRCC can make timely and accurate decisions. The key to determining the efficiency of data forwarding is the quality of the routing protocol. Due to the high dynamics of the marine environment and the limited energy of the marine node, the coverage hole and routing path failure problems occur frequently when using the existing routing algorithm for marine data forwarding. Based on the above background, in this work, we study a low-latency and energy-efficient opportunistic routing protocol for maritime search and rescue wireless sensor networks (MSR-WSNs). Considering the adverse impact of wave shadowing on signal transmission, an effective link reliability prediction method is first investigated to quantify the link connectivity among nodes. To mitigate the end-to-end time delay, an optimal expected packet advancement is then derived by combining link connectivity with geographic progress threshold θ. After that, based on the link connectivity between marine nodes, the optimal expected packet advancement prediction, the distance from the sensing nodes to the sink, and the remaining energy distribution of the nodes, the priority of candidate nodes is calculated and sorted in descending order. Finally, timer-based coordination algorithm is adopted to perform the marine data packet forwarding so as to avoid packet conflict. Computer simulation results demonstrate that compared with benchmark algorithms, the data packet delivery ratio, the delay performance and the average node energy consumption (the average node speed is 20 m/s) of the proposed opportunistic routing protocol are improved by more than 21.4%, 39.2% and 18.1%, respectively.

Keywords: maritime search and rescue wireless sensor networks; opportunistic routing; priority scheduling; delay optimization

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1. Introduction

With the rapid development of information technology, wireless sensor networks (WSNs) have been widely used in various scenarios [1]. One of the critical implementations is to deploy maritime search and rescue wireless sensor networks (MSR-WSNs) at sea to assist in marine search and rescue (MSR) tasks after a shipwreck [2]. The over-board target carrying the sensor node could be detected in MSR-WSNs via radio signal transmission, with which the status of passively waiting for rescue for the target could convert into actively positioning [3]. Therefore, the success ratio for search and rescue could be significantly improved.

Regarding the MSR, an efficient and robust routing algorithm is required for the data packet delivery from the source nodes to the sink in MSR-WSNs [4]. Basically, three unique characteristics should be considered in terms of the routing design in MSR-WSNs [5]: (1) highly dynamic topology caused by the winds, waves, and ocean currents; (2) relatively poor communication quality caused by the wave shadowing effect, which limits the capability of the traditional terrestrial routing methods, and (3) limited energy for sensor nodes.

Numerous research has been investigated in terms of routing protocol in WSNs with mobile nodes [6–15]. To name a few. To reduce the network energy consumption, Zhou Y et al. [6] presented a Q-learning-based localization-free any path routing protocol for underwater WSNs, which effectively prolongs the lifespan and reduces the end-to-end delay. In [8], an Energy-Efficient and Reliable Routing protocol was presented for mobile WSNs that minimized routing overhead and overcame unreliable communication links. Toor A S and Jain A K [14] presents Mobile Energy Aware Cluster Based Multi-hop (MEACBM) routing protocol, which introduces mobile nodes as Mobile Data Collector (MDC) to collect Cluster Heads data and transmit it to the Base Station. Unfortunately, none of the above protocols comprehensively consider the end-to-end performance and the characteristics of marine environment, so they are not suitable for highly dynamic MSR-WSNs. It needs to be emphasized that the MSR-WSNs studied in this paper is a more dynamic sea surface wireless sensor networks than underwater WSNs, and the communication technology used between nodes is radio signal propagation.

In contrast with traditional routing algorithms, opportunistic routing could significantly reduce packet retransmission due to link failure by dynamically selecting forwarders from multiple candidate neighboring nodes [15]. The next-hop used for the data packet forwarding depends on which forwarding nodes receive the packet and the priority order of candidate nodes [16]. Therefore, opportunistic routing can better adapt to the unstable and dynamic networks. In recent years, some scholars have also carried out some research on the opportunistic routing protocol design of marine sensor networks [17–26]. To name a few, COUTINHO R W L et al. [17] discussed candidate node set selection and candidate node coordination procedure in opportunistic routing and provided detailed guidance for opportunistic routing design in underwater sensor networks. ISMAIL M et al. [18] proposed a reliable path selection and opportunistic routing protocol, named RPSOR, for underwater WSNs. RPSOR guarantees reliability by adding information from the next forward region to the priority function, thereby reducing network energy voids and reducing packet loss rate. ZOU Z et al. [20] proposed a cluster-based adaptive routing algorithm (CBAR) for large-scale underwater WSNs, which simplifies the format of the transmission data packets to adapt to the clustered network structure. Furthermore, CBAR uses dynamic routing updates to adapt to the specificity of the underwater environment and utilizes power control to diminish routing energy consumption. Zhu R et al. [26] proposed an opportunistic routing protocol (ROEVA) based on reinforcement learning for underwater acoustic sensor networks, which improves the reliability of data transmission while extending the network lifecycle and solving the routing holes problem. All in all, the research on terrestrial WSNs routing technology has become more and more mature, and the research on underwater WSNs routing protocol has gradually deepened. However, the MSR nodes are sparsely deployed on the sea surface and move frequently, the network topology changes dynamically, the delay is high, and there is no end-to-end continuous connection. It has the characteristics of a delay-tolerant and fault-tolerant network, which brings great difficulties to the design of MSR-WSNs routing protocol. In addition, opportunistic routing face two main challenges in MSR-WSNs: (1) the problem of packet duplication under time-varying topology; (2) the waiting-time problem of the sending node under uncertain sea conditions. Simultaneously, real-time updating of routing metrics among marine nodes will yield high communication costs in MSR-WSNs [4]. The comparison of the proposed opportunistic routing protocol and benchmark routing protocols is shown in Table 1.

Aiming at the problem of the instability in marine communication links, this paper first proposes an effective link reliability prediction method to quantify the connectivity between nodes. Next, we choose the candidate nodes whose geographic progress exceeds the threshold θ. We find the optimal θ by computing the minimization of the expected total delay of forwarding a MSR data packet from the farthest node to the sink. By combining network connectivity with geographic progress threshold, the optimal expected packet advancement that balances hop count and network link quality is derived to gain optimal end-to-end performance. Moreover, by considering the extreme movement of nodes, we calculated the minimum time to maintain link connectivity and set it as the node waiting time, thereby further reducing network delay. Subsequently, the priority of candidate nodes is calculated based on the four metrics, elaborated in the Section 3. Finally, after sorting the priority of the candidate nodes in descending order, the marine data packet forwarding is completed using timer-based coordination algorithm. The main contributions of the present work can be summarized as follows:

(1) We consider the situation where all marine nodes move in real-time, which is in line with the real scenario of maritime search and rescue.
(2) A novel link connectivity metric function is proposed to predict the reliability of marine communication links, and combined with the minimum time for maintaining direct link connectivity between nodes to ensure the stability of MSR-WSNs.
(3) We propose a novel candidate nodes priority calculation technique based on the link connectivity between marine nodes, the optimal expected packet advancement prediction, the distance from the sensing nodes to the sink, and the remaining energy distribution of the nodes.
(4) we evaluate our proposed opportunistic routing protocol in a simulated marine environment. Computer simulation experiments validate that the proposed opportunistic routing protocol can effectively increase the data packet delivery ratio, reduce time delay, and prolong the lifetime of MSR-WSNs.

Table 1. The comparison of the proposed opportunistic routing protocol and benchmark routing protocols.

Protocols	Features	Advantages	Disadvantages
POR [4]	Prediction based opportunistic routing	Increases the PDR with an additional 3% energy consumption	Failure to realistically model the ocean dynamic environment
QLFR [6]	Q-learning-based localization-free opportunistic routing	Latency is reduced and network lifespan is increased	Bandwidth and link quality are not considered
E^2R^2 [8]	Hierarchical and cluster-based routing	Throughput is risen	The situation of high-speed movement of nodes is not considered
RPSOR [18]	Depth based opportunistic routing	Improves the PDR and decreases the energy consumption	High end-to-end delay in sparse networks
CBAR [20]	Cluster-Based adaptiverouting	Increases the life cycle of nodes	High end-to-end delay
Optimizing opportunistic routing in asynchronous WSNs [27]	Geographical-based opportunistic routing	End-to-end delay is reduced	Not suitable for mobile WSNs
MAQD [28]	Multi-aware query driven routing based on a neuro-fuzzy inference system	Decreases the End-to-end delay and routing overheads	PDR is reduced to a certain extent
E-Ant-DSR [29]	Enhanced Dynamic Source Routing based on the Ant Colony Optimization	End-to-end delay is reduced with low routing overhead	High computational complexity
DORAHP [30]	Distributed joint optimization routing based on the analytic hierarchy process	Extends network lifetime	High computational complexity
Our proposed opportunistic routing protocol	Marine environmental factors based opportunistic routing	Adaptive dynamic marine environment; Increases the PDR and network lifetime; End-to-end delay is reduced	Medium computational complexity

In summary, in highly dynamic and communication harsh marine environments, the goals of the proposed opportunistic routing protocol are to achieve efficient collection and real-time transmission of the MSR data packets, and to improve the continuity, intelligence and robustness of MSR-WSNs based search and rescue systems to assist the MSRCC makes timely responses and correct decisions after the shipwreck. In addition, the proposed opportunistic routing protocol will play a positive role in promoting the construction of a deep-sea stereoscopic observation system for intelligent communication, networking and exploration, and at the same time have important scientific significance and academic value for the development of multidisciplinary and multi-level major frontier theories of sensor networks in deep-sea observation.

The remainder of this paper is organized as follows. Section 2 presents the system model. The proposed opportunistic routing algorithm is illustrated in Section 3. Section 4 conducts our computer simulation results, and finally, this paper concludes in Section 5.

2. System Model and Problem Statement

2.1. System Model

When a shipwreck accident occurs, we use unmanned drones to quickly deploy N sensor nodes would be used to conduct a self-organizing network in the MSR area. The system model is shown in Figure 1. In what concerns MSR-WSNs, some reasonable assumptions should be emphasized: (1) All sensor nodes are equipped with GPS/Beidou positioning module, with which the location information can be known at each time slot; (2) The wireless channel is completely symmetric; (3) Node movement follows a random movement model; (4) A wake-sleep mechanism is utilized to reduce the network energy consumption. Specifically, the activation period of the node is t_a, and the sleep period t_s is an exponentially distributed random variable with a mean λ^{-1} [27]. According to the analysis in Section 3, we set $t_a = t_{\min}$.

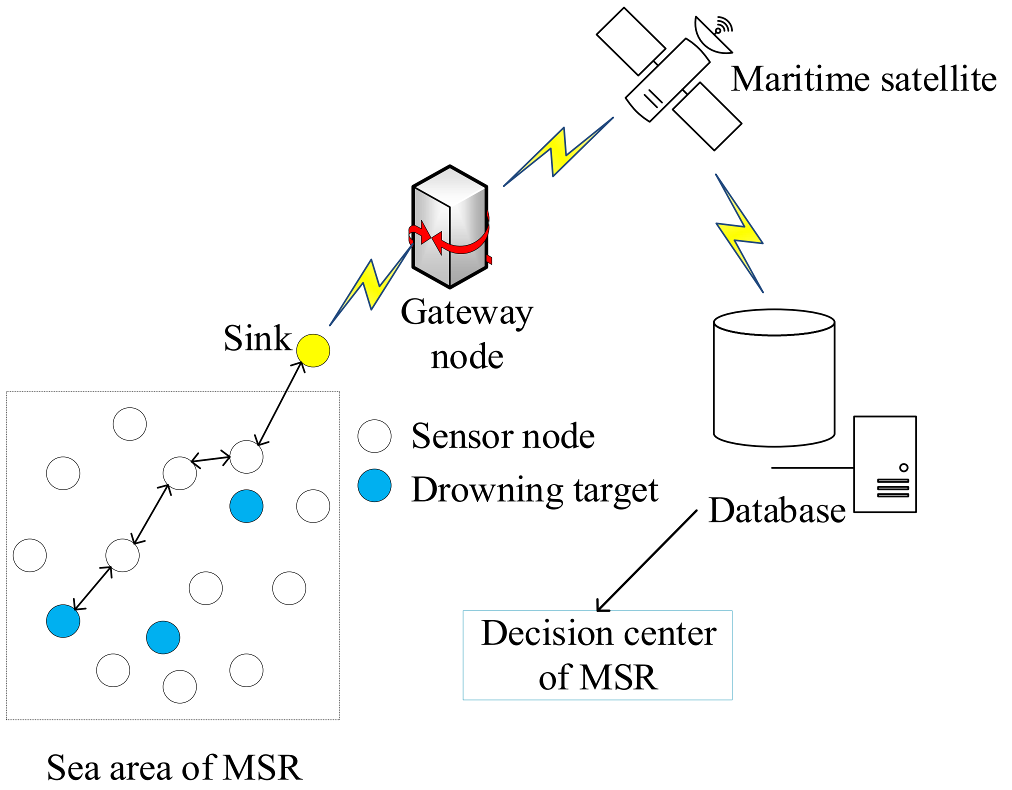

Figure 1. System model of the MSR-WSNs.

Inspired by [28], the energy consumption formula for transmitting b_i-bits data over distance d is as (1), wherein the energy consumption of radio electronic would be considered for the transmitter (TX) and the receiver (RX). Furthermore, the energy consumption of the power amplifiers would be considered for the TX.

$$E_{TX}(b_i, d) = \begin{cases} b_i \times E_{elec} + b_i \times \varepsilon_{mp} \times d^4, d > d_0 \\ b_i \times E_{elec} + b_i \times \varepsilon_{fs} \times d^2, d \le d_0 \end{cases} \quad (1)$$

where E_{elec} is the energy dissipation per bit of the transmitting or the receiving circuit, ε_{fs} and ε_{mp} are the energy consumption of signal amplifiers in free space and multipath scenarios, respectively, and $d_0 = \left(\frac{\varepsilon_{fs}}{\varepsilon_{mp}}\right)^{1/2}$.

The energy consumption of receiving b_i-bits data is

$$E_{RX}(n_i) = b_i \times E_{elec} \quad (2)$$

2.2. Problem Statement

In the highly dynamic maritime search and rescue environment with poor communication link quality, how to design a novel low-delay and energy-efficient opportunistic routing protocol to realize real-time and efficient forwarding of MSR data packets from source node to sink node.

3. Proposed Opportunistic Routing Algorithm

3.1. Link Reliability Prediction

The highly dynamic of the sensor nodes caused by the winds, waves and currents would result in routing failure due to the frequent interruption of the communication links. Therefore, an efficient link quality prediction method would be presented in this section to evaluate the possibility of the interruption. Moreover, the update period (the broadcast period of the "Hello" message) would be conducted to renew the link connectivity metric in real-time to ensure reliability of the routing path. In the light of the theoretical path loss model (Shadowing Model), the received power $P_R(d)$ could be expressed as [2],

$$P_R(d) = P_t - PL(d_0) - 10\alpha \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (3)$$

where P_t is the transmit power of the node, $PL(d_0)$ indicates the signal strength loss when the reference distance is $d_0 = 1$m, α is the path-loss attenuation exponent, X_σ is the wave shadow factor on the propagation path, which follows the Gaussian distribution with zero mean and variance σ^2.

Assuming that the communication radius of the nodes is r (from [29], the average distance between two randomly moving nodes in a circular area of radius r is 0.9054r). Ignoring the shadowing factor, the received signal strength threshold for a node that can successfully receive the data packets should be,

$$P_{R-Th} = P_t - PL(d_0) - 10\alpha \log_{10}\left(\frac{0.9054r}{d_0}\right) \quad (4)$$

The received strength threshold P_{R-Th} represents the minimum signal strength in which the node can receive its neighbor node message. It should be noted that P_{R-Th} is a constant only when P_t, α, and r are determined. By comparing the threshold P_{R-Th} and the received signal strength, the metric LC is defined to quantify the link connectivity between the node and their neighbor nodes. In addition, the proposed LC can be expressed as,

$$LC_{i_j} = \begin{cases} 0, & if\ P_r(d) \le P_{R-Th} \\ 1 - \mathrm{e}^{1 - \frac{P_{R-Th}}{P_r(d)}}, & if\ P_r(d) > P_{R-Th} \end{cases} \quad (5)$$

where LC_{i_j} represents the link connection probability between node i and its neighbor node j. Theoretically, the larger the value of LC_{i_j}, the more reliable the link. If $LC_{i_j} = 0$, it represents the link is disconnected or will be interrupted.

In a highly dynamic marine environment, the network topology is constantly changing, and the established reliable communication link among marine nodes cannot maintain for a long time. Therefore, it is necessary to periodically update LC_{i_j}. In [29], one of the extreme situations was considered, in which two nodes are assumed to move in a opposite direction at the maximum speed. Then the minimum time for the direct link of the node to maintain connectivity is,

$$t_{\min} = \frac{r - 0.9054r}{2v_{\max}} = \frac{0.0473r}{v_{\max}} \tag{6}$$

where $v_{\max}$ is the maximum movement speed of the marine node. The update period T is set to $t_{\min}$ for the sake of ensuring the real-time nature of LC_{i_j} and avoiding unnecessary routing overhead.

3.2. Optimal Expected Packet Advancement Prediction

Referring to the analysis in [27], we define the distance from the source node i to the sink as Y_i^t at time t. Forwarding path of the proposed opportunistic routing protocol is shown in Figure 2. The MSR data packets generated by the source node i is transmitted to the sink through a multi-hop random path, and the selection of the next-hop forwarding node depends on the priority of the candidate nodes and the sleep/active mechanism. The average number of the candidate forwarding nodes for the node i is $N_i = \overline{\rho} A_i^t$, where $\overline{\rho}$ is the average node density in the MSR area, and A_i^t is the sea area where the candidate forwarding nodes are located. Without loss of generality, A_i^t that needs to be calculated in this section could be expressed as,

$$A_i^t(Y_i^t, \theta) = \int_\theta^r 2(Y_i^t - x)\arccos\left(\frac{(Y_i^t)^2 + (Y_i^t - x)^2 - r^2}{2Y_i^t(Y_i^t - x)}\right)dx \tag{7}$$

where θ is control parameter of the packet advancement.

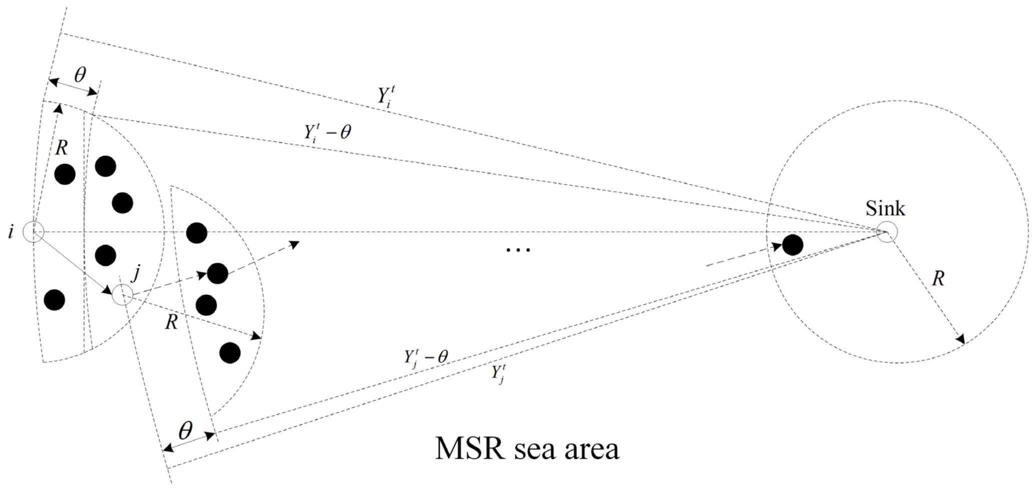

Figure 2. Forwarding path of the proposed opportunistic routing protocol.

Frankly speaking, the higher connectivity of the node, the higher possibility of being the candidate forwarding node. In this context, the calculation formula of the optimal expected packet advancement prediction from the node to the next-hop forwarding node is expressed as follows,

$$h\left(Y_i^t,\theta\right)=\int_{x=\theta}^{x=r}\frac{2\left(Y_i^t-x\right)\arccos\left(\frac{\left(Y_i^t\right)^2+\left(Y_i^t-x\right)^2-r^2}{2Y_i^t\left(Y_i^t-x\right)}\right)}{A_i^t}\cdot x\cdot dx \tag{8}$$

Suppose that the marine node i starts to wait at time 0 after collecting the search and rescue data. The probability that one or more candidate forwarding nodes wake up at time t is $N_i\lambda e^{-N_i\lambda t}$. Therefore, the expected waiting time of the node i before the first candidate node wakes up is,

$$T_e\left(Y_i^t,\theta\right)=\int_0^{\infty}t\cdot N_i\lambda e^{-N_i\lambda t}dt=\frac{1}{\lambda N_i}=\frac{1}{\lambda\overline{\rho}A_i^t} \tag{9}$$

Further, the Equation (9) can be transformed into Equation (10).

$$A_i^t=\frac{1}{\lambda\overline{\rho}T_e} \tag{10}$$

With the exception of the waiting delay $T_e\left(Y_i^t,\theta\right)$, the maritime search and rescue data packets also experience an additional transmission delay at each hop, that is, the time delay (T_q) in the exchange of data packets and *ack* message packets between nodes. It is noted that T_h depends mainly on the data packet length and the sea surface wireless communication link quality. Further, the total expected time delay of forwarding a maritime search and rescue packet from a node with a distance of Y to the sink can be calculated as follows:

$$T(Y,\theta)=\begin{cases}T_e(Y,\theta)+T_q+T\left(Y-h\left(Y_i^t,\theta\right),\theta\right), & if\ Y>r\\ T_q, & otherwise\end{cases} \tag{11}$$

Next, we explore to minimize the total expected time delay of marine data packet delivery from the farthest sensing node to the sink.

$$\begin{gathered}\min T(Y_m,\theta)\\ s.t.\ 0<\theta\le r\end{gathered} \tag{12}$$

where Y_m is the Euclidean distance from the farthest sensing node in the MSR-WSNs to Sink.

In the last hop (transmission process from one-hop neighbor node to sink), the average packet advancement value is $\frac{\sqrt{2}}{2}r$, so the estimated value of $T(Y_m,\theta)$ can be obtained as $\widehat{T}(Y_m,\theta)=\frac{\left(Y_m-\frac{\sqrt{2}}{2}r\right)}{h\left(Y_i^t,\theta\right)}\left(\frac{1}{\overline{\rho}\lambda A_i^t\left(Y_i^t,\theta\right)}+T_q\right)+T_q$. From the above analysis combined with the simulation parameter settings, we can easily deduce that the optimal value of θ is 30 m.

3.3. Remaining Energy Distribution

In MSR-WSNs, an important metric for determining the priority of candidate nodes is the node's remaining energy. However, collecting the remaining energy data of the marine node in real-time will generate a large communication overhead. For the sending node i, the energy probability distribution $\widetilde{\xi}_i=\left(\widetilde{\xi}_{i_1},\widetilde{\xi}_{i_2},\ldots,\widetilde{\xi}_{i_j}\right)$ is defined based on the energy regularized random variable $\overline{\xi}_i=\left(\overline{\xi}_{i_1},\overline{\xi}_{i_2},\ldots,\overline{\xi}_{i_j}\right)$, and the expressions of $\overline{\xi}_{i_j}$ and $\widetilde{\xi}_{i_j}$ are as follows [31],

$$\overline{\xi}_{i_j}=1+\left(\frac{\xi_j}{e_0}\right),\forall j\in F_{i_j} \tag{13}$$

$$\widetilde{\xi}_{i_j}=e^{\left(\overline{\xi}_{i_j}\right)^{\gamma_\Phi}}/\sum e^{\left(\overline{\xi}_{i_j}\right)^{\gamma_\Phi}},j\in F_{i_j}\ and\ \gamma_\Phi\ge 0 \tag{14}$$

where: γ_Φ is energy distribution control parameter, ξ_j is the remaining energy of the candidate node j, e_0 is the initial energy of the node, F_{i_j} is the set of candidate nodes. To increase the lifetime of MSR-WSNs, routing metrics should be dynamically updated in cycles $T = t_{\min}$ based on the node's remaining energy. Otherwise, marine nodes with high priority will prematurely exhaust their energy, resulting in routing holes and link failures. We utilize the energy probability distribution (Equation (14)) and combine the state of the marine environment to update the routing metrics. Whenever an marine node loses 5% of its energy, it broadcasts the current energy state to its neighbor nodes. The neighbor nodes then update their energy probability distribution and communication link quality. Among them, the bandwidth resources and energy consumption required to update the communication link quality are very low. The pseudo-code for updating the energy distribution of neighbor nodes is shown in Algorithm 1.

Algorithm 1 Updating the Energy Distribution of Neighbor Nodes

1. **Each** forwarding the sending node i loses 5% of its energy **do**
2. Inform the F_{i_j} about the current remaining energy value.
3. **For each** candidate node $j \in F_{i_j}$ **do**
4. Recalculate $\widetilde{\xi}_i = \left(\widetilde{\xi}_{i_1}, \widetilde{\xi}_{i_2}, \ldots, \widetilde{\xi}_{i_j}\right)$ by Equation (14)
5. Update $P_{i_j}(t)$ by Equation (15)
6. **End for**
7. **For each** candidate node $j \in F_{i_j}$
8. **For each** $P_{i_j}(t)$ **do**
9. **If** $P_{i_j}(t) \geq \frac{1}{1+q_{i_j}}$ **do** // q_{i_j} is the number of neighbor nodes.
10. Add neighbor node j to F_{i_j}
11. **End if**
12. **End for**
13. **End for**

3.4. Priority Calculation and Scheduling of Candidate Forwarding Nodes

After obtaining the link connectivity $LC_{i_j}(t)$ between the marine node and their neighbor nodes, the optimal expected packet advancement prediction $h(Y_i^t)$, the distance to sink $d_{j-Sink}(t)$, and the remaining energy probability distribution $\widetilde{\xi}_{i_j}$, the proposed priority calculation formula of the candidate node j at time t is defined as,

$$P_{i_j}(t) = \ln\left(1 + \frac{LC_{i_j}(t) \cdot h(Y_i^t) \cdot \widetilde{\xi}_{i_j}(t)}{d_{j-Sink}(t)}\right) \tag{15}$$

From Equation (15), we can see that the optimal next-hop node is:

$$j^* = \underset{j}{\operatorname{argmax}} P_{i_j}(t) \tag{16}$$

According to $P_{i_j}(t)$, the priority rank of the candidate forwarding nodes can be obtained. Finally, we executed packet forwarding using timer-based coordination algorithm. The candidate nodes with the highest priority intend to perform the data packet delivery first, while the other candidate forwarding nodes remain dormant. When the high-priority candidate node does not successfully forward the data packet within time $t_{\min}$, a lower-priority candidate node will be activated and attempt to forward the data packet. The above process continues until the marine node's perception data is successfully forwarded as explained in Algorithm 2. The proposed opportunistic routing algorithm has two benefits: (1) Since the number of candidate nodes is less than the number of neighbor nodes, it reduces the number of packet duplications and beacon collisions; (2) For the node with priority k, the waiting time is $T_e(Y_i^t, \theta) + (k-1)t_{\min}$.The subsequent simulation results display that this greatly reduces the time delay in the routing process. The flowchart of the proposed opportunistic routing algorithm is shown in Figure 3.

Algorithm 2 Scheduling of Candidate Forwarding Nodes

1. **When** a marine node i received *ack* message packets **do**
2. Calculate $P_{i_j}(t)$ by Equation (15)
3. **For each** $P_{i_j}(t)$ **do**
4. **If** $P_{i_j}(t) \geq \frac{1}{1+q_{i_j}}$ **do** // q_{i_j} is the number of neighbor nodes.
5. Add neighbor node j to F_{i_j}
6. **End if**
7. **End for**
8. **For each** $j \in F_{i_j}$ **do**
9. **If** candidate node j^* successfully forwards the data packet **then**
10. other candidate nodes remain dormant
11. **else**
12. a lower-priority neighbor node will be activated and attempt to forward the data packet until the marine node's perception data is successfully forwarded
13. **End if**
14. **End for**

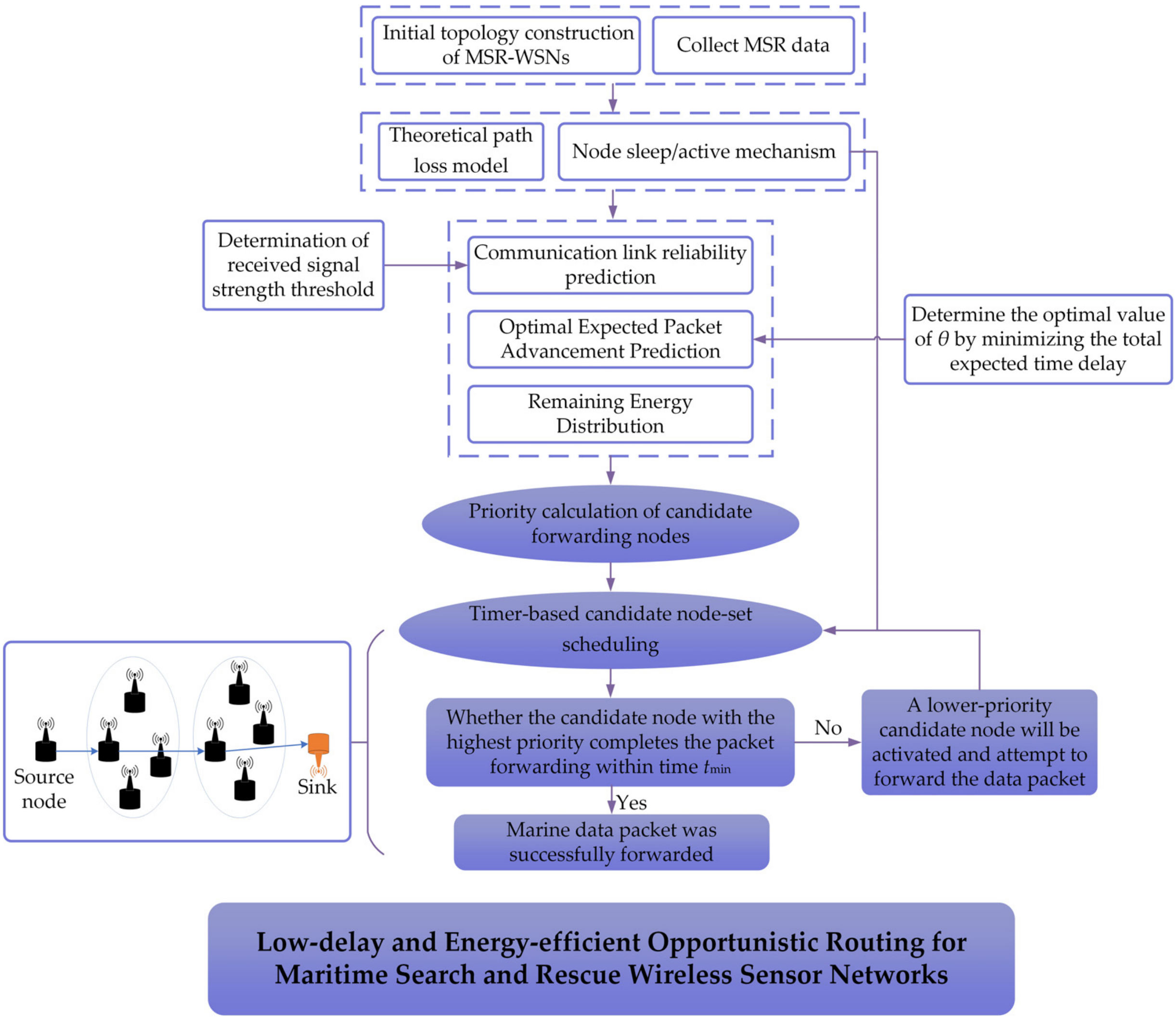

Figure 3. The flowchart of the proposed opportunistic routing algorithm.

3.5. Expected Energy Consumption of MSR Data Forwarding

Considering the worst case (that is, all candidate forwarding nodes are activated in priority order), the energy consumption for transmitting and receiving beacon packets is calculated as follows:

$$\begin{aligned} E_{beacon}(i,j,k_b) &= E_{TX}(i,j,k_b) + \sum_{\forall n_u \in A_i^t} E_{RX}(u,k_b) \\ &= k_b \begin{cases} E_{elec} + \varepsilon_{mp} \times d_{i,j}^4 + E_{elec} \times \overline{\rho} A_i^t, d_{i,j} > d_0 \\ E_{elec} + \varepsilon_{fs} \times d_{i,j}^2 + E_{elec} \times \overline{\rho} A_i^t, d_{i,j} \le d_0 \end{cases} \end{aligned} \tag{17}$$

where: k_b is the size of the beacon packet in bits.

Similarly, the energy consumption of sending back an *ack* message packet to the ith node is formulated as:

$$\begin{aligned} E_{ack}(i,k_a) &= \sum_{\forall n_u \in A_i^t} E_{RX}(i,k_a) + \sum_{\forall n_u \in A_i^t} E_{TX}(u,i,k_a) \\ &= k_a \begin{cases} E_{elec} \times \overline{\rho} A_i^t + \sum\limits_{\forall n_u \in A_i^t} \left(E_{elec} + \varepsilon_{mp} \times d_{u,i}^4 \right), d_{u,i} > d_0 \\ E_{elec} \times \overline{\rho} A_i^t + \sum\limits_{\forall n_u \in A_i^t} \left(E_{elec} + \varepsilon_{fs} \times d_{u,i}^2 \right), d_{u,i} \le d_0 \end{cases} \end{aligned} \tag{18}$$

where: k_a is the size of the *ack* message packet in bits.

Based on Equations (17) and (18), the energy consumption of each transmission stage is:

$$\overline{E}_X(i,j,k,k_b,k_a) = E_{TX}(i,j,k) + E_{RX}(j,k) + E_{beacon}(i,j,k_b) + E_{ack}(i,k_a) \tag{19}$$

where: k is the size of the MSR data packet in bits.

In addition, in the process of MSR data forwarding, assuming that the activation number of candidate nodes are $\zeta(\zeta \ge 1)$, the energy consumption of transmitting and receiving beacon packets is calculated as follows:

$$\begin{aligned} E_{beacon}(i,j,k_b,\zeta) &= E_{TX}(i,j,k_b) + \sum_{u=0}^{\zeta} E_{RX}(u,k_b) \\ &= k_b \begin{cases} E_{elec} + \varepsilon_{mp} \times d_{i,j}^4 + \zeta \times E_{elec}, d_{i,j} > d_0 \\ E_{elec} + \varepsilon_{fs} \times d_{i,j}^2 + \zeta \times E_{elec}, d_{i,j} \le d_0 \end{cases} \end{aligned} \tag{20}$$

Likewise, in the process of MSR data forwarding, the energy consumption of sending back an *ack* message packet to the ith node is formulated as:

$$\begin{aligned} E_{ack}(i,k_a) &= \sum_{u=0}^{\zeta} E_{RX}(i,k_a) + \sum_{u=0}^{\zeta} E_{TX}(u,i,k_a) \\ &= k_a \begin{cases} \zeta \times E_{elec} + \sum\limits_{\forall n_u \in A_i^t} \left(E_{elec} + \varepsilon_{mp} \times d_{u,i}^4 \right), d_{u,i} > d_0 \\ \zeta \times E_{elec} + \sum\limits_{\forall n_u \in A_i^t} \left(E_{elec} + \varepsilon_{fs} \times d_{u,i}^2 \right), d_{u,i} \le d_0 \end{cases} \end{aligned} \tag{21}$$

Correspondingly, for a given source node i (the activation number of candidate nodes during the successful completion of MSR data forwarding is ζ), the energy consumption of each transmission stage is calculated as follows:

$$E_X(i,j,k,k_b,k_a,\zeta) = E_{TX}(i,j,k) + E_{RX}(j,k) + E_{beacon}(i,j,k_b,\zeta) + E_{ack}(i,k_a,\zeta) \tag{22}$$

Finally, based on Equation (22), the expected energy consumption during each transmission is:

$$\begin{aligned} E_{hop}(i,j) &= \frac{1}{\zeta} \times \sum_{u=1}^{\zeta} P(\zeta = u) \times E_X(i,j,k,k_b,k_a,u) \\ &= \frac{1}{\zeta} \times \sum_{u=1}^{\zeta} \frac{u}{N_i} \times E_X(i,j,k,k_b,k_a,u) \end{aligned} \tag{23}$$

In summary, the expected energy consumption of sending MSR packets from the source node to the sink through the routing path $\aleph = \{n_1, n_2, \ldots, n_{\kappa-1}, \text{Sink}\}$ is:

$$\begin{aligned} E_{\aleph} &= \sum_{q}^{\kappa} E_{hop}(q, q+1) \\ &= \left(\frac{1}{\zeta}\right)^{\kappa-1} \times \sum_{q}^{\kappa-1} \sum_{u=1}^{\zeta} \frac{u}{N_i} \times E_X(q, q+1, k, k_b, k_a, u) \end{aligned} \tag{24}$$

where: κ denotes the number of marine nodes on the routing path $\aleph$.

4. Results and Discussion

In this section, we evaluate the performance of the proposed opportunistic routing algorithm. Simulations are implemented on an Intel Core i7-1065G7 1.30 GHz PC with 8G memory and performed in Matlab R2016b. After the shipwreck occurs, 100 marine nodes are supposed to be randomly distributed in the MSR area with a side length of 2 km. The maximum and minimum speed of the sensor node are 20 m/s and 10 m/s, respectively. Other simulation parameters settings are shown in Table 2. Figure 4 is the deployment diagram of marine nodes. To properly verify the proposed routing algorithm, a marine node that is far from the gateway node is selected as the sink. Three routing algorithms including prediction based opportunistic routing (POR) [4], E-Ant-DSR [29], DORAHP [30] are chosen as the benchmark algorithms.

Table 2. Simulation parameters.

Parameter	Value	Parameter	Value
e_0	3 J	ε_{mp}	0.0013 pJ/bit/m4
r	100 m	α	3
Simulation time	70 s	σ^2	30 dB
Channel bandwidth	2 Mbps	λ^{-1}	1 s
E_{elec}	50 nJ/bit	γ_Φ	2
ε_{fs}	10 pJ/bit/m^2	θ	30 m

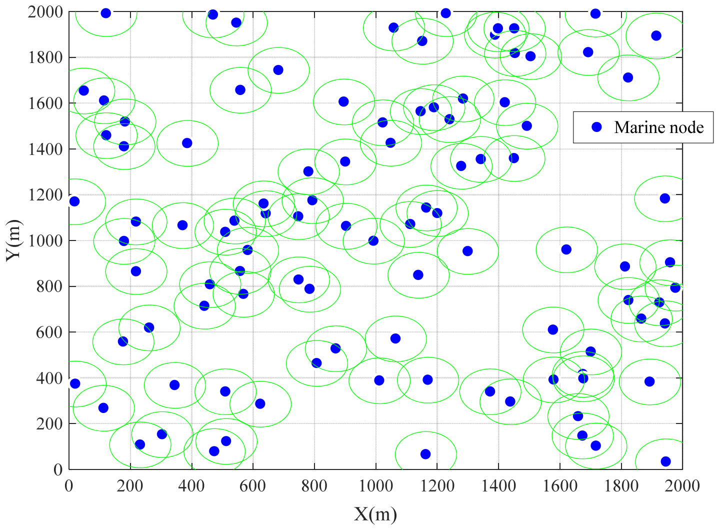

Figure 4. Marine nodes deployed in the MSR sea area.

Figure 5a reveals that our proposed algorithm has a higher packet delivery ratio than that of the benchmark algorithms. The outperformance could be explained by the facts that (1) the proposed algorithm effectively predicts the link connectivity based on the consideration of node mobility, and (2) the proposed methods could periodically update the measurement value of link connectivity, which can, to some extent, delete the link with a smaller metric value and ensure the reliability of the transmission path. Meanwhile, our opportunistic routing algorithm forms multiple communication links, which effectively improves the probability of successfully forwarding marine data packets to the sink. Compared with POR, E-Ant-DSR, and DORAHP, the packet delivery ratio of the proposed opportunistic routing protocol is improved by 21.4%, 23.9% and 42.9%, respectively. Figure 5b shows that the proposed algorithm achieves the lowest end-to-end delay (average time required by the data packets to reach the sink). The proposed algorithm reduces the end-to-end delay by using the opportunistic routing technology incorporated with the optimal packet advancement prediction. Compared with POR, E-Ant-DSR, and DORAHP, the delay performance of the proposed opportunistic routing protocol is improved by 39.2%, 41.9% and 55.5%, respectively, which rises the efficiency of MSR to a certain extent.

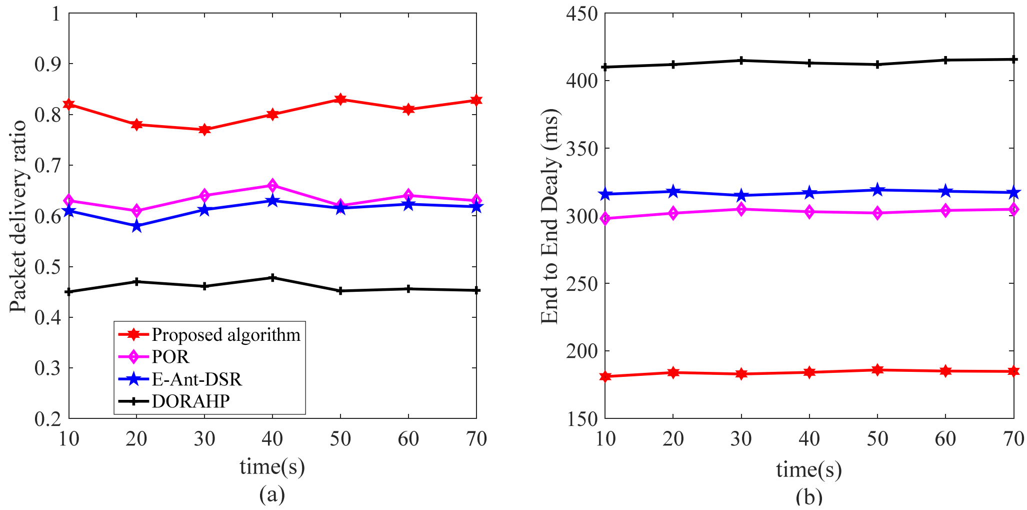

Figure 5. (**a**) Comparison of packet delivery ratio. (**b**) Comparison of end-to-end delay.

It can be seen from Figure 6, as the increase of the node moving speed, the performance of all algorithms has declined to varying degrees. In DOPAHP, due to ignorance of the node mobility and the high computational complexity, the communication link that becomes formed is not stable. New routing path must be formed frequently that will greatly reduce the packet delivery ratio. However, in our proposed algorithm, nodes broadcast the data and attempt to find a better forwarding node at each time slot, which increases the probability of being successfully and timely forwarded for the data. Since our proposed algorithm has a relatively low computational complexity, it has achieved the best results in terms of the energy consumption. To be specific, when the average node speed is 20 m/s, compared with POR, E-Ant-DSR, and DORAHP, the average node energy consumption of the proposed opportunistic routing protocol is decreased by 19.6%, 21.8% and 18.1%, respectively. Figure 7a reflects the packet delivery ratios of the proposed algorithm, POR, and E-Ant-DSR gradually increase to a stable state over the rise in the node's communication radius. Since the DORAHP needs to reform the link frequently in the marine environment with time-varying topology, the packet delivery ratio of DORAHP first increases and then decreases when the node's communication radius grows. If the node's communication radius is relatively small, the number of hops for the data packet transmission would increase. In other words, more energy should be taken for the transmission in terms of the node. Figure 7b shows that the energy consumption is the lowest among the considered methods. In particular, when the node's communication radius changes dynamically, compared with

POR, E-Ant-DSR, and DORAHP, the average node energy consumption of the proposed opportunistic routing protocol is decreased by 13.7%, 19.9% and 4.8%, respectively.

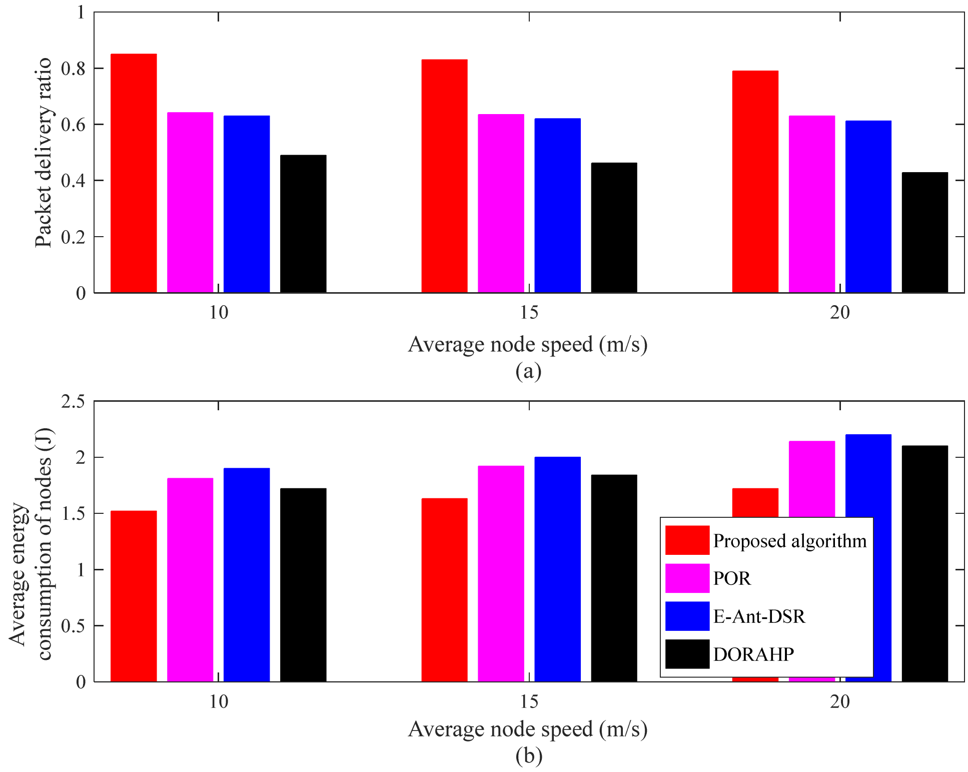

Figure 6. Comparison with variable node moving speed. (**a**) Packet delivery ratio. (**b**) Average energy consumption of nodes.

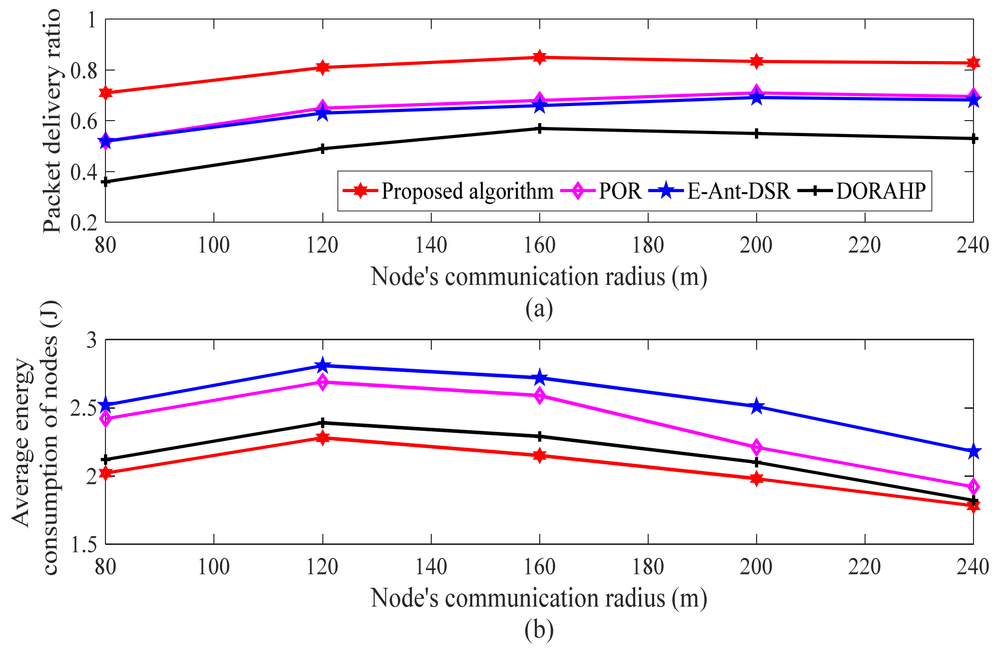

Figure 7. Comparison with variable node's communication radius. (**a**) Packet delivery ratio. (**b**) Average energy consumption of nodes.

To further verify the performance of the algorithm, we use variable σ^2 to simulate changes in sea conditions (the larger the σ^2, the worse the sea conditions). It can be seen from Figure 8 that as σ^2 increases, the performance of all algorithms gradually deteriorates.

Since the proposed algorithm comprehensively considers the link quality, distance metric and the optimal expected packet advancement, it is better than the benchmark algorithms in terms of packet delivery ratio and node's energy consumption. When σ^2 is 50 dB, the packet delivery ratio of the proposed opportunistic routing protocol is 72%, which basically meets the MSR requirements.

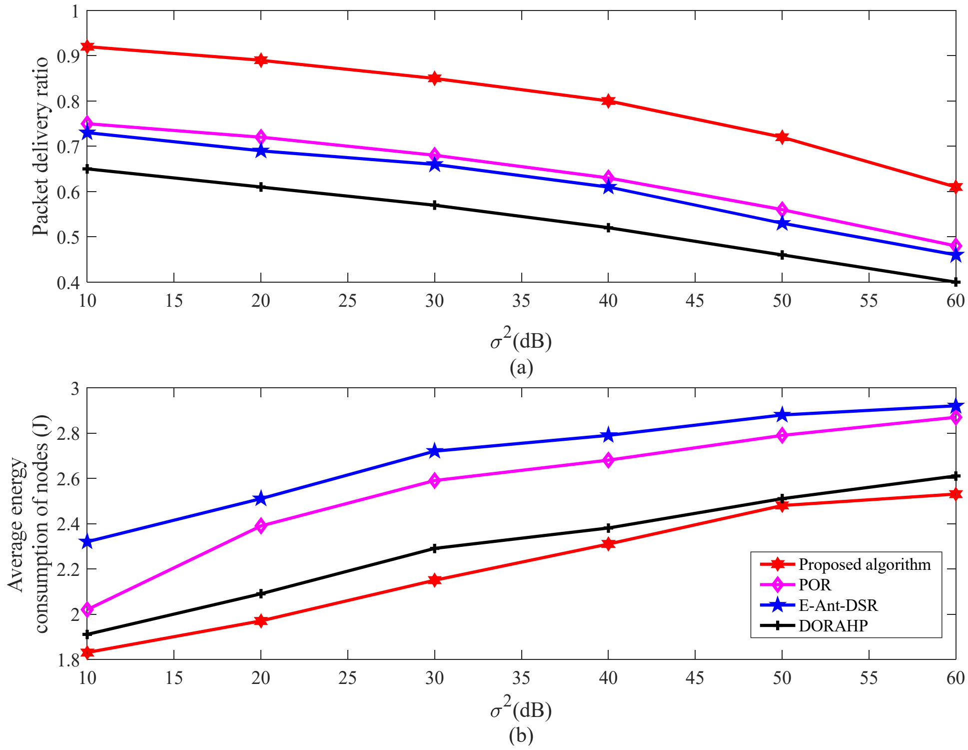

Figure 8. Comparison with variable σ^2. (**a**) Packet delivery ratio. (**b**) Average energy consumption of nodes.

5. Conclusions

This paper proposed a novel low-latency and energy-efficient opportunistic routing protocol to achieve timely and accurate data delivery in MSR-WSNs. Link connectivity among marine nodes, integrated with geographic progress threshold are explicitly considered when selecting candidate nodes for data packet forwarding. Moreover, the optimal expected packet advancement and the minimum waiting-time $t_{\min}$ are utilized to minimize time delay. Subsequently, the priority $P_{i_j}(t)$ of candidate nodes is calculated and sorted in descending order. Eventually, the packet forwarding is completed using timer-based coordination algorithm. Our simulation results validated that the proposed opportunistic routing protocol performs better than the benchmark algorithms in terms of three metrics: data packet delivery ratio (increased by more than 21.4%), time delay (reduced by more than 39.2%) and energy consumption (decreased by more than 18.1% at average node speed is 20 m/s). The work of this paper is expected to greatly improve the efficiency and success rate of maritime search and rescue while reducing the time delay. In the future, we will conduct the actual marine experiments (ship detection [32]) to test the engineering applicability of the proposed opportunistic routing algorithm. Meanwhile, combining the power control mechanism and the existing marine sensor networks localization algorithm [33–36] to assist opportunistic routing design is also one of the directions worth studying. In addition, there is a lack of research on underwater sensor networks in this paper, and how to design an opportunistic routing protocol for heterogeneous underwater sensor networks to achieve reliable high-speed transmission of underwater data is another potential research direction.

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