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Adaptive Power-Controlled Depth-Based Routing Protocol for Underwater Wireless Sensor Networks

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Abstract: Low energy consumption has always been one of the core issues in the routing design of underwater sensor networks. Due to the high cost and difficulty of deployment and replacement of current underwater nodes, many underwater applications require the routing protocol design to consider the network lifetime extension problem. Based on this, we designed a new routing protocol that takes into account both low energy consumption and balanced energy consumption, and achieves effective extension of the network lifetime, called adaptive power-controlled depth-based routing protocol for underwater wireless sensor networks (APCDBRP). The protocol consists of two phases: (1) the route establishment phase and (2) the data transmission phase. In the route establishment phase, the initial path is established by the sink node broadcasting beacon packets at the maximum transmission power. The receiving nodes update their routing tables based on the beacon information and forward the beacon packets. In the data transmission phase, APCDBRP introduces a novel forwarding factor that considers both energy efficiency and energy balance. It selects the optimal next hop based on high energy efficiency and relatively abundant energy, thus extending the network's lifetime. Additionally, APCDBRP proposes a new data protection and route reconstruction mechanism to address issues such as network topology changes due to node mobility and data transmission failures. Our simulation is based on AquaSim-Next Generation, which is a specialized tool built on the NS3 platform for researching underwater networks. Simulation results demonstrate that, compared to other typical routing protocols, APCDBRP exhibits superior performance in reducing network energy consumption and extending the network's lifetime. It also achieves a high packet delivery rate with lower energy consumption.

Keywords: underwater sensor networks; energy balance; energy efficiency; power control



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1. Introduction

While land serves as the primary habitat and activity space for human beings, it only accounts for approximately 20% of the Earth's surface area. In contrast, approximately 80% of the Earth's surface is covered by water bodies. Exploring the oceans, much like exploring space, presents both indispensable opportunities and challenges for humanity. In the deep sea, the task of manually exploring the underwater environment is nearly impossible due to factors such as low visibility, high water pressure, and unpredictable underwater events. However, the emergence of underwater wireless sensor networks (UWSNs), consisting of numerous autonomous and self-organizing sensor nodes, has made it possible to explore natural resources on the seabed and collect data during collaborative monitoring tasks [1,2].

UWSN routing is crucial for enabling underwater applications as it facilitates the transmission of information and data among underwater nodes. However, UWSN routing faces significant differences and poses additional challenges compared to terrestrial wireless sensor networks [3–5]. On one hand, underwater networks require a higher level of energy balance among nodes, as underwater nodes cannot replenish their energy and have limited energy storage. If a node is excessively utilized, it may become ineffective due to premature

energy depletion. The premature demise of such nodes can lead to network fragmentation and disrupt normal network operation. Therefore, when designing routing algorithms, it is important to ensure that the energy of all nodes decreases synchronously. On the other hand, underwater network structures exhibit a certain level of dynamism. Due to water currents, nodes may experience movement within a certain range, resulting in dynamic changes in the network's structure. This necessitates routing protocols that can adapt to changes in the network's topology. These characteristics impose higher requirements on routing protocols, demanding the design of protocols that are more suitable for underwater networks.

In this paper, we propose an adaptive power-controlled depth-based routing protocol (APCDBRP) that achieves efficient packet forwarding at each hop. In APCDBRP, both data packets and control packets contain information such as the sending node's transmission power, remaining energy, and depth. During the route establishment phase, we employ a sender-based routing algorithm. The sink node broadcasts beacon packets at maximum transmission power, and when a relay node receives a beacon packet from a particular node, it measures the received signal strength to determine the required power level for the previous hop node. Based on the information and power level, the relay node calculates the forwarding factor for that node and stores it in the routing table. Finally, the node updates the information in the beacon packet and broadcasts it at maximum power. To avoid redundant beacon packet transmissions, each node only sends a beacon packet once within a certain time period. To address the issues of node mobility and the low channel utilization and high energy consumption caused by frequent beacon packet transmissions, we employ an implicit routing update mechanism. In this mechanism, nodes receive all the data packets and control packets within their communication range. They then update and maintain the routing based on the signal strength and information contained in these packets. The main contributions of this paper are as follows:

1. It has proposed a new routing protocol that utilizes the implicit routing update mechanism, enabling the network to update routing information with fewer control packets.
2. It has introduced a novel forwarding factor that considers both energy efficiency and remaining energy, allowing the sending node to select the optimal next-hop node, and significantly improving network efficiency.
3. It has presented a new data protection and route reconstruction mechanism that employs a localized–globalized integrated strategy, effectively addressing data forwarding failures and routing voids caused by node mobility.
4. It has presented the results of extensive simulations to evaluate the performance of the proposed solutions. The results demonstrate that APCDBRP outperforms other corresponding protocols.

The rest of the paper is organized as follows. In Section 2, we review related work. In Section 3, we present the proposed APCDBRP. In Section 4, we evaluated the performance of the protocol through theoretical analysis and simulation experiments. In Section 5, we conclude the paper.

2. Related Works

Routing protocols play a crucial role in determining the forwarding behavior of nodes, and well-designed routing protocols can ensure the efficient delivery of data packets to their intended destinations at a minimal cost. The unique characteristics of the underwater acoustic channel pose significant challenges to the design of routing protocols for underwater wireless sensor networks (UWSNs). In order to address these challenges, researchers have proposed numerous routing protocols specifically tailored for UWSNs.

The deep-based routing (DBR) protocol, proposed by Yan et al. in 2008 [6], was the first pressure-based routing protocol for underwater sensor networks. DBR effectively avoids the stringent requirement of acquiring full-dimensional location information for sensor nodes. Instead, it utilizes the depth information of each node to select transmission paths and deliver data to the destination node. The advantages of the DBR routing protocol lie in its elimination of node localization, its simple data packet forwarding strategy, and its wide applicability to

various scenarios. However, there are limitations to consider. The greedy strategy employed in DBR, which relies on local information flooding through broadcasts, can result in excessive energy consumption and a reduced network lifetime. Additionally, the absence of intermediate nodes that meet the depth information criteria within the transmission range can lead to routing holes, causing a decline in network performance. To optimize DBR, Wahid et al. proposed the energy-efficient depth-based routing (EEDBR) protocol [7]. EEDBR adopts a sender-based routing strategy, where the sender selects the forwarding nodes based on the information of its neighboring nodes, such as depth and remaining energy. By doing so, the sender can choose a limited number of suitable relay nodes, reducing redundant data packets and achieving a balance in energy consumption among sensor nodes. To address the issue of sensor nodes in the mid-depth region consuming their energy earlier compared to higher-depth regions in EEDBR, Khizar et al. [8] proposed the enhanced energy-efficient depth-based routing protocol (EEEDBR). The study introduced a partitioning approach and deployed backup nodes specifically in the mid-depth region to mitigate this problem. Kumar et al. proposed a hybrid depth-based routing mechanism called energy-balanced hybrid depth-based routing (EBH-DBR) [9] to address the issues of energy imbalance and shortened network lifetime in UWSNs. The study assumed that all nodes were within one-hop range of a surface buoy node. Nodes can transmit data packets directly to the receiving nodes in a one-hop manner or through relay nodes by adjusting their communication range. Network fragmentation is employed to control the number of hops, balancing node energy consumption and achieving a longer network lifetime and higher throughput. Farooq et al. [10] proposed the IoT-enabled depth-based routing method (IDBR) to efficiently utilize energy resources. This method not only achieves energy efficiency but also provides insights for the future development of space–air–ground–sea integrated networks.

Due to the traditional waiting mechanism used in depth-based protocols, there is a trade-off between network latency and the ability to suppress duplicate packets.

The aforementioned depth-based protocols are all multi-route routing protocols. While forwarding duplicate packets improves packet delivery rates, it also introduces issues such as packet collisions and energy consumption. Therefore, in order to reduce energy consumption and enhance the overall performance of UWSNs, many researchers have adopted single-route routing schemes when designing routing protocols. Zhu et al. proposed a layer-based energy-efficient routing (LEER) protocol in [11], where nodes select the next hop based on residual energy and one-hop delay for data forwarding. In [12], Wang et al. presented a distance vector opportunistic routing (DVOR) protocol that utilizes distance vector mechanisms to route data packets to the destination via the shortest path. Liu et al., in [13], drew inspiration from the distance vector mechanism of DVOR and introduced a concurrent working mechanism to reduce forwarding delay. In [14], Wang et al. proposed an energy-aware and hole-avoidance routing protocol for underwater sensor networks. This protocol avoids network holes and provides efficient routing by considering the residual energy of nodes and the communication capability between parent and sibling nodes when selecting the next hop.

Compared to multi-route routing protocols, single-route routing schemes allow only one node to receive the data packet at each hop, which can significantly reduce data packet collisions and energy consumption. Clearly, the latter is suitable for applications that do not require frequent data transmission but may not be suitable for applications that involve a large amount of data [3,15].

In terms of power control, due to the fact that the distance between each pair of connected nodes in an underwater acoustic network is not always the maximum transmission distance for acoustic signals, there is a certain redundancy in the transmission power of the nodes. Therefore, appropriate power control for sensor nodes can improve the energy efficiency of the network. In fact, power control has been emphasized as an effective method for topology control in underwater sensor networks, aiming to improve data transmission and reduce energy costs [16].

The authors in [17] proposed five principles for saving sensor energy and prolonging the network lifetime, which include using finite levels of power, applying the multi-hop transmission, narrowing the scope of transmission, applying the inactivation mode, and balancing energy consumption. In [18], Wang et al. compared the energy consumption between single-hop direct transmission and multi-hop transmission via relay nodes. When transmitting through relay nodes, the source node adjusts the transmission power to cover the relay node's location. Through theoretical analysis, the authors demonstrated that multi-hop transmission is more energy-efficient when the relay node is located on the line between the source and destination nodes or is not far from the line. Ahmed et al. proposed an adaptive power control and depth-aware routing scheme [19]. In their study, each node set its transmission power to the target node based on the received signal strength indicator (RSSI). This technique allows for better adaptation to the communication environment and reduces environmental interference. Therefore, our routing protocol also incorporates this technology in terms of power control.

Segmenting long-distance transmissions into shorter-distance transmissions through power control mechanisms can effectively reduce energy consumption. However, this introduces a certain path delay and node data processing delay. Therefore, when introducing such a mechanism, it is necessary to balance energy consumption and end-to-end delay according to the system's performance requirements.

In addition to the aforementioned protocols, researchers have proposed numerous other routing protocols for underwater sensor networks. A more comprehensive description of these protocols can be found in [20,21].

3. The Proposed Protocol

In this section, we propose an adaptive power-controlled depth-based routing protocol (APCDBRP). The primary objective of the proposed routing protocol is to extend the network's lifetime by balancing the energy consumption of each node in the network and controlling the transmitting power. Additionally, we utilized the depth information of sensor nodes as a substitute for complete geographical location information to reduce overhead. The network model of UWSNs is illustrated in Figure 1. Sensor nodes are distributed randomly in the underwater environment.

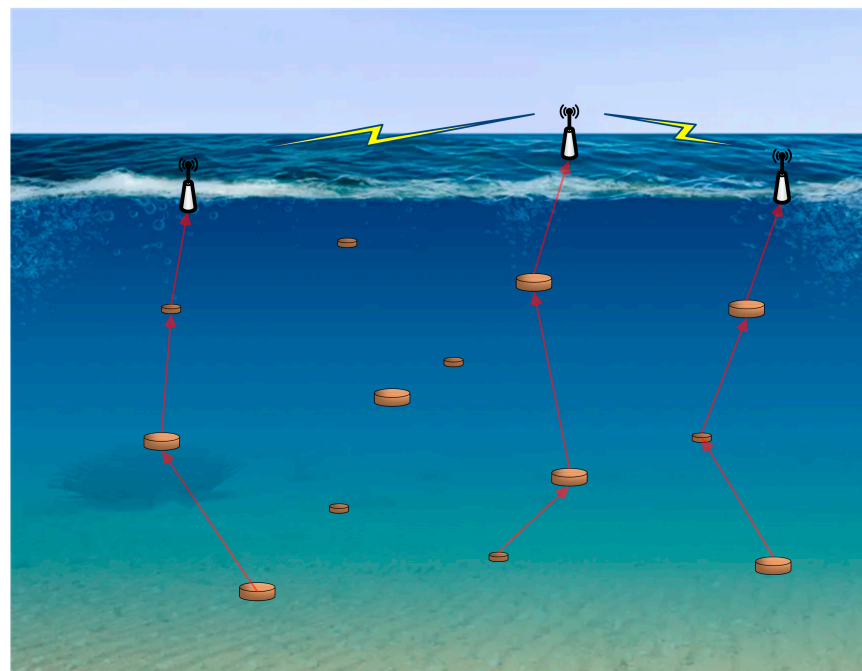


Figure 1. Three-dimensional network structure of underwater sensor network.

3.1. Assumptions

- The network consists of three types of sensor nodes: source nodes, relay nodes, and sink nodes. Source nodes, also known as anchor nodes, are fixed at specific underwater locations and are responsible for collecting data from the underwater environment. They transmit the data to the sink nodes through relay nodes. Relay nodes are deployed at various underwater locations and forward the received data packets to the sink nodes. The sink nodes are located at the water surface and serve as the destination for all data packets in the network. The source nodes and sink nodes are relatively expensive, carrying more energy, while the relay nodes have simple functionality, lower cost, and carry less energy.
- Each node is equipped with a power control module and a signal strength measurement device. Nodes do not require location and distance information. Instead, they measure the received signal strength to estimate the path loss between communicating nodes. Based on the estimated path loss, nodes adjust their transmission power. All nodes have the same maximum transmission power, which corresponds to the maximum transmission distance in the network.
- Each node is equipped with a depth sensor, allowing them to obtain their own depth information when needed.
- A successful delivery is considered as long as the packet arrives at any of sinks on the water surface.
- The channel is reciprocal, meaning that the transmission signal experiences the same channel fading in both the uplink and downlink directions.

3.2. Channel and Energy Consumption Model

In order to better understand the working principles, in this section, we will combine relevant references to provide the acoustic channel model and energy model. Urlick gave an empirical formula in 1967 [22] to describe the underwater path loss and attenuation, as shown in Equation (1).

$$A(d, f) = A_0 d^k a(f)^d \quad (1)$$

Here, d represents distance, f represents frequency, A_0 represents unit-normalizing constant, k represents spreading factor, and $a(f)$ is the absorption coefficient. Furthermore, $10 \log a(f)$ is given by Thorp [23] in dB/km for f in kHz, as shown in Equation (2).

$$10 \log a(f) = 0.11 \frac{f^2}{1 + f^2} + 44 \frac{f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003, f > 0.2 \text{ kHz} \quad (2)$$

The signal-to-noise ratio (SNR) can be derived according to the passive sonar equation [22], as shown in Equation (3).

$$\gamma_b = SL - TL - NL + DI \geq DT \quad (3)$$

Here, γ_b is the SNR at the receiver and DI is the directive coefficient. For omnidirectional hydrophones, $DI = 0$. NL is the underwater ambient noise, which can be found in [24,25]. DT is the minimal SNR required for signal acquisition at the receiver. SL is the output acoustic source level in dB re μPa at the sender.

For spherical spreading, the transmitting power P_0 at the sender can be obtained from [18].

$$P_0 = 4\pi \times 0.67 \times 10^{-18} \times 10^{(DT+TL+NL-DI)/10} \quad (4)$$

If a node sends n data packets and receives m data packets within time t , then the energy consumed by it during t can be expressed as:

$$\begin{aligned} E &= E_{tx} + E_{rx} + E_{idle} \\ &= \frac{L}{Ra} \sum_{i=1}^n P_{tx}(i) + \frac{mL}{Ra} P_{rx} + tP_{idle} \end{aligned} \quad (5)$$

Here, E_{tx} , E_{rx} , and E_{idle} denote the energy consumption in the transmitting, receiving, and idle state, respectively. $P_{tx}(i)$ is the transmitting power for the i -th data packet for the node. P_{rx} and P_{idle} are the receiving and idle power in Watts for one node, respectively. We assume that P_{rx} and P_{idle} are the same for each node. L and Ra represent the packet length and the data rate, measured in bits and bits/s, respectively.

3.3. Detailed Design of APCDBRP

This section presents an adaptive power-controlled depth-based routing protocol (APCDBRP). The routing protocol consists of three main parts: route establishment phase, data forwarding phase, and data protection and route reconstruction mechanism. All packets in the network, including data packets and control packets, record the transmitting power of the sending node. Each node maintains a routing table that stores the forwarding factor in its neighboring nodes, with the neighbor having the highest forwarding factor being selected as the optimal forwarding node. Furthermore, due to the influence of water currents, underwater nodes may shift, resulting in changes to the network topology. This necessitates frequent updates to the routing information, which could lead to data forwarding failures and routing voids. The faster the flow of water, the more pronounced this problem becomes. The implicit routing update mechanism and the data protection and route reconstruction mechanism mentioned later in the text are primarily employed to address this issue.

3.3.1. Route Establishment Phase

In this section, we first describe the structure of data packets and control packets. Then, we discuss the structure of routing table. Finally, we provide a detailed explanation of the route establishment process.

a. The Structure of Packets

APCDBRP defines six packet types: BEACON packet, Data packet, ACK packet, PROBE packet, PROBE REPLY packet, and HOLE packet, as shown in Figure 2. Except for the Data packet, all other packets are categorized as control packets. Among these fields, Type ID and Sender ID are common fields present in all packets. Type ID indicates the packet type, used for distinguishing different types of packets, while Sender ID represents the node ID of the sending packet. Receiver ID and Data Packet ID exist only in Data packets and ACK packets. Receiver ID is used to specify the receiver, while Data Packet ID consists of the node ID and packet number, ensuring the uniqueness of each data packet's Data Packet ID. Residual Energy, Depth, Forwarding Success Rate, and Transmit Power Level represent the information used for calculating the forwarding factor. The detailed calculation of the forwarding factor will be explained in Section 3.3.2. Due to the adoption of the implicit route update mechanism in this protocol, all packets except for the HOLE packet contain Residual Energy, Forwarding Success Rate, and Depth information. Additionally, since the transmitting power of nodes varies when sending Data packets and ACK packets, Data packets and ACK packets also carry Transmit Power Level information. It is important to note that the usage of ACK packets in this protocol differs from the common practice. ACK packets are used only under specific conditions, which will be discussed in detail in Section 3.3.2.

b. The Structure of the Routing Table

Figure 3 displays the structure of the routing table, which consists of the following fields: Node ID, Depth, Residual Energy, Optimal Next Hop ID, and Neighbor List. The Neighbor List contains the Node ID, Forwarding Factor, and Transmit Power Level required for communication between the local node and each neighbor node. The neighbor node with the highest Forwarding Factor is selected as the best next hop. In addition, the Transmit Power Level is used to set the Transmit Power Level field in the packets. The Forwarding Success Rate is the ratio of the number of data packets successfully forwarded by the node to the total number of data packets forwarded by the node.

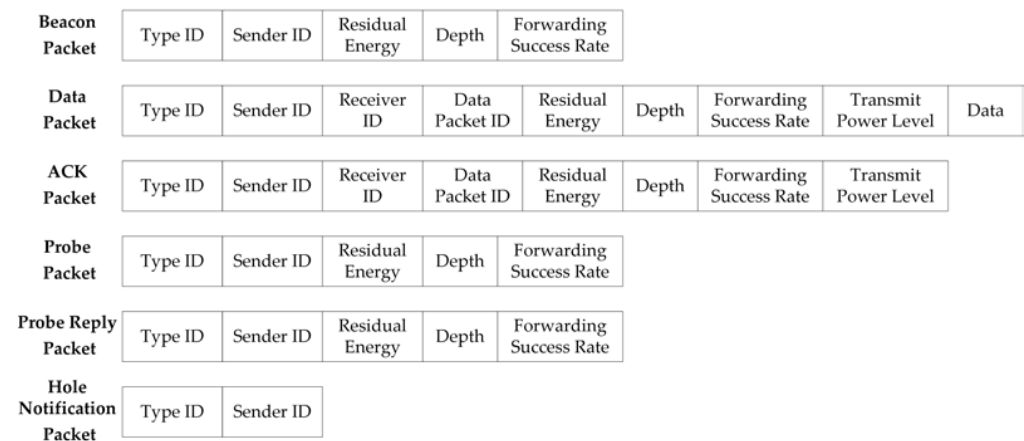


Figure 2. The structure of packets.

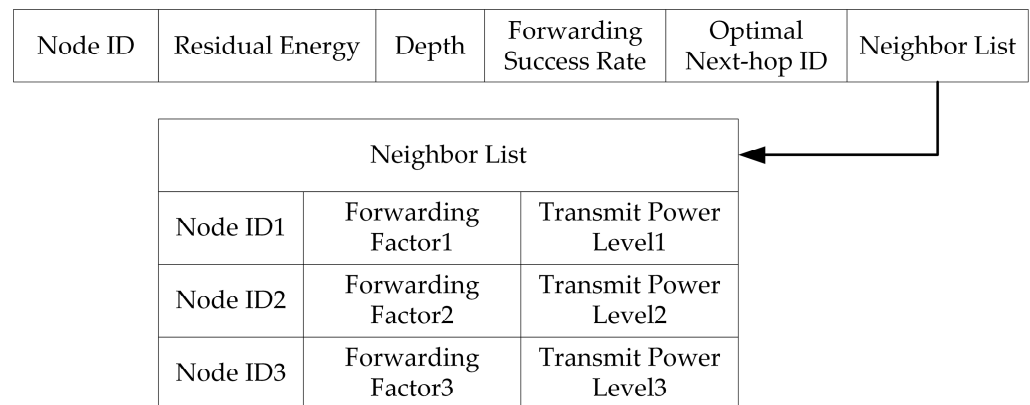


Figure 3. The structure of routing table.

c. The Detail of the Route Establishment Phase

In the route establishment phase, we apply receiver-side routing to establish the initial path by broadcasting the BEACON packet at the maximum transmitting power from the sink node. With the assistance of the forwarding factor, data transmission along this path achieves an optimal trade-off between energy efficiency and energy balance. The receiving node determines the suitability of the beacon sender as the next hop based on depth information. If it does not meet the criteria, the packet is directly discarded; Otherwise, the optimal transmitting power from the current node to the beacon sender is estimated using the recorded transmitting power and received signal strength in the packet. The forwarding factor is then calculated based on the remaining energy information of the current node and stored in the routing table. The neighbor node with the highest forwarding factor is selected as the optimal next hop. Subsequently, the current node generates a BEACON packet and broadcasts it. To prevent duplicate transmissions, a node only sends a BEACON packet once within a certain time period. The entire process of the route establishment phase is illustrated in Algorithm 1. It should be noted that in this study, the depth value of underwater was set to 0, and the depth value of water surface was set to 1500, with units in meters.

Figure 4 illustrates an example of route establishment. The sink node initiates the process by broadcasting the BEACON packet at the maximum transmitting power. The nodes (i.e., N2, N3, or N4) that receive the BEACON packet measure the received signal strength to determine the power level required from their respective positions to reach the sink node. Based on the information in the packet and the power level, they calculate the forwarding factor from their positions to the sink node and store it in their routing tables. Subsequently, each node updates the information in the BEACON packet and broadcasts it

at the maximum power. This process continues until the source node receives the BEACON packet. Nodes (i.e., N1 or N10) that do not receive the BEACON packet do not participate in the communication as they lack a suitable next-hop node.

Algorithm 1: Route establishment procedure

```

1:  $depth_{node} \leftarrow$  depth in routing table of the node
2:  $depth_{packet} \leftarrow$  depth in packet
3:  $T_{send} \leftarrow$  the time of the last broadcasted beacon packet on the node
4:  $T_{min} \leftarrow$  the minimum interval time between consecutive beacon packet broadcasts from the same node
5: procedure SendBeaconPacket
6:   SetBeaconPacket()
7:   broadcast packet
8: end procedure
9:
10: if node  $\in$  sink node then
11:   SendBeaconPacket()
12: end if
13:
14: recv(packet)
15: procedure BeaconPacketIn
16:   if  $depth_{packet} < depth_{node}$  then
17:     drop(packet)
18:   else
19:     UpdataRoutingTable()
20:     if  $nowTime - T_{send} \geq T_{min}$  then
21:       SendBeaconPacket()
22:     end if
23:   end if
24: end procedure

```

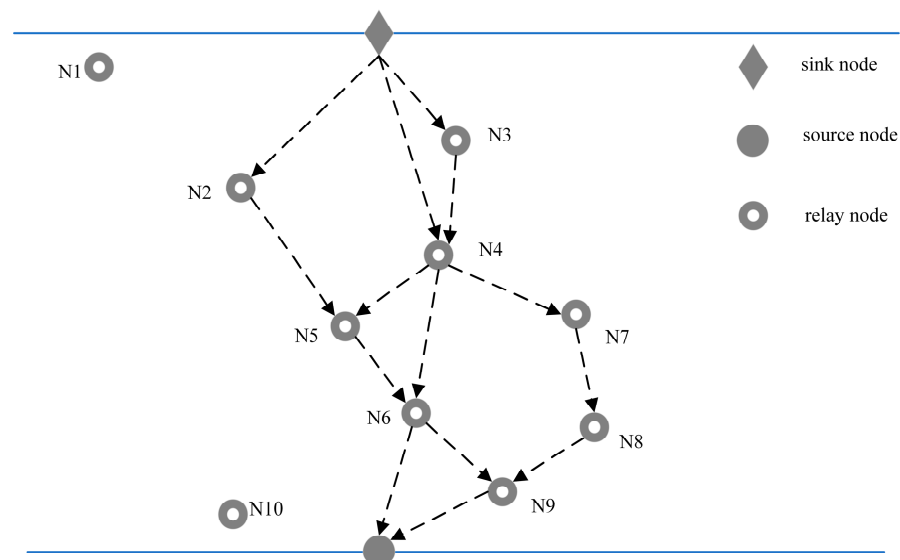


Figure 4. Route establishment example.

3.3.2. Data Transmission Phase

In this section, we first introduce the calculation method for the forwarding factor. We then describe the implicit routing update mechanism, followed by a detailed explanation of the data forwarding process.

a. Forwarding Factor Calculation

The forwarding factor will be used for selecting relay nodes, and the selection of relay nodes plays a crucial role in improving energy-efficient data transmission. In order to make the protocol address both energy reduction and energy balance, we propose a forwarding factor that comprehensively considers energy efficiency, node remaining energy, and the success rate of node forwarding, aiming to select the optimal next-hop node. Next, we will illustrate how to calculate the forwarding factor.

Let node A be the current node and node B be the neighboring node. The specific steps to calculate the forwarding factor from node A to node B are as follows:

Firstly, node A receives the packet (such as the BEACON packet) sent by node B and measures the received signal strength (R_{ss}) of the packet, Equation (6).

$$R_{ss} = 10 \log P_r \quad (6)$$

Here, P_r is the received signal power at node A. Let P_t be the power at which node B transmits the BEACON packet. The path loss between node A and node B, denoted as L_{AB} , can be represented as follows:

$$L_{AB} = \frac{P_t}{P_r} \quad (7)$$

The optimal transmitting power from node A to node B, denoted as P_{optAB} , can be calculated as:

$$P_{optAB} = L_{AB} P_{th} \quad (8)$$

Here, P_{th} represents the signal reception threshold in watts. The transmitting power level P_{ABL} for communication between node A and node B is determined by P_{optAB} , that is:

$$P_{ABL} \leftarrow P_{optAB} \quad (9)$$

The energy consumed when node A sends a data packet to node B can be calculated as follows:

$$E_{AB} = P_{ABL} \frac{L}{Ra} \quad (10)$$

It should be noted that node B also consumes energy when receiving data. However, since the receiving power of the node is much lower than the transmitting power, we can neglect this energy consumption when calculating the forwarding factor.

Let the normalized residual energy of node A be expressed as E_{re} , and the normalized energy efficiency from node A to node B be expressed as $E_{\eta AB}$. The forwarding factor from node A to node B is given by

$$f_{AB} = p_B (\alpha E_{\eta AB} + \beta E_{re}) \quad E_{re}, E_{\eta AB} \in (0, 1] \quad (11)$$

The above formula represents the calculation method of the forwarding factor, describing the specific quantification of the node forwarding success rate, energy efficiency, and remaining energy. In this formula, p_B denotes the forwarding success rate of node B, initially set to 1. After the node forwards a certain number of data packets, this value is updated to the ratio of successfully forwarded data packets to the total number of data packets the node attempted to forward. To balance the impact of energy efficiency and remaining energy, we introduce system parameters α and β , representing the weights for energy efficiency and remaining energy, respectively. These parameters are used to adjust the relative importance of the two metrics in the forwarding factor. To ensure the effectiveness of parameters α and β , and to guarantee that the forwarding factor reasonably considers the influence of both remaining energy and energy efficiency, we set their values within the range of 0 to 1, and they satisfy the condition $\alpha + \beta = 1$. In theory, a larger value of α leads to better energy efficiency for the routing. Conversely, a larger value of β results

in better energy balancing performance for the routing. The energy efficiency $E_{\eta AB}$ can be calculated using the following equation:

$$E_{\eta AB} = \frac{\Delta d_{AB}}{E_{AB}} \quad (12)$$

b. Implicit Routing Update Mechanism

Unlike traditional routing update mechanisms that rely on sending control packets specifically for updating the routing table, the implicit routing update mechanism places more emphasis on completing the routing update process while communicating between nodes, such as sending packets or other control packets. Upon receiving a data packet or control packet, the node first measures the signal strength and reads the information contained in the packet. It then proceeds to iterate through its neighbor list. If the sender of the packet is found in the neighbor list, the node updates the information associated with that particular neighbor. On the other hand, if the sender is not present in the neighbor list, the node evaluates whether the sender satisfies the criteria to become the next hop based on depth information. If the criteria are met, the node adds the sender's information to the neighbor table. If the criteria are not met, the node does not update the routing table. In this protocol, except for the HOLE packet, other packets can be used to update the routing table. The routing update process is outlined in Algorithm 2.

Algorithm 2: Implicit routing update mechanism

```

1:   $depth_{node} \leftarrow$  depth in routing table of the node
2:   $depth_{packet} \leftarrow$  depth in packet
3:   $senderID \leftarrow$  sender ID in packet
4:  procedure UpdataRoutingTable()
5:    calculate the forwarding factor according to Equation (11)
6:    calculate the transmitting power level according to Equation (9)
7:    update routing table
8:  end procedure
9:
10: procedure Hearing(packet)
11:   if  $senderID \in$  Neighbor list then
12:     UpdataRoutingTable()
13:   else
14:     if  $depth_{packet} \geq depth_{node}$  then
15:       UpdataRoutingTable()
16:     end if
17:   end if
18: end procedure

```

c. The Detail of Data Transmission Phase

During the data forwarding phase, nodes maintain a queue of pending acknowledgment packets denoted as Q for confirmation because it takes some time for a node to confirm whether a packet has been successfully transmitted after sending it. When a node sends a data packet, it simultaneously sets a timer T and adds the sent packet to Q. If, before the expiration of the timer T, the node detects the next-hop node forwarding the data packet or receives an ACK packet from the next-hop node, it indicates a successful transmission. The node then removes the packet from Q. Otherwise, if the node does not receive any confirmation within the specified time, it considers the data packet transmission to be unsuccessful and initiates the data protection mechanism, which will be discussed in Section 3.3.3.

When a node receives a data packet, it follows Algorithm 2 to update its routing table. Then, based on the depth information, the node determines the direction of the packet. If

the packet is from the upper direction (surface direction), the node traversal Q. If the packet is in Q, it indicates that the packet has been successfully transmitted, and the node removes it from Q.

If the data packet is from the lower direction, the node checks whether it is the intended destination based on the packet header information. If the node is not the destination, it discards the packet. If it is the destination, the node sets the neighbor node with the maximum forwarding factor in its routing table as the new next-hop node and adds the packet to Q. It then compares the optimal transmitting power level to the destination node with the previously recorded transmitting power level of the previous-hop node in the data packet. If the optimal transmitting power level is greater than or equal to the transmitting power level of the previous-hop node, it means that the previous-hop node can listen to the data packet forwarded by the current node, so the current node forwards the data packet directly. Otherwise, the current node sends an ACK packet to the previous-hop node to inform it that the data packet has been successfully received. The data forwarding process is described in Algorithm 3.

Algorithm 3: Data transmission phase

```

1:   $depth_{node} \leftarrow$  depth in routing table of the node
2:   $depth_{packet} \leftarrow$  depth in packet
3:   $receiverID \leftarrow$  receiver ID in packet
4:   $nodeID \leftarrow$  node ID in routing table
5:   $packetID \leftarrow$  packet ID in packet
6:   $Q \leftarrow$  the queue of pending acknowledgment packets in the node
7:   $recv(packet)$ 
8:  procedure DataTransmission()
9:    if  $depth_{packet} > depth_{node}$  then
10:     if  $packetID \in Q$  then
11:       Remove the packet from the queue
12:     end if
13:      $drop(packet)$ 
14:   else
15:     if  $nodeID == receiverID$  then
16:        $packet.receiverID = routingTable.optimalNextHopID$ 
17:       Update other information
18:        $SendPacket(packet)$ 
19:       Set timer T
20:     if  $newTransmitPowerLevel < oldTransmitPowerLevel$  then
21:        $ReplyACKPacket();$ 
22:     end if
23:   end if
24: end if
25: end procedure

```

Figure 5 illustrates an example of data forwarding. The source node sends a data packet and sets the next hop of the packet to node N5 based on the routing table. Upon receiving the data packet, node N5 only forwards the packet. Then, it adds the packet to Q, but does not send an ACK packet to the source node. This is because the power level used by node N5 for forwarding the packet is higher than the power level at which the source node sent the data packet. Consequently, the source node can directly monitor the data packet forwarded by N5, thereby confirming the successful transmission of the data packet, updating the information of N5 in the routing table and removing the packet from Q. On the other hand, when node N3 forwards the data packet, it needs to send an ACK packet to node N5. This is because the power level used by N3 for forwarding the packet is lower, and N5 cannot monitor the forwarded packet from N3. Additionally, since the sink node does not forward data packets underwater, it also needs to send an ACK packet. Node

N4 in the figure receives the data packet sent by N5, but since it determines that it is not the intended destination node, it discards the packet. At the same time, N4 also receives the data packet and ACK packet sent by N3, and updates the routing table based on the information in the packets and the signal strength.

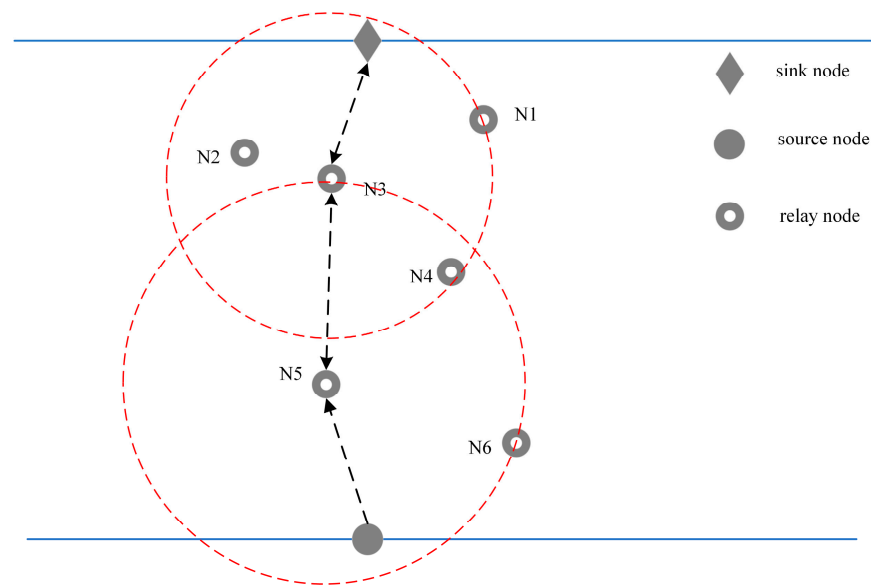


Figure 5. Data forwarding example.

3.3.3. Data Protection and Route Reconstruction Mechanism

Due to the mobility of nodes, data packet forwarding may experience interruptions. To address this situation, we employ a localized–globalized integrated strategy to ensure effective network communication.

Localized Recovery: Due to node mobility, the optimal next-hop relay for data packet forwarding may change its position before receiving the packet, resulting in a failure to forward the packet.

When a transmission fails, the node sends a PROBE packet at maximum power. The nodes that receive the PROBE packet will determine if they meet the criteria to become the next hop. If they meet the criteria, then it will reply with a PROBE REPLY packet at maximum power. Upon receiving the PROBE REPLY packet, the node calculates the forwarding factor and updates the routing table. To reduce the propagation delay, the node immediately forwards the failed DATA packet upon receiving the first PROBE REPLY packet. Subsequent DATA packets are forwarded based on the routing table. Figure 6 presents an example of localized recovery. Node N1 forwards Data packets to N2 with power level p_n . However, N2 has moved out of the communication range at power level p_n , resulting in a transmission failure. Consequently, N1 triggers the Localized Recovery mechanism and sends a PROBE packet at maximum power. Nodes N2, N3, and N4 all receive the PROBE packet. Among them, N4 is located at a depth greater than N1, so it does not send PROBE REPLY packets to N1 but updates its routing table based on the information in the PROBE packet. Both N2 and N3 send PROBE REPLY packets to N1, and N1 updates its routing table accordingly. Since the PROBE REPLY packet from N2 arrives at N1 first, N1 forwards the data to N2 using the newly calculated power level.

Additionally, if the probability of a node successfully forwarding a data packet is low, i.e., when p is below a certain threshold, the node needs to send a Probe Packet to update the routing table before forwarding the data packet. If the node does not receive a Probe reply packet, it sets itself as a hole node and sends a Hole Notification packet to request the nodes that receive it to remove itself from their neighbor tables.

Global Recovery: The sink node determines whether to trigger the global recovery mechanism based on the packet reception rate over a certain period of time.

Global recovery refers to the process of route reconstruction, similar to the routing establishment phase described earlier. Due to node mobility, the network topology undergoes changes, and the sink nodes need to assess the impact of these changes and decide whether to trigger the global recovery mechanism. The specific procedure involves the sharing of received data packets among all sink nodes. Within a time period T , the total number of non-repetitive data packets received is recorded and compared with the total number of data packets sent by the source nodes during the same time period. If the ratio falls below a predefined threshold, the global recovery mechanism is triggered.

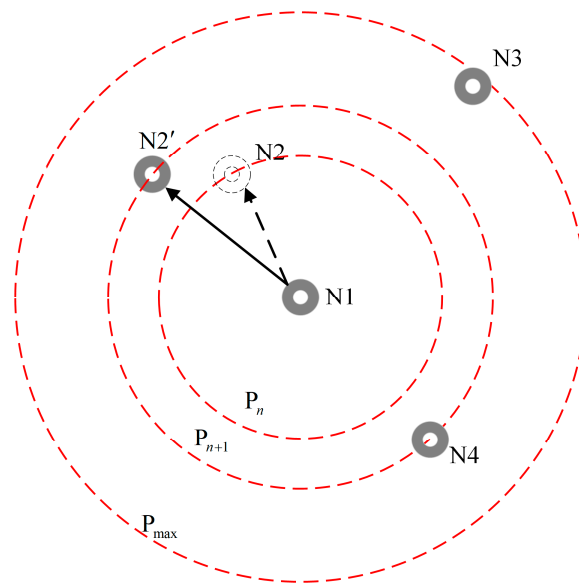


Figure 6. Localized recovery example.

4. Theoretical Analysis and Experimental Results

In this section, we will evaluate the performance of the proposed routing protocol APCDBRP and compare it with several existing protocols, including DBR [6], EEDBR [7], and EAVARP [14]. We will implement our protocol and the comparative protocols using AquaSim–Next Generation [26], which is a simulator for underwater sensor networks based on NS3 [27] and its libraries. We have made modifications to the physical layer design in AquaSim–Next Generation to enable dynamic adjustment of the transmission power for each packet.

4.1. Theoretical Analysis

The main purpose of the proposed protocol is to reduce energy consumption through a power control mechanism and balance energy consumption by considering residual energy information. The rationale behind the power control mechanism's ability to reduce energy consumption can be primarily attributed to two aspects. Firstly, in an underwater acoustic network, the distance between each pair of connected nodes is not always equal to the maximum transmission distance of the acoustic signal. Consequently, there exists some redundancy in the transmission power of the nodes, which can be reduced through the implementation of the power control mechanism. This point is relatively straightforward to comprehend. Secondly, the power control mechanism enables the decomposition of long-distance single-hop transmissions into multiple short-distance hops. It is well known from reference [17] that multi-hop transmission can effectively reduce energy consumption. However, the article does not provide formal proof for this claim. In [18], the authors conducted an analysis of the scenario with only one relay node and demonstrated that under certain conditions, multi-hop transmission is more energy efficient than single-hop transmission. However, in practical scenarios, there is typically more than one relay node involved in data forwarding. Therefore, in the subsequent investigation, we will consider

the more general scenario where multiple nodes participate in relaying. We will analyze the effectiveness of the power control mechanism in reducing energy consumption, thereby demonstrating the effectiveness of our designed routing protocol.

Case 1: When the relay node is deployed on the straight line between the source and the destination.

When there is only one relay node, we can find the energy consumption for this scenario in [18] as follows:

$$E_{1_node} = \frac{LP_0}{Ra} (d_{SR_1}^k a(f)^{d_{SR_1}} + d_{R_1D}^k a(f)^{d_{R_1D}}) \quad (13)$$

Here, E_{1_node} represents the total energy consumption in the case of one relay node. The energy consumption of direct transmission is:

$$E_{direct} = \frac{LP_0 d_{SD}^k a(f)^{d_{SD}}}{Ra} \quad (14)$$

Among them, P_0 is calculated by Equation (4). Since the receiving power and idle power are much smaller than the transmitting power, we neglect them here. The authors in [18] have already demonstrated that when the relay node is not located at the source or destination node, i.e., when it is positioned between the source and destination nodes, we have the following relationship:

$$E_{1_node} < E_{direct} \quad (15)$$

As is shown in Figure 7, when there are n relay nodes, the energy consumption can be represented as:

$$E_{n_node} = \frac{LP_0}{Ra} (d_{SR_1}^k a(f)^{d_{SR_1}} + d_{R_1R_2}^k a(f)^{d_{R_1R_2}} + \dots + d_{R_{n-1}R_n}^k a(f)^{d_{R_{n-1}R_n}} + d_{R_nD}^k a(f)^{d_{R_nD}}) \quad (16)$$

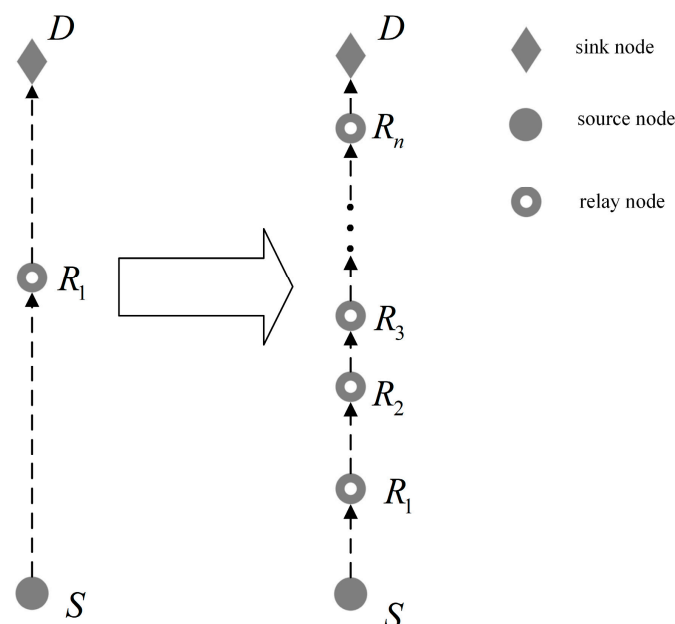


Figure 7. Example of Multi-hop Transmission with n Relay Nodes.

In this case, there are multiple variables in E_{n_node} , and a direct derivation would be quite complex. Therefore, we can use mathematical induction to prove that $E_{n_node} < E_{direct}$.

We have already established that when $n = 1$, we have $E_{direct} > E_{1_node}$, i.e., $E_{direct} > E_{SR_1} + E_{R_1D}$, E_{SR_1} and E_{R_1D} represent the communication energy consumption between node S and R_1 , and between R_1 and D , respectively;

When $n = 2$, as is shown in Figure 8, we can consider node R_2 as a relay node between nodes R_1 and D . In this case, there is only one relay node between R_1 and D . Therefore, we have $E_{R_1D} > E_{R_1R_2} + E_{R_2D}$, and combined with $E_{direct} > E_{SR_1} + E_{R_1D}$, we obtain $E_{direct} > E_{SR_1} + E_{R_1R_2} + E_{R_2D}$, i.e., $E_{direct} > E_{2_node}$;

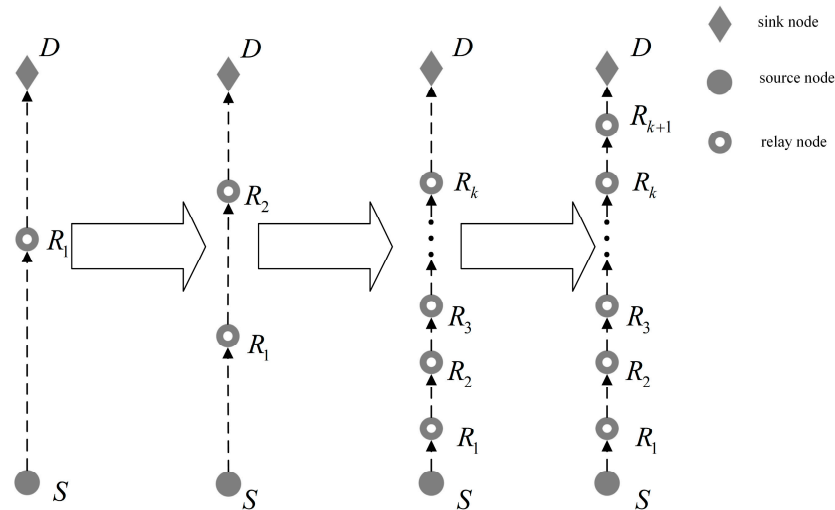


Figure 8. Example of Multi-hop Transmission with $k + 1$ Relay Nodes.

Assuming that when $n = k, k \geq 2$, $E_{direct} > E_{k_node}$ holds, i.e., $E_{direct} > E_{SR_1} + E_{R_1R_2} + \dots + E_{R_kD}$;

Then, when $n = k + 1$, as node R_{k+1} can be regarded as a relay node between R_k and D (similarly when R_{k+1} is positioned between other nodes), we have $E_{R_kD} > E_{R_kR_{k+1}} + E_{R_{k+1}D}$. Consequently, we have:

$$E_{SR_1} + E_{R_1R_2} + \dots + E_{R_kD} > E_{SR_1} + E_{R_1R_2} + \dots + E_{R_kR_{k+1}} + E_{R_{k+1}D}$$

which implies $E_{direct} > E_{k+1_node}$. Thus, we have shown that $E_{direct} > E_{n_node}$ holds.

Case 2: When the relay node is positioned between the source node and the destination node but not directly on the line connecting the source and destination nodes.

According to the analysis carried out by the authors in [18] regarding the scenario with only one relay node, we can conclude that when $d_{SR_1}^k a(f)^{d_{SR_1}} + d_{R_1R_2}^k a(f)^{d_{R_1R_2}} + \dots + d_{R_nD}^k a(f)^{d_{R_nD}} > d_{SD}^k a(f)^{d_{SD}}$ is satisfied, multi-hop transmission will no longer be energy efficient.

In fact, due to nodes having only the information regarding the next hop and not the information regarding all nodes along the entire path, nodes can only choose the next-hop nodes with higher energy efficiency to forward data and maximize energy utilization. Meanwhile, they also need to consider the forwarding success rate and remaining energy of the next-hop nodes.

4.2. Experimental Settings

In our network scenario, each node has a maximum transmission power of 10 W. The area is fixed at $1.5 \times 1.5 \times 1.5 \text{ km}^3$. During network initialization, the sink node is positioned at a specific location on the water surface, while the source nodes are fixed at the bottom of the water. The relay nodes are uniformly and randomly distributed throughout the area, and they should satisfy the condition of having approximately equal numbers of nodes within every 100 m of depth (it should be noted that due to the randomness in node distribution, each data point in this paper represents the average of 30 experiments.) Subsequently, the routing initialization is performed by the sink node (refer to Algorithm 1 in the paper). After the initialization is completed, and the network enters the data forwarding phase, where source nodes are responsible for sensing data and sending data

packets every 40 s. These are then relayed by the relay nodes to the sink node. To cope with network drift, we employ a localized–globalized integrated strategy (see Section 3.3.3). In this process, if a certain relay node fails to forward data, it triggers the Localized Recovery mechanism to reconstruct its own routing table. Furthermore, if the sink node receives a number of packets below the set threshold within a time interval T , it triggers the Global Recovery mechanism, where the sink node sends beacon packets to reconstruct the network routes.

Regarding the models used in the simulation, the underlying models are all default models in AquaSim-ng. Specifically, the underwater acoustic channel follows the model described in reference [22], and the energy model aligns with Equation (5). The detailed parameter settings are shown in Table 1.

Table 1. Simulation settings.

Parameter	Value
Data Rate	10 kbps
Frequency	25 kHz
Node Number	100–500
Deployment Region	3D region of $1.5 \times 1.5 \times 1.5$ (length $\times$ breadth $\times$ depth) km^3
Communication Radius	Maximum coverage 500 m
Initial Position of Sink Node (take the bottom depth value as zero)	(500, 500, 1500), (1000, 500, 1500), (500, 1000, 1500), (1000, 1000, 1500), (750, 750, 1500)
Initial Position of Source Node	(750, 750, 0)
Initial Energy of Sink Node and Source Node	1000 J
Initial Energy of Relay Node	150 J
Payload of Data	50 Bytes
Data Packet Interval	40 s
Transmitting Power	1–10 W
Energy Model	ns3::AquaSimEnergyModel (RX: 0.1 W, Idle: 1 mW)
Node Speed	0–3 m/s
Mobility Model	ns3::RandomWalk2dMobilityModel
MAC Model	ns3::AquaSimBroadcastMac
Physical Layer Model	ns3::AquaSimPhyCmn
Channel Model	ns3::AquaSimChannel
Propagation Model	ns3::AquaSimRangePropagation
Noise Model	ns3::AquaSimConstNoiseGen

4.3. Performance Metrics

Network lifetime: In this paper, we characterize the network lifetime by the number of transmission rounds of the source node when any relay node runs out of energy.

Energy consumption: The energy consumption of each node can be expressed by subtracting the remaining energy of the node at the end of the simulation from the initial total energy of each node; the sum of these is the energy consumption of the network. It can be expressed as:

$$E_{con} = \sum_{i=1}^n (E_{nodei_initial} - E_{nodei_re}) \quad (17)$$

Here, $E_{nodei_initial}$ represents the initial energy of node i , and E_{nodei_re} represents the remaining energy of node i at the end of the simulation.

The average end-to-end delay: For the end-to-end delay of data packets from the source node to the sink node, when receiving duplicate packets, only the earliest one will be considered. It can be expressed as:

$$\bar{t} = \frac{\sum_{i=1}^N (T_{i_recv} - T_{i_send})}{N} \quad (18)$$

Here, N represents the total number of data packets received by the sink node. T_{i_send} represents the time when the source node sends the i -th data packet, which is written into the packet header by the source node at the time of sending. T_{i_recv} represents the time when the sink node receives the data packet.

Packet Delivery Ratio (PDR): The ratio of the total number of data packets received by the sink node to the total number of data packets sent by the source node, considering duplicate packets only once.

4.4. Results and Analysis

In this section, we will first discuss the impact of system parameter variations on network performance. We will then compare APCDBRP with other protocols and analyze the experimental results.

4.4.1. Influence of System Parameter Variations on Network Performance

In our network, the variation in parameters α and β in Equation (11) will impact the performance of the network. In the following study, we investigated the effects of changing α and β on the end-to-end delay, energy consumption, and network lifetime in a static network structure consisting of 500 nodes.

Figures 9–11 illustrate the impact of varying parameter α on network performance. Overall, both energy consumption and network lifetime decrease as α increases, while end-to-end delay initially decreases and then increases with the increase in α . This is because α represents the weight of energy efficiency, and β represents the weight of remaining energy, and they satisfy the condition $\alpha + \beta = 1$. Therefore, when α is small and β is large, nodes in the network primarily select the next hop based on remaining energy. As a result, although energy consumption and end-to-end delay are relatively high, the network lifetime is longer. As α increases, the weight of remaining energy β decreases. Therefore, as energy consumption decreases, the network lifetime gradually decreases as well. According to Equation (12), energy efficiency is the ratio of the depth difference between two nodes and the consumed energy. On one hand, when the distance between nodes is the same, a larger angle between the connecting line and the horizontal line indicates a greater depth difference and higher energy efficiency. This results in a shorter propagation distance of packets reaching the surface, leading to a decrease in end-to-end delay with the increase in α . On the other hand, the power control mechanism that segments long-distance transmission into short-distance transmission reduces energy consumption. However, it introduces a certain path delay and node data processing delay. Therefore, when α is large, the end-to-end delay will experience fluctuations.

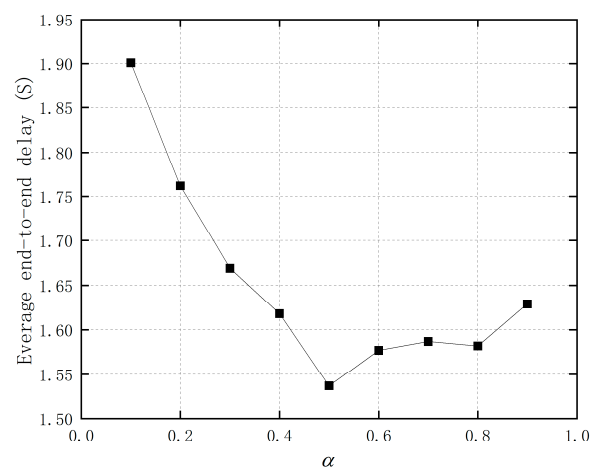


Figure 9. The influence of α on the average end-to-end delay.

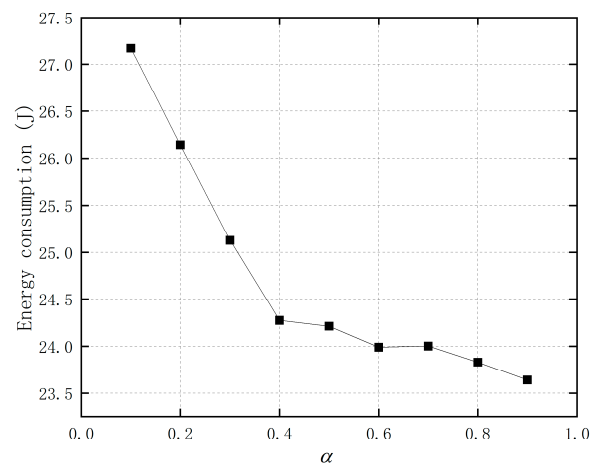


Figure 10. The influence of α on the total energy consumption.

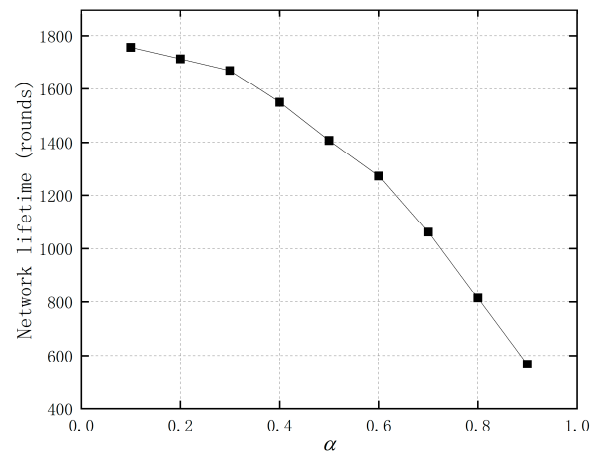


Figure 11. The influence of α on the network lifetime.

4.4.2. Influence of the Node Number on the Average End-to-End Delay

The variation in end-to-end delay with different node numbers is depicted in Figure 12. From the graph, it can be observed that the end-to-end delay of all protocols is highest when the node number is 100. This is because the network density is low at this point, resulting in fewer available next-hop nodes and possibly unfavorable positions, leading to increased delay. Due to the energy-saving nature of the proposed APCDBRP, it introduces an increase in packet hops to some extent, resulting in a slight increase in end-to-end delay.

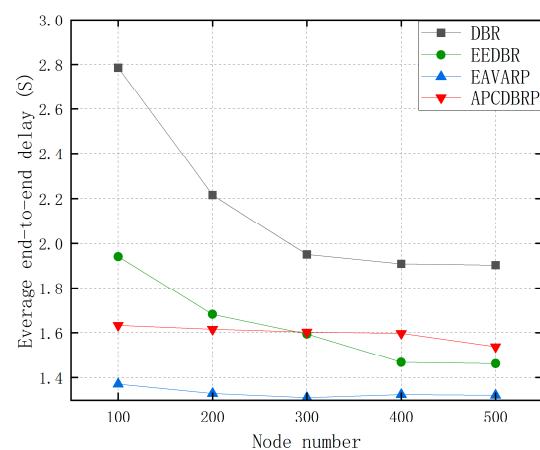


Figure 12. The influence of the node number on the average end-to-end delay.

4.4.3. Influence of the Node Number on Energy Consumption

Figure 13 shows the variation in energy consumption with different numbers of nodes. Due to the fact that nodes consume energy, even in an idle state, the total energy consumption of all protocols increases with an increase in the number of nodes. Specifically, DBR and EEDBR are both multi-route routing protocols, resulting in higher energy consumption. However, EEDBR selects a limited number of forwarding nodes based on neighbor information, leading to lower energy consumption compared to DBR. EAVARP and the proposed APCDBRP are both single-route routing protocols. However, EAVARP requires the constant broadcasting of beacon packets to update routing information, resulting in higher energy consumption in denser node deployments. On the other hand, APCDBRP incorporates power control mechanisms and implicit route update mechanisms, while considering energy efficiency in selecting the next hop. As a result, APCDBRP achieves lower energy consumption compared with other routing protocols.

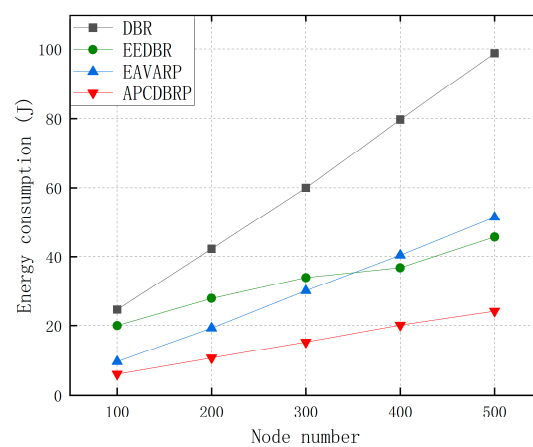


Figure 13. The influence of the node number on the total energy consumption.

4.4.4. Influence of the Node Number on Network Lifetime

Figure 14 shows the impact of the number of nodes on network lifetime. From the graph, it can be observed that when the network adopts DBR, the network lifetime is not sensitive to changes in the number of nodes. This is because as the number of nodes increases, there is an increase in redundant data packets within the network. For networks employing EEDBR and EAVARP, the network lifetime initially increases with an increase in the number of nodes and then levels off. This is due to the fact that as the number of nodes increases, there are more paths from source nodes to sink nodes. However, the presence of redundant data packets or additional control packets results in higher energy consumption. Since APCDBRP exhibits lower energy consumption, it achieves the highest network lifetime.

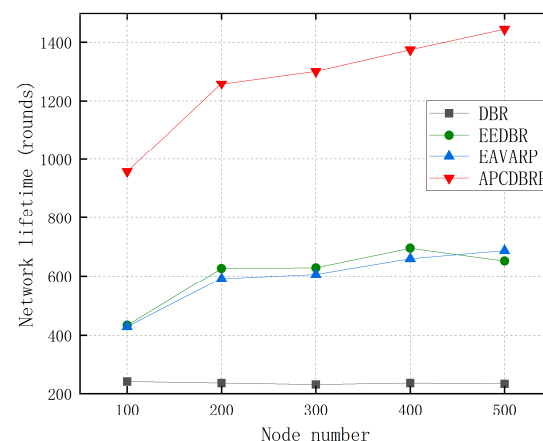


Figure 14. The influence of the node number on network lifetime.

4.4.5. Influence of the Node Speed on Network Performance

Due to the influence of water flow, nodes are subject to movement within a certain range, resulting in dynamic changes in the network structure. To address this issue, we propose a localized–globalized integrated strategy. In this section, we will examine the changes in network performance as the flow velocity increases. Furthermore, we will discuss the advantages and additional overhead introduced by the strategy.

As is shown in Figure 15, when the node speed is low, all protocols exhibit high packet delivery rates. However, as the node speed increases, DBR and EEDBR, which involve a significant amount of redundancy in data transmission, can still ensure packet delivery to the destination node, even if some packets are dropped. However, this comes at the cost of higher energy consumption. In networks using EEDBR, as the node speed increases, the PDR decreases. This is because, compared to DBR, EEDBR limits the number of forwarding nodes. In the case of EAVARP, which employs single-route routing, the PDR significantly decreases with higher node speeds. On the other hand, APCDBRP, which also uses single-route routing, achieves a high PDR due to its localized–globalized integrated strategy. This demonstrates the effectiveness of our proposed strategy in data protection and network recovery.

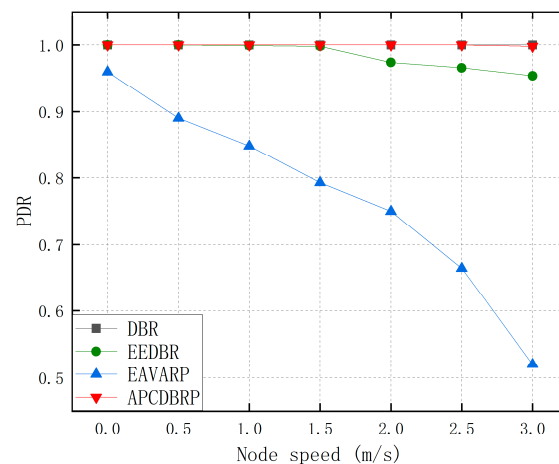


Figure 15. Influence of the node speed on PDR.

The effects of node speed on network end-to-end delay and energy consumption are shown in Figures 16 and 17. In terms of end-to-end delay, DBR and EAVARP are largely unaffected by changes in node speed. However, EEDBR and APCDBRP experience increased end-to-end delay as node speed increases. For EEDBR, this is because the protocol optimizes the packet holding time based on node priority and sets the packet holding time to zero for the best next-hop node. As a result, as node speed increases, the probability of successful forwarding by the best next-hop node and higher-priority nodes decreases, leading to increased end-to-end delay. In the case of APCDBRP, as node speed increases, the probability of successful packet forwarding decreases. When packet forwarding fails, the data protection mechanism is triggered, resulting in packet retransmissions and, consequently, increased end-to-end delay.

Regarding energy consumption, the presented values represent the average energy consumed per successfully delivered packet. EAVARP exhibits higher energy consumption when node speed is high due to lower packet delivery rates. APCDBRP, with its localized–globalized integrated strategy, experiences increased energy consumption as node speed increases. This is because, at higher node speeds, APCDBRP not only retransmits packets in case of forwarding failures but also sends beacon packets to rebuild routes when the sink node detects a decrease in the number of received packets. However, overall, APCDBRP achieves low energy consumption while maintaining a high packet delivery rate.

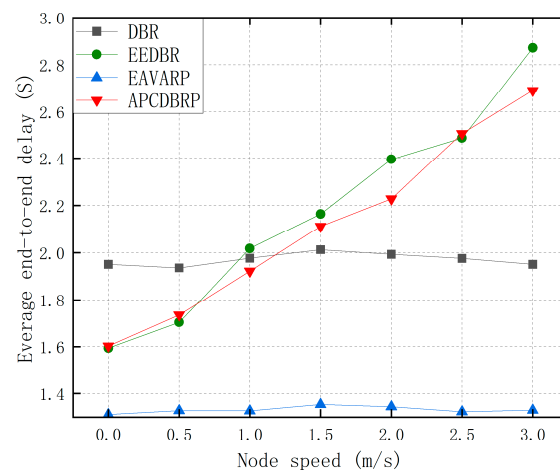


Figure 16. Influence of the node speed on the average end-to-end delay.

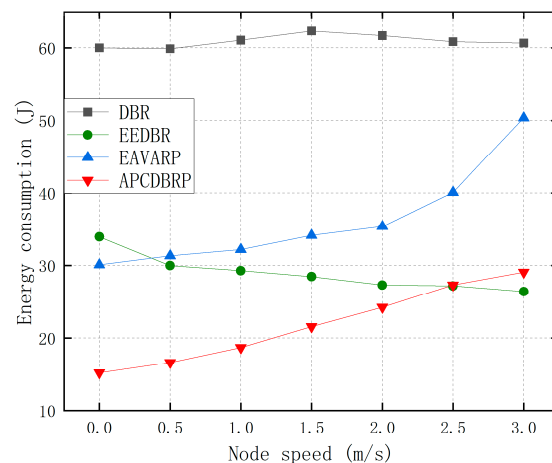


Figure 17. Influence of the node speed on the total energy consumption.

5. Conclusions and Future Work

To address the issues of high energy consumption and short network lifetime in underwater sensor networks, this paper proposed an adaptive power-controlled depth-based routing protocol (APCDBRP). In terms of power control, the protocol estimates the path loss based on the received signal strength and adjusts the transmission power accordingly. In the selection of the next hop, the forwarding factor takes into account various factors such as the transmission power, depth difference, and remaining energy to optimize energy efficiency and energy balance. It selects the next hop node with high energy efficiency and relatively sufficient energy. In order to cope with the mobility of nodes caused by water flow, we adopted an implicit routing update mechanism during the data forwarding phase to address network topology changes resulting from node mobility at a low cost. Additionally, we proposed a data protection and route reconstruction mechanism to handle potential data forwarding failures and routing voids that may occur due to network topology changes.

Simulation results demonstrated that APCDBRP outperforms existing typical protocols in terms of network lifespan, energy consumption, and packet delivery ratio. However, it is worth noting that the power control and data protection mechanisms of APCDBRP introduce a certain end-to-end delay. Therefore, APCDBRP is suitable for systems that are not sensitive to latency but require a long network lifespan, such as underwater pollution monitoring and device monitoring applications with lower real-time requirements.

The current research on routing protocols for underwater wireless sensor networks has made some progress, but further studies still need to be carried out and further improved

due to the limitations of time, funds, and experimental conditions. For the continued research on underwater acoustic sensor networks, we believe that there are still new areas to be explored. For example, with the development of devices, underwater nodes have gradually gained the ability to harvest energy underwater, so the protocol design needs to consider the energy allocation problem of nodes with certain charging capabilities.

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References

1. Akyildiz, I.F.; Pompili, D.; Melodia, T. Underwater acoustic sensor networks: Research challenges. *Ad Hoc Netw.* **2005**, *3*, 257–279. [\[CrossRef\]](#)
2. Wang, Q.; Li, J.; Qi, Q.; Zhou, P.; Wu, D.O. A game theoretic routing protocol for 3D underwater acoustic sensor networks. *IEEE Internet Things J.* **2020**, *7*, 9846–9857. [\[CrossRef\]](#)
3. Heidemann, J.; Ye, W.; Wills, J.; Syed, A.; Li, Y. Research challenges and applications for underwater sensor networking. In Proceedings of the IEEE Wireless Communications & Networking Conference, Las Vegas, NV, USA, 3–6 April 2006.
4. Coutinho, R.W.; Boukerche, A.; Vieira, L.F.; Loureiro, A.A. Geographic and opportunistic routing for underwater sensor networks. *IEEE Trans. Comput.* **2015**, *65*, 548–561. [\[CrossRef\]](#)
5. Yu, H.; Yao, N.; Liu, J. An adaptive routing protocol in underwater sparse acoustic sensor networks. *Ad Hoc Netw.* **2015**, *34*, 121–143. [\[CrossRef\]](#)
6. Yan, H.; Shi, Z.J.; Cui, J.H. DBR: Depth-based routing for underwater sensor networks. In Proceedings of the NETWORKING 2008 Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet: 7th International IFIP-TC6 Networking Conference, Singapore, 5–9 May 2008; pp. 72–86.
7. Wahid, A.; Lee, S.; Jeong, H.J.; Kim, D. EEDBR: Energy-efficient Depth-based Routing Protocol for Underwater Wireless Sensor Networks. In Proceedings of the International Conference on Advanced Computer Science and Information Technology, Seoul, Republic of Korea, 27–29 September 2011; pp. 223–234.
8. Khizar, M.; Wahid, A.; Pervaiz, K.; Sajid, M.; Qasim, U.; Khan, Z.A.; Javaid, N. Enhanced energy efficient depth based routing protocol for underwater WSNs. In Proceedings of the 10th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS), Fukuoka, Japan, 6–8 July 2016; pp. 70–77.
9. Kumar, R.; Bhardwaj, D.; Mishra, M.K. EBH-DBR: Energy-balanced hybrid depth-based routing protocol for underwater wireless sensor networks. *Mod. Phys. Lett. B* **2021**, *35*, 2150061. [\[CrossRef\]](#)
10. Farooq, U.; Ullah, M.; Khan, R.U.; Alharbi, A.; Uddin, M.I.; Haq, M.I.; Alosaimi, W. IDBR: IoT Enabled Depth Base Routing Method for Underwater Wireless Sensor Network. *J. Sens.* **2021**, *2021*, 7777181. [\[CrossRef\]](#)
11. Zhu, J.; Du, X.; Han, D.; Wang, L.; Li, M. LEER: Layer-based and energy-efficient routing protocol for underwater sensor networks. In Proceedings of the 11th EAI International Conference, ADHOCNETS 2019, Queenstown, New Zealand, 18–21 November 2019; pp. 26–39.
12. Guan, Q.; Ji, F.; Liu, Y.; Yu, H.; Chen, W. Distance-vector-based opportunistic routing for underwater acoustic sensor networks. *IEEE Internet Things J.* **2019**, *6*, 3831–3839. [\[CrossRef\]](#)
13. Liu, Z.; Jin, X.; Yang, Y.; Ma, K.; Guan, X. Energy-efficient guiding-network-based routing for underwater wireless sensor networks. *IEEE Internet Things J.* **2022**, *9*, 21702–21711. [\[CrossRef\]](#)
14. Wang, Z.; Han, G.; Qin, H.; Zhang, S.; Sui, Y. An energy-aware and void-avoidable routing protocol for underwater sensor networks. *IEEE Access* **2018**, *6*, 7792–7801. [\[CrossRef\]](#)
15. Xu, Y.; Liu, Z.; Huang, C.; Yuen, C. Robust resource allocation algorithm for energy-harvesting-based D2D communication underlaying UAV-assisted networks. *IEEE Internet Things J.* **2021**, *8*, 17161–17171. [\[CrossRef\]](#)
16. Coutinho, R.W.; Boukerche, A.; Vieira, L.F.; Loureiro, A.A. Underwater wireless sensor networks: A new challenge for topology control-based systems. *ACM Comput. Surv.* **2018**, *51*, 1–36. [\[CrossRef\]](#)

17. Alablani, I.A.; Arafah, M.A. EE-UWSNs: A joint energy-efficient MAC and routing protocol for underwater sensor networks. *J. Mar. Sci. Eng.* **2022**, *10*, 488. [[CrossRef](#)]
18. Wang, H.; Wang, S.; Zhang, E.; Lu, L. An energy balanced and lifetime extended routing protocol for underwater sensor networks. *Sensors* **2018**, *18*, 1596. [[CrossRef](#)] [[PubMed](#)]
19. Ahmed, G.; Islam, S.; Ali, I.; Hayder, I.A.; Ahmed AI, A.; Talha, M.; Alshamrani, S.S.; Ibrahim, A.A.A. Adaptive power control aware depth routing in underwater sensor networks. *CMC Comput. Mater. Contin.* **2021**, *69*, 1301–1322. [[CrossRef](#)]
20. Luo, J.; Chen, Y.; Wu, M.; Yang, Y. A survey of routing protocols for underwater wireless sensor networks. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 137–160. [[CrossRef](#)]
21. Ismail, A.S.; Wang, X.; Hawbani, A.; Alsamhi, S.; Abdel Aziz, S. Routing protocols classification for underwater wireless sensor networks based on localization and mobility. *Wirel. Netw.* **2022**, *28*, 797–826. [[CrossRef](#)]
22. Urick, R.J. *Principles of Underwater Sound for Engineers*; Tata McGraw-Hill Education: New York, NY, USA, 1967.
23. Brekhovskikh, L.M.; Beyer, A.R.T. Fundamentals of Ocean Acoustics. *J. Acoust. Soc. Am.* **1991**, *90*, 3382–3383. [[CrossRef](#)]
24. Wenz, G.M. Acoustic ambient noise in the ocean: Spectra and sources. *J. Acoust. Soc. Am.* **1962**, *34*, 1936–1956. [[CrossRef](#)]
25. Stojanovic, M. On the relationship between capacity and distance in an underwater acoustic communication channel. In Proceedings of the 1st ACM International Workshop on Underwater Networks, Los Angeles, CA, USA, 25–26 September 2006; pp. 41–47.
26. Martin, R.; Zhu, Y.; Pu, L.; Dou, F.; Peng, Z.; Cui, J.H.; Rajasekaran, S. Aqua-sim next generation: A NS-3 based simulator for underwater sensor networks. In Proceedings of the 10th International Conference on Underwater Networks & Systems, Washington, DC, USA; 2015; p. 18.
27. Riley, G.F.; Henderson, T.R. The ns-3 network simulator. In *Modeling and Tools for Network Simulation*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 15–34.

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