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Cooperative Routing for Energy Efficient Underwater Wireless Sensor Networks

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ABSTRACT Underwater Wireless Sensor Networks (UWSNs) serve as a proficient source to monitor aquatic environment. However, data communications and information routing within these systems offer many challenges. To ensure sufficient network lifetime, energy efficiency in routing protocols serves as a major concern in UWSNs. This paper presents an energy competent cooperative routing scheme known as Region Based Courier-nodes Mobility with Incremental Cooperative (RBCMIC) routing. The proposed scheme uses broadcast nature of wireless nodes and performs an incremental cooperative routing. A rigorous evaluation and verification of the proposed scheme with current state-of-the-art yield improved energy efficiency, resulting in extended network lifetime. The results show that an overall improvement of 20% is witnessed in energy usage, whereas a notable 89% improvement is achieved in end-to-end delay in comparison to DEADS protocol.

INDEX TERMS Relay nodes, courier nodes, cooperative routing, energy efficiency, underwater wireless sensor networks.

I. INTRODUCTION

The advancements of technology results in a rapid evolution of underwater network applications such as ocean sampling, coastal areas surveillance, contamination monitoring and assisted course-plotting. To implement these applications in underwater environment, UWSNs are widely used [1]–[5]. In such networks, a wide range of sensor nodes is deployed under the water. In aquatic environment, radio and optical signals do not propagate properly due to which it face absorption problems. Due to harsh surrounding conditions, UWSNs face certain constraints such as added delay, frequency limitations, low data rate and inability to replenish nodes' batteries [6]–[12]. Thus, the limited battery capacity of nodes and difficultly of reinstating node energy in aqueous environment are the major limitations of UWSNs [13]–[15]. To overcome this issue, nodes' energy needs to be efficiently utilised to improve network life time. The routing protocols play an important role in reserving nodes' energy; however, the development of energy-aware routing protocols for UWSNs is a challenging task [16]–[20].

The cooperative routing is a proficient way to enhance network lifetime in such a harsh environment [21], [22]. This routing scheme is suitable for improving energy efficiency and minimizing delay as compared to other routing approaches such as multi-hop approach [23]. The selection criteria of relay and destination nodes depend on parameters like residual energy, link quality and depth of sensor nodes. Moreover, the logical divisions of network, sink nodes' deployment and courier nodes' mobility patterns affect the network performance in UWSNs. Therefore, proposing and designing a cooperative routing mechanism that considers all above discussed aspects in an optimal way, is quite a challenging task [22].

Majority of the cooperative communication mechanisms in UWSNS are designed to address the physical and Medium Access Control (MAC) layers issues; however, the network layer has largely been neglected [24]. The basic purpose of cooperative communication schemes is to improve the reliability and link quality in underwater harsh environment.

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Whereas, the proposed study takes the advantage to use this mechanism at the network layer to enhance the network lifetime. Moreover, the reliable data delivery is one of the biggest issues in underwater environment. For this purpose, depth-based routing is suggested for maintaining reliability and throughput [24]. Some cooperative routing schemes use mobile sinks to improve the packet delivery ratio [23], [25]; however, it increases the network cost. Whereas, utilizing the courier nodes can be a better option to reduce this cost.

Keeping in view the above discussion, in this paper, an incremental depth-based cooperative routing scheme known as Region Based Courier-nodes Mobility with Incremental Cooperation (RBCMIC) has been proposed to enhance network life time in UWSNs. In the proposed scheme, the relay nodes forward data packets from source to destination. Incremental relaying mechanism is used to reduce energy consumption by using relay nodes. The use of relay nodes results in reliable delivery as well as reduced energy consumption no matter which relay path is followed. Moreover, the responsibility of relay nodes is to send replica of packets to destination node in case of data loss; however, re-transmission of packets is the responsibility of MAC or transport layers that is not within the scope of this paper. In addition, the network is split into four vertical sections. Initially, courier nodes are positioned in middle of each section/region. The courier nodes move horizontally in its own section to accumulate information packets from sensor nodes which are located within the range of courier node. The efficient mobility of courier nodes minimize direct transmission of nodes which improves their energy utilization.

In short, in the proposed protocol, each section/region contains courier nodes which collect data from the relevant source nodes. In addition, the proposed scheme uses incremental cooperative routing which enhances the energy conservation.

The main contributions of the proposed work are listed below:

- Proposition of a novel depth-based incremental cooperative routing scheme.
- Integration of region based and incremental cooperative routing protocols to merge the advantages of both and to overcome the limitations of each one
- Use of incremental relaying mechanism to enhance network lifetime
- A rigorous evaluation of proposed scheme with current state-of-the-art schemes.

The organization of rest of the paper is as follows. The relevant work and developments are presented in Section 2. Methodology of the proposed scheme is described in Section 3. Simulation results and relevant discussion is presented in Section 4. Finally, Section 5 concludes the paper.

II. RELATED WORK

In last few years, many cooperative routing schemes have been proposed. Some techniques improve energy efficiency while compromising end-to-end delay, while others achieve reliability with added energy consumption. Some of these protocols are discussed as follows.

A. NETWORK LIFETIME

In [23], a technique named Sink Mobility with Incremental Cooperative (SMIC) routing has been proposed. It includes some moving sinks within the regions in order to maximize reliability as well as to reduce energy consumption. The selection criteria on which relay and destination nodes are to be selected depends on residual energy, depth of sensors and link quality.

In [26], authors propose a scheme that uses the energy aware cooperative scheme (EAC) with variable depth threshold (D_{th}). The proposed scheme uses the ‘‘broadcast nature’’ of nodes. The selection of source node is made on the basis of optimized D_{th}. Furthermore, based on active neighbours, source node is adapted. While selecting the destination node, it should fall outside the D_{th}. In addition, the selection of relay and destination nodes is based on node’s depth, energy left and quality of the link among the nodes.

Chang *et al.* propose a scheme that consists of a shortest cost pathway routing algorithm which improves energy efficiency and network lifetime [27]. The study in [28] presents an energy-aware adaptive and cooperative routing protocol for UWSNs. This protocol, enables re-transmission of failed communications through cooperative nodes. Although, re-transmission causes added energy consumption yet throughput is improved in this work.

In [29], [30], authors propose a cooperative ‘‘Depth and Energy Aware Dominating Set (DEADS)’’ routing scheme. The selection criteria of relay depends on two factors: node depth and residual energy. Few mobile sinks are erratically placed within the network field where neighboring sensor nodes directly forward packets to mobile sink. Otherwise, data is forwarded to appropriate destination. However, due to inefficient sink mobility, the lower depth nodes die earlier that reduces the network lifetime. Similarly, data forwarding irrespective of channel conditions also degrades the performance. Moreover, ineffective movement of mobile sinks causes higher delay.

B. BIT ERROR RATE (BER)

A Region Based Cooperative Routing (RBCRP) has been proposed in [25]. It uses Rayleigh fading concept to analyze the amplifying and forwarding technique. At the destination node, ‘‘Bit Error Rate (BER)’’ is examined. If an acknowledgement is received from destination node, the relay node immediately drops the packet. On the other hand, if feedback is not received, relay re-transmits packet to the destination node. Moreover, the mobile sink (MS) changes its position after some interval and covers the whole network region.

The authors propose an energy balanced data propagation protocol in [31]. In this protocol, transmission of data packets is basically concerned with probabilities. In every stride, sensor node decides whether to send information packets directly to the sink or to pass on the data to its relay node.

In [32], authors propose improved Adaptive Mobility of Courier Nodes in Threshold-Optimized DBR (iAMCTD) routing scheme. It is a reactive protocol which maximizes throughput by reducing the packet drops. In iAMCTD, mobile courier nodes are introduced in the network to reduce network lifetime.

C. THROUGHPUT, DATA RELIABILITY AND DELAY

Cooperative Depth Based Routing (CoDBR) scheme is proposed to improve throughput and data reliability [24]. Based on depth information, relays are chosen. In this technique, source nodes send data packets to relay nodes that ultimately forward it to destination nodes. It helps in reducing packet-drop ratio.

According to Braem *et al.* [33], data is forwarded in an organized manner by a node to increase throughput. ''Link Quality'' and ''Residual Energy'' are the two parameters which are used as a selection criteria of relay node.

The study in [34] anticipate localization free ''Depth Based Routing (DBR)''. It greedily sends data to destination. Nodes that have minimum depth are chosen to forward packets. The end-to-end delay is lower in DBR as higher number of direct transmissions are made. However, this badly affects the network lifetime.

TABLE 1. **Summary of existing cooperative routing protocols**

Protocol	Improved Metrics	Deficit Metrics
DEADS [30]	Network Lifetime	Residual Energy
CoDBR [24]	Throughput	Network Lifetime
SMIC [23]	Network Lifetime	Average End-to-End Delay
EAC [26]	Network Lifetime	Throughput
RBCMIC	Network Lifetime, End-to-End delay	Throughput

In literature, the cooperative mechanism is used on physical and MAC layers to improve link quality; however, it is not much explored on network layer. Moreover, existing schemes use multiple mobile sinks that increases the network cost. The inefficient and arbitrary movement cause higher end-to-end delay. Additionally, the data forwarding irrespective of channel conditions also degrades the performance of the network. Similarly, some existing work prefers the maximum number of direct transmissions to reduce the delay. However, this has a negative impact on overall network lifetime. Hence, to overcome above mentioned issues, an incremental cooperative routing scheme is proposed. This study is aimed at maximizing network lifetime without notably affecting throughput and delay. A summary of existing cooperative routing protocols is presented in Table 1.

III. PROPOSED SCHEME

This paper presents an incremental cooperative routing based protocol named RBCMIC to improve the network lifetime in UWSNs. Further detail of the proposed scheme is presented as follows:

A. NETWORK MODEL

The proposed scheme targets energy efficient communications in under water sensor networks. In the proposed work, the coverage area is logically divided into four vertical regions. The sensor nodes are deployed randomly in the coverage area. A homogeneous network of randomly deployed sensor nodes is formed where all nodes have equal and limited battery power. However, the sinks are assumed to have extended energy as all communications are routed to the sink and they extensively use energy exceeding the requirements of normal nodes. Audio/acoustic modem is used for the purpose of communication among sensor nodes; whereas, the radio modem is used for the communication with the onshore data center. Hence, the sink receives data packets from sensor nodes via acoustic modem and forwards them via radio signals to the base station. In the network, communication takes place in rounds (a round is completed when every sensor node in the network has transmitted a packet towards the sink). The proposed underwater network architecture model consists of static sinks on the top center of every region and mobile courier nodes within the regions. The deployment coordinates of the mobile courier nodes are selected randomly within the region and they are mobilized vertically within the region. The sink is equipped with the acoustic and the radio modems. In this protocol, the relay node is introduced between source and the destination nodes that offers cooperative data communications between source and destination. For each region, forwarding functions are calculated on the basis of depth of the nodes. The efficient utilization of courier and relay nodes has a considerable impact on the energy consumption of the network. The network architecture of proposed scheme is shown in Fig. 1.

B. ENERGY CONSUMPTION MODEL

The energy consumption model provides the basic mathematical equations of energy consumption during the normal operations of a sensor node.

The total amount of energy required by a sensor node in order to transmit data packet of size ps in bits at a distance d is presented in Eq. 1.

$$\boldsymbol{E_{tr}(ps, d) = (ps * E_{disp}) + (ps * t_b)} \tag{1}$$

where t_b indicates the bit duration, E_{disp} stands for radio dissipation and E_{tr} refers to the transmit energy consumption. For reader's convenience, the symbols/variables used in equations are explained in Table 2.

The energy consumed in the reception E_{rcp} of data packet of size ps can be determined by using the following

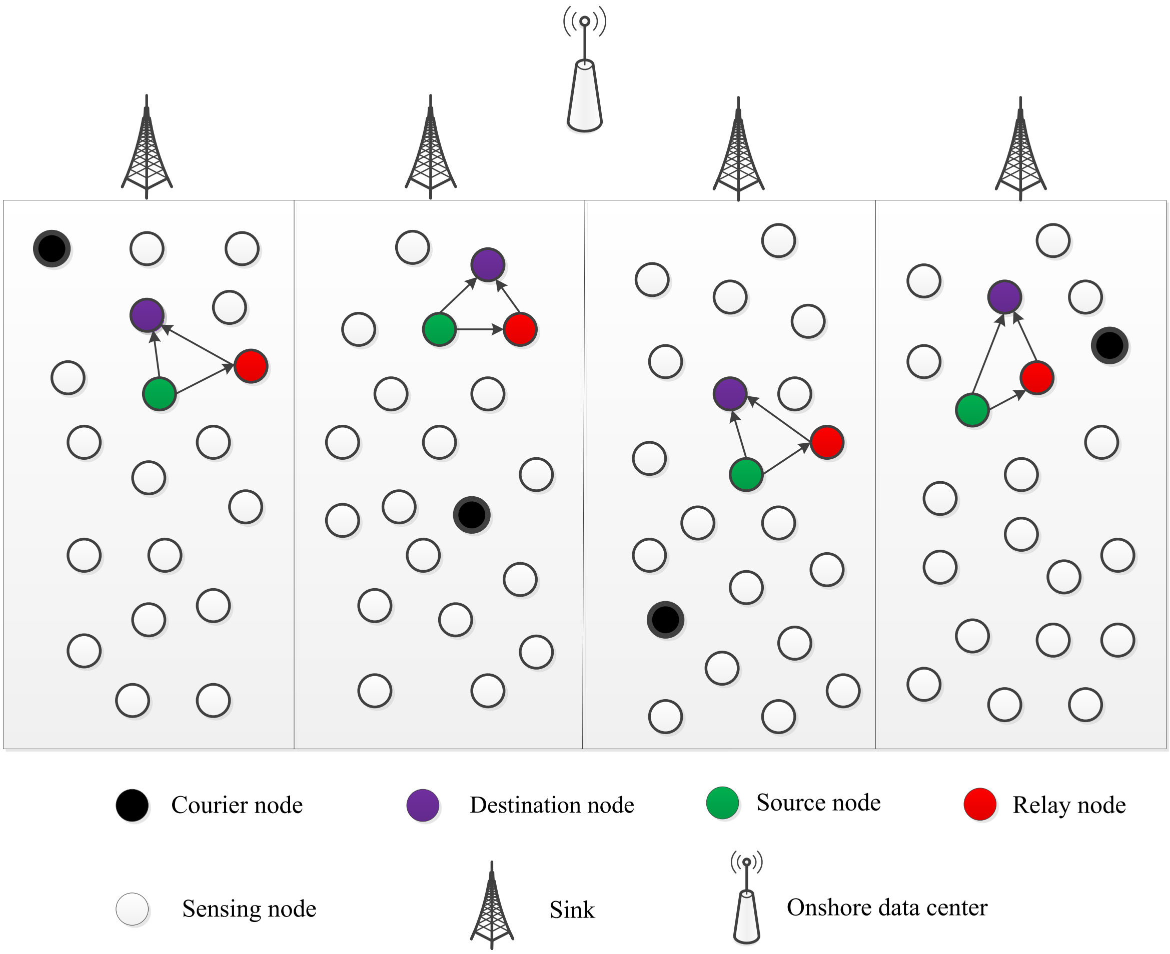

FIGURE 1. Network model of the proposed scheme.

TABLE 2. Notations used in the equations (6), (7) and (8)

Symbols	Description
B	Original signal
A	Received signal
A_{s0}	Received signal at the destination node
A_{s1}	Received signal at the relay node from the source node
A_{s2}	Acknowledged signal at the destination node through relay node
g	Channel Gain
g_{s0}	Channel gain between source and destination link
g_{s1}	Channel gain between source and relay link
g_{s2}	Channel gain from relay to destination link
n	Channel Noise
n_{s0}	Channel noise between source and destination link
n_{s1}	Channel noise between source and relay link
n_{s2}	Channel noise from relay to destination link

formula [5]:

$$\boldsymbol{E_{rcp}(ps, d) = ps * E_{disp}} \tag{2}$$

Hence, the residual energy E_r of any sensor node can be calculated as follows:

$$\boldsymbol{E_r = E_{init} - (E_{rcp} + E_{tr})} \tag{3}$$

where $\boldsymbol{E_{init}}$ stands for initial energy of sensor node. The overall power consumption in both transmission and reception from system's perspective can be presented as below:

ID	Depth	Residual Energy

FIGURE 2. Hello packet format.

SNR of the Link	ID	Depth	Residual Energy

FIGURE 3. Control packet (8 Bytes) format.

$$P_{tx} = P_{dt} + P_{at} + P_a + P_t \tag{4}$$

here P_{dt} and P_{at} depict the power consumption of digital and analog circuits at transmitter side, respectively. P_a is the power consumed by the amplifier and P_t is the power consumed by the transmission of signals. Similarly, on the receiver side, the power consumption can be expressed as follows:

$$P_{rx} = P_{dr} + P_{ar} + P_{LNA} \tag{5}$$

here, P_{dr} and P_{ar} represent the digital and analog circuit losses and P_{LNA} represents the power consumed by low noise amplifier.

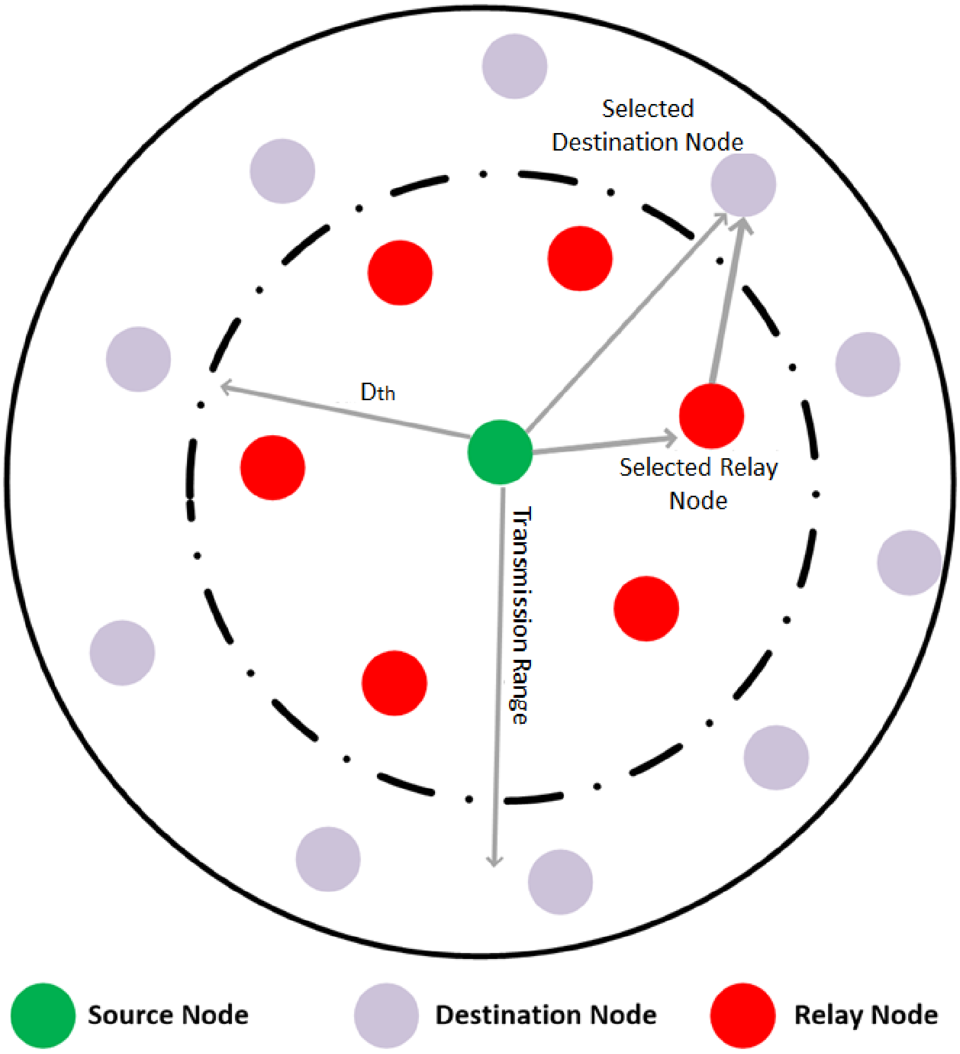

FIGURE 4. Cooperative partner nodes selection.

C. CHANNEL MODEL

The modeling of communication channel plays an important role in accurate analysis of the communication system. Therefore, an extreme care has been taken to provide suitable solutions for underwater communications. The transmitted signal endures Rayleigh fading and Additive White Gaussian Noise (AWGN). In underwater environment, the noise is due to the thermal, shipping, turbulence and wind. The following equations depict the signal acknowledged at the destination node and signal received at the relay node.

$$\boldsymbol{A}_{s0} = \boldsymbol{B}g_{s0} + \boldsymbol{n}_{s0} \quad (6)$$

$$\boldsymbol{A}_{s1} = \boldsymbol{B}g_{s1} + \boldsymbol{n}_{s1} \quad (7)$$

$$\boldsymbol{A}_{s2} = \boldsymbol{B}g_{s2} + \boldsymbol{n}_{s2} \quad (8)$$

Table 2 lists the symbols used in the equations (6), (7) and (8) along with the respective description.

The proposed routing protocol uses incremental cooperative routing which is sub-divided in initialization, depth-threshold selection, route establishment and data transmission phases. Each of these are detailed in Section III-(D-G).

D. INITIALIZATION

In this phase, all nodes in a network broadcast their information through beacon message (i.e. a control packet used for basic communications layout mapping) to nodes which are in its coverage area. Beacon message includes depth of the node, node identification and its residual energy [23]. As a result of the broadcasted beacon message, the receiving nodes send a reply (control packet) to the source node [25].

Beacon messages are sent periodically. In this way, the neighbors' state can be updated. Fig. 2 and Fig. 3 show the formats of beacon message and control packets, respectively. Here, the Signal to Noise Ratio (SNR) of the link represents link strength.

E. DEPTH THRESHOLD SELECTION

Depth threshold (D_{th}) factor is used to avoid the packet flooding. Flooding usually causes network congestion and

Algorithm 1 RBCMIC Routing Algorithm

```
                              ▷ %comment: The operation of RBCMIC
  is divided in three phases initialization, path establishment
  and data communications%
  IC:
  Node Deployment ='Random';
  Node Energy='Max';
  route to destination:'Unknown';
  Neighbors defined='No';
  $D_{th}$ ='undefined'


  if (initiation beacon = True) then
      $Broadcast(control_packet)$
  end if
  $tab = createTable(Neighbours)$
  if (beaconsReceived> $\Delta T$) then $D_{th} = define(val)$
  else $D_{th} = Redefine(val)$
  end if
  for $i = 0$ to $RN$ do
      for $j = 0$ to $DS$ do
          $sort(tab.Re)$
          $sort(tab.depth)$
          $destNode = select(tab.re(max)\&tab.depth(min))$
      end for
  end for
                     ▷ %comment: Initiate data communications with
  information relaying/forwarding to destination%

  $receive(datagram)$
  $datagram.coopRoute(destNode)$
```

eventually results in fast drainage of batteries of the sensor nodes [26]. To avoid congestion, D_{th} is measured to select the forwarding node. In the proposed scheme, D_{th} is optimized based on the nodes' existing transmission range. The source node selects the neighbors based on their depth and residual energy. Hence, the nodes with lower depth as compared to the source node are selected as neighbors and are included in the neighbor table of the source node. The sensor nodes perform recalculation of D_{th} at regular intervals. Cooperative partner nodes' selection is shown in Fig. 4.

F. ROUTE ESTABLISHMENT

After initialization phase, a route is established to link source and destination nodes. The destination node is selected by considering the depth and remaining energy. When neighbors are ordered on the basis of remaining energy and depth, each node elects the most suitable forwarder node. Moreover, a second neighbor is elected as a forwarder node that basically overhears the information sent from originator node to sink node. If the sink node does not get data packet, then relay re-transmits the same packet. This mechanism results in less end-to-end delay and battery consumption.

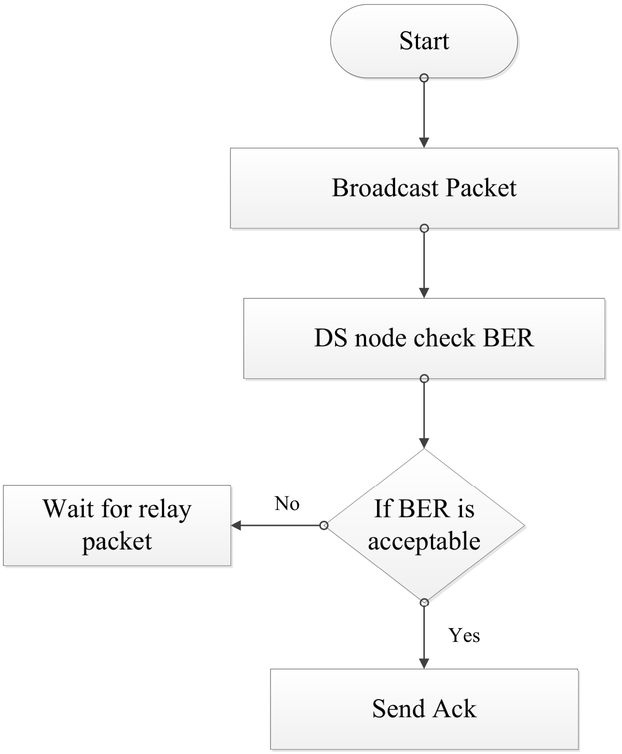

FIGURE 5. Format of source and destination nodes transmission.

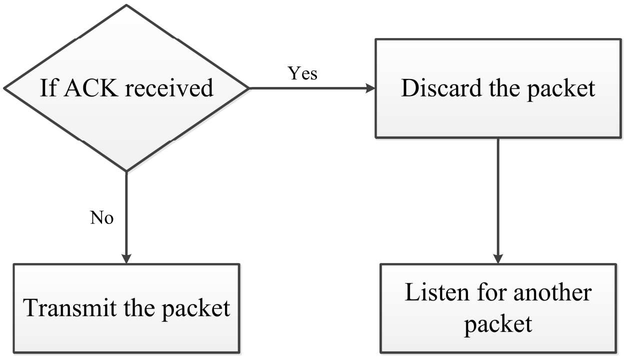

FIGURE 6. Format of relay transmission.

G. DATA TRANSMISSION

Data is transmitted from originator to sink on the established route. The originator node broadcasts data packet to forwarder and sink. If the sink node sends an ACK, then the forwarded node discards the packet. In case, an ACK is not received, an adaptive packet re-transmission from relay to destination node takes place. If the source node finds mobile courier node as a neighboring node, data is relayed to the mobile courier node which will ultimately forward it to the static sink on the water surface. The transmission procedure of source and destination nodes is presented in the Fig. 5; whereas, the transmission procedure of relay node is shown in the Fig. 6.

With the passage of time, density of the network decreases. This results in a decrease in the number of neighbors of

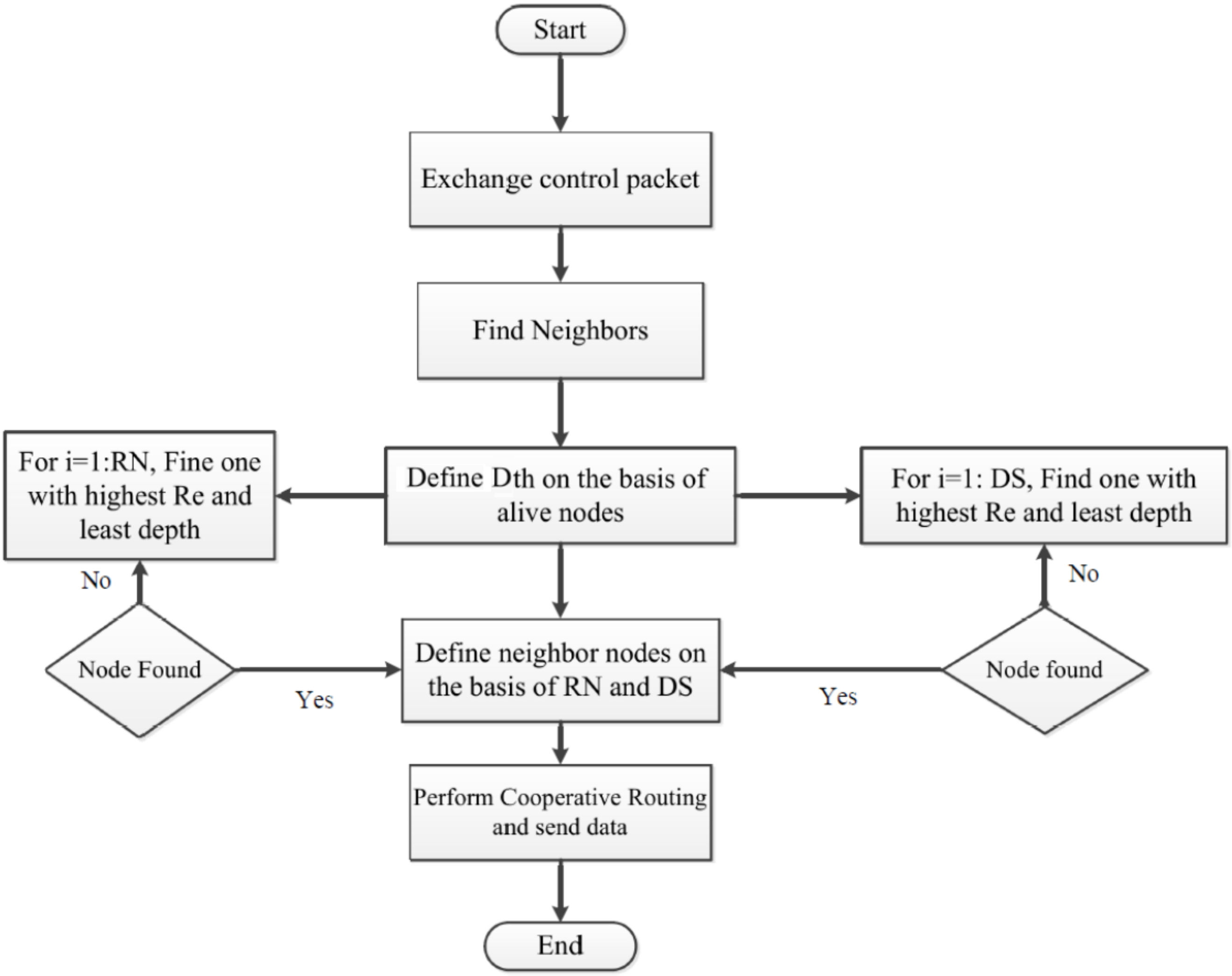

FIGURE 7. Basic flow model of RBCMIC. RN = Relay Node, DS = Dominating Set (in reference to a network modeled as digraph), Re = Residual energy.

a node. In such situation, higher number of transmissions can affect the network lifetime. Therefore, to resolve this situation, the D_{th} is proposed. D_{th} value declines with the decrease in the number of neighboring nodes and thus it prolongs the network lifetime. The basic flow model of RBCMIC is shown in Fig. 7; whereas, a detailed algorithm is presented in algorithm 1.

TABLE 3. Simulation parameters

Parameters	Values
Number of courier nodes	4
Total sinks	4
Transmission range	100 m
Area of the Network	500 x 500 m^2
Total nodes	250
Node's Initial energy	12 Joules
Size of data packet	1000 bits
Number of rounds	1200

IV. PERFORMANCE EVALUATION

A. SIMULATION SETUP

Performance of the proposed scheme is presented in this section where two well-known schemes: DBR [34] and DEADS [29], [30], are used to compare the results. Simulations are performed in rounds where a round is used as a unit [35]. When each sensor node in the network has sent a packet towards sink then a round is said to be completed. For the simulation purposes, Matlab is used [35], [36]. In the simulation, 1200 rounds are run. Random distribution is used for placement of all 250 nodes in the network in an underwater field of 500 sq. meter. Communication range of individual sensor is limited to 100 meters. Initially, each sensor node contains 12 Joules of total energy. As explained earlier, the network is split in 4 sections/regions, one courier node and one sink is deployed in each region. The summary of the simulation parameters is shown in Table 3.

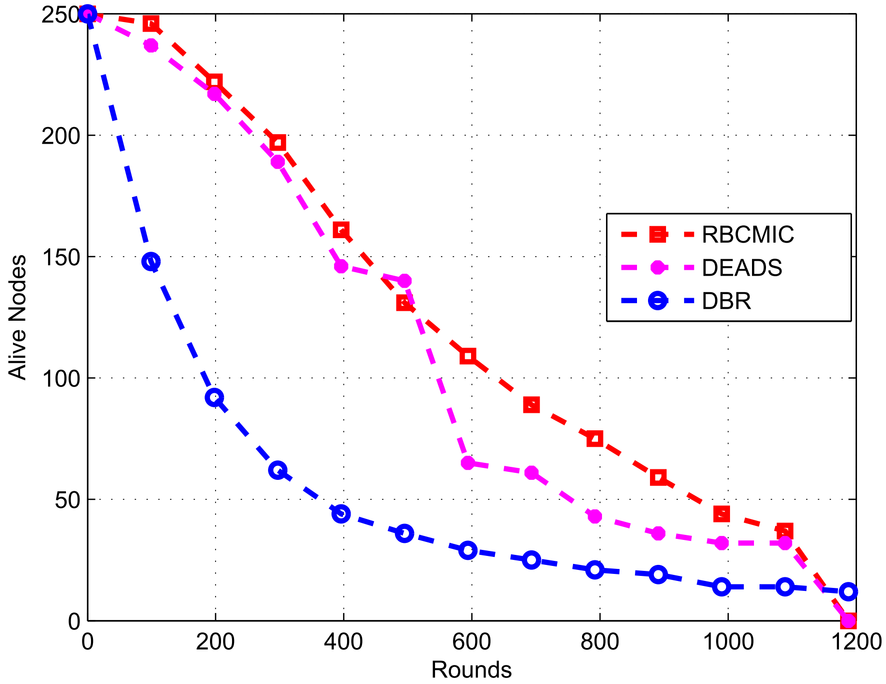

FIGURE 8. Network lifetime under considered routing schemes.

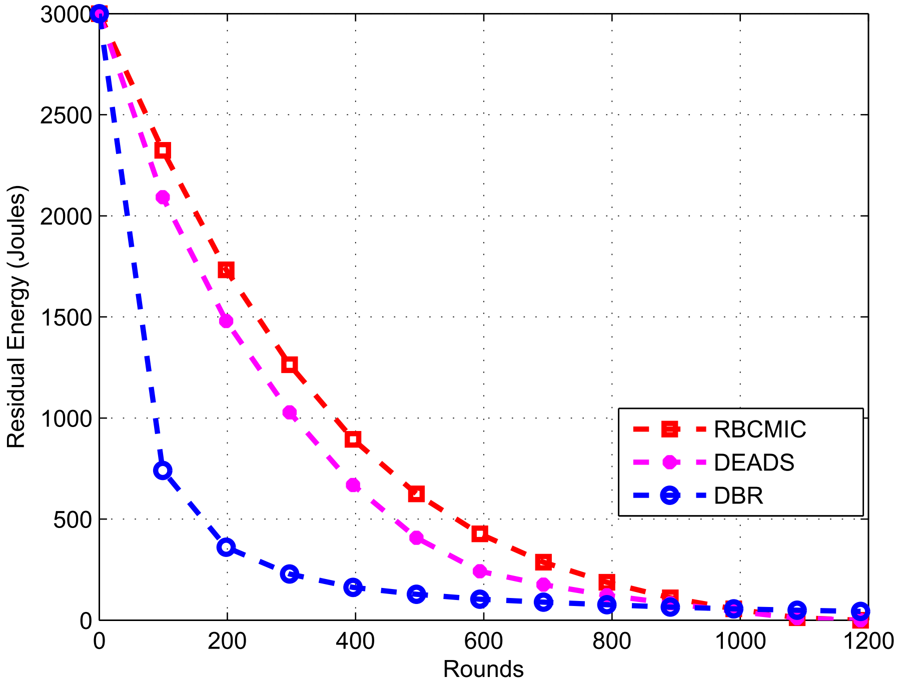

FIGURE 9. Behavior of energy depletion of network during simulation rounds.

B. PERFORMANCE METRICS

For evaluating the proposed scheme, network lifetime, residual energy in the network, throughput of each round, throughput at sink and end-to-end delay are selected to evaluate the proposed strategy.

- Network lifetime: Lifetime of the network signifies the duration from beginning of network to the death of last node. It can be measured in terms of alive and dead nodes.
- Alive nodes: These are the nodes in the network which have satisfactory remaining power to be able to transmit packets.
- Dead nodes: The nodes that do not have sufficient energy to transmit data are known as dead nodes.
- Residual Energy: The amount of energy left in the network at any specific round is called the residual energy. It is calculated in Joules.

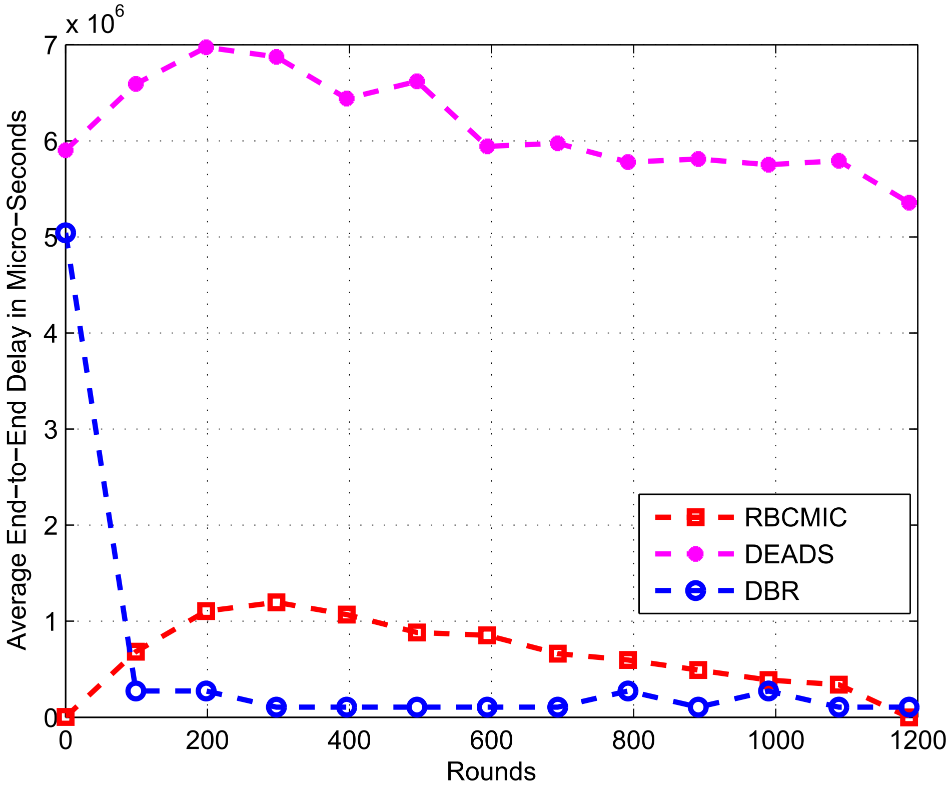

FIGURE 10. End-to-end delay in communications among source nodes and surface sinks.

- Throughput: It is presented as the packets received by the sink from start of the simulation.
- End-to-End delay: It is the calculated average time of packets transmitted from source to the destination nodes. It is calculated in milliseconds.

C. RESULTS AND DISCUSSION

1) NETWORK LIFETIME

The lifetime of the networks in DEADS, DBR and RBCMIC is presented in Fig. 8. It is clear from the figures that the nodes in the DEADS and DBR start to die after few hundred rounds. In DBR and DEADS, the data is forwarded irrespective of the channel conditions. The least depth nodes expire at an early stage because of higher data forwarding rate. Whereas, the proposed scheme exhibits lower energy consumption due to incremental cooperative routing and mobile courier nodes. Moreover, the vertical movement of the courier nodes within the region covers maximum network field and hence sensor nodes within the range of courier nodes transmit directly to courier nodes. Therefore, in the proposed scheme, energy consumption is potentially balanced, thus improving overall network lifetime. These improvements can be seen in the Fig. 8. Moreover, in the proposed approach, the stability period (The time duration for which no node died within network) is also highest in comparison to other protocols considered in our simulations. It is due to the usage of courier nodes and their efficient mobility that limits the transmission distance of nodes. As shown in eq. 1, the transmission distance notably affects node's energy consumption. Hence, the energy consumption of sensor nodes is reduced in RBCMIC approach.

2) RESIDUAL ENERGY

In Fig. 9, energy consumption of the network in DEADS and RBCMIC is presented. As cooperation is performed in both protocols; therefore, energy consumption is high. However, energy consumption in the proposed protocol, RBCMIC, is lower as compared to DEADS because selection of relay and destination nodes is made on the basis of two parameters - node's depth and residual energy. Moreover, in RBCMIC, one courier node is placed in each region that covers it completely by moving vertically. The sensor nodes which come in the range of courier nodes, transmit directly to courier nodes, hence, minimum energy is consumed. Whereas, in DEADS, fixed cooperative nodes always forward the data packet to the destination using relay path which causes multiple transmissions of the same packet. The network region of DEADS is further logically divided into four sub-regions each having one mobile sink. The use of mobile sinks and their mobility patterns cause the earlier death of lower depth nodes. This is due to multi-hopping; however, in RBCMIC, courier nodes cover the whole region and gather data from the destination node.

3) END-TO-END DELAY

The average delay in communication between source and destination nodes for the proposed scheme, DEADS and DBR,

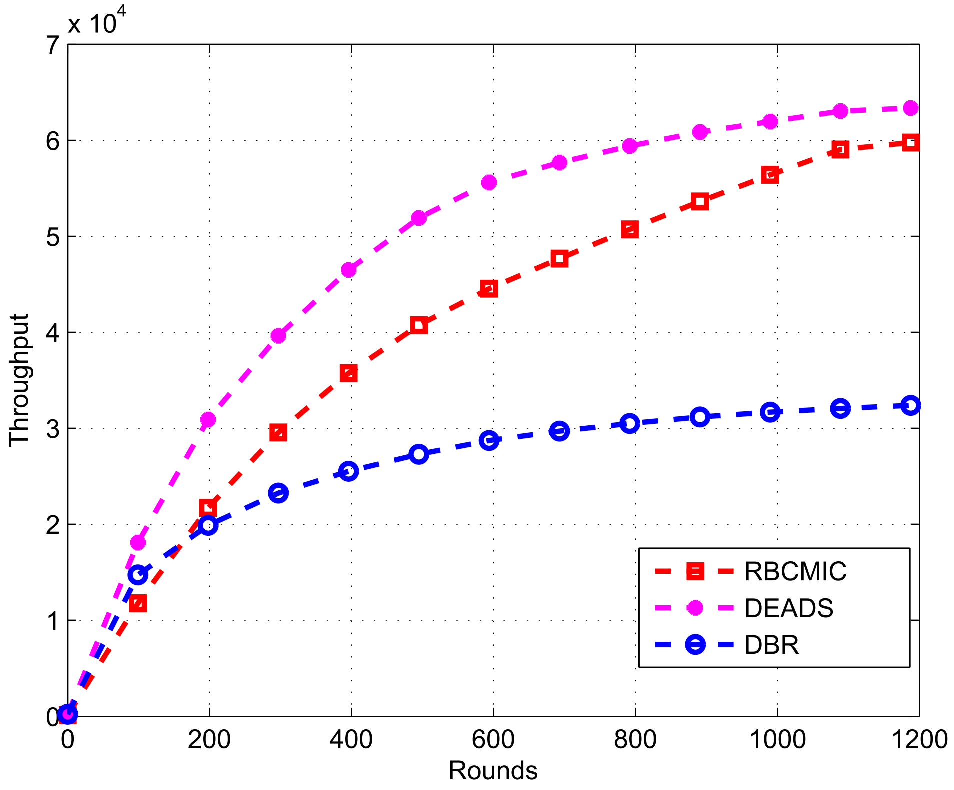

FIGURE 11. **Overall network throughput.**

is presented in Fig. 10. It can be seen that the overall delay of RBCMIC is relatively lower than DEADS. The utilization of the mobile sinks in DEADS causes higher end-to-end delay. Whereas, in RBCMIC, courier nodes are restricted to vertical movements. Moreover, the sinks are deployed at the top of each region. Whenever, courier nodes reaches to the top, it transmits all the sensed packets to the sink as depicted in Fig. 1. The perfect placement of sinks and restricted mobility of courier nodes result in lower delay in comparison to DEADS. Consequently, it shows the feasibility of proposed scheme for delay sensitive applications. Lower delay in DBR is ensured due to higher number of direct transmissions. On the other hand, direct transmissions in DBR cause the high energy consumption and consequently the lifetime of network is reduced as depicted in Fig. 8.

4) THROUGHPUT

Fig. 11 presents the comparison of throughput per round in RBCMIC, DEADS and DBR. In the proposed scheme, less number of packets are received that results in lower throughput as shown in Fig. 11. It is due to the use of relay nodes which prevents the delivery of redundant packets to the destination node. In DEADS and DBR, check of redundancy is not incorporated. The restriction of the delivery of redundant packet in the proposed scheme results in lower throughput. Moreover, due to the restricted transmissions, the collision probability will surely be reduced. However, studying the collision effects and bandwidth usage is beyond the scope of this paper.

V. CONCLUSION

In the proposed work, a novel region based cooperative routing scheme (RBCMIC) is anticipated to increase network lifetime in UWSNs. The proposed scheme utilizes mobile courier nodes to effectively handle energy consumption in the network. To efficiently exploit the mobility of courier nodes, the network is distributed into logical regions. Consequently, incremental relaying mechanism is used to foster better power consumption in UWSNs. A rigorous evaluation of the proposed scheme is performed through extensive simulations. The comparison of the proposed scheme with state-of-the-art shows promising results, improving overall network lifetime, average end-to-end delay and throughput. In RBCMIC, courier nodes cover the whole region and gather data from the destination node. Afterwards, data is forwarded to destination, thus reducing the energy consumption of each sensor node. In DEADS and DBR, the data is forwarded irrespective of channel conditions which degrades the network lifetime. On the contrary, the proposed scheme overcomes this issue and results into improved network lifetime. Hence, RBCMIC offers 20% improvement in energy consumption and 89% improvement in end-to-end delay in comparison to DEADS protocol.

As a further investigation, dynamic selection and formation of the number of regions is expected to improve the outcomes of this work.

REFERENCES

[1] A. Ahmad, A. Wahid, and D. Kim, "AEERP: AUV aided energy efficient routing protocol for underwater acoustic sensor network," in *Proc. 8th ACM Workshop Perform. Monit. Meas. Heterogeneous Wireless Wired Netw.*, 2013, pp. 53–60.

[2] M. Garcia, S. Sendra, M. Atenas, and J. Lloret, "Underwater wireless ad-hoc networks: A survey," in *Mobile Ad Hoc Networks: Current Status and Future Trends*. 2011, pp. 379–411.

[3] S. Sendra, J. Lloret, J. M. Jimenez, and L. Parra, "Underwater acoustic modems," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4063–4071, Jun. 2016.

[4] M. Tariq, M. S. A. Latiff, M. Ayaz, Y. Coulibaly, and A. Wahid, "Pressure sensor based reliable (PSBR) routing protocol for underwater acoustic sensor networks," *Ad Hoc Sensor Wireless Netw.*, vol. 32, nos. 3–4, pp. 175–196, 2016.

[5] A. Yahya, S. U. Islam, A. Akhunzada, G. Ahmed, S. Shamshirband, and J. Lloret, "Towards efficient sink mobility in underwater wireless sensor networks," *Energies*, vol. 11, no. 6, p. 1471, 2018.

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

[7] M. Faheem, G. Tuna, and V. C. Gungor, "QERP: Quality-of-service (QoS) aware evolutionary routing protocol for underwater wireless sensor networks," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2066–2073, Sep. 2018.

[8] J. Lloret, S. Sendra, M. Ardid, and J. J. P. C. Rodrigues, "Underwater wireless sensor communications in the 2.4 GHz ISM frequency band," *Sensors*, vol. 12, no. 4, pp. 4237–4264, Mar. 2012.

[9] S. Sendra, J. Lloret, J. J. P. C. Rodrigues, and J. M. Aguiar, "Underwater wireless communications in freshwater at 2.4 GHz," *IEEE Commun. Lett.*, vol. 17, no. 9, pp. 1794–1797, Sep. 2013.

[10] S. Sendra, J. V. Lamparero, J. Lloret, and M. Ardid, "Study of the optimum frequency at 2.4 GHz ISM band for underwater wireless ad hoc communications," in *Proc. Int. Conf. Ad-Hoc Netw. Wireless*. Berlin, Germany: Springer, 2012, pp. 260–273.

[11] J. S. Abbasi, N. Javaid, S. Gull, S. Islam, M. Imran, N. Hassan, and K. Nasr, "Balanced energy efficient rectangular routing protocol for underwater wireless sensor networks," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jun. 2017, pp. 1634–1640.

[12] B. Ali, N. Javaid, A. R. Hameed, F. Ahmad, J. S. Abbasi, S. Islam, and M. Imran, "Energy hole avoidance based routing for underwater WSNs," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jun. 2017, pp. 1654–1659.

[13] A. Mateen, M. Awais, N. Javaid, F. Ishmanov, M. K. Afzal, and S. Kazmi, "Geographic and opportunistic recovery with depth and power transmission adjustment for energy-efficiency and void hole alleviation in UWSNs," *Sensors*, vol. 19, no. 3, p. 709, 2019.

[14] S. Sahana, K. Singh, R. Kumar, and S. Das, "A review of underwater wireless sensor network routing protocols and challenges," in *Next-Generation Networks*. Singapore: Springer, 2018, pp. 505–512.

[15] B. Ali, A. Sher, N. Javaid, S. U. Islam, K. Aurangzeb, and S. I. Haider, "Retransmission avoidance for reliable data delivery in underwater WSNs," *Sensors*, vol. 18, no. 1, p. 149, 2018.

[16] A. Khasawneh, M. S. B. A. Latiff, O. Kaiwartya, and H. Chizari, "A reliable energy-efficient pressure-based routing protocol for underwater wireless sensor network," *Wireless Netw.*, vol. 24, no. 6, pp. 2061–2075, 2017.

[17] M. Ahmed, M. Salleh, and M. I. Channa, "Routing protocols for underwater wireless sensor network based on location: A survey," *Adhoc Sensor Wireless Netw.*, vol. 38, nos. 1–4, pp. 67–101, 2017.

[18] B. Ali, N. Javaid, S. U. Islam, G. Ahmed, U. Qasim, and Z. A. Khan, "RSM and VSM: Two new routing protocols for underwater WSNs," in *Proc. Int. Conf. Intell. Netw. Collaborative Syst. (INCoS)*, Sep. 2016, pp. 173–179.

[19] A. R. Hameed, N. Javaid, S. U. Islam, G. Ahmed, U. Qasim, and Z. A. Khan, "BEEC: Balanced energy efficient circular routing protocol for underwater wireless sensor networks," in *Proc. Int. Conf. Intell. Netw. Collaborative Syst. (INCoS)* Sep. 2016, pp. 20–26.

[20] A. Sher, N. Javaid, G. Ahmed, S. U. Islam, U. Qasim, and Z. A. Khan, "MC: Maximum coverage routing protocol for underwater wireless sensor networks," in *Proc. 19th Int. Conf. Netw.-Based Inf. Syst. (NBiS)*, Sep. 2016, pp. 91–98.

[21] A. Shaf, T. Ali, W. Farooq, U. Draz, and S. Yasin, "Comparison of DBR and L2-ABF routing protocols in underwater wireless sensor network," in *Proc. 15th Int. Bhurban Conf. Appl. Sci. Technol. (IBCAST)*, Jan. 2018, pp. 746–750.

[22] T. M. Rajeh, A. I. Saleh, and L. M. Labib, "A new cooperative balancing routing (CBR) protocol to enhance the lifetime of wireless sensor networks," *Wireless Pers. Commun.*, vol. 98, no. 3, pp. 2623–2656, 2018.

[23] M. Sajid, A. Wahid, K. Pervaiz, M. Khizar, Z. A. Khan, U. Qasim, and N. Javaid, "SMIC: Sink mobility with incremental cooperative routing protocol for underwater wireless sensor networks," in *Proc. 10th Int. Conf. Complex, Intell., Softw. Intensive Syst. (CISIS)*, Jul. 2016, pp. 256–263.

[24] H. Nasir, N. Javaid, H. Ashraf, S. Manzoor, Z. A. Khan, U. Qasim, and M. Sher, "CoDBR: Cooperative depth based routing for underwater wireless sensor networks," in *Proc. 9th Int. Conf. Broadband Wireless Comput., Commun. Appl. (BWCCA)*, Nov. 2014, pp. 52–57.

[25] S. Hussain, N. Javaid, Muhammad, I. Ahmad, U. Qasim, and Z. A. Khan, "Performance analysis of amplify and forward technique in region based cooperative routing for underwater wireless sensor networks," in *Proc. 10th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput. (IMIS)*, Jul. 2016, pp. 33–41.

[26] K. Pervaiz, A. Wahid, M. Sajid, M. Khizar, Z. A. Khan, U. Qasim, and N. Javaid, "DEAC: Depth and energy aware cooperative routing protocol for underwater wireless sensor networks," in *Proc. 10th Int. Conf. Complex, Intell., Softw. Intensive Syst. (CISIS)*, Jul. 2016, pp. 150–158.

[27] J.-H. Chang and L. Tassiulas, "Maximum lifetime routing in wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 12, no. 4, pp. 609–619, Aug. 2004.

[28] T. Hafeez, N. Javaid, U. Shakeel, Muhammad, S. Hussain, and H. Maqsood, "An energy efficient adaptive cooperative routing protocol for underwater WSNs," in *Proc. 10th Int. Conf. Broadband Wireless Comput., Commun. Appl. (BWCCA)*, Nov. 2015, pp. 304–310.

[29] A. Umar, M. Akbar, S. Ahmed, N. Javaid, Z. A. Khan, and U. Qasim, "Underwater wireless sensor network's performance enhancement with cooperative routing and sink mobility," in *Proc. 9th Int. Conf. Broadband Wireless Comput., Commun. Appl. (BWCCA)*, Nov. 2014, pp. 26–33.

[30] A. Umar, N. Javaid, A. Ahmad, Z. A. Khan, U. Qasim, N. Alrajeh, and A. Hayat, "DEADS: Depth and energy aware dominating set based algorithm for cooperative routing along with sink mobility in underwater WSNs," *Sensors*, vol. 15, no. 6, pp. 14458–14486, 2015.

[31] A. F. Harris, III, M. Stojanovic, and M. Zorzi, "When underwater acoustic nodes should sleep with one eye open: Idle-time power management in underwater sensor networks," in *Proc. 1st ACM Int. Workshop Underwater Netw.*, 2006, pp. 105–108.

[32] N. Javaid, M. R. Jafri, Z. A. Khan, U. Qasim, T. A. Alghamdi, and M. Ali, "iAMCTD: Improved adaptive mobility of courier nodes in threshold-optimized DBR protocol for underwater wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 11, 2014, Art. no. 213012.

[33] B. Braem, B. Latre, I. Moerman, C. Blondia, E. Reusens, W. Joseph, L. Martens, and P. Demeester, "The need for cooperation and relaying in short-range high path loss sensor networks," in *Proc. Int. Conf. Sensor Technol. Appl.*, Oct. 2007, pp. 566–571.

[34] H. Yan, Z. J. Shi, and J.-H. Cui, "DBR: Depth-based routing for underwater sensor networks," in *Proc. Int. Conf. Res. Netw.* Berlin, Germany: Springer, 2008, pp. 72–86.

[35] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci.*, Jan. 2000, p. 10.

[36] A. P. Das and S. M. Thampi, "Simulation tools for underwater sensor networks: A survey," *Netw. Protocols Algorithms*, vol. 8, no. 4, pp. 41–55, 2017.

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