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Survey on Recent Advancements in Energy-Efficient Routing Protocols for Underwater Wireless Sensor Networks

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ABSTRACT Underwater wireless sensor networks (UWSNs) have become highly efficient in conducting various operations in maritime environments. Compared to terrestrial wireless sensor networks, routing protocols in UWSNs are prone to high propagation delay, high energy consumption, low bandwidth, and low throughput. UWSNs are remotely located and operate without the need for human intervention. Most sensor batteries are energy restricted and very difficult to replace. One of the major challenges of UWSNs is the uneven utilization of energy resources, which reduces the network lifetime. Therefore, an energy-efficient routing mechanism is necessary to overcome the aforementioned problems. Many significant studies have attempted to realize this goal by designing energy-efficient routing protocols to provide efficient packet routing from source to destination. In this paper, we focus on discussing various energy-efficient routing protocols that are currently available for UWSNs, categorize them with a new taxonomy, and provide a comparative discussion. Finally, we present various research problems that remain open and challenges for future research.

INDEX TERMS Acoustic communication, energy efficiency, maritime environment, network lifetime, routing protocol, underwater wireless sensor network.

I. INTRODUCTION

Oceans account for approximately 96.5% of all terrestrial water. The ocean is therefore an immensely important component on Earth for the survival of humans and other living organisms. Unfortunately, approximately 95% of the area occupied by the ocean is still undiscovered because of the absence of sufficient acoustic communication technologies. Underwater Wireless Sensor Networks (UWSNs) have aided the procedure of exploring the oceans by linking various pervasive sensor devices to allow efficient and reliable data gathering by UWSNs [1], [2]. UWSNs are becoming popular owing to the various scenarios in which they could be applied such as for underwater environment monitoring [3], pollution monitoring [4], the surveillance of coastal areas, and the exploration of rare minerals. The conventional UWSN architecture is composed of a wide range of battery-constrained sensors, and autonomous vehicles are deployed underwater or on the water surface to collect data within a particular environment. The topology of UWSNs is highly dynamic, and the sensors move with the ocean currents.

UWSNs differ considerably in many respects compared with terrestrial wireless sensor networks. First, underwater sensor nodes are battery powered and cannot harvest solar energy, unlike terrestrial sensor nodes. Moreover, it is highly burdensome to restore the battery because of the harsh environment on the ocean floor. Communication between the sensor nodes is adversely affected owing to the low speed of signal propagation [5], [6] which makes underwater communication challenging, consuming large amounts of energy. The ultimate goal of most UWSN applications is to maximize the network throughput in lieu of fairness among the sensor nodes. Furthermore, in UWSNs, because of the energy concerns, packet transmission over multiple short hops instead

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of long links is preferred. This is because multi-hop delivery was proven to be more energy-efficient for UWSNs than single-hop delivery [7].

However, the use of multi-hops degrades the end-to-end reliability in harsh underwater environments. Finally, because the high-frequency radio communication used by the global positioning system (GPS) is quickly absorbed in the underwater environment, the method of placing and obtaining the location information of sensor nodes becomes difficult in UWSNs compared to terrestrial wireless sensor networks. Other important matters affecting the transmission of data packets between sensor devices in UWSNs are low bandwidth, path loss, noise, Doppler spreads, and multipath effects [8] as opposed to terrestrial wireless sensor networks. Therefore, designing energy-efficient routing is highly important for UWSNs.

Several routing schemes have been developed with the goal of energy-efficient data collection in underwater environments and have been reported in literature. The features of sensor nodes and device specifications were considered by the routing mechanisms. In this paper, we consider energy-efficient routing protocols that have been designed for UWSNs in recent years. Our goal is to improve the understanding of current energy-efficient routing protocols for UWSNs and highlight open research problems that could form the topic of further research and analysis.

The main contributions of this study can be summarized as follows: First, we address and analyze the network architecture of UWSNs along with the energy model. Second, we present a new taxonomy of existing energy-efficient routing protocols adapted to UWSNs based on routing strategies. The new classification divides the existing energy-efficient routing protocols into five separate groups: depth-based, cluster-based, cooperative-reliability-based, reinforcement-learning (RL)-based, and bio-inspired routing protocols. Third, we review the key concepts, operating principles, advantages, and limitations, and provide a comparative discussion of routing protocols. Finally, we summarize and discuss the important research questions and challenges that still need to be addressed.

The remainder of this article is organized as follows. Section II reviews past surveys on UWSNs. In Section III, we present the network architecture and energy model of the UWSNs. In Section IV, a new taxonomy of the existing energy-efficient routing protocols for UWSNs is provided, and all protocols are reviewed and discussed. In Section V, important open problems and remaining research challenges are discussed. The conclusions are presented in Section VI.

II. REVIEW OF EXISTING SURVEYS

The growing interest in UWSNs and the continuous emergence of new innovative techniques have motivated previous attempts to study the features, implementation, and communication protocols of this applied field [9]–[11]. Many studies have been devoted to UWSNs, and new research efforts focusing on the development of routing protocols for UWSNs have been emerging. Generally, the application requirements and architecture of the network play an important role in the design and development of protocols. However, certain factors should be considered when designing a routing protocol.

The most significant aspect is the energy efficiency of the sensor, which directly affects the life extension of the network. Several surveys have been conducted on the basis of existing routing protocols for UWSNs. Here, we discuss these existing surveys and present the differences between their approaches and ours. In this section, we highlight the characteristics that differentiate our survey from others.

- Ayaz *et al.* [9] surveyed state-of-the-art routing protocols for UWSNs, but not all of them were designed with energy efficiency in mind. They discussed different application-specific routing protocols for UWSNs and compared terrestrial WSNs with UWSNs. However, the surveyed protocol description does not seem to be complete. In addition, this survey is dated and mostly covers the routing protocols until 2011. Many new protocols have been proposed in recent years. In contrast, our survey mainly focuses on the energy-efficient aspects of UWSNs. At the same time, we provide a classification of the existing energy-efficient routing protocols and define directions that enable readers to select the most appropriate routing protocol for their network.
- Zenia *et al.* [12] addressed both energy-efficient and reliable MAC and routing protocols for UWSNs in their survey published in 2016. They classified the surveyed routing protocols based on the routing strategy into seven categories: location-based, layered, path cost-based, clustering, multipath, spatio-temporal multicast, and reinforcement learning-based. However, they did not provide any proper classification of the MAC protocols and did not discuss the MAC protocols in depth, which did not match the scope of the given survey. They presented a total of 18 routing protocols and additionally summarized the network architecture and provided a quantitative comparison of a few of the mentioned routing techniques. However, this study did not provide any direction in terms of open research problems. In contrast, in our work, we mainly focused on the aspects of UWSNs relating to energy efficiency. We also compare the mentioned protocols in detail with the aim of providing guidance to researchers for their future work. We also suggest significant open research problems and challenges that will need to be taken into consideration in future.
- Li *et al.* [13] classified existing routing protocols into two groups: cross-layer and non-cross-layer protocols. They then classified the cross-layer protocol into two more categories, intelligent algorithm-based cross layer and traditional cross layer, and categorized non-cross-layer algorithms into three different categories: mobility-based, energy-efficient, and time-delay-based. The characteristics of the UWSNs with design

TABLE 1. Comparison of existing surveys and our work.

Survey work and publication year	Energy awareness	Clustering	Energy model	Network architecture	Addressing open challenges	Year range covered by surveyed protocols
Reference [9], 2011	Not all	Not all	No	Yes	Yes	2000-2010
Reference [12], 2016	Not all	Not all	No	Yes	No	2005-2015
Reference [13], 2016	Not all	Not all	No	No	Yes	2000-2015
Reference [10], 2017	Not all	Not all	No	No	No	2004-2015
Reference [14], 2017	Not all	Not all	No	No	Yes	2006-2015
Our work, 2021	All	Not all	Yes	Yes	Yes	2010-2020

considerations and selected crucial factors for designing cross-layer protocols were also summarized. However, not all energy-efficient protocols were discussed, and a comparative discussion of the mentioned protocols was omitted. In contrast, our work only includes protocols with energy-efficient policies. That is, we debate the advantages and limitations of the discussed protocols in a way that enables readers to easily select the most appropriate energy-efficient routing protocols for their network.

- Khalid *et al.* [10] classified routing protocols based on localization and localization-free aspects. They discussed a total of 11 routing techniques. They also summarized certain major and popular routing protocols used in terrestrial wireless sensor networks. They focused on the UWSN node architecture and pertinent design problems that need to be solved when developing routing protocols for UWSNs. However, their survey did not mention open research problems and challenges.
- Ahmed *et al.* [14] focused on node mobility-based routing protocols. They classified the routing protocols into five categories based on node mobility: vector-based, depth-based, clustered-based, AUV-based, and path-based. Different types of node mobility models were discussed. They only surveyed protocols that considered the mobility of UWSN nodes. However, this approach did not consider the aspect of energy efficiency, and the comparative discussion is not detailed.

Table 1 compares existing surveys and our work. Although several surveys in literature discuss the routing protocols for UWSNs, our work concentrates on matters relating to the energy efficiency of the routing protocols of UWSNs. The main aim of our survey was to provide directions to readers and engineers on selecting the most suitable energy-efficient routing protocol for their network. In addition, our paper presents recent state-of-the-art routing research by providing a detailed list of recently proposed protocols for routing. Furthermore, we present the advantages and limitations of each protocol by comparing them.

III. NETWORK ARCHITECTURE AND ENERGY MODEL OF UWSNs

UWSNs consist of numerous sensor nodes that are deployed on the seabed. One or more sink nodes are used for data collection. Finally, the sink nodes transmit the data to the control station for further processing. Previously, nearly all sink nodes were considered to be static. However, recently, autonomous underwater vehicle (AUV)-aided mobile sinks have also become popular. This is because AUV-aided data collection provides more flexibility, reliability, and energy efficiency. The sink nodes are assumed to be more powerful than the sensors. The base station or control center can either be located in the sea or remotely. Depending on the application scenario and requirements, different mechanisms are used. However, multi-hop routing from source to destination for packet delivery is more popular than single-hop routing. Fig. 1 illustrates the network architecture of UWSNs.

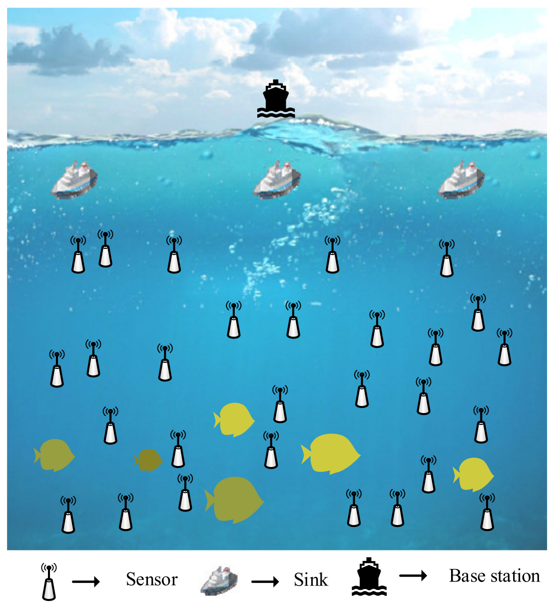

FIGURE 1. Network architecture of UWSNs.

In a terrestrial network, the energy consumption of the sensor nodes depends on the communication and processing load. Energy consumption for data transmission is associated with the communication environment and the distance between the sender, receiver, and size of the data packet. In general, the energy consumed by the source node to transmit data packets is expressed by the following equation:

$$E_{tx} = \begin{cases} l\varepsilon_{elec} + l\varepsilon_{fs}d^2, & d < d_0 \\ l\varepsilon_{elec} + l\varepsilon_{mp}d^4, & d \geq d_0, \end{cases} \quad (1)$$

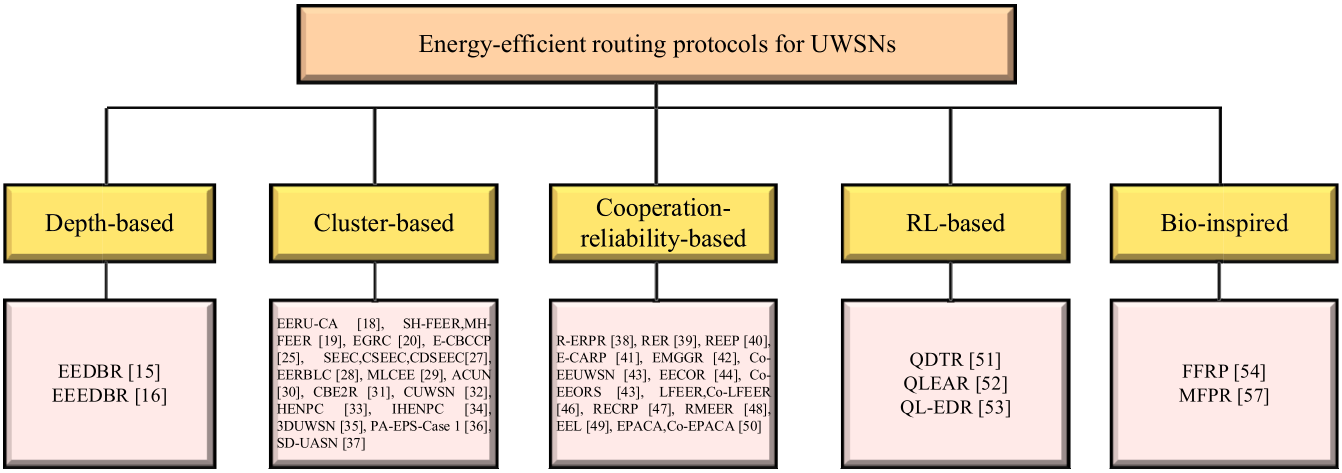

FIGURE 2. Taxonomy of existing energy-efficient routing protocols for UWSNs.

where l represents the number of bits in a single packet, d represents the distance between the transmitter and receiver, d_0 is the threshold distance for data transmission, ε_{elec} represents the radio transmission energy, and ε_{fs} and ε_{mp} represent the transmit amplifier coefficients of free space and the multipath model, respectively.

However, the energy consumption model of a terrestrial WSN network is not suitable for UWSNs, because the energy consumption of an acoustic signal differs from that of a radio signal. In UWSNs, both free-space and multipath models use the amplifier coefficient, which is defined as $a(f^d)$, where a represents the absorption coefficient, d is defined as the distance between the transmitter and receiver, and f is the frequency of the acoustic signal. The value of $a(f)$ can be approximated by using Thorp's empirical formula. For example, if the frequency is 1000 Hz,

$$\log_a(f) = 0.011\frac{f^2}{1+f^2} + 4.4\frac{f^2}{4100+f^2} + 2.75 \times 10^{-5} f^2 + 0.003. \quad (2)$$

Therefore, we can calculate the definition of the energy consumption in UWSNs as follows: the transmission of data packets in an underwater environment, where the distance between the two nodes is d with the frequency f, is modified as

$$E_{tx} = \begin{cases} l\varepsilon_{elec} + la(f)^d d^2, & d < d_0 \\ l\varepsilon_{elec} + la(f)^d d^4, & d \geq d_0. \end{cases} \quad (3)$$

The energy consumption to receive data packets is expressed by the following equation:

$$E_{rx} = l\varepsilon_{elec}. \quad (4)$$

IV. ENERGY-EFFICIENT ROUTING PROTOCOLS FOR UWSNs

The network layer seeks to realize connectivity, data routing, and cooperative sensing between the sensors and observers. In terms of the energy efficiency, scalability, robustness, and convergence, the routing protocols in UWSNs must be configured to meet the necessary performance requirements. The main objective of these protocols is to provide nodes with a stable and energy-efficient path and to prolong the entire lifetime of UWSNs. Neighborhood discovery, communication, and computational costs are major factors that affect the energy consumption of a routing protocol.

We introduce a novel taxonomy based on the routing strategy of existing energy-efficient routing protocols for UWSNs, as shown in Fig. 2. Existing energy-efficient routing protocols for UWSNs are classified into five individual classes: depth-based, cluster-based, cooperative-reliability-based, reinforcement learning (RL)-based, and bio-inspired routing protocols. Most routing strategies have cluster-based and cooperative-reliability-based protocols. However, owing to rapid advances in artificial intelligence, bio-inspired and RL-based routing protocols are receiving much attention. This is because they can easily adapt to the dynamic environment that exists underwater and can take the best routing decision. In this section, a detailed discussion of the existing energy-efficient routing protocols for UWSNs is discussed with regard to the operating principles. A comparative analysis of their key and operational characteristics is also provided.

A. DEPTH-BASED ROUTING PROTOCOLS

Depth-based routing is a common routing mechanism in UWSNs. In depth-based routing, the forwarder node is selected based on the depth of the node. The network topology follows a hierarchical approach. The forwarder chosen by the source is a node of which the depth level is always lower than the current position of the source node. This means that the chosen forwarder is a node that is closer to the sink node. In this section, energy-efficient depth-based routing protocols for UWSNs are discussed.

TABLE 2. Comparison of depth-based routing protocols.

Protocol (year)	Node deployment	Number of depth levels	Hello or control packets	Need for localization	Energy-efficient strategy	Exceptional feature	Application scope	Advantages	Limitations
EEDBR [15](2012)	Layer-based, random	Not given	Yes	No	Forwarder node is selected based on residual energy	Application based data packet suppression scheme	Monitoring application, military surveillance	Reduce redundant data transmission	Early death of medium depth nodes
EEEDBR [16](2016)	Layer-based, random	3	Yes	No	A node closer to the sink and with high residual energy is selected as forwarder node.	Idle nodes at medium depth	Time critical application	Lifetime increase in medium depth nodes	Low throughput

1) EEDBR

Wahid et al. [15] proposed a localization-free energy-efficient depth-based routing (EEDBR) protocol to enhance the network lifetime by reducing the number of transmissions. This protocol is an improved form of depth-based routing (DBR) [17]. The entire communication scenario is divided into two phases: the knowledge acquisition phase and data forwarding phase. In the knowledge acquisition phase, the sensor nodes broadcast a ''Hello'' packet to their neighboring nodes, which includes their depth and residual energy. Upon receiving the ''Hello'' packet, the neighboring nodes retain the information about the depth and residual energy of the sensor nodes located at a smaller depth. During the data forwarding phase, data are forwarded toward the destination or sink node using the information in the ''Hello'' packet. To minimize the number of data transfers, the sending node selects a set of forwarding nodes from among its neighbors with a smaller depth than its own. This is because the nodes that have smaller depths are nearer to the sink node. The forwarding nodes hold the data packet for as long as they can, depending on their residual energy.

For improved energy balancing among the nodes, a node with a large amount of residual energy can hold the packet for a shorter time than nodes with less residual energy. A priority value is used to calculate the holding time to differentiate between nodes with the same energy level and to prevent multiple forwarding. Owing to the inclusion of the amount of residual energy in the Hello packet, EEDBR can reduce energy consumption by selecting a set of nodes for data forwarding and preventing redundant data transmission. This protocol is more efficient compared to other depth-based routing protocols with respect to energy consumption and endto- end delay. Efficient data transmission requires the information about neighboring nodes, such as the depth and residual energy, to be updated periodically. The network lifetime of EEDBR is 40% higher than that of DBR.

2) EEEDBR

To enhance the lifespan of the nodes that reside at a medium depth level, an improved version of EEDBR [16], enhanced energy-efficient DBR (EEEDBR), was proposed. Similar to EEDBR [15], if a source node has a data packet, it selects a forwarder node that is closer to the sink node. A node with a greater depth level and more residual energy would have the opportunity to be the forwarder node. Upon receipt of the data packet, the forwarder node calculates the hold time based on the residual energy and a priority value. The priority value assists the nodes with the dilemma that arises when different nodes have the same level of energy. In this case, a node with a high priority value is chosen as the relay node. However, unlike EEDBR [15], EEEDBR implements a reactive routing approach to accommodate sudden changes in the network.

3) COMPARISON OF DEPTH-BASED ROUTING PROTOCOLS

Depth-based routing protocols are regarded as the building blocks of routing techniques in UWSNs. All other routing techniques of UWSNs were developed on the basis of this idea. This is because sea level depth is the most fundamental feature of the underwater environment, and sensor nodes are deployed at different depth levels underwater. Depth-based routing protocols take this major attribute into consideration, and routing techniques are designed on the basis of depth. Although the techniques of depth routing are highly primitive, the energy-efficient aspects of depth-based routing of UWSNs have not been explored much.

Table 2 compares the presented depth-based routing protocols. The first energy-efficient depth-based routing protocol, which was presented in 2012, was an improved version of the DBR that handled redundant data transmission. The main mechanisms of EEDBR and EEEDBR are similar. The major difference between EEDBR and EEEDBR is the introduction of new types of nodes known as idle nodes at the medium level in EEDBR. The idle nodes support the medium-level normal nodes when they run out of energy. Simulation with EEDBR involves varying the total number of sensor nodes. In contrast, the performance of EEEDBR is evaluated with a constant number of nodes. Both use multiple sinks as destinations.

B. CLUSTER-BASED ROUTING PROTOCOLS

Cluster-based routing is one of the most popular routing techniques for UWSNs. In cluster-based routing, sensor nodes are clustered into groups, each of which has a cluster head (CH). The CH gathers data from cluster members (CMs) and aggregates them before sending to the sink node. Electing a CH wisely is an important matter because the CH bears most of the load; hence, the CH consumes the most amount of energy. In UWSNs, two types of clustering architectures are used: layer-based and grid-based.

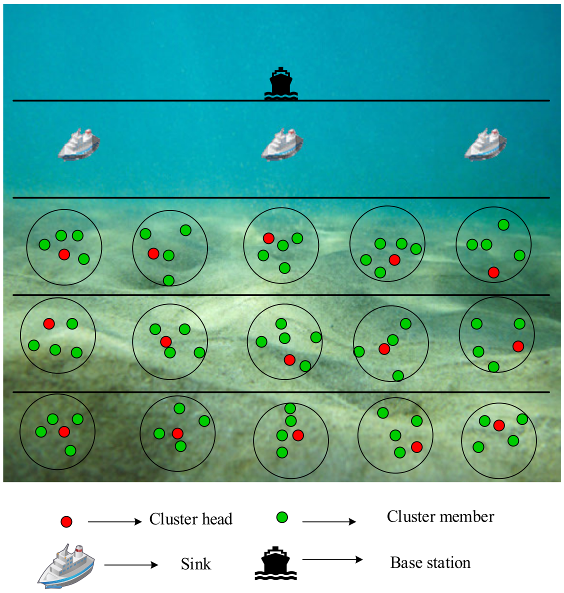

FIGURE 3. **Layer-based clustering.**

As shown in Fig. 3, layer-based clustering divides the seabed into different layers and the sensor nodes in each layer form several clusters. The CH collects data from the CM and aggregates the data. The final data packet after data aggregation is sent to the next CH layer. In this multi-hop method, data are forwarded from the bottom to the destination sink node. Fig. 4 illustrates the grid-based clustering technique. The idea of grid-based clustering is similar to that of layer-based clustering. The major difference between them is that in grid-based clustering, the seabed is divided into a number of grids, and each grid is considered as a cluster, whereas in layer-based clustering, the seabed is divided into layers. In this subsection, we discuss energy-efficient cluster-based routing protocols for UWSNs in detail.

1) EERU-CA

Although the mechanism of clustering is well known, the initiation of energy-efficient clustering for UWSNs only took place recently. The first energy-efficient cluster-based routing protocol for UWSNs was proposed in 2015. In energy-efficient routing for the UWSN clustering approach (EERU-CA) [18], a specialized node acts as a CH. The specialized node is deployed in such a way that each specialized node is connected to a receiving unit, and the other nodes are placed in every cluster. The CM selects the CH according to the minimum distance. The use of specialized nodes helps reduce energy consumption. However, in reality, the deployment of specialized nodes in such a manner is difficult and unrealistic.

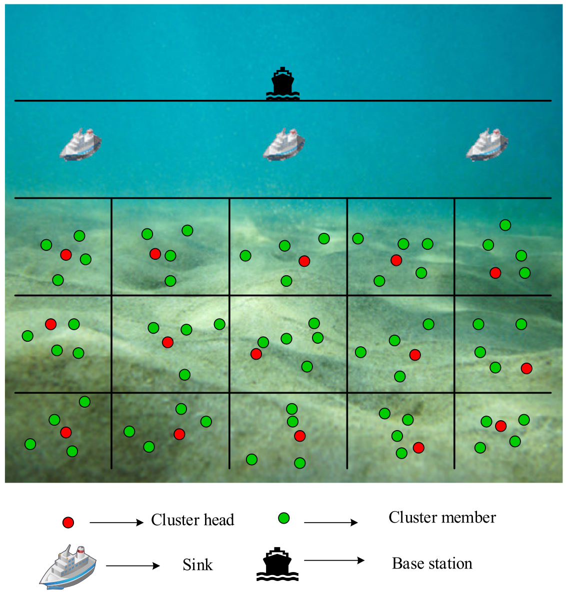

FIGURE 4. **Grid-based clustering.**

2) SH-FEER AND MH-FEER

A single-hop fuzzy-based energy efficient routing (SH-FEER) and a multi-hop fuzzy-based energy efficient routing (MH-FEER) were proposed by Souiki *et al.* in [19]. Both SHFEER and MH-FEER follow the same mechanism for cluster formation and CH selection. First, a cluster is formed by using Fuzzy-C means clustering. Next, during the primary stage, a CH is selected based on the residual energy among the nodes. The key difference between SH-FEER and MH-FEER lies in the data transmission process. In SH-FEER, data are transferred directly to the sink node. In contrast, MH-FEER follows a multi-hop route for data transmission to the sink. Owing to the use of Fuzzy-C means clustering, these protocols are not suitable for dense networks. Simulations consider the static and dynamic topologies of the nodes.

3) EGRC

This refers to energy-efficient grid-routing based on a 3D cube (EGRC) [20] and was initiated by Wang *et al.* in 2016. The entire monitoring area was assumed to be a cube, and the cube was divided into a number of grids. Each grid formed a cluster. The base station (BS) broadcasts a cube-length message, which informs the nodes about the grid area. The nodes set a timer and send a message to their neighbors with information of the residual energy, distance to the sink node, and grid area. The receiving node with the same grid area compares its residual energy and the distance to the sink node included in the received message. If the residual energy in the received message is greater, the timer stops; otherwise, it continues.

Finally, the node with the higher residual energy and that is closer to the sink is nominated as the CH. Data transmission from the CH to the sink is performed in a multi-hop manner. However, the selection of the next forwarder node is a slightly more difficult. The CH of which the grid value is smaller than that of the source calculates the weight based on the value of the residual energy and distance to the sink. The CH with the smallest weight value is chosen as the next forwarder for data transmission. Performance evaluation results show that EGRC can produce superior outputs over other conventional clustering protocols such as LEACH [21], EL-LEACH [22], ERP^{2}R [23] and VBF [24].

4) E-CBCCP

The energy-efficient chain-based routing protocol (E-CBCCP) [25] is an extended version of ME-CBCCP [26]. The CH of the region aggregates the data and forwards them with the help of a relay node. A special node known as a cluster coordinator performs interregional communication. The relay node for data forwarding is selected according to the minimum distance from the sending node. To prevent data packet redundancy, if a node has to transmit data, it broadcasts a control packet to its neighboring node. The node located at the shortest distance from the broadcasting node receives the packet and replies with another control packet to notify about the reception and forward it to the next shortest hop.

E-CBCCP considers the link quality and hop count for the optimal selection of relay nodes by calculating the confidence level of each node. The higher the confidence level of the nodes, the more suitable they are to perform as the relay node. However, if more than one node has the same confidence level, the relay node is selected on the basis of its residual energy. E-CBCCP optimizes the energy consumption by selecting the optimal route that would allow the packet to be transmitted successfully within an optimal delay, resulting in an improvement in the network lifetime. However, the early death of relay nodes, poor load balancing, and network congestion are the primary concerns for sensors near the sink.

5) SEEC, CSEEC, AND CDSEEC

A three-cluster-based routing protocol was proposed to achieve energy efficiency in a sparse region [27]. The three clusters are based on sparsity-aware energy-efficient clustering (SEEC), circular sparsity-aware energy-efficient clustering (CSEEC), and circular-depth-based sparsity-aware energy-efficient clustering (CDSEEC). The main difference between these three algorithms is the network architecture. In SEEC, the entire area is divided into a number of logical regions. In CSEEC, the network area is divided into a number of concentric circles, and each circle is divided into equal parts. In contrast, in CDSEEC, the network is divided into two semicircles. The bottom semicircle is further divided into concentric semicircles.

The network is considered to be either sparse or dense by calculating the network density in each region. The network employs both static and mobile sinks. In SEEC, a hello message is broadcast by each sink. The sensor nodes calculate their hop count from the sink node upon receiving the hello message. The sensor nodes broadcast a hello message to the sensor nodes within their communication range, and those sensor nodes with a lower hop count discard the message. Otherwise, the sensor nodes update the number of hops counts and rebroadcast the hello message. The CH is selected on the basis of its node depth and residual energy. Data transmission is performed along either single-hop or multi-hop routes. If the sink is within the transmission range of the CH, it transfers the data directly; otherwise, it transfers the data in a multi-hop fashion. The CSEEC follows the same approach as the SEEC for network setup and data transmission. However, in CDSEEC, a depth-based routing mechanism is applied during data transmission. The next forwarder node is selected based on the depth. The simulation results show that SEEC can outperform other protocols in terms of energy consumption. However, among the three protocols, CDSEEC performed the best in terms of packet delivery ratio and residual energy.

6) EERBLC

Zhu *et al.* [28] proposed an energy-efficient layer-based routing protocol for UWSNs. The sensor nodes compete among themselves to become a CH, and the CH is selected based on the waiting time, which is determined by the residual energy. The sensor node whose waiting time has expired becomes the CH and broadcasts the fact that it has become the CH to its neighboring nodes. Nodes that are located at greater depths in the water have more nodes in one cluster than clusters that are situated close to the surface. This can reduce the forwarding tasks of the CH near the sink. The CH is updated if the residual energy of the CH is lower than the average energy of the cluster. The method that is used to update the CH helps to balance the load among the sensor nodes. However, network congestion and high routing overhead are predicted owing to the use of flooding techniques.

7) MLCEE

Multi-layer cluster-based energy-efficient (MLCEE) routing was proposed in [29]. This protocol assumes that the sink nodes have unlimited energy, and that the nodes are deployed in layers on the seabed. Every node calculates its layer number using the node depth and the total number of layers in the network. Each node has a holding time, which is calculated using the residual energy and initial energy. If a node has a large amount of residual energy, its holding time is small, offering the node the opportunity of becoming a CH soon. After the holding time expires, the node sends a message to its neighbor.

If a neighboring node receives the message before its own holding time expires, it is no longer being considered to become a CH. If more than two nodes have the same holding time, the CH is selected according to the Bayesian spam filtering method. The node with the higher probability has the opportunity to become the CH. The data transmission from

CM to CH follows the TDMA mechanism. In MLCEE, the nodes that reside in the first layer do not form a cluster; rather, they send data to the sink node directly. This helps to solve the hotspot problem, which occurs owing to the unbalanced load transmission over sensor nodes near the sink on the surface. However, the CH updates are not considered; thus, the energy of the CH is depleted over time, and eventually, the network ceases to exist.

8) ACUN

An energy-efficient adaptive clustering (ACUN) algorithm was proposed for UWSN [30]. The algorithm can prevent the early death of a distant CH from the sink node. It follows a multilevel hierarchical approach in a sphere-shaped monitoring area. The sink was assumed to reside in the center of the application area. The entire monitoring area is divided into a number of layers, and a layer is formed based on the competition radius of the CH. It also considers the residual energy of the CH to calculate the width of each layer.

Nodes with residual energy greater than the threshold value can be nominated as a candidate CH node. Among these candidates, the CH node with the highest weight value is finally chosen as the CH. The weight value is calculated using the residual energy, number of neighbor nodes, average residual energy of neighbor nodes, sum distance from the candidate CH to the neighboring nodes, distance from the candidate CH to the sink, and maximum radius of the CH. Both multi-hop and single-hop data transmissions are adopted, and the transmission mode is selected on the basis of the residual energy of the CH. Single-hop transmission is selected if it requires less energy than multi-hop transmission. Otherwise, data transmission is performed using a multi-hop mechanism. Simulations were performed using the NS2 simulation platform [30], and the simulation results showed that single-hop transmission is more energy-efficient than multi-hop transmission.

9) CBE2R

Cluster-based energy-efficient routing (CBE2R) [31] uses four types of nodes for its system model: sink nodes, courier nodes, source nodes, and ordinary source nodes. The network operation is performed in three phases: cluster formation, route development, and data transformation. The courier nodes act as the CH, and during the cluster formation phase, a cluster is formed around the courier nodes. During the route development phase, the source node calculates the weighted value of its neighboring nodes. The weighted value is measured based on the residual energy, the number of adjacent nodes, the distance to the CH, energy consumption rate, and number of packets. Although CBE2R adopts a layer-based clustering approach, the CH is fixed and deployed in a predefined manner. The forwarder node is selected based on the distance matrix and residual energy of the neighboring nodes. However, the deployment of a fixed CH with sufficient resources is expensive.

10) CUWSN

A grid-based clustering approach was presented [32]. In this approach, each grid formed one cluster. The CH was selected based on residual energy. A node with a high residual energy becomes a CH. A special node known as a coordinator node is deployed to assist with inter-cluster communication and data transfer to the sink node. Although CUWSN can provide improved throughput owing to the use of the coordinator node, early death of the CH and coordinator nodes is likely.

11) HENPC AND IHENPC

High-energy node priority clustering (HENPC) was proposed [33] for magnetic induction-based UWSNs. The cluster is formed in a hexagonal shape to ensure that each cluster has the same number of members. The CH is updated in every round based on the fixed cluster radius, and the residual energy of each CM is compared with those of others. An AUV was utilized for data collection from the CH. However, HENPC only focuses on a uniformly distributed random network and the distribution density is not considered, which creates an energy hole problem. To overcome this problem, improved high-energy node priority clustering (IHENPC) was proposed [34]. The sensor nodes were distributed randomly. The CH is updated based on the residual energy in each round and the geometric distance. The clusters are formed following a jellyfish breathing process, and the clusters can dynamically adapt their cluster size based on the node density. IHENPC follows a Voronoi diagram to determine the optimal cluster, which can provide the best coverage.

12) 3D UWSN

Similar to EGRC [20], 3D UWSNs follow a cube grid-based clustering technique [35]. Each small grid functions as a single cluster. The entire communication process is performed in a number of rounds. Each round is composed of two stages: optimized cluster formation and data transmission. The CH can be selected on a round basis, and every node has the opportunity to be selected at least once. The node with the highest residual energy is selected as the CH. Although cluster formation is performed only once, the CH can be updated. In contrast to EGRC, 3D UWSNs can calculate the optimal number of clusters using the volume of the sphere, number of sensors, and distance between the sensors and sink nodes. Data transmission from the CM to CH is single-hop, and that from the CH to base station is multi-hop.

13) PA-EPS-CASE 1

A region-aware proactive routing protocol was proposed [36]. PA-EPS-Case 1 is an adaptive protocol that can adapt itself based on the network density extents, such as those of dense, partially dense, and sparse networks. In the case of dense and partially dense networks, the number of sensor nodes, their depth, and their coordinates were measured first in each layer. The protocol follows a proactive approach and finds the shortest distance from the source to the destination using Dijkstra's algorithm. Finally, in a sparse situation, a cluster is formed among the sensor nodes, and the CH collects data from the cluster members and forwards the data to the next CH.

14) SD-UASN

A clustering mechanism based on software-defined networking (SDN) for UWSNs is presented in [37]. The entire network architecture was constructed following the SDN model. The sensor nodes perform the role of the SDN data plane. The nodes are designed as OpenFlow switches and operate with TinyOS. The sink nodes of a UWSN form the SDN controller and are responsible for all the centralized management of the network. OpenDayLight (ODL) software was utilized for controller operation. SD-UASN classifies existing sensor nodes into three categories: CM, temporal head (TH), and CH. After deployment of the network, all sensor nodes are considered as the CM. The controller issues an energy threshold level and broadcasts it to all the CMs. Each CM generates a random number between 0 and 1. If the random number is greater than the energy threshold value, the node remains a CM; otherwise, it becomes a TH. The CH informs all neighboring nodes about its nomination. The neighboring nodes reply with a message that includes the communication capability.

The communication capability value is calculated using the residual energy and CPU frequency. The TH nodes compare their communication capability values, and the node with the largest value is nominated as the CH. The simulation was performed using Mininet and WOSS. The simulation results show that SD-UASN can prolong the lifetime of CMs. However, unnecessary energy is consumed owing to overhearing and the high number of transmissions of control packets.

15) COMPARISON OF CLUSTER-BASED ROUTING PROTOCOLS

Table 3 presents a comparative overview of the cluster-based routing protocols discussed in terms of their main ideas. Cluster-based routing protocols are supposed to conserve energy by reducing the number of transmissions. As energy efficiency is the main concern for all the mentioned protocols, the residual energy of the sensor nodes is the major factor that is considered during CH selection. However, other metrics, such as the distance to the sink and cluster center, also play a major role during CH selection. Cluster-based routing protocols are likely to achieve high energy efficiency and network performance. However, the major drawback of these protocols is the high load and early death of the CH in the case of a highly dense network. Various CH update methods [19], [20], [28], [30], [33], [34], [36] can effectively provide load balancing among all nodes, but they incur additional computational cost.

Use of layer-based or hierarchical approaches during node deployment is highly effective to achieve more efficient cluster formation with high network performance. Considering this, most of the cluster-based protocols adopted a layer-based approach to achieve high performance. Although all intra-cluster communication is performed in a single-hop manner, multi-hop data forwarding seems to be more popular in inter-cluster communication. This is because multi-hop communication consumes less energy than single-hop communication because of the shorter distance between nodes. In contrast, in a dynamic UWSN environment, localization of sensor nodes is highly challenging, requires additional hardware, and consumes more energy. Therefore, localization-free approaches are becoming increasingly popular owing to their high energy efficiency and low cost.

C. COOPERATIVE-RELIABILITY-BASED ROUTING PROTOCOLS

Cooperative-reliability-routing is one of the latest research areas in UWSNs to consider harsh underwater environment by enabling reliable data transmission from source to destination. In cooperative-reliability-based routing, packet forwarding is performed using relay nodes from the source to the destination. The selection of relay nodes depends mostly on the application requirements. The cooperative-reliability-based routing technique helps to achieve a reliable link from source to destination, thereby boosting the throughput and packet delivery ratio. The destination nodes always receive two or more copies of the same packet, one from the source node and another from the relay nodes. The destination node aggregates the packets and extracts the desired information. This mechanism ensures that, in the case of paths that are affected by unstable links, another link would be able to help with successful data delivery. However, it enhances the end-to-end delay and cannot solve duplicate data transmissions. Fig. 5 depicts the strategy of the cooperative routing protocol for UWSNs.

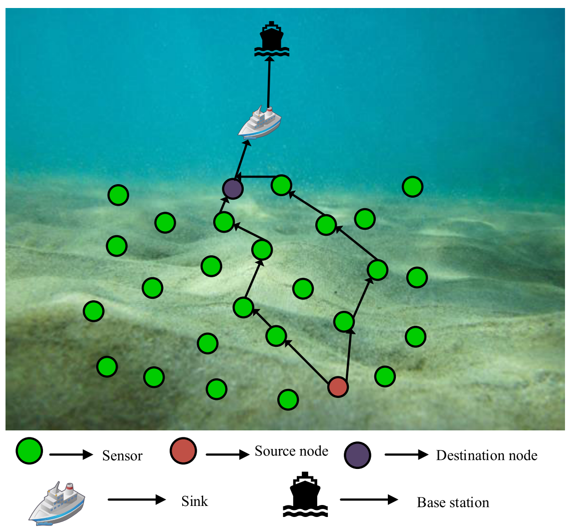

FIGURE 5. Cooperative-reliability-based routing.

1) R-ERP^2R

A reliable energy-efficient routing protocol based on physical distance and residual energy (R-ERP^{2}R) [38] forwards data

TABLE 3. Comparison of cluster-based routing protocols.

Protocol (year)	Node position	Selection of CH	Intra-cluster routing	Inter-cluster routing	Update for new CH	Cluster unit	Need for localization	Advantages	Limitations
EERU-CA [18] (2015)	Layer-based	A specialized node functions as the CH	Single-hop	Multi-hop	No	Not given	No	CH has sufficiently high energy	High end-to-end delay
SH-FEER [19] (2015)	Random	Close to center, residual energy	Single-hop	Single-hop	Yes	Unequal	No	Fall into local optima early, which causes fast cluster formation	Not suitable for dense network
EGRC [20] (2016)	Cube-based grid and random	Residual energy and distance to sink	Single-hop	Multi-hop	Yes	Not given	Yes	Finds shortest path to sink	High control overhead
E-CBCCP [25] (2017)	Layer-based	Residual energy	Single-hop	Multi-hop	No	Fixed and equal	No	Find the optimal path for routing	Computational overhead of CH selection, early death of CH and cluster coordinators
SEEC, CSEEC & CDSEEC [27] (2017)	Random	Residual energy and depth	Single-hop	Multi-hop	No	Circular and equal	No	High cluster stability	Low throughput, high delay, and high computational cost
3D UWSN [35] 2017	Cube-based grid and random	Residual energy	Single-hop	Multi-hop	Yes	Not given	No	Can find optimal number of clusters	High end-to-end delay
EERBLC [28] (2018)	Layer-based	Residual energy	Single-hop	Multi-hop	Yes	Unequal	No	Load balancing	Network congestion and high routing overhead
ACUN [30] (2018)	Layer-based	Residual energy of CH, average residual energy of neighboring nodes, distance from CH to sink	Single-hop	Multi-hop	No	Round shape and equal	Yes	Less load on first layer	High exchange of control packets
HENPC [33] (2018)	Hexagon	Residual energy	Single-hop	Single-hop	Yes	Hexagonal and equal	Yes	Finds shortest path for data collection	Increased network delay
CBE2R [31] (2018)	Layer-based	A specialized node functions as the CH	Single-hop	Multi-hop	No	Fixed and equal	No	Improved communicati on link	High end-to-end delay
CUWSN [32] (2019)	Grid	Residual energy	Single-hop	Multi-hop	No	Grid and equal	Yes	Coordinator node provides better throughput	Early death of CH and cluster coordinators
IHENPC [34] (2019)	Tree-based	Residual energy and geometry distances	Single-hop	Multi-hop	Yes	Voronoi diagram and equal	Yes	Finds optimal cluster for best coverage	Surface collision, operational and maintenance complexity
PA-EPS-Case 1 [36] (2019)	Layer-based	Residual energy	Single-hop	Multi-hop	Yes	Not given	Yes	Can avoid void node problem	Overhearing, increased control overhead
MLCEE [29] (2019)	Layer-based	Residual energy	Single-hop	Multi-hop	No	Round shape and equal	No	Less load on first layer nodes	No update of CH node
SD-UASN [37] (2019)	Random	Residual energy	Single-hop	Multi-hop	Yes	Not given	No	Adaptable to both sparse and dense network	High control overhead

based on the link quality and residual energy of neighboring nodes. The protocol is divided into two phases: the cost development phase and data forwarding. During the cost development phase, each sink broadcasts a hello message, which the sensor nodes receive and use to calculate the cost. The cost is calculated using the physical distance toward the sink node and the residual energy of each node. This process continues until all nodes calculate their cost. During the data transmission phase, the source node broadcasts a data packet to a node of which the cost value is less than that of the sender node. The neighboring nodes are listed according to their residual energies. A node with high residual energy is prioritized for selection as a forwarder node. In the case of more than one node with the same residual energy, the node with the lowest cost value is selected as the forwarder node.

2) RER

The reliable and energy-efficient underwater routing (RER) protocol [39] develops a route from the source to the destination to minimize transmission delay. First, the source node broadcasts an RTS packet to its neighboring nodes. The neighboring nodes reply with the packet transmission delay to the source node. The source node compares the packet transmission delay and selects the next hop, which is the hop with the least packet transmission delay. The newly established route is broadcast to every neighboring node.

3) REEP

In a reliable and energy-efficient protocol for UWSNs (REEP) [40], communication occurs in two phases: the network setup phase and data transmission phase. In the network setup phase, the sink node broadcasts a hello packet. Upon reception of the hello packet, the sensor nodes calculate the time of arrival (TOA) value to measure its distance from the sink. During the data transmission phase, the source node broadcasts a hello packet to its neighboring nodes. These nodes receive the hello packet and compare their distance to the sink and the distance mentioned in the hello packet. The nodes with shorter distances reply to the source node, which selects the next forwarder node based on the residual energy and the distance to the sink. The protocol was evaluated using the NS2 extension with Aquasim and delivered superior performance in terms of network lifetime and end-to-end delay.

4) E-CARP

E-CARP [41] is an extension of the channel-aware routing protocol (CARP). In both CARP and the enhanced channel-aware routing protocol (E-CARP), the network topology is initialized at the beginning of the network deployment, and all the sensor nodes calculate their hop distance from the sink node and become aware of the distance between them and the sink node. When a source node has a data packet to send, the relay node for data forwarding is selected based on the link quality among all neighboring nodes. The source node broadcasts a PING control packet to its one-hop neighbors, and the nodes that receive the control packet respond by sending a PONG packet that includes their buffer space, residual energy, link asymmetries, and interferences.

The source node calculates the link quality from the information contained in the PONG packets and chooses the node with the best link quality. The main difference between CARP and E-CARP is the storage of the value of link qualities. CARP does not store the link quality of the sensor nodes. Instead, the source node calculates the link quality every time it needs to send a data packet. In contrast, E-CARP considers a steady ocean environment in which the location of sensor nodes and the environment of the ocean change less frequently. In E-CARP, each source node stores the value of the link quality, and the next time it needs to send a data packet, it checks the stored value and selects the relay node based on the previous data. Moreover, a neighboring node only replies with a PONG packet when it is a more appropriate candidate node than the relay node that is used in the previous transmission. This mechanism helps E-CARP to save energy and reduce additional calculations for relay node selection.

5) EMGGR

EMGGR [42] follows a grid-based multipath routing mechanism. In each grid, a gateway node is selected based on the selection weight, which is related to the energy level and distance to the center of the grid cell. The gateway node serves as a relay node to carry data from one grid to another grid. The gateway node is updated if the current gateway residual energy falls below the threshold level. When the source node has a data packet to send, it forwards the data packet to the local gateway. The local gateway selects a valid path to the destination by following a round-robin mechanism. In the absence of a valid route, the packet returns to the source gateway and attempts to find another valid path. This protocol resulted in a high end-to-end delay.

6) CO-EEUWSN

Cooperative energy-efficient routing for UWSNs (Co-EEUWSN) was proposed [43]. The relay node is selected from the source to the destination based on the signal-to-noise ratio (SNR) and channel capacity.

7) EECOR

An energy-efficient cooperative opportunistic routing (EECOR) protocol was proposed in [44]. A source node first decides a forwarding set, and fuzzy logic is utilized to choose the best relay set among the set of neighboring relay nodes. To prevent packets from being overheard by relay nodes that are not chosen for the forwarder set, a holding time is implemented. The protocol delivers improved performance with respect to energy consumption, packet delivery ratio, and end-to-end delay. However, in a sparse scenario, if the nodes are located far away from each other, the relay selection mechanism results in poor performance. In addition, when the positions of the nodes change because of ocean waves, it becomes challenging to forward the packets to the selected relay nodes, which causes additional delay.

8) CO-EEORS

Using both location information and the depth of the sensor nodes, an energy-efficient cooperative protocol was developed in [45]. The source node selects the destination node with the lowest depth and location values. The node that is closer to the sink node has the lowest location value. In contrast, the neighboring node situated closer to the destination node is chosen as the relay node for data forwarding. However, unnecessary energy consumption occurs owing to overhearing, and increased end-to-end delay is observed.

9) LFEER AND CO-LFEER

Two energy-efficient cooperation-based routing protocols were proposed in [46]. In the first algorithm, the localization-free energy-efficient routing protocol (LFEER), the next hop is chosen based on the maximum residual energy, fewest hops, and the lowest bit error rate. The protocol follows a multi-hop mechanism to reach the final sink node. The second algorithm is known as the cooperative localization free energy efficient routing protocol (Co-LFEER) and is an improved version of LFEER. In Co-LFEER, the source node chooses a relay node and only a normal sensor node as the next hop to route the packet to the final sink node. The next hop and relay nodes are selected on the basis of a cost function. However, these two mechanisms cannot solve network congestion, duplicate packet transmission, and high end-to-end delay.

10) RECRP

To ensure excellent packet delivery, a reliable energy-efficient cross-layer routing protocol (RECRP) [47] was proposed. RECRP has two phases: a route update phase and a routing phase. During the route update phase, each node updates its routing information, which includes the node ID, residual energy, distance, and node level. The distance to the neighboring nodes is determined by using the received signal strength indicator (RSSI) value. Data transmission occurs by selecting the next hop based on the routing table information.

11) RMEER

Similar to RECRP [47], the reliable multipath energy efficient routing protocol (RMEER) [48] also has two phases: a route development phase and a data forwarding phase. A special kind of node known as a courier node, which has a direct connection to the sink node, is deployed in every layer. During the route development phase, the ordinary sensor nodes develop a path from the source to the courier node following the multipath disjoint method. The courier nodes broadcast a hello message, and upon receiving it, the neighboring nodes update their neighbor table and become part of the multipath. During the data forwarding phase, the source node broadcasts a route request via multiple links. Upon receiving the route request, the neighboring nodes update the routing table. The route is selected based on a lower link cost. However, unlike RECRP [47], RMEER follows multipath routing. Although RMEER can achieve reliability, it cannot handle data redundancy.

12) EEL

The energy-efficient localization-based geographic routing protocol (EEL) [49] utilizes three types of beacon nodes: original beacon nodes, promoted beacon nodes, and unknown nodes. The original beacon nodes are deployed on water surface, and GPS is employed to learn about their location information. An unknown node near the surface can become a promoted beacon node at three edge locations. Data forwarding from the source node to the destination follows the normalized advancement (NADV) link metric model. Using NADV, the next forwarder hop is selected based on the residual energy and distance from the source node to the destination node.

13) EPACA AND COEPACA

Two channel-aware cooperative routing protocols were investigated in [50]. The first one, the energy path and channel aware (EPACA) protocol, forwards data to the sink node by calculating the node residual energy, packet history, distance, and bit error rate. In EPACA, the source node first broadcasts a hello message, which includes the source ID, packet sequence, residual energy, packet history, bit error rate, and location. After receiving the hello message, the neighboring nodes calculate the weight function using the information in the hello message. The node with the highest weight value is selected as the destination node. In the second protocol, cooperative-energy path and channel aware (CoEPACA), a cooperative relay is used for data transmission to enhance the reliability. This protocol uses the same mechanism as EPACA for selecting the relay and destination nodes. If the chosen destination node does not meet the criteria for the desired parameters with a low bit error rate, the source node transmits another control message to select the next priority node as the next forwarder. The destination node receives multiple copies of the data packet and combines them using the maximum ratio combining technique. If the sink is near the source node, it receives the data packet directly without many relay mechanisms.

14) COMPARISON OF COOPERATIVE-RELIABILITY-BASED ROUTING PROTOCOLS

Table 4 presents the cooperative-reliability-based routing protocols in terms of their main characteristics. As discussed above, the routing protocols in this category aim to provide reliable data delivery and are highly energy efficient. These protocols can mitigate the multipath fading problem without using multiple antennas. The energy conservation technique is mainly concerned with the proper selection of relay nodes. Thus, the wise selection of relay nodes is essential to improve energy-efficient data transmission with high reliability. A high-quality relay node can produce a high diversity gain. Optimal selection of relay nodes theoretically increases the performance of the system and achieves cooperative routing goals such as low energy consumption, throughput, and packet delivery ratio. As far as the energy of the entire system is concerned, most of the existing protocols have utilized the residual energy parameter for the selection of relay nodes.

As indicated in Table 4, not only the residual energy but also the measurement of the link quality plays a crucial role during relay node selection. Moreover, the selection of multiple relay nodes, instead of one, is another popular way to ensure guaranteed data delivery with a lower error rate. The main limitation of this type of routing is that it compromises the delay requirements to ensure data reliability. Furthermore, multi-path routing incurs the data duplication problem, which results in unnecessary energy consumption. Moreover, the energy consumption is hampered in a sparse network. In such a scenario, the nodes have to transmit data over a long distance. Therefore, during simulations, a sparse to dense network size is considered to prove the adaptability of the protocol. In contrast, if the cost is not a significant problem, using multiple sinks is preferable to using a single sink.

D. RL-BASED ROUTING PROTOCOLS

Reinforcement learning (RL) is motivated by human relationships with the world. The primary concern of RL is how intelligent agents act in an uncertain environment. By communicating with and learning from its environment, an agent in RL achieves its target. To achieve a numerical reward, RL learns about the world, what to do, and how to outline the circumstances for the current behavior. The agent is mostly not instructed on which actions to perform and has to follow a trial-and-error approach to determine which actions yield the highest reward. Q-learning is one of the most popular RL techniques. In Q-learning, the agent makes decisions according to a certain Q-value. A few routing strategies have been proposed on the basis of Q-learning to increase the network lifetime of UWSNs. In this section, the routing techniques based on RL are discussed in detail.

1) QDTR

The first Q-learning-based energy-efficient routing was proposed for an underwater delay tolerant network [51] named the Q-learning-based DTN routing protocol (QDTR). A packet that is ready to be sent by a sensor node defines the system state. The reward function is constructed by combining three criteria: distance to the sink node, density of the neighboring node, and residual energy. The first criterion implies that if a node chooses a relay node that is closer to the sink node, it receives the highest reward. The second criterion gives a reward based on the node density in the current and next layers. A high reward should be given if a node chooses a forwarder node, which resides in a high-density area that makes forwarding easier. The last criterion is the residual energy of the node. A node that selects a node with high residual energy obtains a more lucrative reward. In addition, each packet is provided with a deadline value based on packet urgency. The packet is forwarded within the packet deadline. The packet with the nearest deadline is transmitted first. The simulation results demonstrate that QDTR can provide a high delivery ratio with less energy.

2) QLEAR

A Q-learning-based energy-efficient and lifetime aware routing protocol (QLEAR) was presented in [52]. In QLEAR, the Q-value is determined based on the successful transmission of a packet. In Q-learning, the performance of an agent is based on the reward value that is given based on the action. The reward function of QLEAR is formulated using the residual energy and energy distribution of the node. The protocol always chooses a route that has more residual energy than the shortest path. If a route with low residual energy is chosen, a negative reward is provided. Although the network lifetime is increased compared with VBF [53], unnecessary energy consumption occurs because packets are overheard.

3) QL-EDR

A Q-learning-based energy-efficient routing protocol named QL-EDR [53] aims to explore efficient resource management in hierarchical cluster-based networks. The Qlearning algorithm is executed after the first round of data collection when the base station has information on the timeliness of routing and energy consumption for data processing. The Q-value is calculated on the basis of the remaining energy and transmission delay. In contrast, the reward depends on a regulatory factor that balances transmission delay and energy consumption. When the regulatory factor is set to 0, the QL-EDR considers only the remaining energy, and when the regulatory factor is 1, QLEDR focuses on reducing the transmission delay. QL-EDR demonstrated improved performance in terms of network lifetime, throughput, and energy consumption.

4) COMPARISON OF Q-LEARNING-BASED ROUTING PROTOCOLS

A comparison among the presented RL-based routing protocols is provided in Table 5. RL-based algorithms are becoming increasingly popular owing to their high adaptability to the environment. Although the concept of RL has been known for many years, the energy-efficient aspect of Q-learning-based routing for UWSNs remained unexplored until 2010. Q-learning-based algorithms can achieve high performance in a dynamic environment by using trial and error. Most Q-learning-based routing protocols are formulated as Markov decision problems. The model of the network state space, action space, and reward function is difficult to use and mostly inclined toward application goals and requirements.

According to Table 5, most of the existing protocols consider an individual packet as a state of the system. Moreover, the reward function is closely related to the residual energy of the next forwarder node and the distance to the sink.

TABLE 4. Comparison of cooperative-reliability-based routing protocols.

Protocol (year)	Cooperative strategy	Relay selection	Optimality of relay selection	Number of relay nodes in each level	Hello or control packets	Sink & Mobility	Need for localization	Advantages	Limitations
R-ERP^{2}R [38] (2014)	Adaptive	Link quality, distance from sink, and residual energy	Yes	Single	Yes	Multi & static	Yes	Reduced end-to-end delay	Control overhead
RER [39] (2014)	First adaptive then fixed	Packet transmission delay	Yes	Single	Yes	Single & static	No	Transmit packet with minimum transmission delay	Full reliability is not achieved owing to lack of multipath
REEP [40] (2015)	Adaptive	Distance to sink	Yes	Single	Yes	Multi & static	Yes	Reduce end-to-end delay and improve throughput	Increased control overhead, overhearing
E-CARP [41] (2015)	Fixed and adaptive	Buffer space, residual energy, link asymmetries , and interferences	Yes	Single	Yes	Single & static	No	Reduce unnecessary data transmission and reduce energy consumption	Increased control overhead
EMGGR [42] (2016)	Adaptive	Distance from the center of the cell to the node and residual energy	Yes	Single	Yes	Single & static	Yes	Load balancing among the sensor nodes.	Failure in gateway node can disturb the entire network.
Co-EEUWSN [43] (2017)	Fixed	Signal-to-noise-ratio (SNR) and channel capacity	Yes	Multiple	No	Multi & static	Yes	Non-overlapping data forwarding	High infrastructure cost
EECOR [44] (2017)	Adaptive	Fitness value and fuzzy logic	Yes	Multiple		Single & static		Finds shortest path for routing	Poor performance in sparse network, high delay
Co-EEORS [45] (2018)	Adaptive	Minimum distance from destination node	No	Single	Yes	Single & static	No	Increased packet delivery ratio	High end-to-end-delay
LFEER, Co-LFEER [46] (2018)	Adaptive	Residual energy, hop number, bit error rate	No	Single & Multiple	Yes	Multi & static	No	Ensures reliability by multi-path routing	High-end-to-end delay
RECRP [47] (2018)	Adaptive	Node level, residual energy, residual energy of neighboring nodes, and the distance between current and neighboring node.	Yes	Single	Yes	Multi & static	No	Reduced packet redundancy	Unnecessary energy consumption because of overhearing.
RMEER [48] (2018)	Adaptive	Residual energy and link quality	No	Multiple	Yes	Multi & static	No	Reliable data delivery	Redundant packet delivery
EEL [49] (2018)	Adaptive	Location information and residual energy	Yes	Single	Yes	Multi & static	Yes	Provides better result in terms of energy consumption.	Low packet delivery ratio, increased overhead
EPACA, CoEPACA [50] (2020)	Adaptive	Residual energy, packet history, bit error rate, and distance	Yes	Single	Yes	Multi & static	No	Improves network link quality and provides reliability	High transmission of duplicate data

TABLE 5. Comparison of RL-based routing protocols.

Protocol (year)	Objective	State space	Action space	Q-value update method	Reward	Need for localization	Number of sinks	Energy-efficient strategy	Advantages	Limitations
QDTR [51] (2010)	Reduce energy consumption and increase adaptability	Individual packet	Packet forwarding	Successful packet delivery	Distance to the sink, node density, and residual energy	No	Single	By reducing duplicate packet transmission	Reduced control overhead	Not suitable for dense network
QLEAR [52] (2010)	Increase network lifetime with distributed residual energy	Individual Packet	Packet forwarding	Value function and transition probabilities	Residual energy, average residual energy, and transition probabilities	No	Single	Energy distribution among the nodes	Increased network lifetime	Unnecessary energy consumption owing to overhearing
QL-EDR [53] (2019)	Increase network lifetime with reduced transmission delay	Position of the sensor node	Next hop	Energy and distance	Transmission distance	Yes	Single	Selection of forwarder node based on distance and residual energy	Finds optimal path from source to destination	Link stability is not considered

In contrast to the protocols of other categories, Q-learning-based energy-efficient protocols still consider single and static sink nodes. Therefore, huge scope exists for multi-sink-based Q-learning-based protocols research. The main limitation of the Q-learning-based algorithm is that it needs to update and store its Q-value every time, which increases its complexity in a large network. Considering this disadvantage, existing protocols do not consider a large network, and simulations are performed with no more than 125 nodes. Hence, the performance of Q-learning-based protocols remain questionable in the sense that the actions of the protocols on large-scale UWSNs need to be refined.

E. BIO-INSPIRED ROUTING PROTOCOLS

In various fields of science, biological concepts have led to different technical innovations. The following protocols reflect their application to energy-efficient routing in UWSNs.

1) FFRP

A bio-inspired dynamic firefly mating optimization routing (FFRP) scheme was proposed in [54]. The result of firefly mating optimization relies significantly on pheromones, which are emitted from the body. Two types of fireflies were employed: male fireflies and female fireflies. The FFRP selects the best forwarder node based on the priority value. The priority value depends on the level at which the node is positioned in the water, residual energy, angle of departure, and distance to the neighboring nodes. A special parameter known as buffer overflow time helps to control the buffer overflow in the node. FFRP estimates the link quality based on the residual energy and the ratio of successful packet delivery over the link. This mechanism ensures reliable and stable links with high data rates. The simulation was performed with NS2 with AquaSim extensions, and the results obtained for different node densities were compared with those of protocols such as MERP [55] and QERP [56]. The simulation verified that FFRP outperforms the other relevant protocols in terms of packet delivery ratio, throughput, and energy consumption.

2) MFPR

To enhance the quality of service (QoS), an energy-efficient memetic flower pollination routing (MFPR) protocol was proposed [57]. The main purpose of the algorithm is to select the optimized route with the highest packet delivery ratio and less delay. The fitness value of MFPR helps to transmit the packet via stable links with minimum energy consumption. The MFPR was evaluated using MATLAB and compared with the QERP and BMOOR schemes. MFPR delivers superior results in terms of the packet delivery ratio because the best links are selected for data transmission.

3) COMPARISON OF BIO-INSPIRED ROUTING PROTOCOLS

A comparative overview of the features of the biologically influenced optimization routing protocols discussed in this section is presented in Table 6. Biological insect behavior modeling can assist with the development of optimal algorithms to solve various self-organization and self-configuration problems in UWSNs. Moreover, the

TABLE 6. Comparison of bio-inspired routing protocols.

Protocol (year)	Objective	Inspiring animal	Agent	Need for localization	Congestion control	Implementation	Energy-efficient strategy	Advantages	Limitations
FFRP [54] (2020)	Find stable and reliable routing	Firefly	Male and female fireflies	Yes	Yes	Simulation	Balancing data traffic load among the nodes	Improved link quality	High computational cost
MFPR [57] (2020)	Improve QoS	Flower	Pollen	Yes	No	Simulation	Selecting optimal route for data transmission	Avoids transmitting duplicate packet	Not much improvement in energy consumption

bio-inspired routing protocol is a more suitable candidate for large-scale underwater sensor networks. In addition, most bio-inspired routings are highly robust. Therefore, they are able to maintain an acceptable level of performance despite network disruptions. However, achieving the optimal global outcomes is challenging. It should be noted that specialized energy model was not suggested for any of the proposed protocols in this category; FFRP uses the basic energy consumption model for data transmission and reception.

V. OPEN PROBLEMS AND RESEARCH CHALLENGES

In this section, the open research problems and challenges relevant to designing an energy-efficient routing protocol for UWSNs are considered. Unlike terrestrial networks, aquatic signals in UWSN networks experience high propagation delay, multipath fading, and a high bit error rate. These challenges result in low reliability and high energy consumption during data transmission. Apart from these traditional challenges of UWSN networks, there are certain specific issues that prevent the network lifetime from becoming prolonged. These include lack of security and privacy, link instability, high routing overhead, lack of optimal energy efficient routing, void node problems, and hotspot problems. The challenges and problems highlighted in this survey are expected to help interested researchers and engineers.

A. SECURITY AND PRIVACY

Ensuring security and privacy is one of the greatest challenges for any kind of network, and UWSNs are not an exception. As UWSN applications are remotely located, they are highly prone to malicious attacks. Without sufficient security, the entire UWSN system may be corrupted, and hence, all the efforts would be in vain. However, providing security in routing imposes additional energy costs. Therefore, a tradeoff should be maintained between security and energy efficiency.

B. LINK STABILITY

Owing to the ocean waves, the sensors in UWSNs are always moving. Hence, the topology of UWSNs is highly dynamic, and the link for routing is highly unstable. Unreliable links result in frequent packet drops and low throughput, which contribute to significant energy consumption. Therefore, designing a stable link quality for reliable packet routing is a major concern.

C. ROUTING OVERHEAD

Different techniques are being applied to UWSNs to achieve energy efficiency. These techniques, such as Q-learning, help to improve the adaptability of the routing to dynamic changes in the UWSN environment. However, new techniques always generate additional overhead for routing, which causes network congestion and additional energy consumption.

D. OPTIMAL ENERGY-EFFICIENT PATH

Finding the shortest energy-efficient routing path from the source to the destination is a major challenge in the routing of UWSNs. The main dilemma during the process of searching for the shortest path is whether to choose the most energy-efficient path or the shortest path for routing. The energy-efficient path may not be the shortest and requires more time to deliver data to the sink node. However, the shortest path may not be highly energy- efficient. It is important to balance the shortest path and the most energy efficient path to reduce the delay in an energy-efficient way during data delivery.

E. VOID NODE PROBLEM

In sparse UWSNs, where the sensor nodes are deployed across a large area, the void node problem is a significant problem in energy-efficient routing. The large distance between sensor nodes in sparse UWSNs requires long-distance transmission, which increases the energy consumption considerably. Cooperative routing strategies are negatively affected to a significant extent in sparse networks. Although cluster-based routing can overcome the void node problem more effectively, the early death of the CH due to transmission over long distances cannot be avoided.

F. HOTSPOT PROBLEM

In most scenarios in which UWSNs find applications, the sensor nodes are deployed in a hierarchical fashion based on the depth of the sea. Data routing from the bottom of the seabed to the top-level sink node is performed in a multi-hop manner. The nodes situated close to the surface level have a heavy workload for data transmission. Therefore, the sensor devices close to the sink node are more likely to run out of energy than the nodes at the bottom level. This problem is known as the hotspot problem. Very few studies have addressed the hotspot problem. A major approach to solving this problem is to prevent the sensors close to the sink from forming clusters, to reduce the load of data aggregation. However, this cannot completely avoid the early death problem of near-surface-layer sensors. Therefore, the hotspot problem requires attention to prolong the network lifetime.

G. ROUTING WITH QoS

Many current QoS routing protocols are limited to unique applications and consider only a few metrics. The balance between energy conservation and QoS assurance is lacking. In this regard, QoS energy-efficient routing can be seen as an important area for future research in various applications or diverse UWSNs.

H. TESTBED IMPLEMENTATION

Most of the existing energy-efficient routing protocols for UWSNs were evaluated using simulation platforms such as NS2 [38], [40], [48], [49], MATLAB [45], OPNET [39], Qualnet, and Java. However, these protocols have not been implemented in practice. Therefore, these protocols should be implemented not only using simulation tools but also on actual UWSN hardware and testbeds.

VI. CONCLUSION

In this paper, energy-efficient routing schemes for UWSNs are extensively reviewed and comparatively discussed. A new taxonomy for existing energy-efficient routing protocols for UWSNs was derived based on the routing strategy. We also provided a comparative summary of the current energy-efficient routing protocols for each class. Cluster and cooperative-reliability-based routing protocols were more widely investigated than other classes. Recently, however, routing techniques based on artificial intelligence have become popular owing to their adaptive capability in a dynamic environment, and they can meet diverse application requirements. Furthermore, the use of mobile sinks for data collection can contribute additional benefits to real-time data collection and offer large coverage, energy efficiency, and energy balance, even though the deployment costs are higher. Finally, important open research problems and challenges regarding energy-efficient routing protocols in UWSNs are highlighted as topics for future research.

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