IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received November 16, 2020, accepted December 7, 2020, date of publication December 14, 2020, date of current version May 4, 2021.

Digital Object Identifier 10.1109/ACCESS.2020.3044700

EH-IRSP: Energy Harvesting Based Intelligent Relay Selection Protocol

ADIL KHAN[1], MUKHTAJ KHAN[1], SHEERAZ AHMED[2], NADEEM IQBAL[1], (Senior Member, IEEE), MOHD AMIRUDDIN ABD RAHMAN[3], (Member, IEEE), MUHAMMAD KHALIS ABDUL KARIM[3], MOHD SHAFIE MUSTAFA[3], AND YAZID YAAKOB[3]

[1]Department of Computer Science, Abdul Wali Khan University Mardan, Mardan 23200, Pakistan
[2]Department of Computer Science, Iqra National University, Mardan 25000, Pakistan
[3]Faculty of Science, Universiti Putra Malaysia, UPM Serdang 43400, Malaysia

Corresponding author: Mohd Amiruddin Abd Rahman (mohdamir@upm.edu.my)

This work was supported by the Ministry of Higher Education Malaysia through the Fundamental Research Grant Scheme (FRGS) under Grant reference number of FRGS/1/2020/ICT02/UPM/02/3.

ABSTRACT Underwater Sensor Networks (UWSNs) are deployed to monitor various phenomena in marine environment such as pollution control, fuel exploration and underwater seismic activities. Various challenges such as, limited and non-replaceable batteries in sensor nodes, high path loss and high propagation delay exist for UWSNs, to name a few. Successful design deployment of an energy efficient routing scheme is an intense need of the day for successful operation of UWSNs. In this paper we have presented an energy efficient routing protocol by the name of Energy Harvesting Intelligent Relay Selection Protocol (EH-IRSP). The scheme uses task-specific energy harvested relay nodes using piezoelectric technique utilizing dynamic transmission radius incorporated in all sensor nodes. EH-IRSP protocol is compared with existing UWSNs protocols Cooperative UWSN (Co-UWSN) and Energy Harvested Analytical approach towards Reliability with Cooperation for Underwater WSNs (EH-ARCUN). The Co-UWSN focuses on strengthening the sound-to-noise ratio on the minimum distance communication channel in order to reduce the path loss. The EH-ARCUN scheme selects relay nodes based on energy harvesting level in combination with Amplify and Forward (AF) technique. The proposed scheme employs a Euclidean distance between the source-destination and source-relay nodes pairs. Each source node selects the most feasible energy harvested relay node by computing cosine of the angles between itself, relay node, and destination nodes and sends the data using cooperative communication. Based on these computed parameters, each source node adjusts its transmission radius hence conserving energy. Performance parameters for this comparison are based on stability period, packet delivery ratio, end-to-end delay and path loss. Simulation results show enhanced performance of proposed scheme EH-IRSP in contrast to Co-UWSN and EH-ARCUN.

INDEX TERMS UWSN, relay, piezoelectric, energy harvesting.

I. INTRODUCTION

Underwater sensor nodes and vehicles should possess self-configuration capabilities, i.e., they should be able to coordinate their operation by exchanging configuration, location and movement information, and to relay monitored data to an onshore station. Cluster heads creation is not efficient in UWSN because of the high energy consumption in each cluster head for receiving and sending data and because of radio signals which requires high power antennas which cannot be utilized in underwater sensor networks because of high absorption rate of these signals.

Since the protocols proposed for terrestrial sensor networks are developed on the basis of radio signal characteristics such as low propagation delay and high bandwidth, so they cannot be directly applied to UWSNs. Lot of efforts has been made for designing efficient communication protocols while taking into account the characteristics of the UWSNs. Protocols proposed for UWSNs have addressed various issues concerning their characteristics. Improving network lifetime

The associate editor coordinating the review of this manuscript and approving it for publication was Christian Esposito.

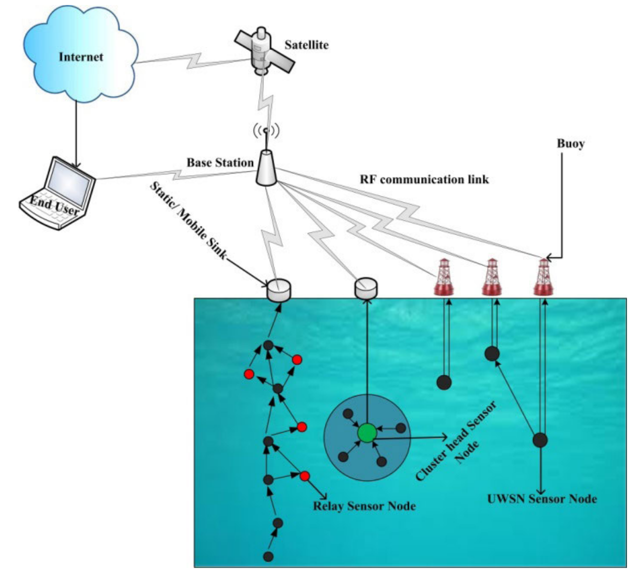

FIGURE 1. Generic architecture of UWSN depicting different modes of communication.

is an important issue in UWSN since replacement of batteries in nodes is very expensive due to harsh underwater environment. A network protocol in UWSNs should be designed considering energy efficiency to improve network lifetime because sensor nodes consume more energy in transmitting a data packet as compared to receiving a data packet.

In order to reduce energy consumption and consequently improve network life-time, unnecessary transmissions need to be reduced. Another important issue for improving the network lifetime is to balance the energy consumption among sensor nodes. For balancing energy consumption of a network, data transmission load is equally divided among all the sensor nodes. Several protocols in this regard have been proposed as in [1]–[4].

Data in UWSNs can be forwarded in different modes such as nodes attached with fixed buoys, clusters of nodes communicating with each other, and cooperative forwarding mode. Fig.1. depicts different communication modes in UWSNs.

In direct transmission mode, each sensor node selects best forwarder node in its neighboring nodes queue. Data is received at sink via ad-hoc routes. The cooperative forwarding mode is employed in protocol such as [5], in this protocol, each node can forward data to closest neighboring node as well as on alternative path using relay node. In this method data is forwarded on multiple independent paths. At the relay node, different amplification techniques can be applied to improve signal quality. At destination node, signal combining techniques are applied to check for the quality of a signal from both the source node and relay node respectively.

In this paper we have proposed a novel energy harvesting based protocol namely EH-IRSP (Energy Harvesting based Intelligent Relay Selection Protocol). In this protocol, a source node s can select at most two energy harvesting capable relay nodes in order to forward a data towards the destination node. Selection of relay nodes is based on two parameters, 1: the residual harvested energy of relay nodes and 2: distance of relay nodes from a source node. Hybrid transmission is employed i.e. (direct transmission mode and cooperation based transmission mode using relay nodes). When nodes are in direct line of sight to the sink in upper region of underwater area, then direct transmission mode is employed. In middle and high depth regions of network, hybrid communication is utilized.

In the proposed scheme, balancing the energy consumption is achieved by utilizing the special energy harvesting relay nodes. In the proposed scheme, source node s takes into account three scenarios i.e. (1) source node s can send data towards the destination node d without a relay node, (2) source node s can send data towards the destination node d using one relay node, (3) the source node s can send data towards the destination node d using two or more relay nodes. In all the scenarios the source node s takes into consideration not only the distance between itself and the relay nodes and the destination node but all also the cosine angle calculation of the relay nodes and the destination node. The source node can dynamically adjust the communication radius resulting into more balanced energy consumption as well as enhancing the overall network lifetime by using special energy harvesting relay nodes.

Extensive simulation results show the significant reduction in the packets drop ratio due to the availability of multiple physically independent communication paths. Moreover, the number of packets received at sink is improved in EH-IRSP which shows the increase in reliability of a network.

Rest of the paper is arranged in a following order. Section II discusses related work. Section III lays out proposed scheme in detail. Section IV presents performance evaluation of the proposed scheme. Conclusion of the paper is presented in section V.

II. RELATED WORK

In section a different cooperation based communication schemes deployed in UWSNs are discussed. In Section B different energy harvesting based schemes deployed in UWSNs are discussed with theirs corresponding pros and cons.

A. COOPERATIVE UNDERWATER WIRELESS SENSOR NETWORKS

In underwater wireless sensor networks relay nodes can be assumed in three different operation modes. First mode of the relay nodes is to consider each individual node as the relay node based on its residual energy information or successful forwarding of a data packet to its next hop neighbor, this operation can be termed as non-cooperative based communication of a network. Second mode of operation of the relay node is to deploy special relay nodes which can overhear transmission between the source and the destination sensor node. Both the relay nodes and the source nodes deliver the data packet cooperatively to the destination node. This mode of operation for data communication provides reliability and robustness. Third mode of operation for the relay nodes is to consider it as the Cluster Head (CH) node inside the clusters of nodes having variable sizes. The CH node forwards a data on behalf of all the nodes in the specific cluster. Second and third modes of data communication can be termed as the cooperation based communication in a network.

In [6], the authors presented two protocols namely Effective Energy and Reliable Delivery (EERD) and Cooperative Effective Energy and Reliable Delivery (CoEERD). The EERD protocol is unreliable because of the fact that it does not opt for the use of a relay node during data packet delivery on a single routed path for a data packet. The authors have handled the reliability issue in the CoEERD protocol by selecting the relay node on demand based on the weight function. In the CoEERD protocol, the destination node requests from the relay node to resend the data packet in case bit error ratio of a data packet is more than some threshold value. This factor can introduce more end-to-end delay. In [7], the authors proposed Depth and Noise-Aware Routing (DNAR) and Cooperative DNAR (Co-DNAR). The working of these two protocols are very similar to the protocols presented in [6], however the key difference is that CoEERD [6] uses one relay node and Co-DNAR [7] uses two relay nodes. In The Co-DNAR protocol, the source node selects three nodes based on the weight function value. The weight function incorporates the depth of each node alongside the noise value of the communication link. The value generated from the weight function is between 0 and 1. The best value of the weight function is reserved for the destination node, while second and third best values are reserved for the relay nodes. Consequently the Co-DNAR protocol inherently introduces low reliability in the selection of the communication links for the relay nodes. In [8] the authors proposed Channel Aware Routing Protocol (CARP), CARP select relay nodes on the basis of successful transmission of data packets by individual nodes. Nodes without energy harvesting capability operate as relay nodes by avoiding network holes and reducing outage probabilities. Authors analyzed proposed routing protocol in context of packet delivery ratio, end-to-end delay and total energy consumption. In [9] the authors proposed Geographic Forwarding based on Geospatial Division (GFGD), the authors in GFGD discusses reduction in energy consumption of network in terms of propagation delay by geographically finding nearest group of neighboring nodes for source node and selecting target destination node as a cluster head inside the cluster of nodes. Reduced energy consumption is achieved by avoiding redundant data transmissions during route finding and also reducing the propagation delay. The main drawback of this scheme is the time consumed for finding the nearest geographical cluster of nodes.

The idea introduced in Cluster Depth Based Routing (CDBR) [10] presents the creation of clusters having different number of nodes. Cluster head node in each cluster reduces the total number of messages between the nodes thus improving energy consumption and network lifetime. This mechanism is achieved by altering the behavior of Depth Based Routing (DBR) protocol to adopt clustering mechanism with cooperation based communication. This scheme has a drawback of increased end-to-end delay and network lifetime. The cluster creation takes time and consumes extra energy on part of each individual sensor node during the selection process of a node as a cluster head, which consequently decreases the network lifetime and increases the path loss of the network.

In Stochastic Performance Analysis with Reliability and Cooperation (SPARCO) [2], the authors propose cooperation based routing protocol using stochastic process technique to estimate underwater channel conditions. Authors have employed single and multi-hop data forwarding. Multi hop data transmission consumes more energy. Without energy harvesting relay nodes the network stability period further degrades the performance of the network. In Mobile Sink (MobiSink) [11], the authors have employed cooperation based communication with mobility of sinks to collect the data from the sensor nodes. Nodes cooperate with each other using their respective transmission ranges to find the nearest sink. The main drawback of this scheme is the extra time taken by an individual node in finding the nearest sink, this incur increase in end-to-end delay.

In Opportunistic Void Avoidance Routing (OVAR) [12], the authors proposed underwater routing scheme in which nodes uses adjacency matrix for its neighboring nodes, the adjacency matrix can be created at any angle from the source node by avoiding routing holes or voids. The critical aspect of this scheme is finding the balance between the energy consumption and reliability. Better reliability is achieved in terms of better packet delivery ratio but at the cost of increased end-to-end delay. In Adaptive Cooperation in Energy (ACE) [13], authors proposed the idea of gradually increasing the number of relay nodes upon failure of data forwarding by the source node. Relay nodes are increased to the point where optimal signal can be received by the destination node. In this scheme holding time information about the data packet held by the relay nodes is managed by the source node. Source node waits for a specific amount of time for receiving acknowledgement packet from the destination node. Upon failure, the source node increase the number of relay nodes. This behavior increases the number of data transmissions and extra energy is consumed by the source node. In EH-ARCUN (Energy Harvesting Analytical approach towards Reliability with Cooperation for UWSNs) [14], the authors deployed multiple energy harvesting relay nodes. The protocol works in cooperation based communication mode. This scheme employed Monterey-Miami Parabolic Equation (MMPE) [24] technique for communication channel modeling which is best suited for shallow waters and cannot be easily adopted in deep underwater environments. Table 1 shows the comparison of different state of the art cooperation based UWSNs protocols.

TABLE 1. Cooperative UWSNs protocols.

Protocol	Characteristic	Achievements
CoEERD [6]	On-demand relay selection	Reliable packet transfer
Co-DNAR [7]	Noise value Consideration	Increased Reliability
CARP [8]	Avoiding network holes	Reduced outage probability
GFGD [9]	Geographically finding nearest nodes	Reduced propagation delay
CDBR [10]	Variable length clusters of nodes	Clustering with cooperation based communication
SPARCO [2]	Stochastic process technique	Single and multi-hop data transimission
MobiSink [11]	Mobility of sinks	Reduced propagation delay
OVAR [12]	Adjacency matrix for neighboring nodes	Avoiding routing holes
ACE [13]	Incremental increase in relay nodes	Three way handshake communication
EH-ARCUN [14]	Multiple energy harvesting relay nodes	Increased network lifetime

B. ENERGY HARVESTING BASED SCHEMES FOR UNDERWATER SENSOR NETWORKS

In [15], the authors proposed architecture of the sensor node which can harvest energy from the Microbial Fuel Cell (MFC) and the piezoelectric energy. The authors have derived the analytical expressions for the energy conversion efficiency of both the techniques. The MFC can produce up to 52μW of power on average and the piezoelectric technique can produce up to 42μW of power on average. The aforementioned techniques can enhance the lifetime of the UWSNs if proper sleep wake scheduling algorithms for the sensor nodes can be developed to conserve and predict the amount of harvested energy.

In [16], the authors have deployed two main techniques for energy harvesting. The first technique is energy harvesting based on MFC and the second technique for energy harvesting is based on piezoelectric enabled hydrophones similar to the [15]. The power produced by these two techniques is same as [15]. The integration of these two techniques is named as hybrid energy harvesting as a third technique by the authors. While MFC and piezoelectric energy harvesting techniques are considered as the most reliable techniques for energy harvesting [15], however the authors mentioned the Hybrid Access Point (HAP) technique as the fourth technique for energy harvesting which is not feasible in the underwater environment due to the high potential of the outage probability of a communication link. The HAP harvests the energy from the solar panels and the wind waves. The HAP does not states the clear mechanism for transmitting the harvested energy to the nodes deployed in the high depth regions.

In [17], the authors have modeled a novel water current propeller for energy harvesting from water currents. The propellers can generate 4 watts of power at the rate of 42 revolutions per minute (RPM) if the sea water current travels at 1 knot. The energy conversion efficiency is feasible for the long lasting operation of UWSNs but the deployment cost of such a network is not feasible if a large number of nodes are deployed. In [18], the authors employed hybrid scheme for energy harvesting by integrating water current propellers and solar panels. The propellers are used for the sensor nodes deployed at sea bottom generating output power as in [17] and solar panels are utilized for the nodes deployed closer to the sea surface with output power of 200 Watts. The main drawback of this scheme is the high deployment cost. The comparison of different energy harvesting techniques with their corresponding rate of energy harvesting from the environment is given in Table 2.

TABLE 2. Energy harvesting UWSNs protocols.

Protocol	Energy Harvesting Technique	Rate of Acquiring Harvesting Energy
Multi-source Energy Harvesting [16]	MFC/ Piezoelectric	MFC = 52µW, Piezo = 42µW
RBCRP [17]	MFC/ Piezoelectric	MFC = 52µW, Piezo = 42µW
S-SDCS [18]	Water Current Propeller	Propeller = 4W/42 RPM
HADR [19]	Water Current Propeller/ Solar Panel	Propeller= 4W/42 RPM, Solar Panel= 200W (shallow waters)

III. EH-IRSP THE PROPOSED SCHEME

The proposed scheme is divided into three sections. Section A lays out the foundation for data communication channel. The length of the communication path is determined by dynamically changing the transmission range of the relay nodes. Communication range of the relay nodes depends on the physical distance between source node and relay nodes. Section B discusses the discovery process of relay nodes by a source node. Section C discusses the cooperation based communication in EH-MRP.

A. CHANNEL MODELING WITH DYNAMIC TRANSMISSION RANGE

The function ζ (s→d) in equation (1) defines the Euclidian distance between source node s and destination node d respectively in a 3D acoustic underwater sensor network as

$$\zeta : X^xY^xZ \rightarrow \xi : \zeta(s \rightarrow d)$$
$$\zeta(s \rightarrow d) = \sqrt{}(d_x - s_x)^2 + \sqrt{}(d_y - s_y)^2 + \sqrt{}(d_z - s_z)^2 \quad (1)$$

where x, y and z in equation (1) represents 3D acoustic network. Each sensor node can adjust its transmission radius from minimum to maximum range according to the minimum distance from the corresponding target node. In 3D underwater acoustic sensor network, we have assumed the deployment of special sensor nodes with energy harvesting capability using piezoelectric energy harvesting technique. We call these nodes energy harvesting relay nodes R. These nodes can overhear the data transmission between any pair of source and destination nodes. Special relay nodes R can cooperatively relay data towards destination node d. We have assumed that the source node can select two relay nodes at maximum. For calculating minimum transmission radius r_{min} of a source node s, we have assumed the following three cases:

Case 1: Source node with a data to forward do not find relay node R :

$$\text{Transmission Radius} = \begin{cases} s_{r_{min}} = r_{min} \\ d_{r_{min}} = r_{min} \end{cases} \tag{2}$$

In *Case 1,* the source node s will adjust its transmission radius to minimum i.e. equal to the minimum transmission radius of the destination node d and will send data to the destination node directly without any relay nodes as shown in equation (2).

Case 2: Source node finds a relay node R in its immediate neighborhood:

$$\text{Transmission Radius} = \left\{R_{r_{min}} - s_{r_{min}} = r_{min}\right\} \tag{3}$$

In Case 2, source node s will adjust its transmission radius equal to the minimum transmission radius of the relay node R by subtracting its minimum transmission range from the minimum transmission range of the relay node R as shown in equation (3).

Case 3: Source node finds two relay nodes $\mathrm{R_i}$ and $\mathrm{R_j}$:

$$r_{min} = \mathrm{R_i} r_{min - s_{r_{min}}} + \mathrm{R_j} r_{min} - s_{r_{min}} \tag{4}$$

In *Case 3,* source node s transmission radius will be equal to the sum of minimum transmission radiuses of both the relays $\mathrm{R_i}$ and $\mathrm{R_j}$ as shown in equation (4).

Signal strength indicates the quality of signal, and Sound to Noise Ratio (SNR) is a measurement method to indicate the power of the signal, the passive sonar equation determines SNR of a signal and is represented in equation (5) as [19]:

$$\mathrm{SNR} = \mathrm{SL} - \mathrm{TL} - \mathrm{NL} + \mathrm{DI} \tag{5}$$

SL in equation (5) indicates source level or loudness of the sound. SL can be calculated according to the following equation for deep waters as:

$$\mathrm{SL} = 20\log_2 \frac{I_t}{1\mu Pa} \tag{6}$$

where I_t in equation (6) is average sound intensity in unit time t and its value is represented as μPa. I_t value can be obtained as [20]:

$$\mathrm{I_t} = 20^{\frac{SL}{20}} * 0.67 * 10^{-18} \tag{7}$$

Signal intensity I_t requires certain transmission power in order to propagate properly, Transmission power P_t for signal intensity It at a distance of 1 meter can be calculated as [20]:

$$\mathrm{P_t} = 4\pi * 1\mathrm{m}^2 * \mathrm{H} * \mathrm{I_t} \tag{8}$$

where in equation (8) above, the power unit used for P_t is watts and H is the depth in deep waters.

TL as shown in equation (5) above is transmission loss, as we are assuming deep water communication where max water depth is assumed to be 300m, so spherical spreading

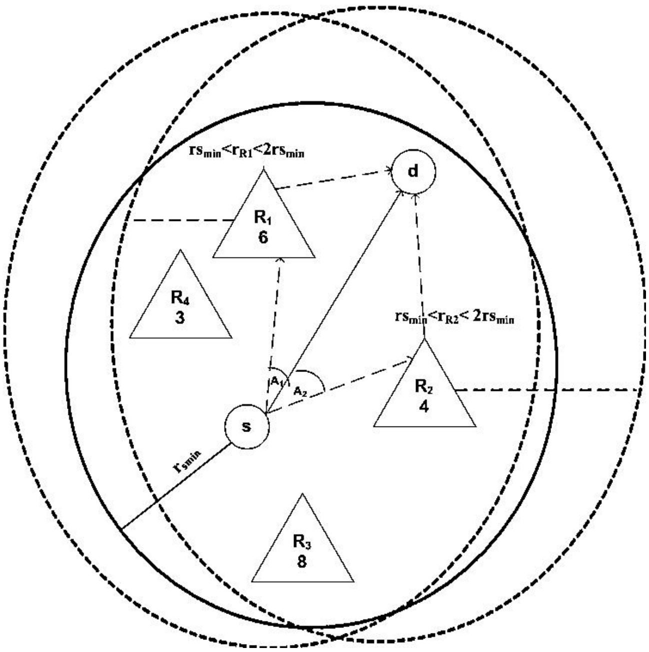

FIGURE 2. Discovery of relay nodes and data forwarding.

is considered for signal intensity, accordingly TL can be calculated as:

$$\mathrm{TL} = 20\log_2 \zeta(\mathrm{s, d}) + a\zeta(\mathrm{s, d}) \times 10^{-3} \tag{9}$$

where ζ (s,d) in equation (9) is Euclidian distance and a is the frequency dependent absorption coefficient. a can be calculated using Thorp's formula [19] as:

$$a = \frac{0.11 f^2}{1 + f^2} + \frac{44 f^2}{4100 + f^2} + 2.75 \times 10^{-4} \mathrm{f}^2 + 0.003 \tag{10}$$

NL in equation (7.5) represents Noise Level in Underwater environment. The acoustic underwater environment is surrounded by four main types of noises namely, turbulence, shipping, wave, and thermal noises respectively. The Gaussian representation of these noises can be represented as [20]:

$$NL = N_{\mathrm{t}}(f) + N_{\mathrm{s}}(f) + N_{\mathrm{w}}(f) + N_{\mathrm{th}}(f) \tag{11}$$

For EH-IRSP, NL value in equation (11) is assumed to be 30dB [20] for maximum underwater depth of 300m. *DI* in equation (5) represents Directivity Index, as we have assumed the use of sensor nodes integrated with omnidirectional hydrophones, accordingly *DI* is assumed to be zero.

B. DISCOVERY OF ENERGY HARVESTING RELAY SENSOR NODES

We have assumed four energy harvesting relay nodes $\mathrm{R_1}$, $\mathrm{R_2}$, $\mathrm{R_3}$ and $\mathrm{R_4}$ which are arbitrarily deployed in a 3D space as shown in Fig. 1. Sensor node s is a source node with a data to forward towards destination node d. Initially source node s broadcast a packet for relay discovery. The transmission range $\mathrm{r_{min}}$ is represented as a solid circle in Fig. 2. Assuming that source node s initially finds two relay nodes, then transmission range for source node s can be obtained from *Case 3* equation (4).

In this scheme, the source node s selects two energy harvesting relay nodes in descending order of residual energy. The generic number in each relay represents residual harvested energy. As shown in Fig. 2, R_1, R_2 are the closest relay nodes to source node s, these two relay nodes will simultaneously transmit response packets immediately after the reception of source node s broadcast packet. The dashed circles with radiuses r_{R_1} for the relay node R_1 and r_{R_2} for the relay node R_2 respectively represents the transmission ranges for both the relay nodes R_1's and R_2's response packets, which are larger than the transmission range of source node s. After the relay node R_3 and R_4 receives source node s broadcast packet with R_1 and R_2 response packet, it reads the information from these calls. As both the R_3 and R_4 residual energies are less than that of R_1 and R_2, these two relay nodes will not broadcast any response packets in order to save energy.

Static sink node is assumed at the surface of water. Sink node broadcast its position initially during network deployment phase, this broadcast does not require any significant energy and energy dissipation can be considered as negligible [21]. Each data packet carries the positions of the source node s and the destination node d. As R_1 and R_2 are the closest relay nodes to the source node s with enough residual energy, they will calculate the cosine of the angles between the directions from s to R_1 and s to R_2 respectively (denoted by A_1 and A_2 in Fig.2). The Function of Angle **FA** for both the relays R_1 and R_2 are given in the equations (12) and (13) respectively.

$$\text{FA} = \frac{R_1^{res}.cosA_1}{\zeta(\text{s} \rightarrow \text{d})} \tag{12}$$

$$\text{FA} = \frac{R_2^{res}.cosA_2}{\zeta(\text{s} \rightarrow \text{d})} \tag{13}$$

R_1^{res}, R_2^{res} are the residual energies of both the relay nodes R_1 and R_2. $\zeta(s \rightarrow d)$ in the equations (12) and (13) represents Euclidian distance between the source node s and the destination node d.

When a broadcast packet is received from source node s, both the relay nodes checks the cosine value, if the value is not below zero, both R_1 and R_2 will send response packet with radiuses r_{R_1} and r_{R_2} for relays R_1 and R_2, which are calculated as in equation (14) and (15) respectively [22]:

$$r_{R_1} = \min\left\{\left(1 + \frac{P1_{harv}^{res}}{P1_{harv}^{max}}\right).r_{s_{min}}, r_{max}\right\} \tag{14}$$

$$r_{R_2} = \min\left\{\left(1 + \frac{P2_{harv}^{res}}{P2_{harv}^{max}}\right).r_{s_{min}}, r_{max}\right\} \tag{15}$$

where $\frac{\mathbf{P1_{harv}^{res}}}{\mathbf{P1_{harv}^{max}}}$ and $\frac{\mathbf{P2_{harv}^{res}}}{\mathbf{P2_{harv}^{max}}}$ represents ratios of harvesting energy for transmission power P_1 and P_2 respectively using piezoelectric technology from hydrophones. $\mathbf{P_{harv}}$ is harvesting energy power of hydrophones which can be calculated as [23]:

$$\text{P}_{\text{harv}} = \frac{0.7 * n * 10^{\frac{(RL+RVS)}{20}}}{4 * R_p} \tag{16}$$

where RL is Received Level of strength of an acoustic signal, RVS is Received Voltage Sensitivity, n is number of hydrophones, and R_p denotes number of hydrophones [23]. Using equation (14) and (15), both the relay nodes R_1 and R_2 calculate their respective transmission limits. The transmission limits for r_{R_1} and r_{R_2} ranges from r_s to $2r_s$. If both the relay nodes R_1 and R_2 have maximum harvested energy, then their transmission ranges will be $2r_{s_{min}}$ respectively, where $2\ r_{s_{min}} < r_{R_{1_{max}}}$ and $2\ r_{s_{min}} < r_{R_{2_{max}}}$.

Relay node R_3 can also overhear the communication between a source node s and responses from both the R_1, R_2 relays. R_3 will sideline itself from sending response packet, although its harvested energy is greater than both the R_1 and R_2 relays as depicted in Fig.2, but the cosine of the angle between the direction from source node s to R_3 and the destination node d is non-positive value. The data forwarding mechanism is depicted in algorithm 1.

C. COOPERATIVE DATA TRANSMISSION WITH EH-RELAY NODES

Network Initialization Phase:

As depicted in algorithm 1, the network is initialized with arbitrary deployment of 100 sensor nodes according to **step 2** of the algorithm 1 in three dimensional underwater acoustic environment. 70 nodes are assumed as normal sensor nodes and 30 nodes are assumed to be special relay nodes with the energy harvesting capability. All the sensor nodes alongside the sink node broadcast their positions in **step 3**. Each sensor node initializes and populates its neighboring nodes queue n() and relay nodes populates queue r() in **step 4**. In **step 5** each node calculates its Euclidian distance using equation 1. In **step 6-8**, if the source node does not find a relay node in its neighboring relay node queue r() then using **case 1** it directly sends the data towards the destination node d. In **step 9-11,** if the source node finds one relay node in the r() queue then using **case 2**, the source node s will adjust its transmission radius according to **equation (3)** to conserve energy and will send the data towards the relay node and the destination node simultaneously on the physically independent communication channels. In **steps 12-15** if the source node s finds two or more relay nodes in its neighboring relay node queue r(), then in **step 13** the source node will first calculate the cosine of these relay nodes. If the two relay nodes angles are found to be closer to the destination node d then the source node s will select these two relay nodes according to the angle calculation of FA using equations (12) and (13) respectively and using **case 3** the source node s will apply the equation (4) to adjust its transmission radius in order to save energy and will forward the data packet to the destination node d and relay nodes R_1 and R_2 simultaneously on independent physical paths. In **step 19-20,** if the sink is inside the transmission range of any node then that specific node will send the data directly towards the sin without utilizing any relay nodes.

The data forwarding can be divided into two phases i.e. phase 1 and phase 2:

Algorithm 1 Energy Harvesting Multiple Relay Protocol (EH-IRSP)

Start
Arbitrary deployment of 100 sensor nodes in 3D grid
Sink and nodes broadcasts their positions
Each node initializes and populates its neighboring nodes queue n() and relay nodes queue r()
Each node calculates its distance from neighboring nodes using equation 1
If (r() == empty) **(case 1)**
Send data to destination node d
End if
If (length(r()) == 1) // source node s finds one relay node
$R_{r_{min}} - s_{r_{min}} = r_{min}$ (case 2)
Send data to to relay node and destination node d
Elseif (length(r()) == 2 or more) // source node s finds two relay nodes
Calculate positions of relay nodes using cosine and PR_{1harv}, PR_{2harv}
Set $r_{min} = R_i r_{min-s_{r_{min}}} + R_j r_{min}$ - $s_{r_{min}}$ **(case 3)**

    Send data to R1, R2 and destination node d
  Endif
Endif
If d transmission range == sink transmission range
Send data to sink
End if
End

Phase 1: In *Phase 1* data is transmitted by the source node s to the destination node d and the relay nodes R_1 and R_2 simultaneously on physically independent communication channels. Data received at the relay nodes R_1, R_2 and the destination node d can be mathematically represented as [25]:

$$y_{sR_1} = \sqrt{P}_1 h_{sR_1} x_s + N_{sR_1}(\mathrm{f}) \tag{17}$$

$$y_{sR_2} = \sqrt{P}_1 h_{sR_2} x_s + N_{sR_2}(\mathrm{f}) \tag{18}$$

$$y_{sd} = \sqrt{P}_1 h_{sd_1} x_s + N_{sd}(\mathrm{f}) \tag{19}$$

where P_1 in equations (17-19) is the power intensity as presented in equation (8), x_s is the transmitted data, h_{sR_1} and h_{sR_2} and h_{sd_1} are the underwater channel coefficients from s to R_1, s to R_2 and s to d respectively.

Phase 2: In *phase 2* both the relays R_1 and R_2 use Amplify and Forward technique (AF) [26] for forwarding data towards the destination node d modeled as [25]:

$$y_{R_1d} = \sqrt{P}_2 h_{R_1} \mathrm{d}x\prime_s + N_{R_1d} \tag{20}$$

$$y_{R_2d} = \sqrt{P}_2 h_{R_2} \mathrm{d}x\prime_s + N_{R_2d} \tag{21}$$

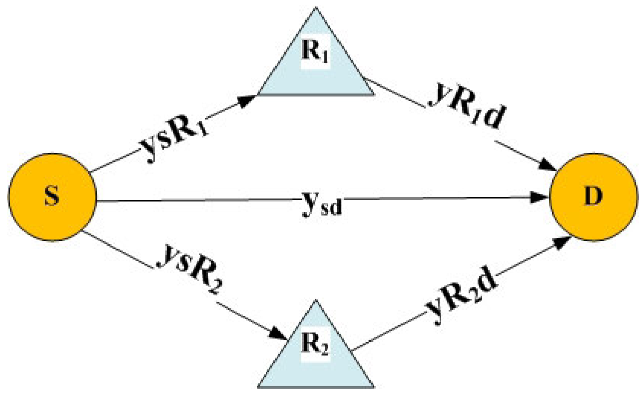

FIGURE 3. Phase 1 and Phase 2 Communication.

P_2 indicates signal power intensity shift because of the amplification process, $x\prime_s$ indicates that data signal may change in case of attenuation after passing through s->R_1 and s->R_2 links. Destination node d combines the signals from s, R_1 and R_2. Finally data is combined using Fixed Ratio Combining (FRC) [27] technique which is one of the techniques in diversity combining techniques. In this technique constant weights are multiplied with channel coefficients. Destination node can easily distinguish the incoming signals from different sources and based on weighted values can identify the optimal channel having best signal quality. Using FRC we can obtain equations (22) and (23) as:

$$y_d = k_1 y_{sd} + k_2 y_{R_1d} + k_3 y_{R_2d} \tag{22}$$

where y_d in equation (20) is the aggregate signal at destination node d, and k_1, k_2, k_3 in equation (20) are constant weights assigned to the paths coming from the source node s towards the destination node d and from the two relays R_1 and R_2 respectively. The ratio of weights can be expressed as [6]:

$$\frac{k_1}{k_2 + k_3} = \frac{\sqrt{P}_1 h_{sd}}{\sqrt{P'}_2 h_{R1d} + \sqrt{P'}_3 h_{R2d}} \tag{23}$$

The whole process of cooperation based data communication is depicted in Fig.3.

IV. PERFORMANCE EVALUATION OF EH-IRSP

The simulation parameters for Co-UWSN, EH-ARCUN, and EH-IRSP are given in Table 3.

Co-UWSN and EH-ARCUN schemes are compared with EH-IRSP. 70 normal sensor nodes and 30 special energy harvesting relay sensor nodes are deployed arbitrarily in 300 × 300 × 300 3D grid. Each sensor node and relay sensor node is initialized with 70J energy. Simulations are carried out in seconds with 5000 total number of seconds. The characteristics of acoustic link-quest UWM2200 modem [28] is adopted for each sensor node. The transmission range varies for each sensor node depending on the availability of the relay node. The variation for transmission range is adjusted from 100m to 250m. The transmission power is 6W and the receiving power is 1W. Size of the data packet is 1024 bits and the data rate is 19kbps.

TABLE 3. The simulation parameter of Co-UWSN, EH-ARCUN, and EH-IRSP

Parameters	Value
Normal sensor nodes	70
Energy harvesting nod	30
Network Region	300 m × 300 m × 300 m
Initial Energy	70 J
Bit Error Rate threshol	0.5
Communication model	UMW 2200
Transmission range of sensor	100 m to 250 m
Size of data packet	1024 bits
Data rate	19kbps
Transmission power	6W
Receiving power	1W

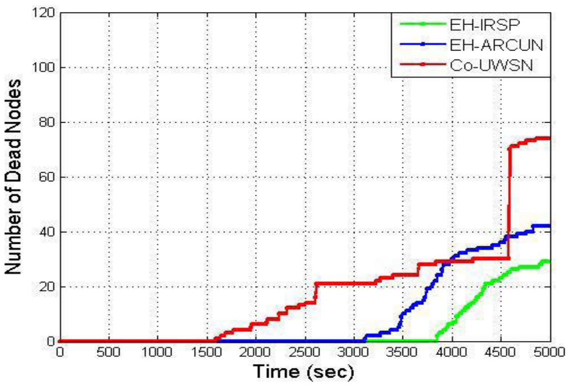

FIGURE 4. Number of dead nodes vs Time.

To calculate the confidence interval for the range of values of the harvested energy, the confidence level is assumed to be 80%. For the calculation of the standard deviation, 10 energy harvesting relay nodes are randomly selected out of the 30 total energy harvesting relay nodes.

After 10 simulations, the values of the harvested energies for the 10 energy harvesting relay sensor nodes in joules are given as: 10j, 15j, 7j, 5j, 3j, 18j, 9j, 8j, 3j, 12j. The mean

$$\text{Value is } \overline{x} = \frac{10+15+7+5+3+18+9+8+3+12}{10} = 9.0$$

The variance is given as: $S^2 = 24.4$. The standard deviation σ is 4.93. Considering the calculated values of $\overline{x}$, σ and n=10 randomely selected energy harvesting relay nodes the margin of error is: $1.28\times(4.93\div 3.16) = 1.99 \approx \pm 2.0$. The 80% **confidence interval** for the mean harvested energy of the energy harvesting realy nodes is 9.0j ±2.0j.

Fig.4 shows the comparison of stability period. Stability period of a network is defined as the specific time instant at which the first node dies in a network. As simulation result in Fig.4 shows, the number of total dead nodes in Co-UWSN scheme are above 70 while in EH-ARCUN scheme the dead nodes are above 40 and in the proposed EH-IRSP scheme the dead nodes are below 30. The specific time instant at which the first node dies for Co-UWSN is at 1500th second, for EH-ARCUN the first node dies at 3000th second.

In EH-IRSP the complete energy depletion of the first node occurs at 4000th second. Numerically it can be shown that, Co-UWSN$_{\Delta R}$ = 3500, EH-ARCUN$_{\Delta R}$ = 2000 and EH-IRSP$_{\Delta R}$ = 1000, where ΔR represents the difference as:

$$\textit{total number of seconds} - \textit{the second at which a first node dies}$$

Clearly as shown in the simulation result of Fig. 4, EH-IRSP has the minimum difference and shows better stability of a whole network as compared to EH-ARCUN and Co-UWSN. The better stability period of EH-IRSP reflects its dynamic adjustment of transmission radius for source node s. When source node does not find any energy harvesting relay node it directly sends data towards destination node d in its immediate neighborhood table of neighboring nodes with minimum transmission range, Co-UWSN and EH-ARCUN do not exhibit this behavior which results in more energy consumption of sensor nodes. In Co-UWSN there is no special energy harvesting relay nodes, each node can also act as a relay node which puts extra data forwarding load on each node that is why the stability period for Co-UWSN is minimum among the three schemes. While EH-ARCUN does deploy energy harvesting nodes but it does not calculate transmission radius dynamically, each data transmission is carried out at maximum transmission range which consumes more energy on part of normal sensor nodes.

Simulation result in Fig.5 shows that EH-IRSP has a stable packets delivery ratio as compared to EH-ARCUN and Co-UWSN. The packet delivery ratio is calculated as the number of packets received at sink divided by the number of packets originally sent by the nodes. In Co-UWSN, packet delivery ratio gradually decreases from approximately 90% to 40%. This behavior shows high instability of a network as shown in figure 4. EH-IRSP and EH-ARCUN shows stable packet delivery ratio during the whole simulation time, the sudden change in packet delivery ratio depicted for EH-ARCUN around 4000th second reflects the sudden change in energy levels for

Some nodes operating at maximum transmission range. Fig.6 shows the end-to-end delay, EH-IRSP shows improvement in end-to-end delay over the EH-ARCUN scheme.

In EH-IRSP, a source node with a data to forward, do not wait for the relay node, if it does not find a relay node it sends data towards destination node in a non-cooperative mode of communication, this behavior slightly improves the delivery time of a data packet. As shown in Fig.6, the end-to-end delay varies uniformly for both the EH-ARCUN and EH-IRSP schemes. For the EH-ARCUN scheme, the end-to-end delay increases from 10sec to 13sec in the 1500 to 2000 seconds interval, similarly for the EH-ARCUN scheme, the end-to-end delay increases from 5sec to 7sec in the 1500 to 2000 seconds interval. This behavior is the result of the

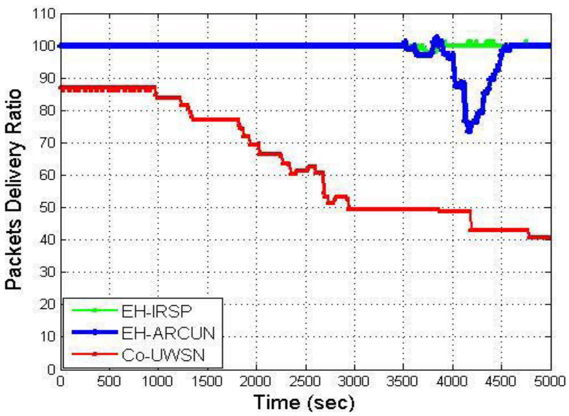

FIGURE 5. Packet delivery ratio vs Time.

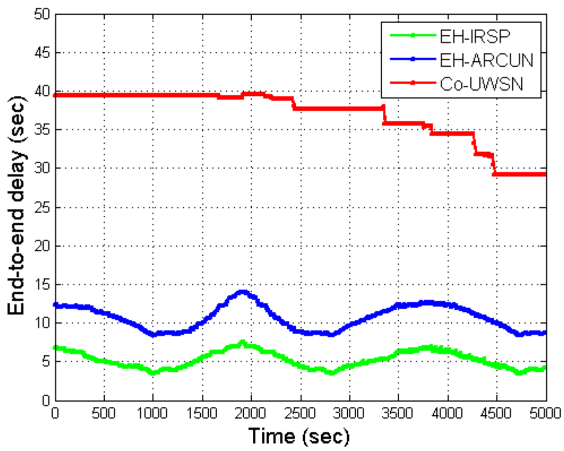

FIGURE 6. End-to-end delay vs Time.

tradeoff between energy harvesting time of the relay nodes and the end-to-end delay time. When relay nodes are harvesting the energy it holds the data packet for certain amount of time, in that time the data packet from the source node on direct communication path is received by the destination node. The destination node waits for the data packets from the relay nodes in order to apply the FRC technique. This behavior can be seen in Fig.6 up-to the last time interval of 5000^{th} second. Co-UWSN shows a big difference in end-to-end delay as compared to both the EH-IRSP and EH-ARCUN schemes. In Co-UWSN, each node also acts as a relay node which quickly drains the node energy consequently creating the network holes in a communication path which further increases the propagation time of a data signal.

Fig.7 shows path loss of all the three schemes.

EH-IRSP and EH-ARCUN exhibits approximately the same behavior. The sharp increase in the Path loss i.e. from 30dB to 60dB in 1000 to 2000 seconds interval reveals the accuracy of the thorp attenuation model. Both the schemes employs thorp attenuation model for calculating the transmission frequency, bandwidth efficiency, and noise effects. Also both the schemes consider the threshold value of the harvested energy in the relay nodes as well as the salinity and the water temperature on the communication paths. If the

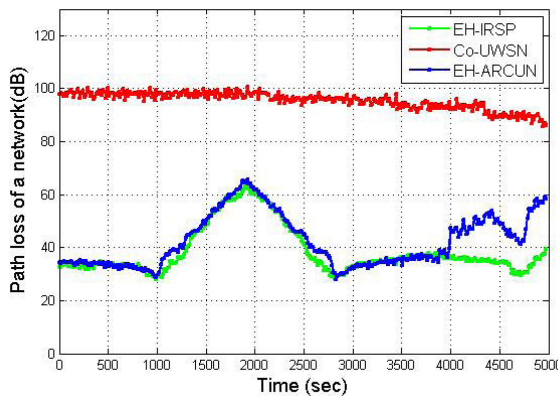

FIGURE 7. Path loss vs Time.

harvesting energy in the relay node is less than the threshold value, then it directly affects the transmission frequency and the bandwidth efficiency between the source and the relay node pair which results in the sharp increase of the path loss. Path loss improvement for EH-IRSP is 20% over EH-ARCUN. The aggregate path loss for EH-IRSP is 40dB while for EH-ARCUN the path loss is 60dB. The improvement in path loss for EH-IRSP suggests the efficient working of a passive sonar equation [19] in deep waters for EH-IRSP as compared to Monterey-Miami Parabolic Equation [24] employed in EH-ARCUN.

V. CONCLUSION

In this research, we have proposed an energy efficient harvesting protocol EH-IRSP. In this protocol each source node dynamically adjusts its transmission radius in order to balance energy consumption. In the proposed protocol, a source node can send data in hybrid mode i.e. if it does not find any relay node it sends data to a destination node otherwise it can select one or more relay node to send data in cooperation based communication towards the destination node. The decision for selecting a relay node is based on cosine angle which determines the physical distance of the relay nodes and residual harvested energy of the relay nodes.

The performance evaluation shows that energy harvesting as well as intelligent relay selection based on the cosine angle between the source node and relay node increases the overall network lifetime of EH-IRSP. The dynamic adjustments of the transmission radius also add up to the increase in overall operational time of a network. In EH-IRSP a source node does not wait for the availability of a relay node, this saves data packet arrival time for the destination node which improves the end-to-end delay of a network. Multiple simulations also show improvements in the packet delivery ratio and path loss as compared to Co-UWSN and EH-ARCUN. EH-IRSP can be adopted as an efficient solution for monitoring marine environments in non-real time applications.

REFERENCES

[1] S. Ahmed, M. Akbar, R. Ullah, S. Ahmed, Atta-ur-Rehman, M. Raza, Z. A. Khan, U. Qasim, and N. Javaid, "ARCUN: Analytical approach towards reliability with cooperation for underwater WSNs," *Procedia Comput. Sci.*, vol. 52, pp. 576–583, Dec. 2015.

[2] S. Ahmed, N. Javaid, A. Ahmad, I. Ahmed, M. Y. Durrani, A. Ali, S. B. Haider, and M. Ilahi, "SPARCO: Stochastic performance analysis with reliability and cooperation for underwater wireless sensor networks," *J. Sens.*, vol. 2016, pp. 1–17, Aug. 2016.
[3] I. Yoon, D. K. Noh, and H. Shin, "Energy-aware hierarchical topology control for wireless sensor networks with energy-harvesting nodes," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 6, Jun. 2015, Art. no. 617383.
[4] H. H. Sneessens, L. Vandendorpe, and J. N. Laneman, "Adaptive Compress-and-Forward relaying in fading environments with or without wyner-ziv coding," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2009, pp. 1–5.
[5] S. Ahmed, N. Javaid, F. A. Khan, M. Y. Durrani, A. Ali, and A. U. Shaukat Qasim, "CoUWSN: Cooperative energy-efficient protocol for Underwater WSNs," *Int. J. Distrib. Sensor Netw.*, vol. 2015, p. 75, May 2015.
[6] U. Ullah, A. Khan, M. Zareei, I. Ali, H. A. Khattak, and I. U. Din, "Energy-effective cooperative and reliable delivery routing protocols for underwater wireless sensor networks," *Energies*, vol. 12, no. 13, p. 2630, Jul. 2019.
[7] J. Qadir, A. Khan, M. Zareei, and C. Vargas-Rosales, "Energy balanced localization-free cooperative noise-aware routing protocols for underwater wireless sensor networks," *Energies*, vol. 12, no. 22, p. 4263, Nov. 2019.
[8] S. Basagni, C. Petrioli, R. Petroccia, and D. Spaccini, "CARP: A channel-aware routing protocol for underwater acoustic wireless networks," *Ad Hoc Netw.*, vol. 34, pp. 92–104, Nov. 2015.
[9] J. Jiang, G. Han, H. Guo, L. Shu, and J. J. Rodrigues, "Geographic multi path routing based on geospatial division in duty-cycled underwater wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 59, pp. 4–13, Jan. 2016.
[10] T. Khan, I. Ahmad, W. Aman, I. Azam, Z. A. Khan, U. Qasim, S. Avais, and N. Javaid, "Clustering depth based routing for underwater wireless sensor networks," in *Proc. IEEE 30th Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, Mar. 2016, pp. 506–515.
[11] P. M. Shah, I. Ullah, T. Khan, M. S. Hussain, Z. A. Khan, U. Qasim, and N. Javaid, "MobiSink: Cooperative routing protocol for underwater sensor networks with sink mobility," in *Proc. IEEE 30th Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, Mar. 2016, pp. 189–197.
[12] S. Ghoreyshi, A. Shahrabi, and T. Boutaleb, "A novel cooperative opportunistic routing scheme for underwater sensor networks," *Sensors*, vol. 16, no. 3, p. 297, Feb. 2016.
[13] H. Nasir, N. Javaid, M. Sher, U. Qasim, Z. Khan, N. Alrajeh, and I. Niaz, "Exploiting outage and error probability of cooperative incremental relaying in underwater wireless sensor networks," *Sensors*, vol. 16, no. 7, p. 1076, Jul. 2016.
[14] A. Khan, M. Khan, S. Ahmed, M. A. Abd Rahman, and M. Khan, "Energy harvesting based routing protocol for underwater sensor networks," *PLoS ONE*, vol. 14, no. 7, Jul. 2019, Art. no. e0219459.
[15] B. S. Srujana, Neha, P. Mathews, and V. P. Harigovindan, "Multi-source energy harvesting system for underwater wireless sensor networks," *Procedia Comput. Sci.*, vol. 46, pp. 1041–1048, 2015.
[16] N. Javaid, S. Hussain, A. Ahmad, M. Imran, A. Khan, and M. Guizani, "Region based cooperative routing in underwater wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 92, pp. 31–41, Aug. 2017.
[17] G. Cario, A. Casavola, P. Gjanci, M. Lupia, C. Petrioli, and D. Spaccini, "Long lasting underwater wireless sensors network for water quality monitoring in fish farms," in *Proc. OCEANS*, Jun. 2017, pp. 1–6.
[18] S. Basagni, V. Di Valerio, P. Gjanci, and C. Petrioli, "Harnessing HyDRO: harvesting-aware data ROuting for underwater wireless sensor networks," in *Proc. 18th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, Jun. 2018, pp. 271–279.
[19] R. J. Urick, *Principles of Underwater Sound*. Lower Parel, Mumbai: Peninsula, 1996.
[20] A. Khan, I. Ali, A. U. Rahman, M. Imran, Fazal-E-Amin, and H. Mahmood, "Co-EEORS: Cooperative energy efficient optimal relay selection protocol for underwater wireless sensor networks," *IEEE Access*, vol. 6, pp. 28777–28789, 2018.
[21] R. W. L. Coutinho and A. Boukerche, "Exploiting mobility to improve underwater sensor networks," in *Proc. 16th ACM Int. Symp. Mobility Manage. Wireless Access*, 2018, pp. 89–94.
[22] M. Xu, G. Liu, and H. Wu, "An energy-efficient routing algorithm for underwater wireless sensor networks inspired by ultrasonic frogs," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 2, Feb. 2014, Art. no. 351520.
[23] A. Bereketli and S. Bilgen, "Remotely powered underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 12, no. 12, pp. 3467–3472, Dec. 2012.
[24] R.-Y. Liu and Z.-L. Li, "Effects of rough surface on sound propagation in shallow water," *Chin. Phys. B*, vol. 28, no. 1, Jan. 2019, Art. no. 014302.
[25] M. E. Bayrakdar, "Cooperative communication based access technique for sensor networks," *Int. J. Electron.*, vol. 107, no. 2, pp. 212–225, Feb. 2020.
[26] N. Javaid, U. Shakeel, A. Ahmad, N. Alrajeh, Z. A. Khan, and N. Guizani, "DRADS: Depth and reliability aware delay sensitive cooperative routing for underwater wireless sensor networks," *Wireless Netw.*, vol. 25, no. 2, pp. 777–789, Feb. 2019.
[27] H. Khan, S. Ali Hassan, and H. Jung, "On underwater wireless sensor networks routing protocols: A review," *IEEE Sensors J.*, vol. 20, no. 18, pp. 10371–10386, May 2020.
[28] *LinkQuest Underwater Acoustic Modems UWM2200 Specifications*. Accessed: Nov. 1, 2020. [Online]. Available: http://www.link-quest.com/html/uwm2200.htm

ADIL KHAN was born in Peshawar, Pakistan, in 1978. He received the master's degree from the University of Peshawar, Pakistan, in 2000, and the M.S. degree in computer networks from International Islamic University Islamabad, Pakistan, in 2007. He is currently pursuing the Ph.D. degree with the Department of Computer Science, Abdul Wali Khan University Mardan, Pakistan. He has been working as an Assistant professor with Abdul Wali Khan University Mardan, since 2009. His research interest includes underwater sensor networks.

MUKHTAJ KHAN received the M.Sc. degree in mobile computer system from Staffordshire University, U.K., in 2006, and the Ph.D. degree from the School of Engineering and Design, Brunel University, U.K. The Ph.D. study is sponsored by Abdul Wali Khan University Mardan, Pakistan. His research interests include high performance computing for big data analysis, underwater sensor networks, and machine learning in neural networks.

SHEERAZ AHMED received the Ph.D. degree in underwater sensor networks from COMSATS University Islamabad, in 2016. He has served as a Lecturer and an Assistant Professor for the City University of Science and Information Technology from 2003 to 2007. He has also served as a Visiting Faculty for the University of Engineering and Technology (UET) Peshawar. He was an Assistant Professor with Abasyn University, Peshawar. He is currently serving as the Dean for Iqra National University, Peshawar.

NADEEM IQBAL (Senior Member, IEEE) received the Ph.D. degree in bio and brain engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2013. He was a Postdoctoral Fellow with the School of Mechanical Engineering, University of Leeds, U.K. He is currently working as an Assistant Professor with the Department of Computer Science, Abdul Wali Khan University Mardan, Pakistan. His research interests include supervised and unsupervised machine learning techniques for control prosthesis, biological information processing mechanism in brain, bioinformatics, artificial intelligence, and biomedical engineering.

MOHD AMIRUDDIN ABD RAHMAN (Member, IEEE) received the B.S. degree in electrical engineering from Purdue University, USA, in 2006, the M.S. degree in sensors and instrumentation from Universiti Putra Malaysia (UPM), in 2011, and the joint Ph.D. degree in electronic and electrical engineering from The University of Sheffield and UPM, in 2016. During his Ph.D. study, he has been with Alcatel-Lucent Bell Labs in Ireland and Belgium as a Post-Graduate Researcher working on indoor localization project. He is currently attached to the Indian Institute Technology Kanpur, India, as a Postdoctoral Fellow working on peer-to-peer networks. He also holds a faculty position as a Senior Lecturer with the Department of Physics, UPM, and leads the research in pattern recognition, indoor localization, machine learning algorithms, predictive analytics, and game theory application.

MUHAMMAD KHALIS ABDUL KARIM received the B.Sc. degree (Hons.) in imaging diagnostic and radiotherapy from Universiti Kebangsaan Malaysia (UKM), in 2008, and the M.Sc. and Ph.D. degrees in physics from Universiti Teknologi Malaysia (UTM), in 2013 and December 2016, respectively. He has expertise in medical physics particularly radiation dosimetry in medical imaging and has been appointed as an advisory member in several technical committee during his work. Aside from working in clinical environment, he also actively involved giving lecture in several workshops on radiation protection and nuclear security. To date, he has authored/coauthored 35 international journals (with impact factor ranging from 0.2 to 5.1), ten international proceedings, and three national proceedings. He has reviewed 20 international journal articles from reputable and well-established publisher. His research interests include medical imaging, radiation dosimeters, and image processing.

MOHD SHAFIE MUSTAFA received the Ph.D. degree from Universiti Putra Malaysia. He is currently a Senior Lecturer with the Department of Mathematics and an Associate Researcher with the Institute for Mathematical Research. His research interests include applications of statistical modeling, robust designs, and experimental designs in some industrial problems, such as food science and chemical engineering study. He also expands his research interest in problems of response surface methodology with the development of robust techniques for designed experiments. His research interests also include regression analysis, small area estimation, and machine learning algorithms.

YAZID YAAKOB received the B.Eng. degree in electrical and electronic engineering, the M.Eng. degree in physics, electrics and mechanics, and the Ph.D. degree in frontier materials from the Nagoya Institute of Technology (NITech), Japan, in 2010, 2012, and 2015, respectively. During his Ph.D. at NITech, he worked on synthesis of ion-induced composite carbon nanofibers and nanomaterials characterization by In situ Transmission Electron Microscopy (TEM). He is currently a Senior Lecturer with the Department of Physics, Faculty of Science, Universiti Putra Malaysia (UPM). His current research interests include synthesis of carbon nanostructures from waste materials by using chemical vapor deposition (CVD). His other projects also include optimization of the carbon nanomaterials for sustainable energy application.