Survey on underwater delay/disruption tolerant wireless sensor network routing

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Abstract: Underwater wireless sensor networks (UWSNs) have recently received a significant amount of attention. Since they have delay/disruption-tolerant networks (DTNs) characteristics, the design of any UWSN scheme must take DTN influences into account, especially in routing protocols. Many researchers have proposed various DTN routing techniques for different types of DTN routing schemes in UWSNs. The authors survey state-of-the-art DTN routing protocols, and use the definition of DTN to classify these proposals into scheduled contact, opportunistic contact and predicted contact. Furthermore, the authors analyse the detailed information in order to draw up a comparison table and also expect to inspire more research into this topic in the future.

1 Introduction

Since most terrestrial resources have been mined almost to exhaustion, companies have begun to look for new areas to exploit. These new areas include any regions that can be reached, but have not yet been explored. There has been increasing interest in such unexplored areas [1], with areas on the seabed attracting significant attention, since some resources under the ocean are easier to reach than those in outer space or the earth’s core. To detect such undersea terrain, biological ecosystems or resources, a large number of sensors distributed around the field of interest is required [2]. These distributions of sensors differ from terrestrial wireless sensor networks (WSNs) in that the transmission media in these environments mean that they have different transfer rates [3, 4]. Although many different types of media can be used on land and under the sea, such as acoustic transmission, radio frequency (RF) electromagnetic wave transmission and optical wave transmission [5, 6], in general, acoustic transmission is most commonly used in seabed environments [7]. However, it is well known that the speed of underwater acoustic transmission is slower than in air. Thus, the methods of routing, localisation and other schemes are not the same as in terrestrial WSNs [8–11]. Some researchers therefore classify these networks as a new type of network, called underwater wireless sensor networks (UWSNs). Rapid technological advancement and high demand for such networks has made UWSNs one of the hottest topics in WSN research today.

Whether the wireless sensors are on land or under the sea, their basic functions include information collection, detection, measurement, and so on. To ensure that these functions are available, routing mechanisms are a very important part of the overall network architecture. This is because a well-designed routing protocol can avoid data collision, increase performance and reduce power consumption [12, 13], so the required information can be successfully obtained. Both WSNs and UWSNs encounter very similar problems, however, UWSNs design take uncertainty into account. This leads to a continuously varying network topology which is very difficult to control. This uncertainty phenomenon refers instances in which some underwater sensors are unable to communicate with each other since their times do not have a synchronous connection. Both acoustic and RF transmission are slowed down, since they must travel through the refraction of water to reach their destinations, however, the refractive index is different at different angles [14]. Another cause for sensors’ inability to communicate with each other is that the sensors are affected by ocean currents, which have uncertain mobility, so sensors are unable to obtain correct location information of any other sensors in an epoch [15]. All these phenomena result in the entire UWSNs having a high delay, and even a high probability of disruption environment. Therefore, it is important to develop delay/disruption-tolerant network (DTN) schemes to address issues arising from such scenarios [16, 17]. To summarise, UWSNs must have DTN characteristics, and these characteristics must be taken into account when designing UWSN routing schemes.

According to the definition of DTNs, routing schemes are divided into two categories: scheduled contact and unscheduled contact. Unscheduled contact is subdivided into two subcategories: opportunistic contact and predicted contact. These mechanisms have been overviewed in previous studies. All of these schemes have their own
characteristics, and are each suitable for specific situations. However, their shared goal is to ensure better link quality, although the biggest difference between them is their contact methods. These are described in more detail in the following sections.

The remainder of this paper is organised as follows: In Section 2, we first introduce the categories of DTNs, mainly divided into scheduled contact and unscheduled contact, as well as the unscheduled contact subdivisions of opportunistic contact and predicted contact [18]. Next, the evaluation metrics are introduced in Section 3. In Sections 4–6, we briefly discuss related literature and analyse advantages and disadvantages of the various categories in order to provide comparisons between the related studies. Finally, we conclude this survey in Section 5.

2 Background

In general, UWSNs are always regarded as DTNs since they exhibit network intermittency, high delay and their transmission rates are asymmetric. Because of these adverse underwater conditions, DTNs must be able to tolerate high delay for extended periods of time, as well as synchronise transmission rates. Over the past few decades, a considerable number of studies have been conducted on UWSN DTN routing. In this section, we introduce some of the more popular routing protocols. According to various routing methods (the types of contacts), DTNs can be classified into scheduled contact and unscheduled contact [19, 20]. We will therefore first give a brief introduction to these two types of routing.

2.1 Scheduled contact

Some DTNs use scheduled contact as a routing method. Generally, scheduled contact assumes that the whole network is in an orderly environment. The orderly environment means that any links are direction-specific, and connect periodically. However, there are some factors of uncertainty in UWSNs, such that the direction can sometimes not be determined, and this asynchronous environment means that the connection cannot be made periodically. In order to address these issues, the base station is used as a solution for schedule arrangement. The main concept is that the base station must ensure the necessary connection between any two nodes that want to communicate, but they may often break the link since they are in an uncertain environment. The base station, then, must have a priori knowledge of the schedule of all sensors. In simple terms, the base station acts as a scheduler and a relay node at the same time. As long as sensors are deployed around the base station, and both the sensors and the base station have absolute links, then this network environment is viable, as shown in Fig. 1.

2.2 Unscheduled contact

Unscheduled contact assumes that any packets or sensor processes cannot be scheduled. In other words, even if the network situation is observed for an extended period of time, it does not exhibit any form of regularity. In general, any schemes for this environment must operate with themselves. Although such conditions are particularly harsh, we still can subdivide unscheduled contact into opportunistic contact and predicted contact, according to whether the scheme uses a global collector (relay/sink).

(1) Opportunistic contact: Base stations are not suitable for certain scenarios, such as bio-ecological monitoring, deep sea mineral detection, the submarine rescue, and so on. In these cases there is very limited available time to deploy the network, or sensors’ positions may vary over each epoch. In other words, because the target has a higher mobility, base stations cannot be effectively established in the vicinity, since planning costs would be wasted because the base station would not be able to cover the entire target. Therefore, we must deploy relays instead of a base station. If any two sensors want to communicate with each other, but cannot create a direct link, they can convey information through these relays. These relays are similar in concept to a relay node, and have a feature similar to a buffer. When a source sensor wants to send data to a destination, it will copy the information to relays, and then wait until the next hop sensor meets one of them. It should be clear now that this method is based on the probability of the occurrence of the next link. The scheme is shown in Fig. 2.

(2) Predicted contact: In some cases, the contact restrictions are more lax than in scheduled contact or opportunistic contact. There are no base stations, sinks or relays in these situations, and thus no scheduling or forwarding. In short, this is a very simple mode of communication, dependent only on the current situation to establish a connection. Therefore, a prediction scheme is needed. Since such
contact is not scheduled, predictions must be made after previous observations have been analysed. These observations include the movement trajectory, relative position, traffic flow or past frequencies of contacts, and so on. No matter which metric is used, errors almost always occur. However, it is difficult to deploy deep-sea relays and base stations, and thus a well-designed prediction mechanism becomes essential. This scheme is shown in Fig. 3.

This scenario is usually based on the community model, which assumes that the entire network is divided into several communities, and for any two sensors to communicate with each other, they must be in the same community.

3 Evaluation metrics

To effectively evaluate the performance of UWSN routing, it may be helpful to consider some important metrics for these mechanisms [21]. Although each environment is different, we can still be fairly certain that any situation will exhibit the following challenges, which are also widely used in the related literature.

3.1 Average end-to-end delay

The end-to-end delay is one of the most critical evaluation metrics in any wireless network. Since there is an immediate demand for many services or applications [22], this requirement exists not only in end terminals, but also between any two sensors. The sensors must exchange their own information in an epoch. If a sensor cannot send its packet to another sensor on time, coverage holes will occur. This means that the current topology will not be established, since part of its exploration is missing. The end-to-end delay also is a fundamental metric that significantly affects other factors, for example, increased power consumption, packet loss and collisions will occur with any incurred delays. Furthermore, the considered environment is a DTN, so that the overall network delay will face more demanding challenges.

3.2 Packet delivery ratio

Packet delivery ratio is defined as the ratio of packets received successfully at the sink to the total number of packets generated from the sources. Since a UWSN is a mobile and uncertain scenario, it is impossible to obtain information on the next hop sensor at any place or time. Even if the current sensor is able to obtain the next hop sensor on time, the connection between them may still be interrupted if one of them has moved out of the transmission range. The packet will therefore not arrive at its destination, and the delivery ratio will decrease. From the above, the packet delivery ratio is a metric that ensures the required information is not lost, and the fundamental function of a UWSN will operate normally.

3.3 Energy consumption

In general, sensors must monitor an area for a long time in order to obtain comprehensive and accurate information. However, sensor lifetimes, and thus the network lifetime, are dependent on their battery life [23], so it is desirable that not all sensors operate at the same time [24]. Sensors may exist in three states, awake, asleep and idle, respectively. The main purpose of this is to schedule the working time of each sensor according to the relationship between the states and the area of interest. Note that this issue is not unique to UWSNs, and is also of significant importance in terrestrial WSNs. However, an important point to emphasize is that the high mobility and uncertainty of UWSNs significantly affect their scheduling. For instance, if a sensor wants to create a link to a destination, but is unable to find the next hop for a long time, that sensor will have to retransmit the request packet until the next hop sensor is found. In this case, the sensor will spend a significant amount of time waiting and retransmitting, thus increasing its overall power consumption. From this, it is clear that UWSNs face greater challenges to power conservation than do terrestrial WSNs.

4 Scheduled contact schemes

Scheduled contact schemes are a practical mechanism due to their architecture, or the fact that they have a powerful component, called a base station. The base station has greater computation capability, so it is responsible for dealing with most of the complex work, such as resource allocation, relieving traffic loading and maintaining connectivity. This means that the base station is the manager, agent and connection keeper. In brief, it is possible to manage an entire network through a base station. Many schemes focusing on the base station have been developed, and we will introduce them in the next subsection. The comparison table is shown in Table 1.

4.1 Depth-based routing (DBR)

Hai Yan et al. [25] proposed a mechanism that requires only sensors’ local depth information. Depth information is in a two-dimensional space, at most, as opposed to full-dimensional information, which requires more transmission power, transmission time and computation ability. In addition to using the plain data by depth information, they planned many sinks on the water surface, which provided a lot of help for data collection.

The main concept here is that the sensors know their own depth information. Before the packet forwarding algorithm begins running, the depth threshold was defined, and then used to determine the qualified forwarder. When a node
Table 1 Comparison of scheduled contact schemes

| Schemes                                      | Algorithm type | Simulator            | Important assumption                                                                 | Advantage                                      | Disadvantage                                                                 | Suitable environment               |
|----------------------------------------------|----------------|----------------------|--------------------------------------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------------------------|------------------------------------|
| depth-based routing [25]                     | greedy         | NS2-aqua-sim         | when a data packet arrives at any sink, it can be delivered to other sinks or remote  | achieves very high packet delivery ratios     | the depth threshold cannot be defined as too large                            | it has good performance in dense networks                                     |
| method by Yujun Li et al. [26]               | greedy         | —                    | all the sensor nodes are distributed over the geographic region S (Xbs, R) according  | can be easily extended to other underwater    | the probability calculation will incur more power overhead and more end-to-end delay | it has good performance in homogeneous Poisson process network               |
| delay-tolerant data dolphin [27]            | —              | QualNet-modified as  | each stationary sensor already knows its position and dolphin nodes are supposed to    | saving more battery power                    | the dolphin still has greater uncertainty                                      | periodic monitoring applications                                           |
| HydroCast routing protocol [29]             | greedy         | QualNet              | have large memory and energy reserves each node measures the pairwise distance via    | can perform offline calculation to reduce the computational cost | sensors must be ordered                                                        |                                    |
|                                               |                |                      | time of arrival (ToA)                                                               | more in line with real world and reducing the power consumption |                                                                                |                                    |
| link-state based adaptive feedback routing   | —              | C++                  | the beam width is θ (0 < θ < 360), then the communication range of the node becomes  | not suitable for high dynamic environment     |                                                                                 | 3D environment                     |
| [30]                                         |                |                      | θ/360 times when the beam width is not considered                                  |                                                                                |                                                                                |                                    |

received a packet, it had to obtain a forwarder from the set of sensors determined to be qualified forwarders. As long as the difference between the depth of the packet’s previous hop and the depth of the current node is larger than the threshold, the node can be seen as a qualified forwarder. In short, the depth is an expression of distance that limits the number of forwarded packets. This is because the authors considered that if the forwarding node was closer to the destination, its depth was also smaller, so the sensors other than that related to the distance difference is not considered, and power consumption is thus indirectly reduced. The authors therefore consider the depth threshold to be the tradeoff between packet delivery ratio and energy consumption.

However, the DBR does have the following drawbacks. If the depth threshold defined is too large, it may lead to a decreased delivery ratio since there will be fewer forwarding nodes in the transmission range. We can thus confidently surmise that this routing mechanism is only suitable for dense networks, otherwise, higher delay and higher power consumption will be incurred.

4.2 Method by Yujun Li et al.

Yujun Li et al. [26] proposed a mechanism which states that greedy routing can successfully deliver a packet to its destination if a node has at least one neighbour within the base station’s transmission range. This is a typical example of the scheduled contact routing method, since the base station is responsible for managing most of the works. In other cases, some sensors may not have any neighbours to forward the packet to, so there is no way for the packet to reach the base station. Since the authors assumed that this situation will always be present in UWSNs, they began to analyse the relationship between the probability of the existence of void sensors and the probability of guaranteed delivery. They then used the calculated probability to derive the upper bound of the critical transmission radius that converges that the sensor will avoid to find the void sensors be a forwarder. In other words, they exclude as much as possible the possibility that the next hop sensor will be unable to directly connect to the base station. However, underwater networks are a mobile environment, with a great deal of uncertainty, and as a result the probability calculation will require more power overhead, and incur more end-to-end delay.

4.3 Delay-tolerant data dolphin (DDD)

Eugenio Magistretti et al. [27] proposed delay-tolerant data dolphin (DDD). This mechanism uses many stationary sensors fixed to the seabed, which perform uninterrupted information collection, and a few mobile collector nodes called dolphins. The seabed sensors send the collected information to the nearest dolphin within one hop. Dolphins move randomly within the region of interest, and the seabed sensors can receive the periodic beacons from the dolphins to confirm that the dolphins are present, as well as whether their current position is within a short one-hop distance. The dolphin then forwards the packet to the base station when it receives a packet from a seabed sensor. However, the current position of a dolphin may not be within the communication range of the base station. In this case, it will store the information in its memory until it can create a connection with the base station. According to the above descriptions, it is clear that the dolphins are an important component in this mechanism. However, some required
too much traffic and the speed of the dolphins $v$ to derive the period $t = r/v$. This calculated period $t$ ensures that the dolphin is within the communication range of a seabed sensor in the specified epoch. However, the dolphin also has an uncertainty factor that may cause delay if the dolphin does not move into the communication range.

4.4 HydroCast routing protocol

Uichin Lee et al. [29] exploited sea floor pressure levels to deliver packets to surface sinks. They consider pressure to be a key factor in UWSNsug, because the bandwidth of an underwater acoustic channel is not sufficient to withstand too much traffic, and the transmission speed of an underwater acoustic channel is slower than the speed of a terrestrial transmission; one study shows that the propagation latency is almost five orders of magnitude higher than that of a radio channel [31]. This phenomenon is more obvious as depth increases. In order to address this shortcoming, depth information plays a very important role. However, to measure the depth of each node is very difficult, since the widely used 3D geographic localisation requires more computation cost. Therefore, the authors used onboard hydraulic pressure gauges to obtain depth information, which was then sent back to the monitoring centre. This method allows some localisation mechanisms to carry out offline calculating.

In addition to depth, there is a relationship between the distance and channel signal strength, such that the greater the distance, the greater the signal attenuation encountered. The authors thus derived the following equation

$$
\frac{d_P^0}{1/P_n} = d_P^0 \times P_n
$$

Equation (1) is a normalisation, which represents that a neighbour node $n$ has a packet delivery ratio $P_n$ to progress to the destination for a given sensor. When the relationship between the distance and the delivery ratio is found, and combined with an analysis of the signal-to-noise ratio (SNR) over distance $d$, the main forwarding strategy will be produced using the result. The concept is that a sensor that is closer to the destination and that has a higher delivery ratio, updated from the SNR analysis, will have a higher forwarding priority. They also presented a ‘dead end’ recovery method based on the proposed HydroCast routing protocol to provide better routing efficiency [32].

4.5 Link-state-based adaptive feedback routing

Song et al. [30] also focused on the 3D underwater routing. They consider that every node can send the signal to any direction even if their technologies and structures of acoustic transducer are different, and they have a slight gap only that just affects the beam width without global impact. Furthermore, there are many factors that affect the linked states, such as the angle, the transmission radius and the interference. Based on the above viewpoints, they have plenty of reason to assume that the underwater routing not only has the symmetric situation but also has the asymmetric situation. Finally, their proposed methods follow such observations to design an energy-efficient routing mechanism.

There are two important parts of link-state-based adaptive feedback routing: the routing discovery and the routing maintenance. In the routing discovery, link states are the necessary information for each node to determine whether the encountered situation is symmetric or asymmetric. The main idea is that if a node ID exists in the downstream and upstream nodes table at the same time, then this link is called symmetric link. When the link states are determined then the routing query will start, and the query rules must be according to the routing information of each node. In this paper, the most important is the feedback mechanism. After the query is completed, the kind of link states may affect the way of feedback. Since the symmetric link is more stable, the feedback message takes the path reversal method directly. Otherwise, the asymmetric link belongs to a kind of the random process so that the feedback message forwarding must be through the relay node using the reverse routing search method. In order to balance the influence caused by the asymmetry, the forwarding strategy used the time-based priority as the main sort order, and the sink node will wait for the else messages when it received the feedback message sent by first feedback message, so that this method can achieve the aim of DTN.

5 Opportunistic contact schemes

Opportunistic contact schemes create links by chance, meaning that this category of contact is not scheduled. In simple terms, any sensors that want to send packets rely on the chance movement of mobile relays/sinks or transmission mediums into their transmission ranges. While the unscheduled situation involves significant uncertainty, it has greater scalability for coverage extension, the addition of new sensors and other applications. The opportunistic contact situation has a self-organisation feature. We give examples of this type of contact scheme in the following section, and comparisons are shown in Table 2.

5.1 Zheng Guo et al. proposed method

In some scenarios, it is difficult to deploy a base station, such as in space exploration, volcano resource detection and other areas that have harsh terrain constraints. For the above reasons, it is clear that such scenarios require a specialised routing protocol. Zheng Guo et al. [33] proposed a method for application to water pollution surveillance. Pollution incidents occur sporadically, and underwater sensors must therefore be distributed over the entire area of interest, with a few sinks on the sea surface, ready to detect pollution incidents as and when they occur. In general, water pollution surveillance is divided into two modes, one is the change of quality of water in a stable state, and the other is a sudden pollution event. The former assumes that the changes under the water can be mastered, since there are no significant changes, and the user only intermittently detects and handles these stable data. The latter assumes that emergencies may occur which require a higher priority, transmitting data to the base station as soon as possible. This method divides the area of interest into several levels, distinguished according to depth. The underwater sensors are deployed at different levels, and can move freely in their own level. The important assumption is that all
sensors can obtain their three-dimensional coordinates via a centralised server. Since the primary goal is to achieve an adaptive routing protocol, the trade-off of the packet transmission becomes an important point. Some routing mechanisms use the packet emergency level as the key metric for deciding on packet transmission. The authors state that the packet priority should be based on the packet characteristics in order to make a reliable decision. The HELLO packet must include information on the packet emergency level, packet age, node spatial–temporal density and node battery level. This information can then be used to make the trade-off. Each sensor will periodically broadcast HELLO packets so that all sensors can obtain each sensor’s information and current position, and then decide whether the received packet should be dropped. The packet priority value is calculated by the packet emergency level $E$, packet age $A$, node spatial–temporal density $D$ and node battery level $B$. The priority $P$ is calculated as

$$P = \alpha_1 E + \alpha_2 A + \alpha_3 D + \alpha_4 B$$  \hfill (2)

$$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$$  \hfill (3)

$$\alpha_1, \alpha_2, \alpha_3, \alpha_4 \in [0, 1]$$  \hfill (4)

Since the authors are only concerned with the potential forwarding opportunity, the priority calculations only occur when a new neighbour is added. Once the sensors have calculated the packet priority, they can make the routing decision. The authors proposed a new concept, called a forwarding area. Each state $i$ has a corresponding forwarding area $A_i$, represented by the intersecting regions of two spheres. Sensors have higher priorities corresponding to larger forwarding areas. This means that the higher the priority a sensor has, the higher the probability it has of contacting other sensors which move into the forwarding area.

5.2 Tiansi Hu et al. proposed method [34]

To address the adverse characteristics of underwater communications, Tiansi Hu used the $Q$-learning technique to develop ways to deal with the dynamic changes resulting from the uncertainty of underwater environments. First, they defined all components by the Markov decision process (MDP), which are states, actions, state transition probabilities and rewards for taking actions at states, respectively. The MDP is associated with state-action probabilities and rewards for taking actions at states, represented by the intersecting regions of two spheres. Sensors have higher priorities corresponding to larger forwarding areas. This means that the higher the priority a sensor has, the higher the probability it has of contacting other sensors which move into the forwarding area.

Table 2. Comparison of opportunistic contact schemes

| Schemes                        | Algorithm type   | Simulator       | Important assumption                                                                 | Advantage                                           | Disadvantage                                         | Suitable environment  |
|--------------------------------|------------------|-----------------|--------------------------------------------------------------------------------------|-----------------------------------------------------|------------------------------------------------------|------------------------|
| Zheng Gu et al. proposed method [33] | greedy           | —               | all sensors know their 3D positions through a certain localization service            | achieves a good trade-off between delivery ratio, delay and energy consumption | if there is low mobility, the packet priority may not be changed | it has good performance in sparse networks              |
| Tiansi Hu proposed method [34]  | reinforcement learning | NS2            | only possible to communicate with sensors in the same layer and the neighbouring layers | it has self-learning ability, thus achieving the effect of adaptive | it needs large buffer space; if there are high delays | layered architecture                                          |
| RBAR [35]                      | greedy           | J-Sim           | the node buffer is assumed to be infinite, and no overflow happens                   | they not only consider single application requirements, but also multiple application requirements | needs extra memory space to save training information | delay requirements are different                         |
| D. Dario Pompili et al. proposed method [36] | greedy           | NS2-HydroCast   | no forward error correction                                                           | decreases PER                                       | high mobility will lead to accelerated hop count growth in dense network can incur increased power consumption | suitable for a situation which is relatively stable          |
| CARP [37]                      | greedy           | NS2-aqua-sim    | sensor nodes in UWSNs are equipped with some special devices                         | high packet delivery ratio                          | high packet delivery ratio                             | suitable for a situation which is relatively stable          |
| vector-based forwarding (VBF) [38] | greedy           | —               | all sensor nodes know their own locations through a certain localisation service, and the sink nodes are stationary | high adaptability of obstacles                      | in high mobility environment, the evolution time cannot keep up the impact of moving | low mobility or static. The environment has barriers        |
| MFA [39]                       | evolutionary      | NS2-aqua-sim    | all sensor nodes know their own locations through a certain localisation service     | high adaptability of obstacles                      | in high mobility environment, the evolution time cannot keep up the impact of moving | low mobility or static. The environment has barriers        |
\[ V^\pi(s) = E_{\pi}\left[r_i + \gamma \sum_{k=1}^{h} P_{s_{t+1}}^a r_i(s, a)|s_{t+1}\right] \]  
\[ Q(s_t, a_t) = r_i + \gamma \sum_{s_{t+1} \in S} P_{s_{t+1}}^a \max_a Q(s_{t+1}, a) \]

The reward is an important factor of the Q-learning process. The authors suggest that the residual energy and density have the greatest influence on UWSNs. Next, they defined the reward related to density \(D(m)\), and the reward related to residual energy \(E(m)\). However, \(D(m)\) and \(E(m)\) have a trade-off relationship. There are many sensors in an area, so the forwarding chance will increase, but energy consumption will also increase. The reward can therefore be found by the following formula

\[ r_i(n, m) = H(n, m) + \alpha E(m) + BD(m) \]

where \(H(n, m)\) represents a distance relationship between \(n\) and \(m\). The main concept is that the authors expressed the distance relationship between any two sensors under three situations: (i) in a layer closer to the sink, (ii) in the same layer and (iii) in a layer farther from the sink. They use this expression to make a decision when a DTN feature occurs. In short, they formulate an MDP model to express a relationship between these states, actions and rewards, which is used by the Q-learning algorithm. They use an equation to make a definition of the trade-off between energy consumption and performance, and propose a reinforcement learning technique to achieve an adaptive and energy-efficient routing protocol. However, the learning algorithms almost have more time lead. In [40], they used the concept of the multi-level to increase the routing performance.

5.3 Redundancy-based adaptive routing (RBAR) [35]

In general, DTNs mechanisms usually use several copies to increase the probability of contact with the next hop node, because they must make a large number of contact attempts before they can create a route. This results in increased overhead. Therefore, researchers began to explore a means of setting the trade-off between the overhead and performance. However, once the authors observed the real environment, they realised that different UWSN applications required different metrics and limitations for packet forwarding. Some need to be able to tolerate delay, while some have timeliness requirements. This shows that a switch scheme is necessary.

Zheng Guo et al. proposed a redundancy-based adaptive routing scheme called RBAR. In order to address the DTN issues, RBAR allows sensors to keep packets for as long as possible until one of its copies meets the delay requirement. The forwarding procedure of a packet is based on a continuous Markov chain with an absorbing state. All sensors use a binary tree-based forwarding procedure to achieve a common replication sequence. The copies will increase over time, therefore the main goal and motivation are to decrease the number of copies but still ensure high opportunities to establish multiple potential routes to the destination. Although the inter-contact times of all sensors are independent and identically distributed, they can be easily analysed via the binary tree-based forwarding procedure with continuous Markov chain. Finally, the minimum number of copies is derived by RBAR, while the delay tolerance time is usually lower than the upper bound of the delay distribution.

5.4 Dario Pompili et al. proposed method

Dario Pompili et al. [36] observed a situation in which there was a trade-off relationship between the efficiency of the acoustic channel and the packet error rate, since increasing the efficiency of the acoustic channel requires longer packets, and decreasing the packet error rate on each link requires smaller packets. However, packet size directly affects power consumption. In other words, there is a contradictory relationship between them. The authors suggest that a high success rate can still be maintained, without increased power consumption, even when using short packets. In response to these shorter packets, the channel must be so hard that the single-packet transmission scheme can be successfully applied. In order to solve the packet error by short packets, the authors exploit the concept of a packet train. The main concept is to allow a sender to transmit a train of short packets back-to-back, without releasing the channel. In other words, the train can collect ACK from any neighbours. This means that a train includes partial topology information which is integrated via its neighbours.

The establishment of the routing is based on basic greedy mode and recovery mode. This means that a sensor forwards a packet to the next hop sensor while the next hop neighbour is found, otherwise, it goes into recovery mode, which lets this packet go back to the last hop sensor. In particular, it allows each node to jointly select its best next hop sensor so that it compares the trains. This method can reduce packet size, and thus decrease power consumption. In addition, the authors defined a retransmission rule, since they believe a selective repeat approach that can avoid significant overhead generation.

5.5 Channel-aware routing protocol (CARP)

Stefano Basagni et al. [37] proposed a cross-layer routing protocol for UWSSNs called the channel-aware routing protocol (CARP). In the previous studies, some methods used the control packets to book an idle channel, and to decide the next hop relay closest to the sink. This control packet is a short packet which has a fast transmission characteristic, so even the use of low-power transmission is not subject to interference. Since this method is effective for UWSSNs, it has been widely used. Although the use of shorter control packets can increase the transmission efficiency, it can also mean that the shorter control packets cannot include longer distance information in low-power situations, especially in a rapidly changing environment. In short, the main motivation and goal is to find a way to correctly select the relay.

To solve the bit errors caused by the use of shorter control packets to select the next relay, the authors defined a hop
count HC(x), which is a set in each sensor. It includes distance and hop information. The hop count of a sensor will add 1 when it receives a HELLO message. The highest ratio HC (x) sensor is selected as the relay, since it represents that sensor was functional in the last few moments. After the computation of the relay judgment, they can obtain a set of viable relays. The proposed CARP will choose the viable relay with the highest residual energy as the final decision relay. The authors use the hop count to define the availability of relays, and base the relay selection on remaining power in order to achieve low end-to-end delay, energy consumption and a low packet error rate (PER).

5.6 Vector-based forwarding (VBF)

Peng Xie et al. [38] proposed vector-based forwarding (VBF) to address issues encountered in UWSNs. VBF assumes that a sensor cannot find a best next relay by itself. The authors suggest that in order to make the best decision, each of the sender’s neighbouring nodes must be involved. In simple terms, the sensors monitor each other, and thus recognise each sensor’s relative position. The main concept is that every packet must include the position information of sensors and relays. The routing vector represents a packet forward path from the sender to the destination, and the routing vector is regarded as the virtual pipe. A sensor’s relative position is computed when the packet is received. If it is close enough to the virtual pipe, then this sensor can save its own information in the packet, and thus forward that information, including the position, remaining power, and so on. To ensure the forwarder is able to forward packets, they make a threshold to measure its capacity to do so. They also defined the time interval for packet forwarding in order to minimise the impact of mobility.

The authors proposed a location-based routing protocol that is robust and has high scalability. Importantly, they used a very simple method to achieve a high data delivery ratio. Since this method has a strong structure, some researchers try to consider more metrics in it; for instance, the network lifetime [41] or energy consumption [42]. As a result, we can see that this method has become the foundation of many studies, hence there are some VBF-like methods that have been proposed [43].

5.7 Multi-population firefly algorithm (MFA)

Firefly algorithm is an effective method for the signalling system. In the basic characteristics of WSNs, the signal may have intermittent characteristics. Ming Xu et al. [39] believe that this phenomenon must be considered. Firefly algorithm belongs to the evolutionary algorithm category. It suits for parallel processing and is applicable to the WSNs and distributed systems. However, the original Firefly algorithm cannot deal with some cases that have many stochastic factors, such as fish interference, ship, tides and some barriers, and the UWSN has more mobility which can affect the localisation accuracy. In order to avoid the influence of the obstacle, the authors used the three fireflies as the capturer for the detection of network mobility properties. Compared with the original Firefly algorithm, this method is more reliable.

This algorithm design is based on the time-to-live value. In this way, it can reflect the neighbouring situation directly. Even the physical phenomena cannot be changed, so the authors used the concept of point-to-point (P2P). The sink nodes are like the P2P power node that is responsible for collecting any data. If any route between the sensor node and sink is interrupted, then they will find the other node which still has the ability to connect with sinks. In case the capable nodes are not found, the general sensors will hold the data until it finds out the capable nodes. As a result, DTN environmental impact will be minimised.

6 Predicted contact schemes

The predicted contact environment is a form of unscheduled contact. The difference between predicted contact and opportunistic contact is that the uncertainty of a predicted contact environment is higher than that of an opportunistic contact environment. The viewpoint of the architecture is that a predicted contact environment does not have relays or sinks, and many previous studies have therefore focused on its self-organisation characteristics. The comparison table is shown in Table 3.

### 6.1 Prediction-based delay-tolerant protocol (PBDTP)

Zhanyang Zhang et al. [44] proposed a prediction-based delay-tolerant protocol (PBDTP) to solve the long delay problem. Previous studies have used the round-trip-time (RTT) as the benchmark for estimating the transmission time between any two sensors. However, sensors did not obtain the RTT packet in the same time, since the obstruction and propagation rates were different in the underwater environment. Therefore, from this point of view RTT is not a fair indicator.

Thus, in order to achieve an accurate RTT estimation, it is necessary to use a unique prediction approach. To ensure the reliability of the mechanism, the authors used a cluster base as

| Table 3 | Comparison of predicted contact schemes |
|---------|---------------------------------------|
| Schemes | Algorithm type | Simulator | Important assumption | Advantage | Disadvantage | Suitable environment |
| PBDTP [44] | heuristic | — | if time interval is short enough and distance gap is close enough, then the values are the same | decreases end to end delay | timeout is difficult define | suitable for a situation which is relatively stable |
| PASR [45] | greedy and heuristic | — | the destination node must know the trends of movement direction of source nodes | low communication overhead high accuracy | requires large memory to store the results from ACPG broadcast overhead is too large | low mobility environment |
| SBR-DLP [46] | greedy | — | the network operates in a slotted manner | — | — | full mobility environment |

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their primary architecture. In this, the cluster head plays the role of a sink. They then defined five states for all sensors: Idle state, SendingCRP state, WaitingConverge state, ReceivingSRP state and DataSending state. The cluster head is defined as being in six possible states: Idle state, WaitConvReg state, NoteReg state, SendingSRP state, Wait state and Predict state. The first five states are basic sensor functions. Most importantly, the sixth cluster head states can be triggered when the data packet arrives within the timeout period, but the head does not return to the SendingSRP state and reruns the same cycle. In short, if there are no expected data packets that are received from the target sensors within the specified time, it is likely that the data packet has been lost. At this point, the cluster head can use previous data to predict the data value and return to the SendingSRP state. The main concept of this prediction scheme is to meet the two hypotheses based on the rule of thumb. The authors suggest that as long as the time interval is short enough, the former value can be very similar to the latter, and while the distance gap is small enough, the values of these sensors will be very similar.

6.2 Prediction-assisted single-copy routing (PASR)

Many previous studies have used multiple copies to establish communication. However, the dramatic changes in UWSNs mean that some copies simply cannot accomplish their tasks, and the overhead will thus increase. Therefore, Zheng Guo et al. [45] suggest that if a single copy can successfully establish a route, the use of multiple copies would be superfluous.

Before the prediction method can be used, they must obtain the common characteristics between the near optimal routes. The authors proposed an aggressive chronological projected graph (ACPG), the concept of which is to integrate the dynamic network topology and connectivity into a single graph \( G(V, E) \). They can thus consider this chronological information as the mobility pattern, and this mobility pattern is the key to determining the optimal route. In simple terms, this method is similar to the set cover method which can compare common elements in a union of several sets. The element found means that it can make connections to its neighbours. When this result combines with the concept of time, the underlying mobility pattern can be derived easily.

The mobility pattern can be observed for a long time, and collected for PASR. PASR treats this long-term observation as historical information. According to the geographic preference and contact frequency, a route which has a better chance of delivering the packet to the destination can be predicted, because the next hop sensor has more neighbours and higher stability. This ensures that the link cannot be easily broken.

The authors use the ACPG to collect the historical information. They thus use PASR to determine the optimal route, and this single-copy method is able to reduce unnecessary overhead. The detail prediction update procedure has been analysed in [47].

6.3 Sector-based routing with destination location prediction (SBR-DLP)

Nittitha Chirdchoo et al. [46] proposed sector-based routing with destination location prediction (SBR-DLP), which can be applied in fully mobile UWSNs. A fully mobile environment is one in which all nodes will definitely be moving. This situation results in low connectivity, and may also cause the acoustic channel to encounter shadow zones. Some studies have assumed that sensor locations are known, and that all sensors can recognise each other’s positions. However, this is not a realistic description. Therefore, the authors suggest that the routing protocol must have a location-prediction capability.

In this environment, the destination node must be a mobile receiver, and it can pre-move to an appropriate position so that it can successfully receive data. The main concept is that the destination node will move according to observed trends of movement of source nodes. However, some sensors may move off track. Accordingly, finding the next relay node is an important issue. The authors introduced the concept of greed. They suggested that a node nearest to the destination node, even if it was off track, does not have serious impact, because the moving node will send the packet before it moves out of the transmission range. In the best-case scenario, it may still be the nearest node to the destination. However, this method requires periodically broadcasting the notification (NTF) for each sensor so that all sensors can obtain the up-to-date information. This step means that the cycle of all sensors can be calculated. The time cycle information makes the analysis of trends in the mobile environment more accurate.

7 Conclusions

Since UWSNs exist in a uniquely harsh environment that includes high latency and high mobility, many researchers have developed various techniques, proposing different types of strengthening mechanisms for DTNs. In this paper, we first describe UWSNs and their DTN characteristics. We then introduce some recent studies on scheduled contact, opportunistic contact and predicted contact. According to our observations, we found that most scheduled contact schemes showed good performance for UWSNs. While they incur greater cost for base station planning, their effectiveness in long-term monitoring means that they are still worth the investment. Opportunistic contact can be used for semi-known environments such as in fishing activities, which are dependent on ocean currents. Finally, unscheduled contact schemes are suitable for the exploration of unknown environments.

These routing protocols have their own suitable environments and applications [48], no matter what kind of contact type is used. This paper will benefit researchers, and make this research field more complete. Everybody knows that routing protocols are the fundamental way to send data. Nevertheless, the routing is just not enough for constructing an entire UWSN. The high performance and the long enough network lifetime are the necessary conditions for maintaining the basic functions of UWSNs. Since the routing schemes may be affected by some mechanisms from other fields, we will investigate the awake/asleep scheduling schemes, planning of sinks and security issues in our future works to make this research field more comprehensive.

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