Multimodal Acoustic-RF Adaptive Routing Protocols for Underwater Wireless Sensor Networks

HANJIANG LUO1, (Member, IEEE), XIUMEI XIE1, GUANGJIE HAN2,5, (Senior Member, IEEE) RUKHSANA RUBY3, (Member, IEEE), HONG FENG4, (MEMBER, IEEE), AND YONGQUAN LIANG1

1School of Computer Science & Engineering, Shandong University of Science and Technology, Qingdao, China (e-mail: [hjl, xxm, lyc]@sdust.edu.cn)
2Department of Information and Communication Systems, Hohai University, Changzhou, China (e-mail: hanguangjie@gmail.com)
3Department of Computer Science, Ocean University of China, Qingdao, China (e-mail: longfeng@ouc.edu.cn)
4Department of Computer Science, Shenzhen University, Shenzhen, China (e-mail: hanguangjie@gmail.com)
5State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences, Beijing, China (e-mail: hanguangjie@gmail.com)

Corresponding authors: Hanjiang Luo (hjlueo@sdust.edu.cn) and Guangjie Han (hanguangjie@gmail.com)

ABSTRACT In multi-function underwater wireless sensor networks (UWSNs), multiple applications share the same physical infrastructure to fully exploit network resources. Under such scenarios, diverse packets coexist in the same network which require differentiated delivery strategies to satisfy application demands, such as ocean monitoring packets and multimedia-based intrusion detection packets (e.g., video streams, voice or images) demand versatile support for data forwarding operation. However, the limited bandwidth and high propagation delay of acoustic channel pose great challenges to satisfy such demands. A feasible solution to solve such a problem is to exploit multimodal networks which integrate complementary acoustic and non-acoustic technologies to enhance transmission capability. Therefore, in this paper, we leverage both surface wireless radio frequency (RF) and underwater acoustic technology to fulfill different performance requirements of underwater sensor networks. We first propose two multimodal acoustic-RF adaptive routing schemes, and identify the major factors which influence the performance of these adaptive protocols. Then, we conduct extensive evaluations of the algorithms for both grid and random deployment scenarios. The simulation results confirm the feasibility of the proposed multimodal acoustic-RF routing protocols under diverse communication scenarios and channels.

INDEX TERMS Underwater acoustic networks, routing, ocean sensor networks, surveillance networks

I. INTRODUCTION

As humans have only explored 5% of the ocean which covers nearly two-thirds of our earth’s surface, UWSNs are considered as a promising technology to help humans explore the ocean further [1]–[3]. Via UWSNs, we can monitor the ocean environment and marine assets, conduct commercial exploitation, protect harbour, prevent disaster, perform military surveillance and so on [4], [5]. To further improve the utilization efficiency of network resources, one network can support multiple applications by sharing the same network infrastructure. For example, ocean monitoring and intrusion detection can share the same hardware infrastructure. Under such scenarios, the packets generated from different applications may have diverse delivery requirements of quality of service (QoS). Furthermore, multimedia data of tactical surveillance application (e.g., intrusion detection images, voice and even video streams) is expected to advance network utilities significantly.

However, it poses great challenges to leverage acoustic technology alone to satisfy diverse data transmission requirements of multiple multimedia-based applications. First, acoustic technology has a higher transmission delay compared to the radio frequency one because of its slow propagation speed, which is $1.5 \times 10^3 \text{m/s}$. Second, acoustic channel has a roughly $40 \text{km} \times \text{kbps}$ bandwidth capacity, which makes multimedia data transmission a challenging task with such a lower-order of $\text{kbps}$ bandwidth. Third, the bulky, costly and power-hungry acoustic communication devices are prone to failures in the ocean, and the complex acoustic channel has high bit error rate (BER) affected by multipath and fading.
To address the aforementioned challenges, we present a novel approach to integrate two types of communication channels, i.e., surface RF and underwater acoustic channel, to improve routing reliability and adaptability. Our initial work was in [9], and in this paper we extended it further to both grid-based and random deployment scenarios, and provide two routing algorithms to meet diverse routing demands for different types of data packets. As far as we know, this is the first one to combine both the acoustic and RF channels to satisfy differentiated multi-application data transmission requirements. We summarize the main contributions as follows.

- We propose two multimodal acoustic-RF adaptive routing schemes for both the grid-based and random deployment scenarios in UWSNs, via which we leverage the benefits of these complementary channels to enhance network reliability and throughput.
- We analyze the routing models of the surface floating network, and then propose two routing models (i.e., high transmission power model and delay tolerant networking model) as well as the deployment requirements to save energy.
- We categorize multi-application packets into four classes in accordance with two primary criteria, i.e., packet delivery latency and reliability. Consequently, we provide a differentiated delivery strategy for these classes while selecting the next-hop relay node by taking channel quality, residual energy and the distance to the sink into account.

We present the structure of this paper as follows. Section II introduces the acoustic-RF network architecture as well as channel characteristics. The analysis and design of the adaptive routing solutions are discussed in Section III. In Section IV and Section V, we present the routing algorithms for the grid-based deployment and random deployment scenarios, respectively. We conduct simulations to evaluate the performance of the routing schemes in Section VI. The related work in the context of this paper are reviewed in Section VII. Finally, we conclude the paper in Section VIII.

II. NETWORK ARCHITECTURE

In this section, we describe the network architecture for the grid-based and random deployment scenarios, the floating model of surface nodes and the complementary characteristics of acoustic and RF channels. The terms related to the paper are listed in Table 2.

The network architecture is constructed by a number of group-nodes. As depicted in Figure 2(a), each group-node consists of an ocean surface node and an underwater moored node. The ocean surface node integrates two communication technologies with a RF communication system over the ocean surface while the acoustic communication system underwater. The two systems are connected via cables, and the whole device is assembled together within a drifting buoy.

To prevent the group-node from moving away with the current, the underwater node deployed on the seabed is attached...
to a heavy anchor underwater, while the surface node is also attached to this anchor via a mooring line. The sensors can be equipped with image sensors, and there should be one or more resource-intensive sink nodes in the deployment area with long-range communication capabilities for transmitting data packets to its final destination.

This architecture forms a two-tier network. As depicted in Figure 1, the first tier of the network is on the ocean surface, which monitors both the ocean surface and the upper layer of the ocean. The other tier of the network is deployed on the seabed, which communicates with each other via the acoustic technology. We could leverage the two-tier network to detect intrusion vehicles such as ships, submarines, UUVs and AUVs.

![Diagram of a group-node](image)

**FIGURE 2:** The floating model of a group-node.

As shown in Figure 3, in DR-OSNs, floating node $F_A$ and $F_B$ are deployed on the ocean surface, while their moored nodes $M_A$ and $M_B$ are deployed on the seafloor. Therefore, when a floating sensor node has a packet for the sink, it can be assigned two different channels (i.e., acoustic and RF), to forward the packet. Nevertheless, we should take the channel qualities into consideration, as these channels not only have different characteristics, but also change constantly in accordance with both time and space.

Although the RF channel over the ocean surface is more preferable compared to the underwater acoustic channel while dealing with delay-sensitive packets, we cannot always reap the benefits of the RF channel as it might become deteriorated with extreme weather conditions, such as heavy rains, severe storms and so on, which result in poor channel quality with high BER.

**A. GRID-BASED AND RANDOM DEPLOYMENT SCENARIOS**

The network can be constructed in either the grid-based or random deployment scenario. With the grid-based scenario, sensor nodes can be manually deployed in the monitoring area of interest with the help of ships, as depicted in Figure 4. However, the sensor nodes could also be deployed through the dropping operation from the planes or flying gliders [10], shown in Figure 5. With the help of specific deployment control methods, e.g., exploiting both gliding and falling operations, the sensor nodes can be uniformly distributed in the targeted region. Although the grid-based scenario is simpler than the random deployment one, we leverage the benefits of both scalability and efficiency especially for intrusion detection surveillance applications. Therefore, we primarily focus on the grid-based deployment scenario in the remainder of the paper.

**B. FLOATING MODEL**

When we deploy the floating sensor node on the ocean surface, the sensor node is not static. On the contrary, accompanied by the ocean currents and waves as well as the constraints of the rope which is linked to the anchor on the sea bed, the floating node has a free drifting area.

The actual movement of the floating node is determined primarily by three factors. Among them, the ocean movement is the major factor which affects the movement of the floating node. Although we now know that a number of factors, e.g., wind, salinity and temperature, have some effect on the ocean movement, it is difficult to precisely model the ocean movement. Some researchers modeled the ocean movement operation in a simplified manner. For example, Caruso et al. classified the ocean movement into looping and downstream motions [11], and then provided a model according to the following equations.

$$
\begin{align*}
\dot{x} &= -\partial_y \psi(x, y, t), \\
\dot{y} &= -\partial_x \psi(x, y, t), \\
B(t) &= A + e\cos(\omega t), \\
\psi(x, y, t) &= -\tanh\left[\frac{y-B(t)\sin(k(x-ct))}{\sqrt{1+k^2B^2(t)\cos^2(k(x-ct))}}\right],
\end{align*}
$$

(1)

where $k$, $c$, $e$ and $\omega$ are the meander numbers, the phase speed, the amplitude and frequency of the modulation, respectively.

Another factor which influences the movement of the floating node is the underwater anchor. Consequently, the joint force generated by the anchor via the rope, the ocean movement and the water floatage render the floating node drift within a restricted area around the anchor with a radius $r$ that satisfies the equation $r = \sqrt{r^2 - h^2}$, in which $h$ and $l$ are denoted as the sea depth and anchor rope length, respectively.

The third factor is the rising and falling events of the ocean (i.e., tides) which affects the depth of the sea. As the node is floating on the ocean surface, the tides leads to a
varying floating radius \( r \). We denote \( H_{\text{max}} \) and \( H_{\text{min}} \) as the maximum and minimum sea depth, respectively. Moreover, the sea depth \( H \) is within \( H_{\text{min}} \leq H \leq H_{\text{max}} \). As depicted in Figure 2(b), \( R_{\text{min}} \) and \( R_{\text{max}} \) are denoted as the minimum and maximum radius, respectively. Therefore, we obtain \( R_{\text{min}} = \sqrt{L^2 - H_{\text{max}}^2} \) and \( R_{\text{max}} = \sqrt{L^2 - H_{\text{min}}^2} \). Thus, the radius \( r \) is within the \( \{R_{\text{min}}, R_{\text{max}}\} \) range.

**C. COMPLEMENTARY CHARACTERISTICS OF ACOUSTIC AND RF CHANNELS**

The network has two different communication channels which can be leveraged for simultaneous multi-path data transmissions. The underwater acoustic communication channel has several unique characteristics which are absent in the RF channel. The signal to noise ratio (SNR) of a hydrophone is influenced by a number of factors, such as the transmitting distance, the signal frequency and the types of both modems and hydrophones. It is confirmed to the passive sonar equation [12], and can be expressed as

\[
\text{SNR}_{(d,f)} = SL + DI - NL - TL, \tag{2}
\]

where \( SL, DI, NL \) and \( TL \) are the source power level, the directive index related to modems and hydrophones, the noise level and the transmission loss, respectively. Note that the quantities in equation (2) are \( \text{dB} \) re \( \mu \text{Pa} \), in which 1 \( \mu \text{Pa} \) equals to \( 0.67 \times 10^{-18} \text{ Watts/m}^2 \), and \( \text{SNR} \) is related to both the transmission distance and the acoustic signal frequency that we will explain later.

We can also obtain the definition of \( SL \) and \( TL \) as

\[
SL = 10 \log \frac{P_T}{4\pi}, \tag{3}
\]

where \( P_T \) is denoted as the transmit power.

\[
TL = 10 \log d + \alpha d \times 10^{-3}, \tag{4}
\]

where \( d \) is the acoustic wave transmission distance, and \( \alpha \) is denoted as absorption coefficient. The absorption coefficient \( \alpha \) can be further calculated with the Thorp’s expression [12] as

\[
\alpha = \frac{0.1 f^2}{1 + f^2} + \frac{40 f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003, \tag{5}
\]

where \( f \) is the sound frequency of the acoustic signal in kilohertz. To note that, the velocity of underwater acoustic wave is not constant, but varies with a number of factors (e.g., the ocean salinity, temperature and press).

There has been few studies on the RF communication over-the-sea [13]. As we deployed a real wireless sensor network testbed in the ocean [14], and via monitoring data analysis, we observed that a few relevant factors (e.g., weather, ocean waves and currents) influence the over-the-sea RF channel.

Overall, the RF channel over the ocean surface and the underwater acoustic channel are complementary to each other. As shown in Table 1, underwater acoustic technology can cover a wide range, such as up to several kilometers, but the RF communication has a shorter transmission range. For example, Zigbee has a less than 100 m transmission range, and so RF communication generally requires more hops to reach the destination via intermediate nodes.

However, unlike the acoustic communication, the RF communication can achieve higher data-rate. For example, Zigbee are able to reach 250 kbps data-rate, while typical underwater commercial acoustic modems can achieve lower than 35 kbps data-rate [15]. Furthermore, RF communication is more energy efficient compared to the acoustic one, and has a very low transmission latency. However, RF communication also suffers from several disadvantages, e.g., RF channel is affected by the ocean waves and severely harsh weather (heavy rainfall or storms). Obviously, the sensed data generated from the sea floor nodes should first be transmitted by the acoustic channel.

**III. THE DESIGN AND ANALYSIS OF ADAPTIVE ROUTING PROCESS**

In this section, we first discuss the general considerations of underwater adaptive routing design, and then present the packet classification and relay nodes selection.

**A. GENERAL CONSIDERATIONS WITH UNDERWATER ADAPTIVE ROUTING DESIGN**

The aim of adaptive routing is to increase the network flexibility and adaptability via a reconfigurable architecture. In such an intelligent network, to make ordinary sensor
TABLE I: Performance figures of different communication technologies.

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Range</th>
<th>Data Rate</th>
<th>Latency</th>
<th>Energy</th>
<th>Weakness</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>~100m</td>
<td>~Kbps</td>
<td>0.003 ms/Km</td>
<td>50,000 bits/Joule</td>
<td>Affected by waves, severe weather, e.g., storm</td>
<td>High data rate, low latency, low energy consumption</td>
</tr>
<tr>
<td>Acoustic</td>
<td>~Km</td>
<td>~Kbps</td>
<td>667 ms/Km</td>
<td>100 bits/Joule</td>
<td>High delay, low bandwidth</td>
<td>Long communication range</td>
</tr>
</tbody>
</table>

node smart, the node should be integrated with emerging intelligent technologies, such as cognitive radio (CR) and software-defined radio (SDR) [3].

Equipped with these technologies, the smart sensors not only carry out ordinary sensor functions (e.g., sensing and generating data, receiving and forwarding packets), but also have the capability of changing its behavior through the real-time environmental sensing and decision making process. It is realized by both CR and SDR, in which CR acts as a virtual brain powered by its policy engine with self-learning capabilities and analyzing sensed data continuously, such as environmental varying information as well as statistical network functional information.

Once CR has made decisions based on the information, it requires SDR to carry out adaptive actions by reconfiguring hardware parameters (e.g., seamless transitions among multiple communication methods, transmit power control and transmit bit-rate selection) to cope with environmental changes. Therefore, they provide both network flexibility and self-adaptivity.

Designing a reconfigurable network requires a cross-layer architecture which bypasses from the rigid vertical OSI-based communication model and shares the lower-layer hardware and communication channel information to the higher-layers (e.g., network- and application-layer). This flexible architecture, integrated with cross-layer design, CR and SDR, will facilitate the network efficiency and adaptability.

B. PACKET CLASSIFICATION

As mentioned before, different network applications might share the same network infrastructure, in order to utilize network resources fully, e.g., both ocean environmental monitoring and intrusion detection surveillance may be deployed using a single network infrastructure. Under such a scenario, different applications may require differentiated services and thus have different priorities. For example, while transmitting packets, these may focus on different metrics, such as transmission quality, packet delivery latency and packet delivery ratio.

If we deploy both ocean monitoring and intrusion detection applications in the same network, these demand differentiated services and thus focus on different metrics. As the intrusion detection system needs to detect intruders (e.g., divers, UUVs and AUVs) on the ocean surface and underwater of targeted area of interest, the detection packets are delay-sensitive, therefore, these packets demand low end-to-end packet latency. Furthermore, the detection application may require to send multimedia packets to the sink for data log or further analysis. Once a detection event is determined by the local data fusion process [16], the system may trigger its image sensors to take intrusion pictures for further verification. Consequently, the packets with intrusion detection are not only delay-sensitive, but the multimedia packets also require reliable high-speed transmission rate. On the contrary, although the ocean environmental monitoring process requires appropriate packet delivery ratio, as most of the packets are not urgent, energy consumption may be more important compared to other metrics.

Among these routing metrics, end-to-end delay which is the time duration from the source to the destination, represents degree of delay-sensitivity of the packets. Another important routing metric is reliability, which is relevant to QoE. The routing reliability can be realized by lowering BER, selecting multipath transmission and improving packets delivery ratio. Overall, the end to end delay and data transmit reliability are two important metrics for adaptive routing in multi-application networks. In this paper, we select both of them to classify network packets into four types.

**LH-packet**: The LH-packet requires both low end-to-end transmission latency and high reliability. Usually, these packets are equipped with urgent and important sensed information, such as marine environmental pollution or intrusion detection events which call for urgent actions. Furthermore, LH-packet may include multimedia data which require high bandwidth and packet delivery ratio.

**LL-packet**: The LL-packet demands both low transmission reliability and delivery latency. This type of packet can be generated from dense networks, and so these packets have high spatial correlation. As these packets usually are small-sized, they demand low to moderate bandwidth for delivery.

**HH-packet**: The HH-packet requires high reliability but demands a relatively high transmission delay. For example, the multimedia packets of ocean environment monitoring, which are used for offline analysis and storage, are such type of packets. However, HH-packet usually demands high transmission bandwidth.

**HL-packet**: The HL-packet requires low reliability and high transmission delay. Therefore, these packets demand low transmission bandwidth. For example, the non-multimedia packets are within this type of packets, which are usually not time-critical.
C. SELECTION OF RELAY SENSOR NODES

During the network initialization phase, the sink can leverage broadcast-based topology discovery protocols [17] (e.g., flooding protocol) to perform fundamental network operations, such as network topology construction, time synchronization, group formation, localization and so on. In order to deal with network communication environments and topological changes, the sink also sends routing reconstruction packets periodically during the operational stage of the network. During these procedures, a sensor node can build and maintain a neighbor table including information such as the remaining number of hops to the sink and the residual energy level. With simple statistical techniques, the neighbor table also records statistically measured information, such as channel link quality. To improve network efficiency, the network can use time-division multiple access (TDMA) technique for channel access.

Assume that the number of adjacent candidate relay nodes of the source node is \( w \), and \( w = 1, 2, 3, 4, \ldots, r \). Let \( S_w \) represent the quality of the candidate relay node \( w \). We assume that the total number of factors to consider while calculating the quality of the candidate relay node is \( m \), such as channel quality, the geographic position and the residual energy level of a node. The corresponding weights of these factors that reflect the relative importance in the routing algorithm are denoted as \( x_1, x_2, \ldots, x_m \), and then \( S_w \) is calculated as

\[
S_w = \sum_{i=1}^{m} x_i y_{s(i)},
\]

where \( \sum_{i=1}^{m} x_i = 1 \), and \( y_{s(i)} \) is the value of factor \( i \).

To choose the relay nodes, we take three factors into consideration in this paper (e.g., channel quality, maximum hops to the sink and residual energy level). The residual energy level and the initial energy of a sensor node are denoted as \( E_R \) and \( E_0 \), respectively. And \( T_{\text{max}} \) is the maximum number of hops to the sink, while \( T_R \) is the remaining number of hops to the sink. We denote the channel link quality as \( C_q \), and \( C_{\text{max}} \) represent the maximum channel link quality.

Consequently, we obtain

\[
S_w = \alpha \times \frac{C_q}{C_{\text{max}}} + \beta \times \frac{T_{\text{max}} - T_R}{T_{\text{max}}} + \gamma \times \frac{E_R}{E_0},
\]

where \( \alpha, \beta, \gamma \) are coefficients, and \( \alpha + \beta + \gamma = 1 \).

Though \( C_q \) can be obtained directly from the packet reception ratio, it is a statistically measured metric which requires a relatively long period of time. As both Link Quality Indicator (LQI) and Received Signal Strength Indicator (RSSI) are tightly related to the channel quality [18], we use these metrics to represent the channel quality. Let \( L_q \) and \( L_{\text{max}} \) denote the link quality indicator and the maximum link quality indicator, respectively. Then the candidate relay nodes can be computed as

\[
S_w = \alpha \times \frac{L_q}{L_{\text{max}}} + \beta \times \frac{T_{\text{max}} - T_R}{T_{\text{max}}} + \gamma \times \frac{E_R}{E_0},
\]

where \( \alpha, \beta, \gamma \) are coefficients, and \( \alpha + \beta + \gamma = 1 \).

After calculating the quality value of the candidate relay nodes, we could choose the relay node \( S_{\text{relay}} \) as

\[
S_{\text{relay}} = \max(S_1, S_2, \ldots, S_r).
\]

IV. THE GRID-BASED ROUTING SCHEME AND ALGORITHMS

In this section, the routing models of surface nodes and underwater nodes are described firstly. Then, we present the proposed routing algorithms for the grid-based deployment scenario.

A. THE ROUTING MODELS

The power control techniques can be used to control routing topology and satisfy different routing requirements [19]. Two transmission models, such as High Transmission Power (HTP) model and Delay Tolerant Networking (DTN) model, are implemented in surface nodes to make trade-offs between metrics such as delay and energy consumption constraints. The HTP and DTN models adopt high and low transmission power, respectively. As different transmission power levels largely determine the communication range of nodes, we present a mathematical analysis for both HTP and DTN models.

As the network is manually deployed in a grid-based line, we select four adjacent nodes from the line, as shown in Figure 6, to analyze the power control model. The positions of four nodes are denoted as \( A, B, C \) and \( D \), and form a square \( ABCD \). To note that, these points are also the nodes’ anchor positions. Therefore, each node has a free drifting radius \( r \). To describe their drifting area, we construct \( ABCD \) around these extended areas.

The distance between node \( D \) and node \( C' \) is denoted as \( L_{DC'} \). And the diagonal lines of the square \( ABCD \) and \( A'B'C'D' \) are denoted as \( L_{AC} \) and \( L_{BD'} \), respectively. Moreover, the communication range of the DTN and HTP models are denoted as \( R_{\text{DTN}} \) and \( R_{\text{HTP}} \), respectively.
By the Right-Angled Triangle theorem, we have

\[ R_{HTP} \geq 2\sqrt{2}r + \sqrt{2}L_{D'C'}. \] (10)

While the HTP model can deliver packets quickly, with delay-tolerant packets, using low transmission power can save energy consumption. As illustrated in Figure 6, if the communication range of nodes cannot satisfy the relation in (10), then the node turns into DTN model. Since the node can only find relay nodes opportunistically, \( R_{DTN} \) should satisfy the following relation,

\[ L_{D'C'} - 2r \leq R_{DTN} \leq 2\sqrt{2}r + \sqrt{2}L_{D'C'}. \] (11)

As the floating nodes drift freely on the ocean surface after deployment, to prevent two adjacent nodes being entangled with each other, we should consider several factors such as rope length \( L \) and the sea depth \( H_{\text{min}} \). As shown in Figure 7, the deployment distance \( L_{D'C'} \) between two adjacent nodes \( D' \) and \( C' \) should satisfy the following relation.

\[ L_{D'C'} > 2r_{\text{max}} \]
\[ = 2\sqrt{L^2 - H_{\text{min}}^2}, \] (12)

where \( L \) represents the rope length, and \( H_{\text{min}} \) is the minimum sea depth with the lowest tide.

Accordingly, the relation in (10) should be changed to

\[ R_{HTP} > 2\sqrt{2}r_{\text{max}} + \sqrt{2}L_{D'C'} \]
\[ = 2\sqrt{2}r_{\text{max}} + 2\sqrt{2}r_{\text{max}} \]
\[ = 4\sqrt{2}r_{\text{max}} \]
\[ = 4\sqrt{2}\sqrt{L^2 - H_{\text{min}}^2}, \] (13)

where \( L = H + h_{\text{tide}} + l_m \), \( H_{\text{min}} \) represents the minimum sea depth when the tide is in its lowest level, \( h_{\text{tide}} \) is the highest height of the tide of the deployed area, and \( l_m \) is the residual rope length which prevents the anchor rope from broken. Similarly, the relation in (11) stands to

\[ D_{\text{min}} \leq R_{DTN} \leq 4\sqrt{2}\sqrt{L^2 - H_{\text{min}}^2}, \] (14)

where \( D_{\text{min}} \) represents the minimum distance of two adjacent surface nodes.

For a moored node deployed on the seafloor, it either selects the acoustic nodes on the seafloor or the acoustic nodes on the sea surface to transmit packets towards the sink. For example, as shown in Figure 3, though node \( M_A \) could choose node \( M_B \), \( F_A \), or \( F_B \) as its relay nodes, as the floating nodes \( F_A \) and \( F_B \) may drift freely around the center of underwater mooring anchor, node \( M_A \) should first select the node which is closer to the sink. All the acoustic nodes only have one power level to select which can have larger communication range compared to the RF communication.

**Algorithm 1** The initialization phase of the routing scheme.

```plaintext
1: procedure NodeInitialization
2: Network initialization
3: Group-node binding
4: Time synchronization
5: Node localization
6: Routing initialization
7: Parameters \( \alpha, \beta, \gamma \) initialization
8: \( L_q, L_{\text{max}}, T_R, T_{\text{max}}, E_R, E_0 \) initialization
9: return TRUE
10: end procedure
11: procedure RelayNodeUpdating
12: GetUpdated \( L_q, L_{\text{max}}, T_R, T_{\text{max}}, E_R \)
13: Compute \( S_w \) using (8)
14: Update NeighbourList
15: return TRUE
16: end procedure
```

**B. THE ROUTING ALGORITHM FOR GRID-BASED DEPLOYMENT SCENARIOS**

To increase the adaptability of the routing scheme, we consider both the application requirements and the transport channel conditions. When a node has a packet to send towards the sink, it first checks the packet type, and then it selects different routing strategies based on routing and channel conditions. As multipath routing mechanism is considered as an effective method both to improve transmission reliability and provide a possible solution for transferring larger files via multiple paths in a parallel fashion [20], we incorporate this mechanism into our routing algorithm. The specific descriptions of the scheme are as follows.

**LH-routing:** As LH-routing demands both low delivery latency and reliability, we select RF surface channel and underwater acoustic media to implement the task. Moreover, in order to improve data transmission delivery ratio and reduce delivery delay, the surface nodes choose the HTP model.

**LL-routing:** To transfer LL-routing packets, we select RF surface channels to construct multiple routing paths. Meanwhile, to satisfy the delay requirement of such packets, the surface nodes transmit the packets in high power HTP model.

**HH-routing:** To increase data transmission reliability, we choose both channels of surface RF and acoustic underwater to deliver packets. At the same time, in order to save energy,
Algorithm 2 The proposed grid-based routing scheme.

1: procedure SOURCE_PACKET_ROUTING_SELECTION
2:     PacketType ← packetType
3:     if PacketType = LH-packet then
4:         LH-Routing()
5:     else if PacketType = LL-packet then
6:         LL-Routing()
7:     else if PacketType = HH-packet then
8:         HH-Routing()
9:     else if PacketType = HL-packet then
10:         HL-Routing()
11:     end if
12:     return TRUE
13: end procedure
14: procedure LH-Routing
15:     if PacketSource = Surface then
16:         SendPacketToSurfaceNode
17:     else
18:         SendPacketToUnderwaterNode
19:     end if
20:     if Node = SurfaceNode then
21:         SurfaceNodeMode ← HTP
22:         Select a HTP neighbour node with highest Sw
23:         Send the packet to this node
24:     else
25:         Select a neighbour node with highest Sw
26:         Send the packet to this node
27:     end if
28:     return TRUE
29: end procedure
30: procedure LL-Routing
31:     if PacketSource = Underwater then
32:         SendPacketToSurfaceNode
33:     end if
34:     SurfaceNodeMode ← HTP
35:     Select a HTP neighbour node with highest Sw
36:     Send the packet to this node
37:     return TRUE
38: end procedure
39: procedure HH-Routing
40:     if PacketSource = Surface then
41:         SendPacketToUnderwaterNode
42:     else
43:         SendPacketToSurfaceNode
44:     end if
45:     if Node = SurfaceNode then
46:         SurfaceNodeMode ← DTN
47:         Select a DTN neighbour node with highest Sw
48:         Send the packet to this node
49:     else
50:         Select a neighbour node with highest Sw
51:         Send the packet to this node
52:     end if
53:     return TRUE
54: end procedure
55: procedure HL-Routing
56:     if PacketSource = Underwater then
57:         SendPacketToSurfaceNode
58:     end if
59:     SurfaceNodeMode ← DTN
60:     Select a DTN neighbour node with highest Sw
61:     Send the packet to the node
62:     return TRUE
63: end procedure
64: procedure PACKET RECEIVING AND RELAY
65:     if Node = SurfaceNode then
66:         Set SurfaceNodeMode
67:     end if
68:     Select one neighbour node with the highest Sw
69:     Send the packet to the node
70: end procedure

FIGURE 8: A sample of random deployment.

the RF surface channel chooses DTN model to construct multipath routing as HH-routing packets tolerate a relatively long transfer latencies.

**HL-routing:** To satisfy the demand of HL-routing packets, we just choose the RF surface communication channels to deliver data packets. As HL-routing packets are not urgent, we select DTN model to save transmission energy.

The steps are briefly described in Algorithm 1 and Algorithm 2.

V. THE ROUTING SCHEME AND ALGORITHMS FOR RANDOM DEPLOYMENT SCENARIOS

In this section, we present a brief discussion on random deployment as well as its corresponding routing protocol design.

Different from the manual grid-based deployment scenario, the floating nodes are not distributed evenly in the target area while adopting the random deployment strategy, as depicted in Figure 8. We also observe that in order to prevent the floating nodes from getting entangled with each other, the random deployment may result in sparse networks. Furthermore, with random deployment approaches, once the network has been sparsely deployed, it either implements incremental deployment, or constructs a sparse network with available limited links. The good news is that the network has both short RF communication links and the long acoustic underwater links, and therefore it is applicable to build a sparse network especially with limited RF links.

A. THE CHARACTERISTICS OF SPARSE NETWORKS AND ROUTING DESIGN

As shown in Figure 8, 30 nodes are deployed in a 1000×1000 m² monitoring area. The floating radius is 30 m, and the sea depth is 100 m. In sparse networks, when the deployment distance between two adjacent nodes is beyond the maximum RF communication range, they could be connected with the long range acoustic technology. Thus, we choose to discover.
the network topology with the help of acoustic systems in order to connect all of the deployed nodes. Efficient topology methods could be used to detect full network topology quickly with acoustic communications [17]. After that, each RF node can broadcast neighbour discovery beacons to collect full topology information and then maintain a neighbour list via both the RF and underwater acoustic links. Naturally, some nodes might not have RF connections available towards the sink, but they can use acoustic channel to forward data towards the sink.

With each node, there might be three types of communication links with their neighbours, which are defined as follows.

\textbf{Acoustic-normal}: the neighbours which can be reached via acoustic links.

\textbf{RF-normal}: the neighbours which can be reached directly via the RF communication technology with high transmission power.

\textbf{RF-DTN}: the neighbours which can be reached opportunistically with either high transmission power or low transmission power.

Accordingly, with each neighbour, the sender has one, two or three communication links to choose for forwarding data. We also denote the neighbour node which can only be reached via acoustic links as bridging node in the sparse network [21].

\section*{B. THE ROUTING ALGORITHM FOR RANDOM DEPLOYMENT SCENARIOS}

In this section, we propose the routing scheme for the random deployment scenarios.

\textbf{LH-routing}: In LH-routing, the packets demand low latency and high reliability in terms of delivery. To meet these requirements, both the RF and underwater acoustic channels are used to transmit packets. As for the RF channel, we set up multiple paths to transmit packets. If the sender has RF-normal neighbours, it selects them firstly. In case of a bridging node, we leverage the acoustic link to forward packets.

\textbf{LL-routing}: LL-routing deals with packets which require low transfer reliability but need to be delivered in a timely manner. To satisfy these demands, the surface RF channel is used to deliver such packets. To meet the short delivery latency, we only choose RF-normal neighbours. When the routing node is a bridging node, it sends data towards the sink via its acoustic link.

\textbf{HH-routing}: The HH-routing transmits those packets which require both high latency and reliability via both the surface RF and underwater acoustic links. The surface node choose \textit{RF-DTN} neighbours firstly instead of RF-normal neighbours. For a bridging node, it chooses acoustic links to deliver packets.

\textbf{HL-routing}: HL-routing scheme is for HL-packets, which are not time-critical and require low level of reliability. To deliver this type of packet, we choose surface channel, and the priority list of candidate neighbours are RF-DTN and RF-normal. If there is only a bridging node available, we use the acoustic link to send data towards the sink.

The initialization procedure for the random deployment network is similar to the grid-based deployment as shown in \textit{Algorithm 1}. The routing algorithm is also similar to \textit{Algorithm 2}. Due to the space limitation and make this paper more concise, we omit specific steps of these algorithms as it is easy to get them from the aforementioned descriptions as well as the steps presented in \textit{Algorithm 2}.

\section*{VI. PERFORMANCE EVALUATION}

In this section, we present the simulation-based evaluation results of the adaptive routing protocols via MATLAB. We deploy the simulated network in a $5000 \times 5000$ m$^2$ targeted monitoring area. As this paper primarily focuses on grid-based deployment scenarios, we simulate networks with such scenarios while considering different RF and acoustic links and network topologies.

\subsection*{A. THE RADIUS OF FLOATING NODE}

As shown in relation of (13) and (14), the surface node routing models $R_{\text{HTP}}$ and $R_{\text{DTN}}$ are influenced by the floating radius $r_{\text{max}}$. We show the variation of $r_{\text{max}}$, and reveal the correlated factors such as rope length, the height of tide, the sea depth, as depicted in Figure 9 and Figure 10.

In Figure 9, the floating radius of a surface node is depicted under different sea depth. The sea depth varies from 20 m to 200 m. Overall, as the deployed area becomes deeper, the floating radius $r_{\text{max}}$ becomes larger accordingly [8]. Observed from the figure, although the height of the ocean tide and the redundant rope length also influence $r_{\text{max}}$ with the fixed sea depth, the sea depth is the decisive factor among these factors.

The continental shelf, extended from the coast to the deep ocean, typically has different inclined seaward slope at different sea depth (e.g., 100-200 m at about $0.1^\circ$, 200-1500 m at about $3^\circ-6^\circ$, and 1500-5000 m at about $1^\circ$). The radius of a floating node with different sea depths and seabed slopes is depicted in Figure 10, in which the slope angle is set at $3^\circ$ within the range from 200 m to 1500 m. As shown in Figure 10, the increment of $r_{\text{max}}$ is slightly affected by the continental shelf slopes.

\subsection*{B. THE PROBABILITY OF FINDING A RELAY NODE}

In order to save energy, the surface nodes can select the DTN model. As shown in Figure 11, $R_{\text{DTN}}$ is the main factor which determines the chance of meeting a relay node among its neighbours. Overall, as $R_{\text{DTN}}$ increases, the probability of finding a relay node also increases. We also explore other factors which have the impact on the probability. As revealed in the figure, both the mooring rope length $L$ and the sea depth $H$ affect the probability. With the same sea depth and $R_{\text{DTN}}$, when the rope length $L$ increases, the probability decreases, due to a larger free drifting area generated from a longer rope mooring length which reduces the probability of finding a relay node. For the similar reason, the increment of
The sea depth also leads to a decreasing probability as it demands a increment of the mooring rope length accordingly.

C. THE ESTIMATED MAXIMUM DELAY FOR THE SURFACE NETWORK

The maximum delay of the surface node is relevant to both the probability of meeting a relay neighbour and its drifting speed. We set the probability at 10%, and vary the drifting velocity of surface node from 0.25 \( \text{m/s} \) to 2.5 \( \text{m/s} \). As observed from Figure 12, the maximum relay time decreases as the drifting velocity of surface node increases. This is because the drifting speed of surface node becomes a critical factor when the probability of finding a relay node is low. In addition to that, other factors influence the estimated delay time, such as rope length and the depth of the sea, as both of them have some effect on the free surface node drifting area.
The routing issue is a core functionality of UWSNs which requires high priority within a cluster as described in the algorithms. The RF links should be selected with careful consideration, as RF systems are more energy efficient compared to the acoustic counterparts. However, the RF systems have a shorter communication range, these clusters are able to be connected with other clusters using RF links. As the acoustic link has a longer communication range, these clusters are connected to the ocean surface. To monitor a 3-D ocean space, the monitoring nodes should be deployed on the seabed, in the ocean, as well as on the ocean surface. Under such scenario, both the monitoring and control data will be transferred vertically towards the sink. As the nodes deployed in the ocean might move with the ocean currents slowly, the characteristic of intermittent connections between nodes should be taken into consideration in the routing design process.

Several research works addressed how to satisfy diversified routing requirements and proposed adaptive routing schemes. For instance, Pompili et al. [27] proposed two routing algorithms by distinguishing different delay requirements in order to reduce the total energy consumption. Faheem et al. [28] proposed a routing protocol, namely QERP, to improve data transfer reliability. Guo et al. [29] presented an adaptive routing protocol which allocates more network resources for urgent packets to reduce delivery delay with DTN networks. Yu et al. [22] proposed a vector-based routing protocol with variable forwarding virtual pipeline radius so as to reduce the total data transmission delay and improve the delivery reliability. Hu et al. [30] exploited machine learning techniques to prolong the lifetime of the network with a balanced trade-offs between delivery latency and network energy consumption. Basagni et al. [31] presented a routing algorithm, namely CARP, which is in a cross-layer architecture in order to leverage both the physical channel quality and the power control technique performing adaptive routing. E-CAPP [32] is an enhanced version of CARP, in which the previously collected data cached in the sink is used to select the most appropriate relay node in order to reduce communication costs.

Multimedia-based applications greatly enhance the utilities of Internet of Things [33], and few studies focused on underwater multimedia protocols design. Ribas et al. [34] conducted a real-time video transmission experiment via a short acoustic link within 200m. Pompli et al. [35] proposed to jointly consider PHY layer, MAC and routing via a cross-layer design to satisfy quality-of-service (QoS) requirements of multimedia packets. Sarissaray-Boluk et al. [36] presented a solution for high quality underwater image delivery by combining retransmission, forward error correction and multipath transmission together. Although these research results confirmed that acoustic link can be used to transfer multi-

![Figure 14: RF and acoustic communication links and network topology.](image-url)
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Multimodal underwater sensor networking is a relatively new research area, and some existing works in this area are [38]–[41]. The idea of this concept is to equip networking devices with several acoustic and non-acoustic communication technologies (e.g., optical, RF, EM and MI) in order to achieve short and long-range communication feature simultaneously using multiple frequency channels. Campagnaro et al. [39] reviewed the recent advances of multimodal underwater networks. Diamant et al. [38] proposed a distributed multimodal routing OMR for optical-acoustic underwater networks, in order to maximize data transfer via available communication channels as well as to utilize network resources in a fair manner. Gjanci et al. [40] provided path finding algorithms for AUVs to maximize value information collection in optical-acoustic multimodal underwater networks. Basagni et al. [41] leveraged reinforcement learning technique to develop a scheme, namely MARLIN-Q, for selecting the best forwarding relay and multimodal modems (e.g., multiple acoustic non-interference frequency channels), so as to enhance transmission reliability and satisfy soft QoS requirements of applications. Although the aforementioned works improved the routing throughput by adopting either multiple acoustic channels or hybrid acoustic-optical channels, none of them exploited both the acoustic and RF channels to enhance the routing reliability of the network.

VIII. CONCLUSIONS

We presented two multimodal acoustic-RF adaptive routing schemes for grid-based and randomly deployed UWSNs, which exploit the complementary strengths of surface RF and underwater acoustic technologies. In the protocols, we categorize the sensor packets into different classes according to two important forwarding quality criteria, i.e., end-to-end packet latency and reliability. Upon sufficient discussion of analytical design, we designed two routing algorithms which balance the quality of the routing channel, the distance to the sink and the residual energy while selecting the next-hop forwarding node. We evaluated the proposed routing protocols, and the simulation results confirm that the proposed methods achieve a reasonable performance under different routing scenarios. In the future, we will test and verify the proposed multimodal acoustic-RF adaptive routing protocols in real testbeds to improve the performance of these protocols further.

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VOLUME X, 2019

TABLE 2: Terms used in the paper.

<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Elaboration</th>
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<tbody>
<tr>
<td>AUVs</td>
<td>Autonomous Underwater Vehicles</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>CR</td>
<td>Cognitive Radio</td>
</tr>
<tr>
<td>DTN</td>
<td>Delay Tolerant Networking</td>
</tr>
<tr>
<td>EM</td>
<td>Electro-Magnetic</td>
</tr>
<tr>
<td>HTP</td>
<td>High Transmission Power</td>
</tr>
<tr>
<td>LQI</td>
<td>Link Quality Indicator</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MI</td>
<td>Magnetic Induction</td>
</tr>
<tr>
<td>OSI</td>
<td>Open System Interconnection</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical Layer</td>
</tr>
<tr>
<td>QoE</td>
<td>Quality of Experience</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indicator</td>
</tr>
<tr>
<td>SDR</td>
<td>Software Defined Radio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time-division Multiple Access</td>
</tr>
<tr>
<td>UUVs</td>
<td>Unmanned Underwater Vehicles</td>
</tr>
<tr>
<td>UWSNs</td>
<td>Underwater Wireless Sensor Networks</td>
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HANJIANG LUO received Ph.D. degree in De-
partment of Computer Science at Ocean University
of China. He is a visiting scholar at HKUST in
2014. His research interests include wireless sen-
sor networks, underwater wireless sensor networks,
Internet of things, smart port, data science and
artificial intelligence. He has published research papers in some prestigious journals and confer-
ces such as ACM COMPUTING SURVEYS, IEEE Communications Surveys & Tutorials, IEEE

XIUMEI XIE received her Master’s degree in
computing science and engineering from Ocean Un-
iversity of China in 2008, and she graduated from
Shandong Normal University in 2005 with a bacher’s degree in computer science. Her re-
search interests include wireless sensor networks, internet of things, data science, artificial intelli-
gence and cloud computing. She has published research papers in well-recognized journals and conferences.
GUANGJIE HAN is currently a Professor with the Department of Information and Communication System, Hohai University, Changzhou, China. He received the Ph.D. degree from Northeastern University, Shenyang, China, in 2004. He is the author of over 330 papers published in related international conference proceedings and journals. He has served on the Editorial Boards of up to 16 international journals, including the IEEE JSAC, IEEE Network, IEEE Systems, IEEE ACCESS, IEEE/CCA JAS, etc. He has guest edited a number of special issues in IEEE Journals and Magazines, including the IEEE Communications, IEEE Wireless Communications, IEEE Transactions on Industrial Informatics, Computer Networks, etc. He had been awarded the ComManTel 2014, ComComAP 2014, Chinacom 2014 and Qshine 2016 Best Paper Awards. His current research interests include Internet of Things, Industrial Internet, Machine Learning and Artificial Intelligence, Mobile Computing, Security and Privacy. He is a Senior Member of IEEE.

RUKHSANA RUBY received her Masters degree from University of Victoria, Canada on 2009, and Ph.D. degree from The University of British Columbia, Canada on 2015. Her research interests include resource management and optimization in next generation wireless networks. She has authored nearly 40 papers in well-recognized journals and conferences. She is serving as the lead guest editor for the special issue on NOMA techniques under EURASIP JWCN.

FENG HONG received his Ph. D. in 2006 from Shanghai Jiao Tong University, China. He is now a full professor with Department of Computer Science and Technology, Ocean University of China. His current research interests include smart sensing, sensor networks and ubiquitous computing. He has authored/co-authored more than 100 technical papers in major journals and conferences on the topic of sensor networks and ubiquitous computing such as ACM COMPUTING SURVEYS, CHI, and Infocom etc. He is also one of the authors of IEEE 1851 standard. He is a member of IEEE Communications Society and IEEE Computer Society. He serves as an Editor for International Journal of Distributed Sensor Networks.

YONGQUAN LIANG received his MS degree in Computer Science from Department of Computer Science, Beijing University of Aeronautics and Astronautics in 1992, and Ph.D. degree from Institute of Computing Technology, the Chinese Academy of Sciences in 1999. He is now with School of Computer Science & Engineering, Shandong University of Science and Technology. His research interests include artificial intelligence, cloud computing, big data analytics and decision making.

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