IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 3, 2017, accepted July 18, 2017, date of publication July 21, 2017, date of current version August 8, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2730233

EECOR: An Energy-Efficient Cooperative Opportunistic Routing Protocol for Underwater Acoustic Sensor Networks

MD ARIFUR RAHMAN, YOUNGDOO LEE, AND INSOO KOO
School of Electrical Engineering, University of Ulsan, Ulsan 44610, South Korea

Corresponding author: Insoo Koo (iskoo@ulsan.ac.kr)

This work was supported by the National Research Foundation of Korea through MEST under Grant NRF-2016K2A9A1A01950711.

ABSTRACT Underwater acoustic sensor networks (UW-ASNs) have recently been proposed for exploring the underwater resources and gathering the scientific data from the aquatic environments. UW-ASNs are faced with different challenges, such as high propagation delay, low bandwidth, and high energy consumption. However, the most notable challenge is perhaps how to efficiently forward the packets to the surface sink by considering the energy constrained sensor devices. The opportunistic routing concept may provide an effective solution for the UW-ASNs by the cooperation of the relay nodes to forward the packets to the surface sink. In this paper, the energy consumption problem is addressed and an energy-efficient cooperative opportunistic routing (EECOR) protocol is proposed to forward the packets toward the surface sink. In the EECOR protocol, a forwarding relay set is firstly determined by the source node based on the local information of the forwarder and then, a fuzzy logic-based relay selection scheme is applied to select the best relay based on considering the energy consumption ratio and the packet delivery probability of the forwarder. In the UW-ASNs, most of the energy is wasted due to the collisions amongst sensor nodes during the packet transmission. To alleviate the packet collisions problem, we have designed a holding timer for each of the forwarder to schedule the packets transmission toward the surface sink. We have performed our extensive simulations of the EECOR protocol on the Aqua-sim platform and compared with existing routing protocols in terms of average packet delivery ratio, average end-to-end delay, average energy consumption, and average network lifetime.

INDEX TERMS Energy consumption ratio, forwarding relay set, fuzzy logic, holding timer, packet delivery probability, opportunistic routing.

I. INTRODUCTION

Underwater acoustic sensor networks (UW-ASNs) consists of sensor devices with sensing, processing, and communication capabilities that are deployed for the underwater environments to support variety of applications e.g., oceanographic data collection, ocean sampling, monitoring of pollution and the environment, offshore exploration, preventing the disaster, assisted navigation, and distributed tactical surveillance [1]. To make the applications viable, efficient communication protocols among underwater devices are essentially required for making successful communications. As like terrestrial wireless sensor networks (TWSNs), radio frequency (RF) signals may propagate through UW-ASNs but requires large antenna and high transmission power. Moreover, the attenuation of the RF transmission through the conductive sea water is also very high. Optical signal can propagate through UW-ASNs which will not suffer from high attenuation compared to the RF signal but it may be affected by the scattering effect and the transmission of optical signals may also require high precision in pointing the narrow laser beams. However, optical signal will be appropriate only for short range broadband communication [2]. Therefore, acoustic signal will be good candidate for UW-ASNs, which can cover long range underwater communications.

Although many routing protocols for TWSNs exist, the unique characteristics of acoustic signal propagation over UW-ASNs, such as energy-constrained sensor devices, narrow bandwidths, poor-quality channels, high propagation delay, and high attenuation in transmission [3], require reliable and efficient routing protocols. Major challenges in the design of the routing protocol are as follows: the batteries of the sensor nodes are energy-constrained and cannot be recharged through energy-harvesting sources; the available bandwidth of underwater acoustic channels is severely limited and is distance-dependent, which possibly leads to high transmission loss over long-distance communication; and propagation delay of acoustic channel is much more higher than RF terrestrial channels due to the low propagation speed of the acoustic signal. Moreover, a significant number of sensor nodes are placed under the sea for monitoring the underwater environment. Each undersea sensor node is equipped with a low-bandwidth acoustic modem for collecting oceanographic data and transmitting the data to the surface sink from the bottom of the sea. Each sensor node in the monitoring area reports relevant data to the surface sink with the aid of multi-hop routing through the acoustic links. The data from the surface sink are offloaded to the monitoring center via radio communications for further offline processing. As is already known, UW-ASNs consume much more energy than terrestrial sensor networks from using an acoustic link between the transmitter and receiver [4]. Thus, employing an energy-efficient routing protocol is essential for UW-ASNs in order to enhance the packet delivery ratio, decrease the end-to-end delay in packet forwarding, reduce energy consumption, and prolong the network lifetime. In addition, opportunistic routing is also an emerging approach in wireless sensor networks because of its remarkable capability to increase communications reliability and network throughput [5], [6]. In this circumstance, data forwarding of the UW-ASNs may be enhanced by taking advantage of data reception at neighboring relay nodes and from their cooperation in forwarding the data to the next-hop destination. On the other hand, the sensor nodes are limited in energy, and it is also impossible to forward packets to the surface sink by utilizing only one hop between source node and the surface sink. Therefore, the source node that has data to send employs multi-hop routing to transmit the packets to the surface sink. In multi-hop routing, when the source node transmits the data, due to the broadcasting nature of wireless communications, all neighboring relay nodes within transmission range of the source node overhear the packets. To forward the packets, we need to efficiently select a relay in each transmission hop until the packets finally reach the surface sink.

Energy efficiency is critical because underwater acoustic transmissions consume much more energy than the terrestrial sensor networks (with a reception-to-transmission power ratio of 1:125 [7]). Our primary goal in this paper is to design an energy-efficient routing protocol that can address the energy consumption challenge of acoustic signal propagation for UW-ASNs. The existing TWSNs routing protocols (e.g., optimized link state routing [8], destination-sequenced distance-vector routing [9], ad hoc on-demand distance vector routing [10], dynamic source routing [11]) can not be implemented directly for UW-ASNs. The major deficiencies in the existing routing protocols are that they essentially require flooding, and also need to maintain a fixed routing path each time in order to reach the surface sink, which is very expensive. Moreover, they may require much more energy to determine a routing path by using the flooding technique. Therefore, to alleviate those shortcomings in the routing protocols, researchers have proposed opportunistic routing for UW-ASNs [12]–[14] where the neighboring relay nodes are selected from the surroundings of the source node using a distance-based timer, end-to-end latency in packet transmission, and a packet delivery probability estimation. However, the initial and the residual energy status of the neighboring relay nodes have not been considered when designing those routing protocols, which is critical for energy-constrained sensor devices. Therefore, our proposed energy-efficient cooperative opportunistic routing (EECOR) protocol can be a solution for UW-ASNs in which the network lifetime and the packet delivery ratio can be enhanced by the energy consumption ratio and the packet delivery probability while the relay is being selected by the source node to forward the packets to the next-hop destination until the packets are finally received at the surface sink.

The following are the key contributions of this paper:

- We propose an EECOR protocol in which the source node first determines a forwarding relay set based on the local depth information, and then, a fuzzy logic-based relay selection (FLRS) scheme is employed to select the best relay from the forwarding relay set for each transmission hop to forward the packets to the next-hop destination until the data finally reach to the surface sink.
- To protect the collisions of the packets, we set a holding time for each neighboring relay node in the forwarding relay set based on a neighbor fitness factor and the relative distance between the source node and each neighboring relay node.
- We also analyze the energy consumption of the EECOR protocol to show the trade-off between the consumed energy and transmission reliability regarding the opportunistic routing concept for UW-ASNs.
- Our simulation results were obtained in Aqua-sim (an NS-2-based underwater simulator), and the evaluated results reveal that the EECOR protocol performs better in terms of average packet delivery ratio, average end-to-end delay, average energy consumption, and average network lifetime when compared with depth-based routing (DBR) [15], fuzzy depth-based routing (FDBR) [16], vector-based forwarding (VBF) [17] and hop-by-hop vector-based forwarding (HH-VBR) [18].

The rest of the paper is prepared as follows. In Section II, we detail background studies of depth-based, location-based, delay-based, and energy-efficient routing protocols that were already adopted for UW-ASNs. We detail the proposed EECOR protocol with the forwarding relay set determination and the packet delivery probability estimation in Section III. The proposed FLRS scheme, the holding timer of the neighboring relay nodes, and the proposed energy consumption analysis are briefly described in Section IV.

Section V presents the simulation results to validate the proposed scheme. Finally, we conclude our paper with future research directions in Section VI.

II. RELATED WORKS

There has been an intensive study in routing protocols for UW-ASNs in the last few years. Because of the unique characteristics of acoustic signal propagation in the underwater environment, there are several drawbacks with regards to the TWSNs. Many different routing protocols have already been designed for UW-ASNs to solve the unique characteristics of underwater acoustic channel features which includes long propagation delay, low data rate, and the high error probability. Depth-based routing (DBR) [15] is the first routing protocol based on the pressure (or depth) level measures at each node. The packets are forwarded to the surface sink with lower depths in greedy fashion which can enhance the packet delivery ratio (PDR) but consumes much more energy and with high end-to-end latency in packet forwarding. To improve the performance of the DBR protocol the fuzzy DBR protocol was proposed by Mohammadi *et al.* [16] where the hop count to the surface sink, the depth information of the forwarder, and the energy status of each forwarding node are considered in selecting forwarding relay nodes for the packets. Therefore, the total energy consumption and the end-to-end delay performances of the FDBR protocol is improved because the forwarding relays are selected based on considering the hop count to the sink, the depth, and the energy status of each relay in the routing path.

Some location-based greedy routing protocols, such as vector-based forwarding protocol [17] and hop-by-hop vector- based forwarding (HH-VBF) [18], were proposed for UW-ASNs in which the forwarding relay nodes are selected based on a virtual pipeline fronting towards the surface sink and those routing protocols also considered a desirable metric to select the forwarding relay nodes inside the pipe. In those protocols, the forwarding relay nodes are selected in such a way that the packets are forwarded through a longest possible hop from the source node but satisfying its nearness to the routing vector. As is known, acoustic signal propagation suffers from distance-dependent bandwidth, high energy consumption, and high error rate when the distances between the transmitter and the receiver are far from each other. Therefore, to alleviate those problems, the radius of the pipe is increased in such a way that more forwarding relay nodes may get involved in packet transmission, which may increase the energy consumption of packet forwarding to the surface sink. However, those protocols still have a problem of solving the collisions and energy consumption issues when more nodes are involved in packet transmission.

A delay-sensitive opportunistic routing protocol [13] for UW-ASNs was proposed to maximize the goodput while satisfying the expected end-to-end latency from the sensor nodes to the destination when at least one of the forwarder is available to cooperate in packet transmission for the source node. To formulate opportunistic routing for UW-ASNs, a two-step heuristic algorithm was developed by the authors, which consists of forwarding set determination and packet forwarding prioritization. The packet-forwarding prioritization is based on the PDP in such a way that at least one of the forwarder in the forwarding relay set can receive the packets. However, the energy consumption of the relay nodes was not considered when consisting the forwarding relay set and packet prioritization which is very critical for acoustic signal propagation over UW-ASNs and needs to be considered in packet forwarding. A simple greedy heuristic algorithm was proposed in [12] that searches for a group of relay nodes based on local topology information, and the forwarding relay set is determined based on packet advancement towards the surface sink. Moreover, the packets are scheduled by setting a back-off timer that is proportional to the distance to the destination. However, the energy of the forwarding relay nodes was not considered when making the forwarding relay set, or when selecting the best relay from the set, which is essential for energy-constrained UW-ASNs. Void aware pressure routing (VAPR) was proposed in [19] where the sonobuoys propagate their reachability information to the sensor nodes with the aid of periodic beaconing. In VAPR, each node's beacon message is augmented with some additional vital information about the networks, namely, the sender's depth information, the hop count to the surface sonobuoy, the sequence number, and its current data forwarding direction to the surface. However, the residual energy of the sensor nodes is also an important variable to reduce the energy consumption for acoustic signal propagation which is very essential to enhance the network lifetime.

In UW-ASNs, the energy consumption issue in acoustic signal propagation can be solved by the power-efficient routing (PER) protocol, which was proposed by Huang *et al.* [20] and consists of two modules, including a forwarding node selector and forwarding tree-trimming mechanism. The forwarding relay selector utilizes three parameters to select the best relay to forward the packet to the surface sink. The three parameters of the forwarding node selector are transmission distance, the angle between two neighbor sensor nodes, and the energy remaining in the sensor node. Consequently, the PER protocol shows similar performance to the DBR protocol in terms of the packet delivery ratio and the PER protocol significantly outperforms in terms of average end-to-end delay. However, the packet-collision and the packet-retransmission issues are not solved by the PER protocol, which is very essential for energy-constrained UW-ASNs. Swarm intelligence-based fuzzy routing for clustered wireless sensor networks for the TWSNs was proposed [21], where the distance to the sink from the sensor nodes, the residual energy of the sensor nodes, and the distances between the sensor nodes and the cluster head are considered as inputs to the proposed fuzzy logic-based relay selection scheme. However, the main objective of the paper is to enhance the network lifetime, but other important performance metrics for wireless sensor networks (e.g., the packet delivery ratio, the end-to-end delay, and energy consumption) were not considered in showing the effectiveness of the proposed scheme. Brante *et al.* [22] proposed distributed fuzzy logic–based relay selection algorithms for cooperative TWSNs where the proposed algorithms only consider the channel state information of the relay-destination link, and the residual energy of the battery is used as input for the fuzzifier to enhance network lifetime and end-to-end throughput. However, these algorithms are not suitable for UW-ASNs due to the unique characteristics of the underwater environment. In UW-ASNs, network throughput and transmission reliability of acoustic signal propagation are enhanced by the novel cooperative opportunistic routing of Mohammad *et al.* [23], where the forwarding relay set is determined with the aid of a distributed beaconing mechanism. The distributed beacon message is initiated by the surface sink; the source node concurrently selects a group of neighboring relay nodes that can provide maximum packet advancement towards the surface sink, and the best relay is selected based on maximizing the PDP in each transmission hop. However, the residual energy status of each sensor node is not considered when selecting the best relay from the forwarding relay set. Therefore, the EECOR protocol is essential for acoustic signal propagation over UW-ASNs. In this paper, we mainly focus on selecting the routing path based on considering the ECR and the PDP of the neighboring relay nodes, and we set a holding time for the neighboring relay nodes to reduce packet collisions and retransmissions.

III. ENERGY-EFFICIENT COOPERATIVE OPPORTUNISTIC ROUTING PROTOCOL

To solve the energy consumption challenge of the acoustic signal propagation, the EECOR protocol utilizes an opportunistic routing concept to enhance communications reliability. By taking advantage of the broadcast nature of wireless communications, the source node locally selects the forwarding relay nodes based on depth information from the embedded depth sensor and the link quality between the source node and each neighbor node.

In the EECOR protocol, we consider a single sink node, as shown in Figure 1, for collecting the packets from the underwater sensor nodes. To establish a routing path, the source node needs the depth information of the sensor nodes and their current residual energy. Therefore, the sink node periodically broadcasts a beacon message to the sensor nodes and the beacon message is augmented with the depth information and the residual energy of the sensor nodes. In the EECOR protocol, the source node first determines a forwarding set, and then, the fuzzy logic-based relay selection scheme is used to select the best relay from the neighbor relay set and to broadcast the packet for the selected relay.

When the source node broadcasts the packet for the selected relay, due to the broadcasting nature of wireless communications, other relay nodes overhear the packet and set a holding time to avoid collisions with the ongoing packet transmission. Moreover, the relay nodes can retransmit the packet to the next-hop destination if the selected relay node fails to transmit. After receiving the packet from the source node, the selected relay will forward the packet to the next-hop destination. The packet will be discarded, if it is overheard by the relay nodes. If the selected relay fails to transmit the packet to the next-hop destination, the second-best relay will be selected by the source node to forward the packet to the next-hop destination, and the packet-forwarding mechanisms will continue until the packets finally reach the surface sink. The overall procedure of the proposed EECOR protocol is detailed in Figure 1.

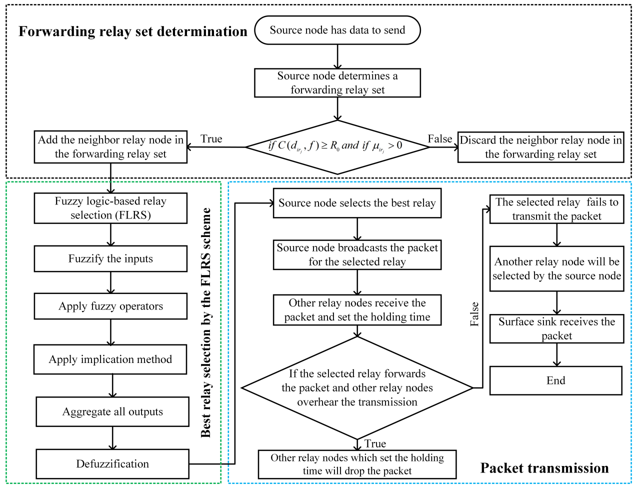

FIGURE 1. **Overview of the proposed EECOR protocol.**

A. SYSTEM MODEL

In this paper, we consider the network in Figure 2, where single surface sink operates to collect the packets from the source node and the surface sink is designed with an acoustic modem for receiving the acoustic signals from the source node and the neighboring relay nodes that are deployed for oceanographic data collection. Moreover, a radio modem is also utilized by the surface sink for sending the radio signal to the offshore monitoring center for offline processing.

When the source node generates the packets for the surface sink, it will use the neighboring relay nodes to deliver them to the surface sink. The source node and the neighboring relay nodes use acoustic signals to transmit their packets. In this paper, it is assumed that each sensor node determines its current depth (i.e., the perpendicular distance from the sensor node to the surface sink) with an embedded depth sensor [15]. Furthermore, the sensor nodes can obtain their residual energy status with the aid of distributed beaconing, as used by Noh *et al.* [19], and the relative distance between the source node and the neighboring relay nodes can be obtained through the received signal strength (RSS) of the receiver [24]. In addition, the sensor nodes randomly move in the horizontal direction due to the water currents, but their horizontal movements are negligible, and it is also assumed that all the sensor nodes are homogenous in terms of energy consumption and transmission range. In the EECOR protocol, we adopted the Thorp propagation model to design the

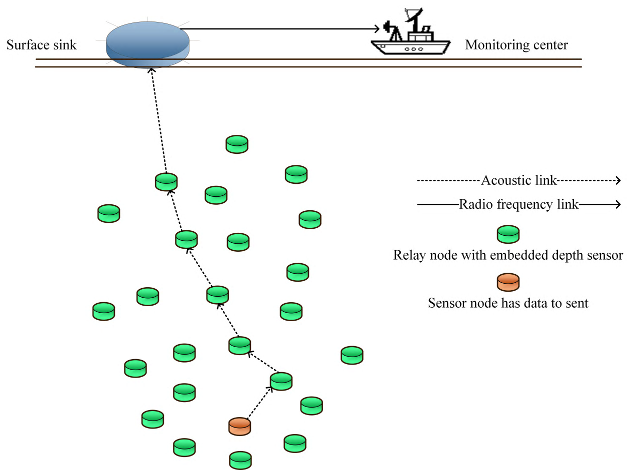

FIGURE 2. Nodes deployment for monitoring the underwater environment.

underwater acoustic channel. The path loss over the distance between the source node and the neighbor relay nodes d_{ir_j} for a single frequency f due to large-scale fading the path loss is defined as follows [25], [26]:

$$A\left(d_{ir_j}, f\right) = d_{ir_j}^{k}\, a\left(f\right)^{d_{ir_j}}, \tag{1}$$

where k and $a(f)$ are the spreading factor and the absorption coefficient, respectively. The propagation geometry is described by using the spreading factor; for a practical spreading k is given as 2. Absorption coefficient $a(f)$ is defined by the Thorp's formula in [27]. Thus, the average signal-to-noise ratio (SNR) over the distance d_{ir_j} for single frequency f is given as

$$\gamma(d_{ir_j}, f) = \frac{E_b}{N_T(f)\, d_{ir_j}^{k}\, a(f)^{d_{ir_j}}}, \tag{2}$$

where E_b and $N_T(f)$ are the average transmission energy per bit and ambient noise power density in an acoustic channel, respectively. The ambient noise of UW-ASNs consist of four main components: turbulence $N_t(f)$, shipping $N_s(f)$, wave $N_w(f)$, and thermal noise $N_{th}(f)$ and the ambient noise of UW-ASNs is defined in [28] as follows:

$$N_T(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{3}$$

In UW-ASNs, the values for the turbulence, shipping, wave, and thermal noise of the acoustic channel can be expressed as

$$10logN_t(f) = 17 - 30log(f), \tag{4}$$

$$10logN_s(f) = 40 + 20(s - 0.5) + 26log(f) - 60log(f + 0.03), \tag{5}$$

$$10logN_w(f) = 50 + 7.5\sqrt{w} + 20log(f) - 40log(f + 0.4), \tag{6}$$

$$10logN_{th}(f) = -15 + 20log(f), \tag{7}$$

where $s \in (0, 1)$ and w are the shipping activity factor and the wind velocity ranging from 0-10 m/s, respectively. In this paper, we have assumed that the ambient noise of UW-ASNs follow a Gaussian distribution and the channel capacity of a Gaussian channel can be expressed as

$$C\left(d_{ir_j}, f\right) = \log_2\left(1 + \gamma\left(d_{ir_j}, f\right)\right). \tag{8}$$

Acoustic signal propagates successfully over a fading channel if the channel link is satisfying the data rate requirement R_0 as

$$C\left(d_{ir_j}, f\right) \geq R_0. \tag{9}$$

Algorithm 1 Forwarding Relay Set Determination

Input: D_{r_j} and d_{ir_j}
Output: $F(i) = \{r_1, r_2, r_3, \ldots\ldots, r_j\}$, where $j = |F(i)|$ denotes the number of relays in $F(i)$
Initialization: $F(i) = \phi$
1: **Max** $= T_r$// **Number of neighboring relay nodes**
2: **for** $j = 1$:**Max**
3: Calculate μ_{ir_j} and $C\left(d_{ir_j}, f\right)$
4: **if** $C\left(d_{ir_j}, f\right) \geq R_0$ **and** $\mu_{ir_j} > 0$ **then**
5: $F(i) = F(i) + \{r_j\}$
6: **end if**
7: **end for**
8: The source node determines a forwarding relay set $F(i)$

B. FORWARDING RELAY SET DETERMINATION

In the EECOR protocol, we first determine a group relay nodes which can concurrently maximize the sensor node advancement and the PDP towards the surface sink. To determine packet advancement towards the surface sink, we developed a neighbor fitness factor μ_{r_j} which represents the difference between the depth of the source node and the neighbor relay nodes depth, and where its normalized value can be expressed as

$$\mu_{r_j} = \frac{D_i - D_{r_j}}{R_{\max}} \quad \text{subject to} : 0 \leq \mu_{r_j} \leq 1, \tag{10}$$

where, $R_{\max}$ is the maximum transmission range of the sensor nodes. According to the neighbor fitness factor, the sensor nodes that are not as deep as the source node can be considered for relaying packets owing to their closeness to the surface sink.

As shown in Figure 3, the negative value of the neighbor fitness factor indicates that the neighbor relay nodes are located below the source node. Cooperation from those relay nodes will provide lower packet advancement towards the surface sink, will decrease the packet deliver probability and will increase energy consumption due to the long distance between the neighboring relay node and the surface sink. In contrast to the majority conventional greedy routing protocols, the EECOR protocol discards from the forwarding relay set those neighbor relay nodes that are at the same depth as the source node or at a greater depth than the source node. Algorithm 1 details the forwarding relay set determination by the source node, which will be repeated for each transmission hop until the packets finally reach the surface sink.

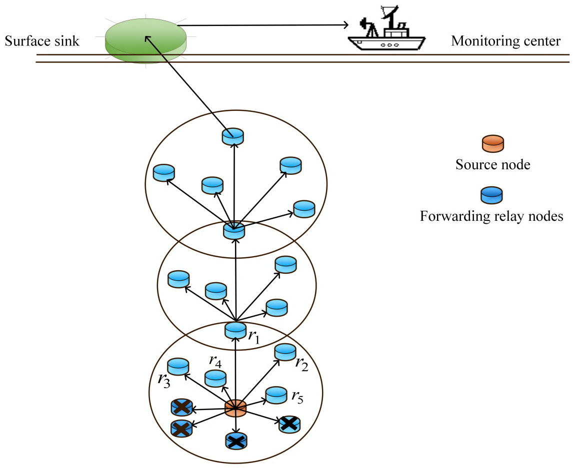

FIGURE 3. Forwarding relay set determination.

C. PACKET DELIVERY PROBABILITY ESTIMATION

Let us assume that a source node i has a packet to the surface sink, and $F(i) = \{r_1, r_2, r_3, \ldots.., r_j\}$ shows the available neighbor relay nodes of the source node, which is determined in Algorithm 1. Let $j = |F(i)|$ denote the number of the candidate relay node in the forwarding relay set, and assume that source node has calculated the PDP of its one-hop neighbor relay nodes. For example, if the source node has received a distributed beacon message from the neighbor relay node r_k where, $1 \leq k \leq j$ and it can compute the distance between the source node and the neighbor relay node $Dist(i, r_k)$ based on the RSS of the receiver, and it records the amount of residual energy of the neighbor relay nodes. Consequently, all the neighbor relay nodes in the forwarding relay set are associated with the PDP between the source node and each of neighbor relay nodes: $P_{ir_j}\,(1 \leq k \leq j)$. Moreover, the ECR of each neighboring relay node can be expressed as

$$E_c\left(r_j\right) = \frac{E_R\left(r_j\right)}{E_I\left(r_j\right)}, \tag{11}$$

where $E_I\left(r_j\right)$ and $E_R\left(r_j\right)$ are the initial and the residual energy of each neighboring relay node, respectively. In this paper, the binary phase shift keying (BPSK) modulation scheme is considered, which is being widely used in state-of-art acoustic modems [7]. In BPSK, each symbol carries a bit, and the bit error probability over distance d_{ir_j} is defined as follows [29]:

$$P_e\left(d_{ir_j}, f\right) = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma\left(d_{ir_j}, f\right)}{1+\gamma\left(d_{ir_j}, f\right)}}\right) \tag{12}$$

For an instance, PDP from the source node to the neighboring relay node r_j for m bits can be expressed as

$$P_{ir_j} = \left(1 - P_e\left(d_{ir_j}, f\right)\right)^m. \tag{13}$$

In conventional routing protocol, the primary objective is to select a neighbor relay node from the forwarding relay set $F(i)$ in such a technique that it can only maximize the PDP.

As can be seen from Figure 4, if the neighbor relay node r_1 is chosen by the source node, then the PDP is equal to P_{ir_1}. However, without considering energy consumption in opportunistic routing, it might ideally select the best neighbor relay node based on maximizing the PDP as $\max\left(p_{ir_1}, p_{ir_2}, p_{ir_3}, \ldots, p_{ir_j}\right)$ in each hop transmission, which is not appropriate from the perspective of energy-constrained UW-ASNs. Consequently, the neighbor relay node that is selected for packet forwarding in each transmission hop will die very soon owing to the forwarding of most of the packets by the same node with the higher PDP. In this context, we propose the FLRS scheme, in which the source node selects the best relay from the forwarding relay set based on PDP and ECR variables.

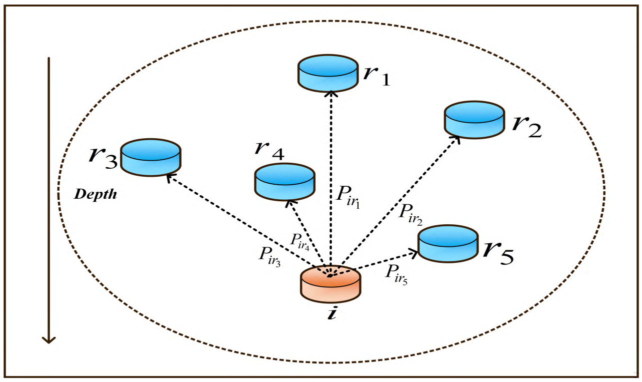

FIGURE 4. Example of the relay selection based on maximizing the PDP.

IV. THE PROPOSED FUZZY LOGIC-BASED RELAY SELECTION

In the proposed EECOR protocol, an FLRS scheme is proposed to select the best relay from the forwarding relay set.

Figure 5 shows the FLRS scheme with two input variables: PDP and ECR. In the FLRS scheme, the fuzzifier performs the membership function that converts the two input variables, ECR and PDP, into appropriate linguistic values, which are needed in the fuzzy inference system (FIS). The FIS uses the fuzzy if-then rules to map the fuzzy inputs to the fuzzy output, and it is composed of a set of linguistic control rules. The FIS simulates human decision-making based on the fuzzy if-then rules and the related input linguistic variables. The defuzzifier acquires the aggregated linguistic values from the FIS and generates a non-fuzzy control output which selects the best relay to forward the packets. The input-output mapping function f_m for the FIS established at each of the neighboring relay nodes in the forwarding relay set can be expressed as

$$K = f_m\left\{E_c\left(r_j\right), P_{ir_j}\right\}. \tag{14}$$

In the proposed FLRS scheme, the crisp values of the two input variables of the FIS (ECR and PDP) lie between 0 and 1. Each of the input variables possesses three different input levels in the fuzzification stage of the proposed

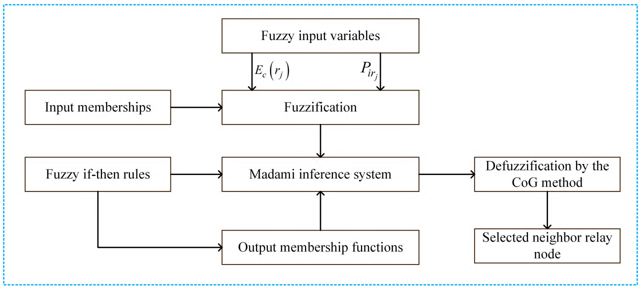

FIGURE 5. **The proposed fuzzy logic-based relay selection scheme.**

FLRS scheme. The input variables and their linguistic levels are listed in Table 1.

TABLE 1. **Fuzzy linguistic labels of the input variables.**

Input	Membership		
ECR	Low	Medium	High
PDP	Minimum	Medium	Maximum

The membership function of the triangle and the trapezoid form is used in the fuzzifier to reduce the complexity of computing. Corresponding to the linguistic levels of Low, Medium, and High, the membership functions for the ECR are respectively defined as

$$\mu_L(x,a,b,c,d)=\begin{cases}0, & x\le a\\ \dfrac{x-a}{b-a}, & a\le x\le b\\ 1, & b\le x\le c\\ \dfrac{d-x}{d-c}, & c\le x\le d\\ 0, & d\ge x,\end{cases} \tag{15}$$

$$\mu_M(x,e,f,g)=\begin{cases}0, & x\le e\\ \dfrac{x-e}{f-g}, & e\le x\le f\\ 1, & x=f\\ \dfrac{g-x}{g-f}, & f\le x\le g\\ 0, & g\ge x,\end{cases} \tag{16}$$

$$\mu_H(x,h,u,v,w)=\begin{cases}0, & x\le h\\ \dfrac{x-h}{u-h}, & h\le x\le u\\ 1, & u\le x\le v\\ \dfrac{w-x}{w-v}, & v\le x\le w\\ 0, & w\le x.\end{cases} \tag{17}$$

From Figure 6 and Figure 7 show the membership function of the ECR and the PDP, respectively. In the proposed FLRS scheme, three linguistic levels (Minimum, Medium, and Maximum) are used to map the PDP variable, and similarly, we also utilize the triangular and trapezoidal

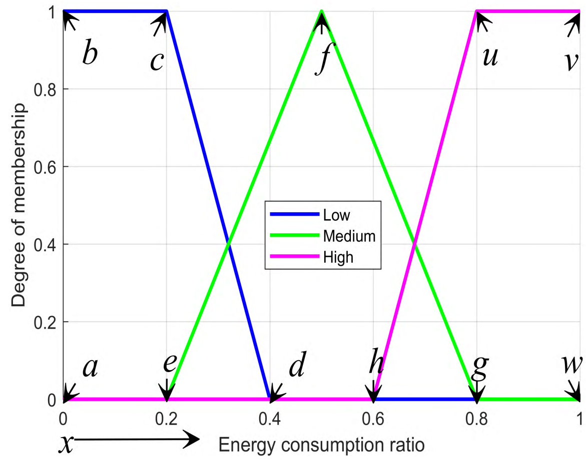

FIGURE 6. **Membership functions of the ECR.**

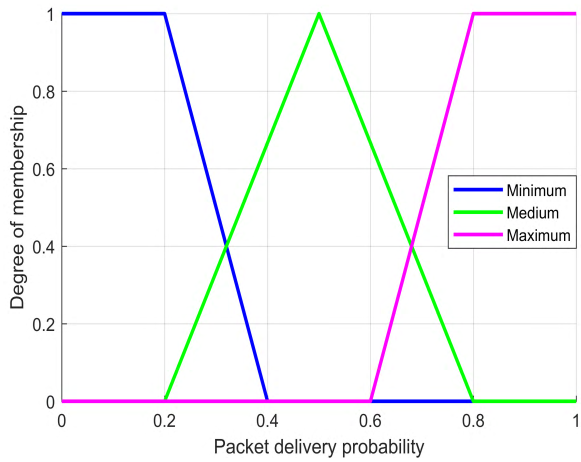

FIGURE 7. **Membership functions of the PDP.**

membership functions to fuzzify the input of the PDP used in Eq. (15), (16), and (17).

The output parameter of the FIS refers to the chance of the neighboring relay node being selected as the relay to forward the packets to the next-hop destination. The maximum value of the chance means that the neighboring node in the forwarding relay has an opportunity to be selected as the best relay for the current packet transmission. The inputs of the fuzzy variables of the proposed FLRS scheme are the ECR and the PDP of the relay nodes in the forwarding relay set. The rules for the FIS are made based on the input ECR and PDP.

In the proposed FLRS scheme, two input variables are used, and each of the input variables contains three different input levels; therefore, to map the fuzzy rules in the FIS, nine different output linguistic values are utilized, and their memberships are listed in Table 2.

A fuzzy inference system maps the input of the fuzzifier to a crisp output value. To obtain the crisp output, we need a defuzzification process. The input of the defuzzification process is a fuzzy set (the aggregated fuzzy output set); the output is a single value, and the relay node with the value

TABLE 2. Fuzzy membership functions for the input variables.

Output	Membership
PDP	Very low, Low, Rather low, Medium low, Medium, Medium high, Rather high, High, Very high

will be selected as the best relay to forward the packets. The collection of the fuzzy rules is summarized in Table 3.

TABLE 3. Fuzzy linguistic labels of the input variables.

$E_c(r_j)/P_{ir_j}$	Maximum	Medium	Minimum
High	Very high	High	Rather high
Medium	Medium high	Medium	Medium low
Low	Rather low	Low	Very low

As can be seen, Figure 8 describes the membership functions of the linguistic output variable chance of selection, and we have used similar membership functions for the input variable ECR in Eq. (15), (16), and (17) to design the membership functions of that chance.

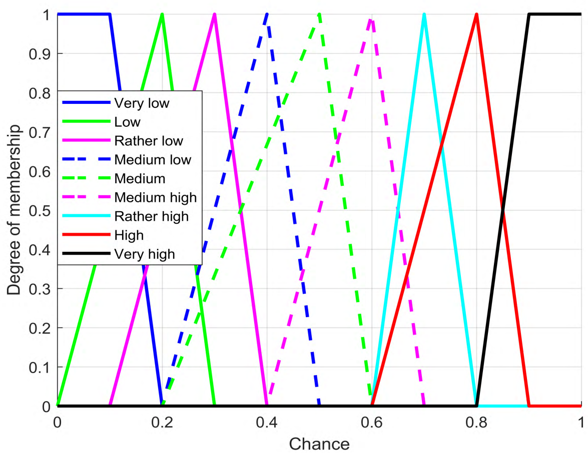

FIGURE 8. Membership functions of the chance.

In this paper, to map the ECR and the PDP into the chance selection, and to select the neighboring relay node from the forwarding relay set, we assume a collection of fuzzy rules in the form: If the ECR is High and the PDP is Maximum, then Chance is Very High (denoted symbolically by High & Maximum → Very High).

Rule 1: High & Maximum → Very High
Rule 2: High & Medium → High
Rule 3: High & Minimum → Rather high
Rule 4: Medium & Maximum → Medium high
Rule 5: Medium & Medium → Medium
Rule 6: Medium & Minimum → Medium low
Rule 7: Low & Maximum → Rather low
Rule 8: Low & Medium → Low Rule
Rule 9: Low & Minimum → Very low

As an example, let us consider that $E_c(r_j) = 0.4$ and $P_{ir_j} = 0.8$ for relay r_j in the forwarding relay set. As can be seen from Figure 8, the ECR is classified as Low with membership of $\mu_{E_c(r_j)} = 0.3$ and as Medium with membership of $\mu_{E_c(r_j)} = 0.5$ which can be represented as

$$\mu_{E_c(r_j)} = \{(Low,\ 0.3),\ (Medium,\ 0.5)\}. \tag{18}$$

According to Figure 8, the PDP can be classified as Maximum with the membership of $\mu_{P_{ir_j}}$, and it can be represented as follows:

$$\mu_{P_{ir_j}} = \{(Maximum,\ 1.0)\}. \tag{19}$$

The output variable Chance in this example is specified by the mixture of two pairs (Low-Maximum and Medium-Maximum), which according to Table 3 result in Rather low and Medium high, respectively, and the degree of membership of the output variable Chance μ_{Chance} in this example can be expressed as

$$\mu_{Chance} = \begin{Bmatrix} (Low - Maximum,\ \min(0.4, 1.0)), \\ (Low - Maximum,\ \min(0.5, 1.0)) \end{Bmatrix},$$
$$\mu_{Chance} = \{((Rather\ low, 0.4),\ (Medium\ high, 0.5))\}. \tag{20}$$

As can be seen in Figure 9, the procedure at the top represent the linguistic fuzzy level pair Low-Maximum and the bottom part represents the pair Medium-Maximum. Then, the two terms of the output variable Chance, $\{(Rather\ low, 0.4),\ (Medium\ high, 0.5))\}$, are represented by the dark areas at top and bottom of Figure 9. Lastly, the numerical result of the above fuzzy operation $f_m\{E_c(r_j), P_{ir_j}\}$ is determined by using the Center of Gravity (CoG) method of the area, as shown in the center of the figure. The discretized value of the CoG is defined as follows [30]:

$$COG = \frac{\sum Chance\ \mu_{Chance}}{\sum \mu_{Chance}}. \tag{21}$$

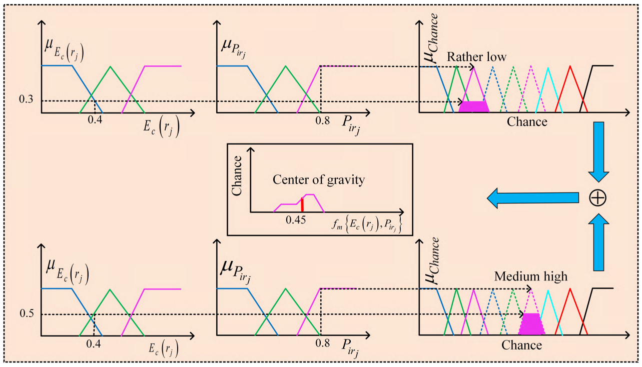

FIGURE 9. Example of the fuzzy operation.

By applying the CoG method, we get a single value for the fuzzy operation $fr_j(0.4, 0.5) = 0.45$. Finally, the output parameters of the FIS refer to the chance of the sensor node being selected as the relay to forward the packets to the next-hop destination. For instance, it is possible that two different relays may have the same ECR, but the PDP of those relays may differ based on the distance from the source node. Algorithm 2 describes the proposed fuzzy logic-based relay selection algorithm, by which the source node can select the best relay in each transmission hop to forward the packets.

Algorithm 2 Fuzzy Logic-Based Relay Selection Scheme

Input: d_{ir_j} and $E_R(r_j)$
Output: S_{r_j}
Initialization: $S_{r_j} = \phi$
Loop process
1: ***for*** $r_j = 1 : j$ ***do***
2: Calculate $P_{ir_j} = \left(1 - P_e\left(d_{ir_j}, f\right)\right)^m$
3: Calculate $E_c(r_j) = \frac{E_R(r_j)}{E_I(r_j)}$
4: Fuzzify the input variables
5: Apply the fuzzy operators
6: Apply implication method
7: Aggregate all output of the implication
8: Defuzzify the aggregated output by the CoG method
9: **end for**
10: **Return** The source node selects the best relay S_{r_j}

A. PROPOSED HOLDING TIMER OF THE FORWARDER

Eventually, the source node locally determines the forwarding relay set $F(i)$ and broadcasts the packets to the neighboring relay nodes in the forwarding relay set. The EECOR protocol is a source-based protocol where the source node will decide which relay nodes will cooperate in forwarding the packets to the next-hop destination. The neighboring relay node must be in the forwarding relay set to accept the packet; otherwise, the packet will be dropped by the relay node. After receiving the packets from the selected forwarding relay node, it will forward them to the next-hop destination by selecting another best relay using the FLRS scheme, and rest of the relay nodes that receive the same packet from the source node will set a holding time proportional to the neighbor fitness factor of Eq. (10). Each relay node in the forwarding relay set will use the holding time to schedule transmitting the packets to the surface sink. If transmission by the selected relay to the next-hop destination is overheard by the rest of the relay nodes, they will drop the packets; otherwise, the second-best relay will be selected for transmitting the packets to the next-hop destination. The forwarding relay nodes with different fitness factor values will have different holding times, even for the same packet. To reduce the number of hops along the forwarding path to the surface sink, the EECOR protocol tries to select the neighbor relay node based on considering maximum packet advancement towards the surface sink along with high energy. It also tries to prevent other neighboring relay nodes from forwarding the same packet, in order to reduce energy consumption. The packet-forwarding process will repeat until the packets finally reach the surface sink.

Figure. 10 shows an example of the holding time calculation of the neighbor relay nodes, where i is the source node,

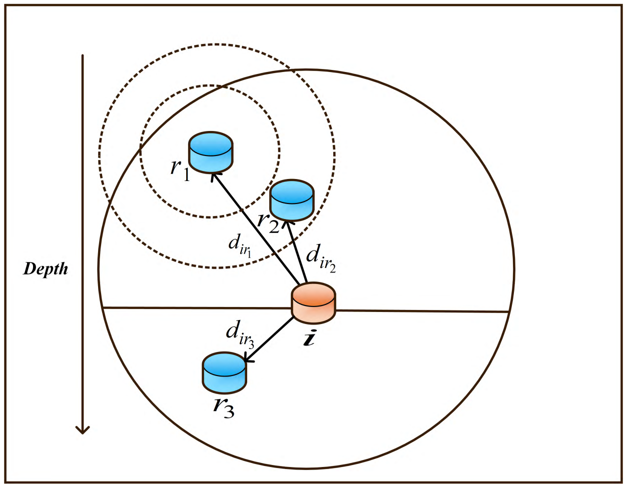

FIGURE 10. **Example of the holding time calculation.**

and relay nodes r_1, r_2, and r_3 are the one-hop neighboring nodes. The solid black line circle represents the maximum transmission range R_{max} of the source node. When the source node i broadcasts a packet, all neighboring nodes within transmission range of the source node will receive the packet. Neighboring node r_3, which is at a higher depth than the source node i, will discard the packet. Although neighboring nodes r_1 and r_2 both qualified to forward the packet to the next-hop destination, relay node r_1 is more preferred to forward the packet to the next-hop destination because it can ensure maximum packet advancement towards the surface sink. For an instance, if the reighboring relay node r_1 fails to transmit the packet, the source node will select the relay node r_2 as the forwarder to the next-hop destination. Data forwarding by the relay node r_2 is prevented in favor of neighboring relay node r_1 due to the nieghbor fitness factor. Therefore, the holding time of each candidate neighbor relay node is calculated as

$$T_{H_{r_j}} = \left(1 - \mu_{r_j}\right)(\tau_{max}) + \frac{R_{max} - \left|\overrightarrow{d_{ir_j}}\right|}{V_{sound}}, \tag{22}$$

where τ_{max} and V_{sound} are the maximum propagation delay and the acoustic signal propagation speed, respectively. The maximum propagation delay needs to be determined in such a way that all the neighbor relay nodes in the forwarding relay set may able to overhear transmission of the selected relay before relaying the packet to the next-hop destination. Relative distance $\overrightarrow{d_{ir_j}}$ designates the distance between the source node and the neighboring relay node, and it can be extracted from the RSS of the receiver or time of arrival of the received signal from the source node. The first part of Eq. (22) shows the maximum holding time of the neighboring relay nodes based on the neighbor's fitness function (the greater value of the fitness factor, shorter the holding time) and the second part of the equation reflects the propagation delay between the source node and the forwarding relay nodes. As known acoustic signal propagation speed

V_{sound} can be directly calculated by the conductivity-temperature-depth (CTD) measures for a certain region and the speed of sound varies by the location and change of the seasons. Thus, a simplified expression of acoustic signal propagation speed is defined as follows [31]:

$$V_{sound}(T, S_t, D) = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S_t - 35) + 0.016D, \tag{23}$$

where T, S_t, and D are the water temperature (in Celsius), the salinity of the sea water, and the depth of the water, respectively. Algorithm 3 details the procedure of the packet transmission of the EECOR protocol.

Algorithm 3 Packet Forwarding Algorithm

```
procedure receiving packet (i, Packet)
  if the source node ID matches the selected relay then
    Forward the packet to the next-hop destination
    Other relay nodes will set the holding time
    if the selected relay transmits the packet then
      Other relay nodes overhear and drop the packet
    else
      The selected relay fails to transmit the packet
      Another relay will be selected by the source node
    end if
  end if
end procedure
```

B. THE PROPOSED ENERGY CONSUMPTION ANALYSIS

The total amount of energy consumption for successful transmission under the proposed EECOR protocol is a combination of the energy consumed to transmit the packets, the energy consumed to receive the packets, the energy consumed to overhear the packets by the forwarding relay nodes that are in the forwarding relay set. Let us consider E_{Tx} and E_{Rx} as the amount of energy consumption by the source node to transmit the packets and the amount of energy consumption to receive the packets, respectively. The total amount of energy consumption by the transmission and reception of m bits over distance d_{ir_j} can be calculated as

$$E_{Total}\{F(i), j\} = E_{Tx}\left(m, d_{ir_j}\right) + j \cdot E_{Rx}(m). \tag{24}$$

The power consumption for transmitting a packet from the source node to the neighboring relay nodes can be calculated as

$$E_{Tx} = P_{Tx}A\left(d_{ir_j}, f\right), \tag{25}$$

where P_{Tx} is the transmission power of the source node. The amount of consumed energy for transmitting m bits over distance d_{ir_j} is defined as follows [32]:

$$E_{Tx}\left(m, d_{ir_j}\right) = m\, t_o\, P_{Tx}\, A\left(d_{ir_j}, f\right), \tag{26}$$

where t_o is the transmission duration of the packets. Similarly, the amount of energy consumed energy for receiving m amount bits can be calculated as

$$E_{Rx}(m) = mP_{Rx}t_o. \tag{27}$$

Assume that neighboring relay node r_j was selected from forwarding relay set $F(i)$ by the fuzzy logic–based relay selection scheme. Then, by removing that selected relay from the forwarding relay set, the amount of energy consumed under the proposed scheme is computed as follows:

$$E_{Total}\{F(i), r_j\} = E_{Tx}\left(m, d_{ir_j}\right) + j \cdot E_{Rx}(m) + \left(j - r_j\right)E_{Re}, \tag{28}$$

where E_{Re} is the required energy to overhear the data packets of the selected relay from the forwarding relay set. In UW-ASNs, most of the energy is wasted due to collisions and retransmissions of the source node packets. However, the EECOR protocol reduces these problems by considering the waiting time of each relay node in the forwarding relay set, and the PDP and ECR of each relay is also considered when selecting the best relay to forward the packet to the surface sink. Therefore, the proposed EECOR protocol can consume much less energy for successful packet transmission.

V. SIMULATION RESULTS

In this section, we evaluate the performance of the EECOR protocol and compare it with FDBR, DBR, VBF and HH-VBF protocols through simulation results. All simulation results were performed by using the network simulator (ns2) [33] with an underwater acoustic sensor network simulator package (called Aqua-sim) extension. To show the performance of the EECOR protocol versus FDBR, DBR, HH-VBF and VBF protocols, we used the following performance metrics throughout the simulations.

A. AVERAGE PACKET DELIVERY RATIO (PDR)

The performance metric is defined as the ratio between the number of received packets at the surface sink and the number of generated packets by the source node.

$$PDR = \frac{\sum_{u=1}^{K} \frac{P_{ru}}{P_{lu}}}{K}, \tag{29}$$

where P_{ru}, P_{lu}, and K are the number of received packets at the surface sink in the uth simulation run, the number of generated packets by the source node in the uth simulation run, and the total number of simulation runs, respectively.

B. AVERAGE END-TO-END DELAY

End-to-end delay is the time taken by the network to forward the packets from the source node to the surface sink, and vice versa. The formulation of average end-to-end delay can be expressed as

$$EED = \frac{\sum_{u=1}^{K} \sum_{m=1}^{P_r} \left\{ (TP_{um} - RP_{um}) + T_{H_{r_j}} \right\}}{P_r K}, \tag{30}$$

where P_r, RP_{um}, and TP_{um} are the total number of received packets at the surface sink, the sending time of the mth packet in the uth simulation run, and the receiving time of the mth packet in the uth simulation run, respectively.

C. AVERAGE ENERGY CONSUMPTION

The average energy consumption for a successful transmission is a combination of the energy consumed to transmit the packets, the amount of energy consumed to receive the packets, and the energy consumed to overhear the packets by the forwarding relay nodes that are in the forwarding relay set. The average energy consumption of the network can be expressed as

$$E_{Avg} = \frac{\sum_{u=1}^{K} E_{Total} \left\{ F(i), r_j \right\}}{K}. \tag{31}$$

D. AVERAGE NETWORK LIFETIME

This is the amount of time that the network would be fully operative. In this paper, network lifetime is defined as the time at which the first sensor node in the network runs out of energy. Therefore, the network lifetime was measured as the difference between the starting time of the simulation run and the time at which the first node in the network running out of energy. The statistical formula for evaluating network lifetime can be expressed as

$$L_{Avg} = \frac{\sum_{u=1}^{K} (ST_u - FT_u)}{K}, \tag{32}$$

where ST_u and FT_u are the starting time of the uth simulation run and the time at which the first node running of energy at the uth simulation run, respectively.

1) SIMULATION SETTINGS

In the simulations, varying number of nodes ranging from 100 to 700 as used in [15]–[20] and [23] were randomly deployed in the 3D region of a size of 500 m × 500 m × 1000 m. In UW-ASNs, the number nodes for collecting the oceanographic data in real scenarios will be very few based on the properties of the commercial acoustic modem. In [33], Micro-modem [7] is used which can provide 80 bps data rate and only 5 nodes are used for collecting the real testbed results. Moreover, by adopting the parameters from the commercial acoustic modem, the existing routing protocol was compared by taking the number of nodes (ranging from 200 to 800) [33]. The horizontal movement of the sensor nodes was set to a speed of 1 m/s, followed by a random way-point mobility model (moving on the X-Y axis), which is typically utilized for underwater routing protocols (e.g., DBR, FDBR, VBF, HH-VBF, VAPR, and PER) [15]–[20]. However, the behavior of the proposed scheme in a hybrid network (e.g., made of fixed and mobile nodes) is not considered in this paper and a static sink node is used for collecting the packets from the underwater sensor nodes by considering only the horizontal movements of the underwater sensor nodes due to the water currents. Mobility of the sink and underwater sensor nodes occurring the interruptions of the communication links due to the movement of the underwater nodes as used in [34] is out of scope of this paper. However, in future, a new routing protocol will be designed based on machine learning algorithm for mobility-based UW-ASNs.

In this paper, we consider a single sink node on the surface of the water and the source node fixed at location (400, 400, 1000). The source node generates the packets to be transferred to the surface sink with the aid of the neighboring relay nodes within its transmission range. The protocol parameters are similar to those on a commercial acoustic modem, LinkQuest UWM1000 [35]: the maximum transmission range of the source node and the relay nodes and the channel bit rate was set to 100 m and 10 kbps, respectively. The required powers to send the packets, to receive the packets, and to overhear the packets were set as 2W, 0.75W, and 8 mW respectively [35]. The packet generation rate of the source node was one packet per second, with a packet size of 100 bytes. The initial energy of each sensor node was considered to be 100 J. We set the signal frequency of the acoustic signal at 10 kHz, and the spreading factor at 2. The same broadcasting medium access control (MAC) protocol for UW-ASNs used by Xie *et al.* [17] was used throughout the simulations. In the broadcasting MAC protocol, when a source node has a packet to send, it first senses the channel, and if the source node finds the channel free, it broadcasts the packet; otherwise, it backs- off. The packet will be dropped if the maximal back-off time expires. The simulation results were averaged from a total of 50 runs.

2) AVERAGE PACKET DELIVERY RATIO

Figure. 11 shows the average PDR of the EECOR protocol, the FDBR, the DBR, the HH-VBF, and the VBF protocols according to the number of nodes. As can be seen, the average PDR increased as the number of nodes increased, because more qualified nodes may have an opportunity to forward the packets to the surface sink. The average PDR of the EECOR protocol and the other protocols converged when the node density is high. The EECOR protocol has a higher average PDR than the other protocols because it fundamentally excludes all the relay nodes that are at the same depth or below the source node, which can provide a higher PDP. Additionally, the EECOR protocol selects the best relay by considering maximum PDP in each transmission hop, and it also reduces collisions during packet transmission with the aid of the holding timer for each forwarder in the relay set. However, the FDBR protocol has an average PDR similar to the DBR protocol because the target of the

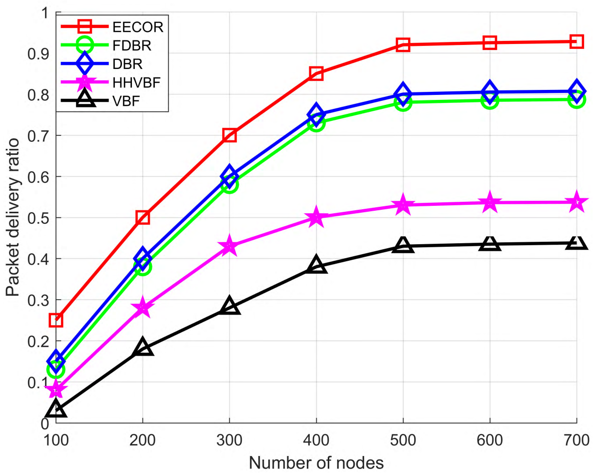

FIGURE 11. **Average packet delivery according to the number of nodes.**

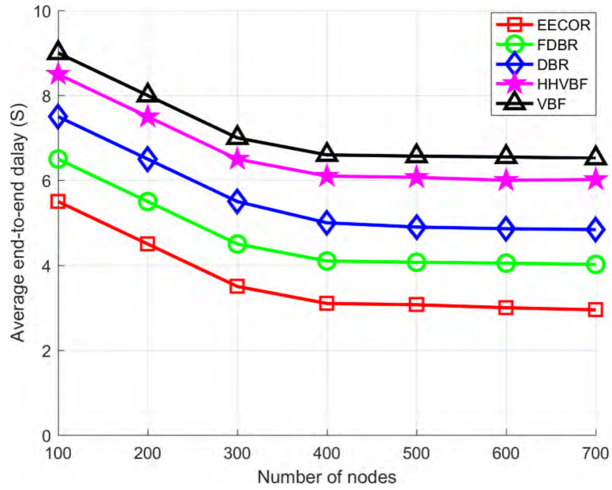

FIGURE 12. **Average end-to-end delay according to the number of nodes.**

FDBR protocol is to reduce the end-to-end delay and total energy consumption in packet transmission. Furthermore, the FDBR and DBR protocols do not consider PDP as a selection criterion for the relay node. In the VBF protocol, packet failure increased when the relay nodes are not available in their routing pipes. The average PDR of the VBF protocol can be improved by increasing the radius of the pipe, and the packet failure problem for the VBF protocol is improved by the HH-VBF protocol by utilizing the hop-by-hop procedure in packet forwarding. Consequently, the HH-VBR protocol shows a better average PDR performance than the VBF protocol.

3) AVERAGE END-TO-END DELAY

This criterion calculates the average end-to-end delay from the instant the packets are generated by the source node until the packets are received successfully by the surface sink, plus the holding time of the relay nodes that participate in packet forwarding.

The average end-to-end delay of each protocol according to the number of nodes is plotted in Figure 12. As shown in Figure 12, the average end-to-end delay for all protocols decreased as the number of nodes increased, because the source node can find more qualified nodes to forward the packets to the surface sink. The average end-to-end delay of the EECOR protocol is similar to the FDBR protocol and lower than the other protocols, because the generated packets of the source node always use the best path to forward the packets to the surface sink, with the fewest possible collisions and retransmissions. The FDBR protocol showed performance similar to the EECOR protocol, and better performance in terms of average end-to-end delay compared with the DBR protocol, because the hop count traveled during packet transmission is not considered in the DBR protocol. In the FDBR protocol, the hop count and the depth difference are considered when selecting the relay nodes to reach the surface sink in the routing path, and consequently, the FDBR protocol has better average end-to-end delay performance than the DBR protocol. However, in the VBF and HH-VBF protocols, the relay nodes that are closer to the surface sink may not be positioned inside the radius of the pipe, and discounting those relay nodes for forwarding the packet may increase average end-to-end delay. Moreover, the VBF and the HH-VBF protocols only provide priority to those nodes that are close to the vector, and essentially do not consider those nodes with a shorter hop distance to the surface sink. Furthermore, in the VBF and the HH-VBR protocols, the forwarding relay nodes may be situated on different sides of the pipe due to the hidden terminal problem, which may cause collisions during packet transmission, increasing the average end-to-end delay. Thus, the average end-to-end delay of those protocols increased as the number of nodes increased. In the EECOR protocol, the hidden terminal problem does not appear, because the source node selects the forwarding relay set based on receiving the beacon message from its one-hop neighbors. Therefore, the EECOR protocol always shows better performance than the other protocols and showed performance similar to the FDBR protocol.

4) AVERAGE ENERGY CONSUMPTION

This criterion measured the amount of energy consumption for successful packet transmission, which includes the amount of energy consumed for packet transmission, the amount of energy consumed for packet reception, and the amount of energy consumed by the forwarding relay nodes in the forwarding relay set to overhear the packets.

The average energy consumption for each protocol according to the number of nodes is plotted in Figure 13. As illustrated in Figure 13, the EECOR protocol consumes much less energy to deliver the packets to the surface sink, because the EECOR protocol selects the forwarding relay set based on the neighbor fitness factor in each packet transmission hop (without a hidden terminal), and the holding time of each forwarding relay node in the forwarding relay set prevents packet collisions and retransmissions. Therefore, the

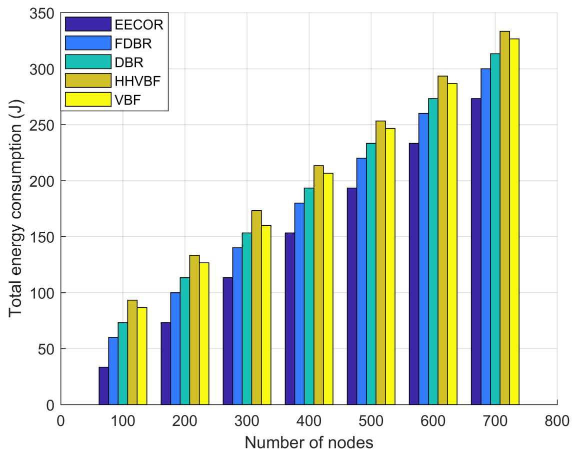

FIGURE 13. Average energy consumption according to the number of nodes.

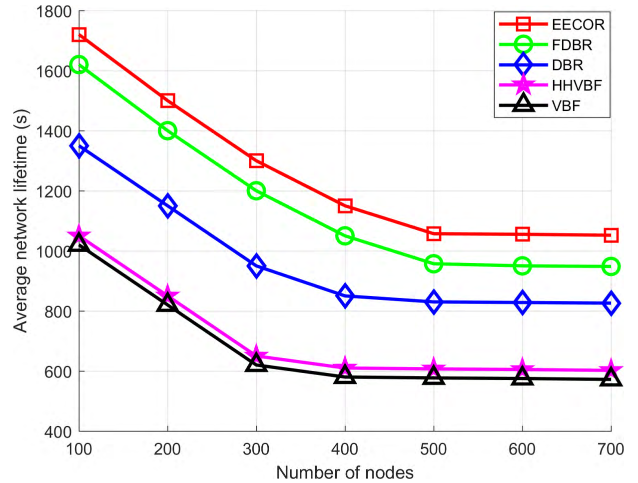

FIGURE 14. Average network lifetime according to the number of nodes.

EECOR protocol shows better performance in terms of average energy consumption, although the range of the pipe in the VBF and the HH-VBF protocols has a robust influence on the average energy consumption and the average packet delivery ratio. Choosing a large radius for the pipe can include more forwarding relay nodes; however, increasing the number of nodes in the routing path may increase duplicated packets, which leads to wasting much more energy. On the other hand, the packet failure probability of the VBF and the HH-VBF protocols is higher when the radius of the pipe is lower for forwarding packets to the surface sink. Therefore, using a vector-based forwarding technique in the opportunistic routing concept is not suited to achieving an acceptable trade-off between lower energy consumption and a higher packet delivery ratio. Moreover, the VBF and the HH-VBF protocols do not utilize the residual energy status of the relay nodes in their relay selection criteria, which leads to high energy consumption in packet transmission. The FDBR protocol has better performance that the DBR protocol because the hop count to the surface sink, the residual energy of each forwarding relay node, and the depth difference between the nodes are considered in forwarding-relay selection. Even though the residual energy of each node is considered as a metric to select the relay node under the FDBR protocol, collisions during packet transmission are not completely solved by the protocol, which also leads to higher energy consumption than the EECOR protocol.

5) AVERAGE NETWORK LIFETIME

The criterion measures the amount of time the networks remain active with the sensor node.

The average network lifetime was measured for the EECOR protocol and compared to the FDBR, DBR, HH-VBF, and VBF protocols, as shown in Figure 14. It is clear that network lifetime under the DBR, HH-VBF, and VBF protocols is lower, compared with the EECOR protocol. This is because the residual energy of the sensor nodes is considered when selecting the best relay from the forwarding relay set under the EECOR protocol. In contrast, relay selection by the DBR, HH-VBF, and VBF protocols depends on the depth information of the forwarder, and sensor nodes that are located at lower depths can be selected for packet forwarding to the surface sink. However, the FDBR and EECOR protocols have a longer network lifetime compared with DBR, HH-VBF, and VBF protocols because the residual energy of the sensor nodes is considered when selecting the best relay to forward the packets. However, the EECOR protocol shows the best performance because it reduces packet collisions through the proposed holding time.

VI. CONCLUSIONS

In UW-ASNs, high energy consumption is a key challenge when designing an energy-efficient routing protocol. In this work, we propose an EECOR protocol in which the source node will first determine a forwarding relay set based on local depth information and network topology information from the depth sensors, and with the aid of a distributed beacon message from the surface sink. And then, an FLRS scheme is used to select the best relay node from the forwarding relay set based on the ECR and the PDP of each relay node. Moreover, the holding time of each forwarding relay node is also considered in order to prevent collisions and retransmissions amongst sensor nodes while the packets are delivered to the surface sink. Our simulation results were carried out in Aqua-sim, an NS-2–based underwater simulator, and the evaluated results reveal that the EECOR protocol performs better in terms of average packet delivery ratio, average end-to-end delay, average energy consumption, and average network lifetime when compared with DBR, FDBR, VBF, and HH-VBR protocols. However, the behavior of the EECOR protocol in a hybrid network (e.g., made of fixed and mobile nodes) is not considered in this paper. In future, a new routing protocol will be designed based on machine learning algorithm (e.g., by applying Q-learning and decision-tree learning) for mobility-based UW-ASNs and we will compare the performance of the machine-learning algorithm with the proposed FLRS scheme.

REFERENCES

[1] D. Pompili, T. Melodia, and I. F. Akyildiz, "Distributed routing algorithms for underwater acoustic sensor networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 9, pp. 2934–2944, Sep. 2010.

[2] *Bluecomm Underwater Optical Communication*, accessed on Jun. 16, 2017. [Online]. Available: https://www.sonardyne.com/product/bluecomm-underwater-optical-communication-system/

[3] M. Zorzi, P. Casari, N. Baldo, and A. F. Harris, "Energy-efficient routing schemes for underwater acoustic networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1754–1766, Dec. 2008.

[4] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," *Ad Hoc Netw.*, vol. 3, no. 3, pp. 257–279, May 2005.

[5] H. Liu, B. Zhang, H. T. Mouftah, X. Shen, and J. Ma, "Opportunistic routing for wireless ad hoc and sensor networks: Present and future directions," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 103–109, Dec. 2009.

[6] L. F. M. Vieira, "Performance and trade-offs of opportunistic routing in underwater networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Shanghai, China, Jun. 2012, pp. 2911–2915.

[7] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI micro-modem: An acoustic communications and navigation system for multiple platforms," in *Proc. OCEANS MTS/IEEE*, vol. 2. Washington, DC, USA, Sep. 2005, pp. 1086–1092.

[8] T. Clausen and P. Jacquet, *Optimized Link State Routing Protocol (OLSR)*, document RFC 3626, 2003.

[9] C. E. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for Mobile Computers," *Comput. Commun. Rev.*, vol. 24, pp. 234–244, Oct. 1994.

[10] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," in *Proc. 2nd IEEE Workshop Mobile Comput. Sys. Appl.*, Feb. 1999, pp. 90–100.

[11] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*, T. Imielinski and H. Korth, Eds. Norwell, MA, USA: Kluwer, 1996, pp. 153–181.

[12] Y. Noh *et al.*, "HydroCast: Pressure routing for underwater sensor networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 333–347, Jan. 2016.

[13] C.-C. Hsu, H.-H. Liu, J. L. G. Gómez, and C.-F. Chou, "Delay-sensitive opportunistic routing for underwater sensor networks," *IEEE Sensors J.*, vol. 15, no. 11, pp. 6584–6591, Nov. 2015.

[14] Y.-D. Chen, Y.-W. Chen, C.-Y. Lien, and K.-P. Shih, "A channel-aware depth-adaptive routing protocol for underwater acoustic sensor networks," in *Proc. OCEANS-TAIPEI*, Taipei, Taiwan, Apr. 2014, pp. 1–6.

[15] H. Yan, Z. Shi, and J.-H. Cui, "DBR: Depth-based routing for underwater sensor networks," in *Proc. IFIP NETWORKING*, May 2008, pp. 72–86.

[16] R. Mohammadi, R. Javidan, and A. Jalili, "Fuzzy depth based routing protocol for underwater acoustic wireless sensor networks," *J. Telecommun., Electron. Comput. Eng.*, vol. 7, no. 1, pp. 81–86, Jan. 2015.

[17] P. Xie, J. H. Cui, and L. Lao, "VBF: Vector-based forwarding protocol for underwater sensor networks," in *Proc. IEEE IFIP Netw.*, vol. 4. May 2006, pp. 228–235.

[18] N. Nicolaou, A. See, P. Xie, J.-H. Cui, and D. Maggiorini, "Improving the robustness of location-based routing for underwater sensor networks," in *Proc. OCEANS-Europe*, Aberdeen, Scotland, 2007, pp. 1–6.

[19] Y. Noh, U. Lee, P. Wang, B. S. C. Choi, and M. Gerla, "VAPR: Void-aware pressure routing for underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 12, no. 5, pp. 895–908, May 2013.

[20] C.-J. Huang, Y.-W. Wang, H.-H. Liao, C.-F. Lin, K.-W. Hu, and T.-Y. Chang, "A power-efficient routing protocol for underwater wireless sensor networks," *Appl. Soft Comput.*, vol. 11, no. 2, pp. 2348–2355, Mar. 2011.

[21] Z. M. Zahedi, R. Akbari, M. Shokouhifar, F. Safaei, and A. Jalali, "Swarm intelligence based fuzzy routing protocol for clustered wireless sensor networks," *Expert Syst. Appl.*, vol. 55, pp. 313–328, Aug. 2016.

[22] G. Brante, G. Peron, R. Souza, and T. Abrao, "Distributed fuzzy logic based relay selection algorithm for cooperative wireless sensor networks," *IEEE Sensors J.*, vol. 13, no. 11, pp. 4375–4386, Jun. 2013.

[23] G. S. Mohammad, A. Shahrabi, and T. Boutaleb, "A novel cooperative opportunistic routing scheme for underwater sensor networks," *Sensors*, vol. 16, no. 3, p. 297, Feb. 2016.

[24] M. A. Rahman, Y. D. Lee, and I. Koo, "An adaptive network allocation vector timer-based carrier sense multiple access with collision avoidance medium access control protocol for underwater acoustic sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 13, no. 1, p. 1550147716687762, Jan. 2017.

[25] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," *ACM SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 11, no. 4, pp. 34–43, 2007.

[26] L. M. Brekhovskikh and Y. Lysanov, *Fundamentals of Ocean Acoustics*, 3rd ed. New York, NY, USA: Springer-Verlag, 2003.

[27] P. C. Etter, *Underwater Acoustic Modeling and Simulation*, 3rd ed. London, U.K.: Spon Press, 2003.

[28] H. Yu, N. Yao, and J. Liu, "An adaptive routing protocol in underwater sparse acoustic sensor networks," *Ad Hoc Netw.*, vol. 34, pp. 121–143, Nov. 2015.

[29] T. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2002.

[30] W. Pedrycz and F. Gomide, *An Introduction to Fuzzy Sets: Analysis and Design*. Cambridge, MA, USA, MIT Press, 1998.

[31] R. Su, R. Venkatesan, and C. Li, "A review of channel modeling techniques for underwater acoustic communications," in *Proc. 19th IEEE Newfoundland Elect. Comput. Eng. Conf.*, Nov. 2010, pp. 1–5.

[32] N. Javaid, M. Shah, A. Ahmad, M. Imran, M. I. Khan, and A. V. Vasilakos, "An enhanced energy balanced data transmission protocol for underwater acoustic sensor networks," *Sensors*, vol. 16, no. 4, p. 487, Apr. 2016.

[33] P. Xie *et al.*, "Aqua-Sim: An NS-2 based simulator for underwater sensor networks," in *Proc. OCEANS*, Biloxi, MS, USA, Oct. 2009, pp. 1–7.

[34] G. Toso, R. Masiero, P. Casari, O. Kebkal, M. Komar, and M. Zorzi, "Field experiments for dynamic source routing: S2C EvoLogics modems run the SUN protocol using the DESERT Underwater libraries," in *Proc. MTS/IEEE OCEANS*, Hampton Roads, VA, USA, Oct. 2012, pp. 1–10.

[35] LinkQuest. *LinkQuest Underwater Acoustic Modem UWM1000 Specifications*, accessed on Jun. 16, 2017. [Online]. Available: http://www.link-quest.com/html/uwm1000.htm

MD ARIFUR RAHMAN received the B.Sc. degree (Hons.) in applied science, electronics, and communication engineering from Islamic University, Kushtia, Bangladesh, and the M.Sc. degree in electronics and communications from Teesside University, Middlesbrough, U.K., in 2010 and 2012, respectively. He is currently pursuing the Ph.D. degree with the School of Electrical Engineering, University of Ulsan, South Korea. His current research interests include relay selection issues in cooperative cognitive radio networks and medium access control and routing protocols design for underwater acoustic sensor networks.

YOUNGDOO LEE received the B.E., M.E., and Ph.D. degrees from the School of Electrical Engineering, University of Ulsan, South Korea, in 2007, 2009, and 2013, respectively. Since 2013, he has been a Research Fellow with the University of Ulsan, South Korea. His current research interests include cognitive radio networks, UW-ASNs, beacon-based service networks, next generation communication systems, and artificial intelligence-based communication system.

INSOO KOO received the B.E. degree from Kon-Kuk University, Seoul, South Korea, in 1996, and the M.Sc. and Ph.D. degrees from the Gwangju Institute of Science and Technology (GIST), Gwangju, South Korea, in 1998 and 2002, respectively. From 2002 to 2004, he was with the Ultrafast Fiber-Optic Networks Research Center, GIST, as a Research Professor. In 2003, he was a Visiting Scholar with the Royal Institute of Science and Technology, Stockholm, Sweden. In 2005, he joined the University of Ulsan, Ulsan, South Korea, where he is currently a Full Professor. His current research interests include spectrum sensing issues for CRNs, channel and power allocation for cognitive radios (CRs) and military networks, SWIPT MIMO issues for CRs, MAC and routing protocol design for UW-ASNs, and relay selection issues in CCRNs.