IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 3, 2017, accepted May 14, 2017, date of publication May 24, 2017, date of current version July 17, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2707531

Establishing a Cooperation-Based and Void Node Avoiding Energy-Efficient Underwater WSN for a Cloud

NADEEM JAVAID[1], (Senior Member, IEEE), TAIMUR HAFEEZ[1], ZAHID WADUD[2,3], NABIL ALRAJEH[4], MOHAMAD SOUHEIL ALABED[4], AND NADRA GUIZANI[5]
[1]COMSATS Institute of Information Technology, Islamabad 44000, Pakistan
[2]University of Engineering and Technology Peshawar, Peshawar 25000, Pakistan
[3]Capital University of Science and Technology, Islamabad 44000, Pakistan
[4]Biomedical Technology Department College of Applied Medical Sciences, King Saud University, Riyadh 11633, Saudi Arabia
[5]Department of ECE, Purdue University, West Lafayette, IN 47907, USA

Corresponding author: Nadeem Javaid (nadeemjavaidqau@gmail.com)

This work was supported by the International Scientific Partnership Program ISPP at King Saud University under ISPP# 0053.

ABSTRACT For energy-efficient resource management, void node avoidance is one of the key objectives in the energy constrained underwater wireless sensor networks (UWSNs). In this paper, we propose two new routing protocols for the UWSN which is one of the end parts of a cloud. The first protocol is avoiding void node with adaptive hop-by-hop vector based forwarding (AVN-AHH-VBF), and the second is cooperation-based AVN-AHH-VBF (CoAVN-AHH-VBF). In both schemes, sensor nodes forward data packets in multi-hop fashion within a virtual pipeline. The nodes outside the pipeline do not forward data packets to avoid flooding in the network. At each hop, forwarding toward void region of the network is avoided by utilizing two hop information. Results of extensive simulations show that our proposed schemes significantly improve the network performance in terms of delivery ratio, energy expenditure and delay as compared with the selected existing scheme (AHH-VBF).

INDEX TERMS Energy waste, void hole, pipeline, vector based forwarding, holding time, cooperative routing protocol, UWSNs.

I. INTRODUCTION

UWSN consists of sensor nodes equipped with acoustic modems and a sink node equipped with both acoustic and radio modems. These networks are used for monitoring rivers, lakes and oceans. Application examples include oceanographic data collection, oil spill monitoring, military training, tactical surveillance, disasters prevention, undersea pollution monitoring, submarine detection, aquatic habitat monitoring, etc. [1]. Generally, acoustic waves are used for underwater communication. However, the detrimental nature of acoustic channel leads to high bit error rate (BER), low bandwidth, high propagation delay, etc. These challenges lead to high energy consumption of the network nodes, and low reliability of the received data [2].

Random deployment of nodes allows for some part of the underwater network area to be less populated (low node density), while leaving other parts more populated (high node density). This deployment technique leaves network areas prone to void holes. In UWSNs, generally data packets travel from the bottom anchored source nodes to the on surface sink nodes. Thus, the sensor nodes near the sink are heavily engaged in data transmission which results in the void regions near the sink. In such situations, no more data packets can be successfully delivered to the sink resulting in large amount of energy loss [3]. Wireless system designers enhance reliability of the transmitted data by taking into account diverse techniques; such as, the number of duplicated data packets at the receiver node. To achieve spatial diversity, Multiple-Input Multiple-Output (MIMO) and multi node cooperative transmission are efficient approaches. However, the former approach requires hardware at each node with higher complexity and cost. The later approach is accomplished via cooperative routing where multiple nodes are exploited to transmit/relay duplicated data packets arriving at the destination after some delay [4].

In the literature, many void node avoidance algorithms for energy efficient routing in UWSNs have been presented. For example, Xie *et al.* in [5] present a vector based

TABLE 1. State-of-the-art related work.

Protocol	Feature(s)	Advantage(s)	Limitation(s)
EEDBR [10]	Takes residual energy along with depth into account	Energy consumption, lifetime and delay are improved	channel characteristics are ignored
AUV-PN [11]	AUV visits path nodes and CH only	Lifetime with minimum overhead in the network	Partial part of the network is not visited by AUV
EEC-VBF [6]	Residual energy and time of data relay are considered while forwarding data packet	Evenly energy consumption	No mechanism for void nodes in the network
CARP [14]	Considers link quality and successful history of communication with neighbors	Saves energy per bit even at different loads	PING and PONG bring overhead in the system
DSDBR, DSEEDBR, DSAMCTD [16]	Delay sensitive routing algorithms	Minimum average end-to-end delay in both sparse and dense networks	Energy consumption on duplicate packets and shorter network lifetime
GEDAR [2]	Void node recovery algorithm	Void nodes are eliminated	Cost to reach neighbor node is not considered and shorter network lifetime
L2-ABF [18]	Forwarding is based on calculated flooding angle at each layer and location information is not required	Addresses the issue of node movement	Duplicate packets and communication void problem
3D-SM [20]	Sink mobility, courier nodes gather data from logical cuboids	Network lifetime prolongation, path loss reduction and throughput maximization	Cost of Sink and Courier node movement is not taken into account
AURP [23]	AUVs gather data from gateway nodes	Improved delivery ratio and energy consumption in the network	Delay is compromised
Coop LEACH [26]	Modified clustering algorithm of LEACH and M CHs in each cluster are used	Achieves higher diversity order and efficient energy consumption	Clustering incurs control overhead in the network
Optimal schemes [27]	Formulated problem with MINLP and solved using Branch and Bound algorithm	Optimal power allocation at each hop and reduced search space of the algorithm	Collision probability with energy consumption is not addressed and the mechanism is not applicable to dynamic topology
Co-UWSN [4]	Destination and relay node are selected using cost function which depends on distance and SNR of the link	End-to-end delay energy consumption	Redundant data forwarding is not avoided and ACK mechanism on every packet is costly in resource constrained networks

forward (VBF) routing protocol which provides the self-adaptation algorithm for coordinating with candidate nodes while selecting the *most desirable ones* to forward the data packet. Other work in [6] considers residual energy along with position information for data packet forwarding. Similarly,Nicolaou *et al.* in [7] enhance the packet delivery ratio in a sparse network. The hop-by-hop VBF (HH-VBF) defines virtual pipelines around one hop vector from each forwarder node to the destination. Yu *et al.* [8], proposed the adaptive adjustment of forwarding range hop-by-hop and transmission power. Xie *et al.* [5], Sun *et al.* [6], Nicolaou *et al.* [7], and Yu *et al.* [8] have focused on the packet delivery ratio. However, these routing protocols are inefficient in the following aspects: (i) forwarder selection for avoiding void nodes, and (ii) holding time calculation for avoiding redundant transmissions of data packets in the network.

In this paper, we propose two new routing schemes for UWSNs: (i) co-operative CoAVN-AHH-VBF and (ii) non-co-operative AVN-AHH-VBF [9]. The later scheme has also been analyzed with the Bit Error Rate (BER); so is given the name AVN-AHH-VBF-B. Both the schemes avoid the void node by checking the status of a node before transmitting the data packet (using two hop information). The proposed schemes efficiently select forwarder nodes on the bases of least depth in the pipeline and regions towards destination (RTD) in the range of the source node. We also modify the holding time equation by finding the number of hops to be traversed and the number of neighbors of a source node in the network. Simulation results show that the proposed schemes perform better than the selected existing scheme in terms of the selected performance metrics.

The rest of the paper is organized as follows. In section II, related work is discussed. Section III presents energy, network and channel models. Our proposed schemes are described in section IV. The holding time is analyzed in section V. Simulation results are given and discussed in section VI. Finally, the paper concludes in section VII.

II. RELATED WORK

In this section, we discuss the existing routing protocols in four categories: (*i*) protocols towards energy efficiency, (*ii*) end-to-end delay focused protocols (*iii*) throughput focused protocols and (*iv*) co-operative routing protocols. A brief comparison of some of the discussed protocols is given in table 1.

A. PROTOCOLS TOWARDS ENERGY EFFICIENCY

Wahid *et al.* [10] present a routing protocol which takes into consideration depth, residual energy and forwarding metrics. [11] uses mobile sinks to gather data from nodes. All nodes form local clusters and choose a cluster head (CH). Instead of visiting each node separately, the sink moves only towards *CHs* and gathers data of all local clusters from their respective CHs. As multi-hopping is restricted to intra cluster communication, the protocol achieves considerable energy efficiency. In [6], a cross layer approach with *VBF* is applied for the selection of forwarder based on distance from virtual vector and residual energy. Thus, protocol achieves longer network lifetime. Similarly, Hao *et al.* [13] use network coding to achieve prolongation in network lifetime. Reference [14] develops a routing protocol which routes around a void region with the help of hop count information. In channel aware routing protocol (*CARP*), a relay is selected on the basis of successful communication history with neighbors. Reference [15] proposes a technique to avoid void nodes in the network by making the routing decisions according to the depth of current node and depth of the next two-hop expected forwarder nodes. Weighting depth forwarding area division depth based routing ($WDFAD-DBR$) calculates holding time for the packets according to the depth difference of two-hop neighbors.

B. END-TO-END DELAY FOCUSED PROTOCOLS

In [16], three delay sensitive routing protocols DSDBR, DSEEDBR and DSAMCTD are proposed with application of different holding time equations. The authors proposed different holding time equations. Holding time equation for DSDBR focuses on depth. While for DSEEDBR, it focuses on depth and residual energy. Calculation of holding time for DSAMCTD is based on the network density. The proposed scheme in [2], combines geographic and opportunistic routing. The former has, there is no requirement of complete path from source to destination. The later, if the priority node is unable to transmit, then any other node become a potential forwarder to forward the data packet. In case of void regions, a node from void region moves towards a comparatively denser region. Thus, end-to-end delay is minimized and packet delivery ratio is improved. An adaptive approach towards end-to-end delay minimization is proposed in [17], where holding time of packet on each node is not fixed. In [18], layer by layer angel based flooding (L2-ABF) protocol is proposed. The protocol explicitly caters movement of the sensor node and end-to-end delay pitfalls. Before data forwarding, every node computes flooding angle towards the sink. To minimize end-to-end delay, time division multiple access (TDMA) based multi-path routing is proposed in [19]. Location information and propagation delay are considered in the forwarding process.

C. THROUGHPUT FOCUSED PROTOCOLS

Akbar *et al.* [20] use either courier node or sink in each logical cuboid to collect data from sensor nodes. Reference [21] proposes relative distance based forwarding (RDBF). In *RDBF* each sending node embeds coordinates of destination (sink) in the data packet. At each hop, neighbor with minimum distance from the sink is the next hop forwarder. Multiple sink architecture based scheme, $H2-DAB$ is proposed in [22]. In this protocol, forwarder is selected on the basis of minimum hop count. If two neighbor nodes with same hop count are there, node with minimum hop count for backup route is selected as next hop. Hop count calculation and backup route increases throughput of the network. Yoon *et al.* [23] proposed an AUV-aided routing protocol. After data collection from gateway sensor nodes, the AUV transmit data to the sink node. Since AUV visits a gateway node for short interval of time, thus, high data rate is used between AUV and gateway node. Hence, a higher throughput is achieved along with the energy efficiency.

D. COOPERATIVE ROUTING PROTOCOLS

Hong, and Scaglione in [24] proposed energy saving with opportunistic large arrays which is a cooperative form of broadcast for wireless sensor networks (WSNs). Moreover, broadcasting policy takes SNR and BER into account. In [25], it is first determined whether cooperative routing is required or not. If required, an optimal relay is selected which fulfills the SNR constraints. In addition, Bellman-Ford routing technique along with mixed the integer linear programming (MILP) are used to achieve minimum energy cooperative routing. A cooperative diversity routing protocol, cooperative LEACH is proposed in [26]. Using cross layer approach spatial diversity is attained. M diversity order is achieved by selecting M number of CHs in each cluster. An analytical approach of energy consumption based on the BER is also given. Mansourkiaie and Ahmed [27] propose collision minimization strategy using cooperative routing. They formulate a problem using (MINLP). Furthermore, branch and bound algorithm with reduced search space is used to solve the integer non linear programming problem. Reference [4] achieved considerable energy efficiency by optimally allocating power at each hop from source to sink. In Co-UWSN, each node computes a cost function which depends on residual energy, distance and SNR of the link. The scheme is efficient in terms of end-to-end delay and lifetime of the network.

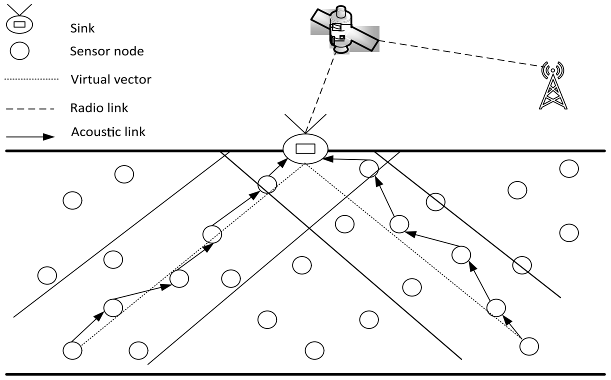


FIGURE 1. Architecture of multi-hop UWSN.

III. SYSTEM MODEL

Let the sensor nodes be randomly deployed in a three dimensional acoustic environment as shown in Fig. 1. The sink is on the surface of the water and in the middle of the region. Sensor nodes are equipped with an acoustic modem only. All sensor nodes forward sensed or received data to the sink with the help of the neighbor sensor nodes. Whereas, nodes near the sink send data packets directly to the sink. Sink is equipped with two modems; an acoustic modem for communication with sensors and a radio modem for communication with off-shore data centers.

The acoustic signal is attenuated while propagating in the harsh underwater environment. If $A(l, f)$ denotes signal attenuation as a function of distance and frequency, then [28]:

$$A(l,f) = l^k a(f)^l \tag{1}$$

where l represents the distance in kilometers km, f denotes the frequency in kilohertz kHz and k is the geometry of propagation. It's values are 1, 1.5 and 2 for cylindrical, practical and spherical spreading, respectively. Whereas, $a(f)$ is the absorption coefficient in dB/km if f is in kHz. $a(f)$ is given by Thorp's model,

$$a(f) = \begin{cases} \dfrac{0.11f^2}{1+f^2} + \dfrac{44f^2}{4100+f^2} + 2.75 \times 10^{-4}f^2 + 0.003, \\ \text{if } f \geq 0.4 \\ 0.002 + 0.11\dfrac{f^2}{1+f^2} + 0.011f^2, \text{if } f < 0.4 \end{cases} \tag{2}$$

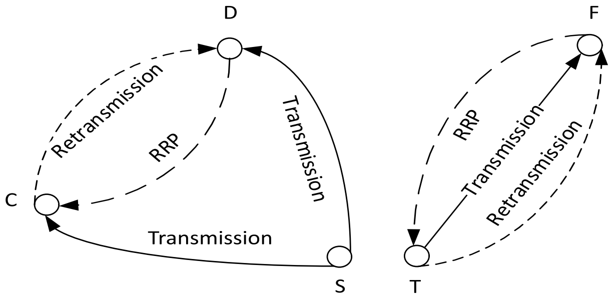


FIGURE 2. Cooperation scenarios.

Cooperative routing with single and no relay is shown in Fig. 2. Before sending data; each sensor node performs modulation using binary phase shifting keying (BPSK) technique.

In Fig. 2, with one relay case, S is the source node, D is the destination node and C is the cooperative relay node. Signal received from S to C can be as [29]:

$$y_{SC} = (h_{SC} \times x_S) + n_{SC}. \tag{3}$$

Similarly, signal received from S to D is given as follows:

$$y_{SD} = (h_{SD} \times x_S) + n_{SD}. \tag{4}$$

Signal received from C to D is given as follows:

$$y_{CD} = h_{CD} \times (y_{SC}) + n_{CD}. \tag{5}$$

In Eq. (3), (4) and (5), h is the channel gain, n is the accumulated noise and x_S is the original signal. In message received at destination from relay, y_{SC} is the message relay C received from previous source node S. Both copies of the signal received at destination are independent of each other. Destination uses diversity combining technique (MRC) to combine the faded copies of the signal.

IV. OUR PROPOSED SCHEMES

In this section, we describe the functioning of our proposed routing schemes; AVN-AHH-VBF and CoAVN-AHH-VBF.

TID	SID	XS	YS	ZS

FIGURE 3. NRP format.

TID	SID	XS	YS	ZS	n_b

FIGURE 4. NAP format.

TID	SID	XS	YS	ZS	DID	XF	YF	ZF	PSN	PR	TR	h_{tr}

FIGURE 5. Header of data packet.

A. THE AVN-AHH-VBF

All phases of AVN-AHH-VBF protocol are described in the following details:

1) NETWORK INITIALIZATION PHASE

To use multi-hop communication mode, each node requires neighbor's location information. For this purpose [8], we defines three types of packets: neighbor request packet (NRP), neighbor acknowledgement packet (NAP) and data packet (DP). Format of *NRP*, *DP* and *NAP* are shown in Fig. 3, Fig. 4 and Fig. 5, respectively.

In each packet, symbols *XS*, *YS* and *ZS* are the coordinates of the source node in a three dimensional network volume. Whereas, *SID* represents *ID* of the sender and *TID* is the type of packet (Its value for *NRP*, *NAP* and *DP* is 00, 01 and 10, respectively). In *NAP* tuple, n_b is the number of neighbors of the node. In the *DP* header, *DID* field is the destination *ID* and *XF*, *YF* and *ZF* are the coordinates of the forwarding node of the source node. *PSN* is the packet sequence number. *PR* and *TR* represent the pipeline radius and transmission radius, respectively. A node using broadcast nature of the network, sends a *NRP*. In response, each node within its vicinity sends a *NAP*.

After communication with the neighbor nodes, all nodes maintain a neighbor table. Entries in the neighbor table are shown in the form of a tuple: *NID*, *XN*, *YN*, *ZN*, *ET*, *NB*, *VN*. First entry is the ID of the neighbor node. Next three consecutive entries are coordinates of the node with ID *NID*. *ET* is the timer to update an entry in the neighbor table. Second last field *NB*, represents the number of neighbors of *NID* node. The *VN* depicts whether a node is void or not. Its value is 1 for a node if its neighbor table is empty, 0 otherwise.

2) SUPPRESSION OF REDUNDANT TRANSMISSIONS

Whenever a node receives a data packet, it extracts coordinates of the forwarding node from the packet. If node's ID and *PSN* match with entries in the packet queue, packet is immediately dropped. Implementation of this mechanism avoids redundant data forwarding in the network and differentiates

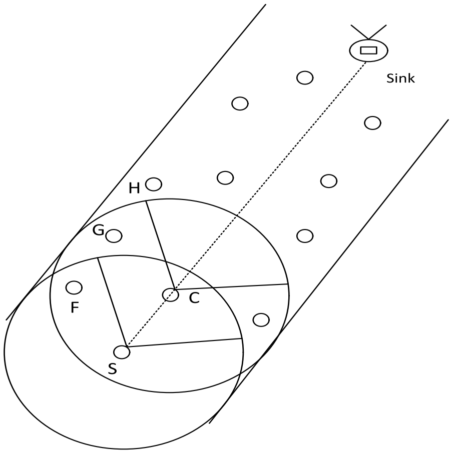


FIGURE 6. **Problem with RTD.**

our scheme from flooding based schemes [12]. Secondly, the node extracts further information from the packet and checks whether destination and forwarder are in transmission range of each other. If found in range, node drops the packet because it has been already received at destination (sink) and there is no need to further multi-hop the data packet. Thirdly, nodes which are outside the pipeline, also drop the data packet. These checks before forwarding, avoid redundant transmissions which in turn reduces energy consumption in the network. In contrast to AHH-VBF as shown in Fig. 6, the proposed AVN-AHH-VBF in which a node is not in *RTD* of the previous hop does not drop the data packet. We, thus, exploit the entire transmission range of previous hop node which is useful in separate network conditions. In this way, we improve packet delivery ratio in our scheme.

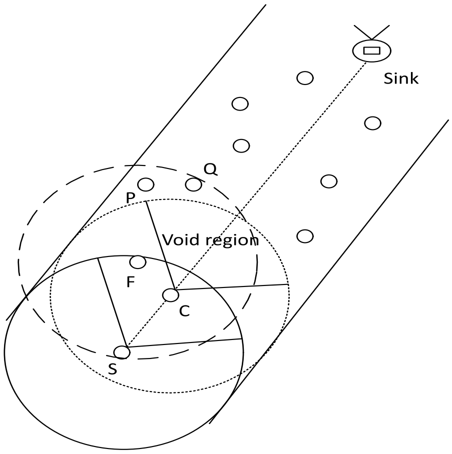


FIGURE 7. **Forwarder selection comparison.**

3) EFFICIENT NEXT HOP SELECTION

If the ultimate decision is to forward the data packet, the node first selects a node from its neighbor table with maximum distance and not a void node. According to AVN-AHH-VBF (Fig. 7), neither node C nor F are void. The check, if either node is void or not, decreases probability of data forwarding towards void regions. Further, it checks if the number of neighbors against selected next hop is greater than or equal to the minimum number of neighbors in its table excluding void node entries. Node F has two neighbors, P and Q and node C has only F node as a neighbor. Hence node F forwards the data packet sent by the source node S. On the other hand, C node defers its transmission on overhearing from F. Thus, we tackle the forwarding of data packets towards a void hole with the help of two hop information. Moreover, the proposed scheme node forwards the data packet in the direction where probability of a successful path to sink is higher. Pipeline radius and transmission radius is changed hop by hop according to [8]. Then, node updates entries in the data packet. After that, it calculates holding time for packet and adds its entry in packet queue. Details of holding time calculation is given in section IV-A.4. During holding time, if a node overhears the same packet from the node which is comparatively near to the sink, it drops the packet. In this way, nodes do not drop the data packets on overhearing when they receive the data packets forwarded by any void node. If holding time is elapsed, packet is transmitted. This improves the delivery ratio in sparse as well as dense networks.

4) HOLDING TIME CALCULATION

Holding time formula given by Yu *et al.* in [8] as follows:

$$H_{time} = \frac{1}{2}\alpha T_{max} + \frac{R_{tx} - |MN|}{v_{sound}} \tag{6}$$

where T_{max} is maximum holding time for a packet. Its value is pre-defined (1, 2 or 3 seconds). α represents desirableness factor which depends on location of node N with respect to virtual vector from node M to destination node (sink). R_{tx} is the transmission range of the previous hop. While, $|MN|$ is the distance between two nodes. v_{sound} is the speed of the acoustic signal which is given by,

$$\begin{aligned} c = {} & 1448.96 + 4.591T_o - 5.304 \times 10^{-2}T_o^2 \\ & + 2.374 \times 10^{-4}T_o^3 + 1.34(S - 35) \\ & + 1.63\times10^{-2}D_p + 1.675\times10^{-7}D_p \\ & + 1.025\times10^{-2}T_o(S - 35) - 7.139\times10^{-3}T_oD_p^3 \end{aligned} \tag{7}$$

where, T_o, D_p and S represent, temperature in Celsius, depth in meters and salinity in parts per thousand. It is evident from Eq. (6) that holding time of AHH-VBF mainly depends on distance from virtual vector and distance from source node M. It does not explicitly reduce the end-to-end delay of the data packet. Logically, a data packet which has traversed h_{tr} hops already, should be on hold for a very short time. Reducing holding time hop by hop reduces end-to-end delay. Thus, we incorporate the number of hops traversed by a data packet in Eq. (8) as follows:

$$H_{time} = \left[\frac{1}{h_{tr}} \times (\frac{1}{2}\alpha T_{max})\right] + \left[\frac{(R_{tx} - |MN|)}{v_{sound}}\right]. \tag{8}$$

To improve the packet delivery ratio, we give priority to node with maximum number of neighbors. Because, the probability that any of the neighbors have a route to sink is high when number of neighbors are more. Hence, we incorporate the number of neighbors of a node into Eq. (8) as follows:

$$H_{time} = \left[\frac{1}{h_{tr} + n_b} \times (\frac{1}{2}\alpha T_{max})\right] + \left[\frac{(R_{tx} - |MN|)}{v_{sound}}\right] \quad (9)$$

where n_b denotes number of neighbors of a node which calculates holding time using Eq. (9). h_{tr} is number of hops the packet has already traversed.

B. THE CoAVN-AHH-VBF

Network initialization phase in $CoAVN - AHH - VBF$ is the same as in $AVN - AHH - VBF$ (see section IV-A).

1) NEXT HOP SELECTION

When a node generates a data packet, it first checks its neighbor table. If there are only two neighbors available, first one being a void node and other only connected to one neighbor. Moreover, it assumes that neighbor node with only one neighbor is considering the neighbor as a void node, thus, it defers its transmission.

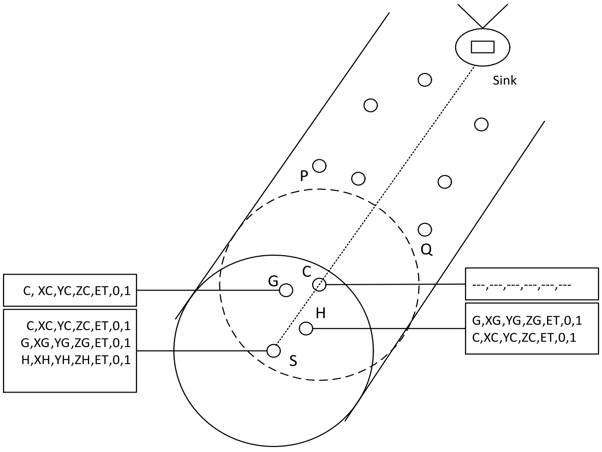


FIGURE 8. **Avoiding void holes with neighbor table.**

Consider the case shown in Fig. 8, node S has 3 neighbors C, G and H. Since the farthest one is C which is void, all nodes in its vicinity do not count this node as a neighbor when updating number of neighbor entry in the packet. In this way, the packet is not forwarded to a void region. To transmit the data packet, either two non void nodes must be available or at least one neighbor with two neighbors in its neighbor table. If two or more non void nodes are available, node computes values for every neighbor according to Eq. (9), and all values are sorted in ascending order. Among the first two values, node with the minimum Euclidean distance to the sink is selected as next hop, whereas other one is selected as a relay node. If only one node with more than two neighbors is available in the list, IDs and coordinates of both nodes are inserted in the header of the data packet. Soon after, the packet is transmitted with power required to deliver the data packet to the next hop node. With the help of adaptive power allocation, energy of sensor node is used efficiently.

2) COOPERATIVE FORWARDING

Whenever, node receives the data packet from any other node, it first checks entries, ID of the next hop and ID of relay node in the header. If first one matches with the ID of node itself then the node further processes data packet and checks BER for the received packet. If value of BER is less than predefined threshold, packet is forwarded without any further delay as described in IV-B.1. This instant forwarding without any delay plays a considerable role in reducing end-to-end delay. If node's ID matches with the relay ID, holding time is computed via Eq. (9) for the packet, and it is placed in Q. If next hop node of previous hop broadcasts (forwards) packet with same ID, packet at relay is dropped. If BER at destination is greater than pre-defined threshold, destination node sends retransmission request packet (RRP) to inform relay node to retransmit the data packet. After receiving RRP, relay node removes the data packet from Q, places address of next hop in the data packet's header and places 0 in the field of relay ID. With the help of this 0, all other nodes perceive that retransmission is complete, thus, they drop the packet instantly. Considering the case when only one non-void neighbor is available at time of sending, source ID and relay ID in the header are equal. This improves packet delivery ratio in spare networks. Because, in case of high BER at destination node, source node will retransmit the data packet.

3) SUPPRESSION OF REDUNDANT TRANSMISSIONS

Whenever a node receives a data packet, it drops the packet without further transmission in cases mentioned below. Firstly, it extracts source ID and destination ID. If ID of node itself matches neither with forwarding nor with relay node ID in the header, packet is immediately dropped. This as a result, avoids transmission of same data packet from multiple nodes. Secondly, packet is dropped when relay node overhears same data packet from forwarder node during holding time. Thirdly, if BER (after MRC) at forwarder node after retransmission is more than threshold.

V. HOLDING TIME ANALYSIS

To verify dependency of Eq. (9) on the number of neighbors and the number of hops traversed, we investigate both Eq. (6) and Eq. (9) under different scenarios.

A. IMPACT OF THE NUMBER OF HOPS

We analyze the effect of h_{tr} on holding time at different values of distance in Fig. 9, and we keep other parameters constant. High value of $|R_{tx} - MN|$ means that node is closer to the source node and vice versa. Each curve in the subplots is for different values of (n_b). Observing all subplots in Fig. 9, we conclude that node at the edge of the transmission range of previous hop node have the least holding time. Furthermore, in all subplots of Fig. 9, we can observe that at any value

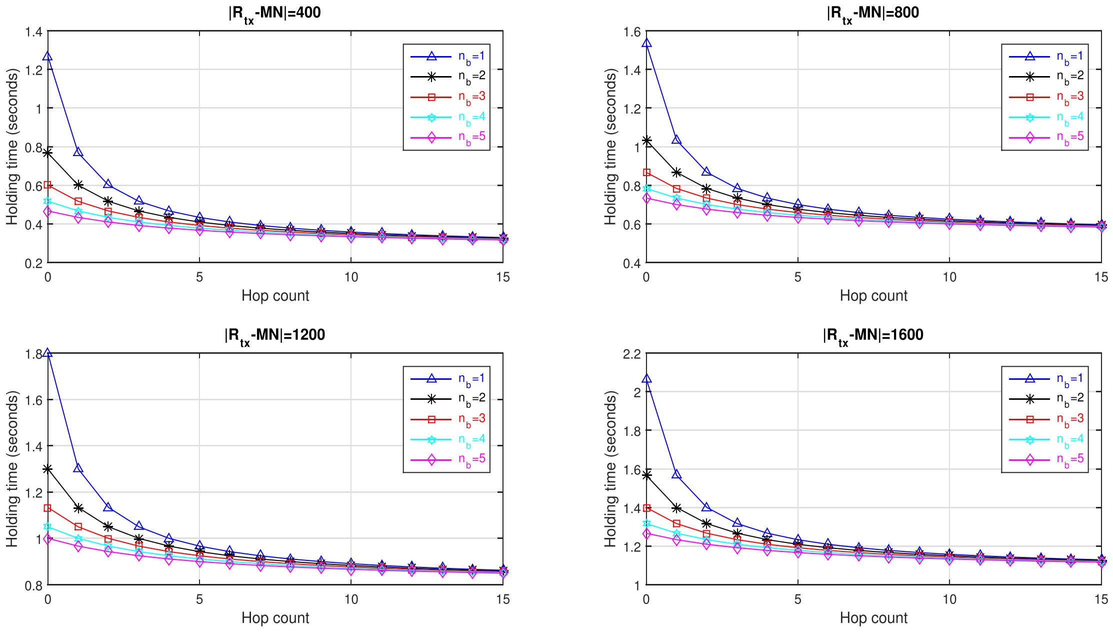


FIGURE 9. **Holding time varying hop count at different values of $|R_{tx} - MN|$.**

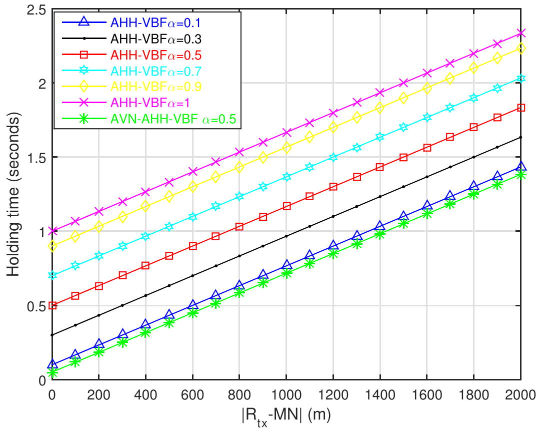


FIGURE 10. **Holding time comparison varying $|R_{tx} - MN|$.**

of $|R_{tx} - MN|$, node with a large number of neighbors has a reduced holding time. Holding time is maximum when nodes have only one neighbor ($n_b = 1$). Holding value decreases at each hop as the number of hops are increased, even if all the other parameters are kept constant. Hence overall minimum value of holding time is obtained when: (i) network is dense, (ii) the packet traverses a greater number of hops, or (iii) α is minimum.

B. IMPACT OF DISTANCE

Fig. 10, compares Eq. (6) with our proposed Eq. (9). We plot Eq. (6) for different values of α. For our new holding time equation, we take $\alpha = 0.5$ and number of hops and neighbor value is 5. On the horizontal axis $|R_{tx} - MN|$ is the difference of transmission range of previous hop and Euclidean distance between current and previous hops. It can be seen clearly that our proposed scheme AVN-AHH-VBF has very low holding time as compared to AHH-VBF. Even at the minimum value of $\alpha = 0.1$ for AHH-VBF, our scheme AVN-AHH-VBF with $\alpha = 0.5$, outperforms the existing technique.

VI. SIMULATION RESULTS

In order to evaluate our proposed AVN-AHH-VBF and CoAVN-AHH-VBF techniques, we compare them with the $AHH - VBF$ technique. We vary the number of nodes in the network from 150 to 600. Nodes are randomly deployed in a three dimensional network of volume $10km \times 10km \times 10km$. Value of α is varied between $0 - 1$. T_{max} is 2 sec. Sink node is placed at coordinates X= 5000, Y = 5000, Z= 0. Size of the data packet is 111 bytes, size of the NRP is 66 bits and that of NAP is 114 bits. Maximum data rate is $16kbps$. 90 $dB\ re\ \mu\ Pa$ is maximum transmission power. Receiving power threshold is 10 $dB\ re\ \mu\ Pa$. BER threshold is 0.5. For each network size simulation results are run over 40 times with randomly generated topology in each simulation. Then the average is plotted for each metric.

In the simulations, we consider the following performance metrics. The simulation parameters are given in Table. 2.

1) End-to-end delay
   Time required for a data packet from the source node to reach the sink node. It is given by,

$$E2ED = D_{prop} + D_{tran} + D_{proc} + H_{time} \qquad (10)$$

where D_{prop} can be expressed as,

$$D_{prop} = \frac{Propagateddistance}{v_{sound}}. \qquad (11)$$

TABLE 2. **Simulation parameters.**

Parameters	Values
Total number of nodes	150 - 600
Node deployment	random
Number of sinks	1
Coordinates of sink	(5000,5000,0m)
Network dimension	10 km x 10 km x 10 km
Maximum transmission range	2 km
Transmitting power	90 dB re μ Pa
Receiving power	10 dB re μ Pa
Data rate	16 kbps
BER threshold	0.50
Data packet size	888 bits

Where D_{tran} is,

$$D_{tran} = \frac{\text{Size of the data packet}}{\text{Transmission rate}} \tag{12}$$

2) Energy tax per received packet (ETR)
The average energy consumed by a node in the network on a packet which has been received at the sink successfully.
3) Energy tax per dropped packet (ETD)
The average energy consumed by a node in the network on a packet which has been dropped during its journey.
4) Delivery ratio (DR)
Ratio of packets received at sink to packet sent by the source node.

$$DR = \frac{\text{Total DPs received at sink}}{\text{Total DPs sent by all source nodes}} \tag{13}$$

5) Propagation deviation factor (PDF)
The ratio of difference of all propagation distance travelled by a packet from the source to the destination and Euclidean distance with sink to the Euclidean distance from source node. Mathematical expression for it is as follows:

$$PDF = \frac{T_{pd} - d_{ec}}{d_{ec}} \tag{14}$$

where T_{pd} is the total propagation distance and d_{ec} is Euclidean distance of the node with respect to the sink.

A. DISCUSSION OF SIMULATION RESULTS

Fig. 11 shows that proposed schemes AVN-AHH-VBF and AVN-AHH-VBF-B have minimum $E2ED$ due to the efficient holding time calculation by using Eq. (9). When node density is low in the network, difference of $E2ED$ between proposed schemes AVN-AHH-VBF, AVN-AHH-VBF-B and counterpart techniques AHH-VBF and AHH-VBF-B is large. The major reasons behind this difference are as follows; in sparse networks, propagation distance between source and destination is large which also increases $E2ED$. For schemes AHH-VBF and AHH-VBF-B, this long propagation delay adds up with inefficient and large holding times (H_t) resulting large E2ED. Whereas, for proposed schemes AVN-AHH-VBF and AVN-AHH-VBF-B, efficient H_t calculation compensates delay incurred by large propagation of the data packet. However, when node density is high, difference in delay is less. This is due to the large neighbors available to the virtual vectors. resulting in small H_t at these nodes with decreased E2ED.

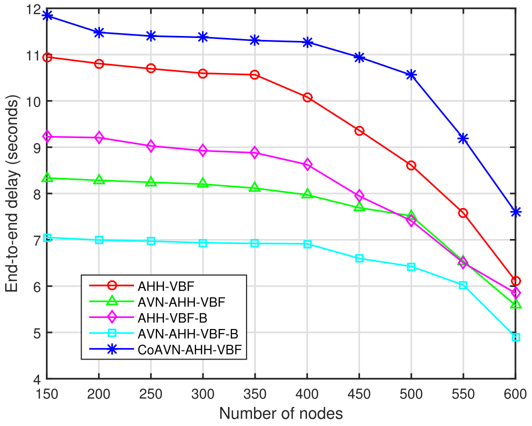


FIGURE 11. **End-to-end delay comparison.**

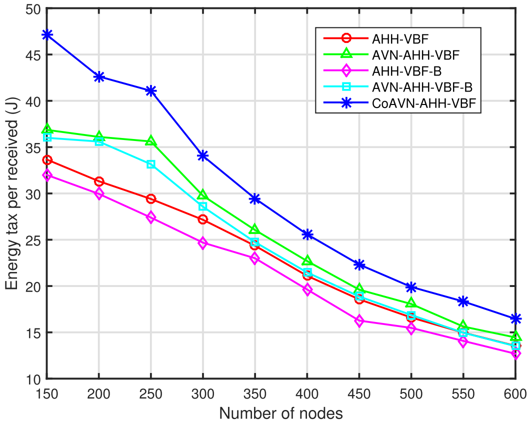


FIGURE 12. **Comparison of average energy per received packet.**

For proposed schemes AVN-AHH-VBF and AVN-AHH-VBF-B, in a dense network, a packet travels through more hops as compared to AHH-VBF and AHH-VBF-B. That is why, in such scenarios E2ED of non-cooperative schemes are almost the same.

It can be seen from Fig. 11, cooperative scheme CoAVN-AHH-VBF has a larger delay as compared to the non-cooperative schemes. Obviously, this trend is because of retransmissions of the data packet. Whether the network is sparse or dense, retransmissions take place whenever BER value is greater than the predefined value. Moreover, retransmission delay increases E2ED and propagation delay from relay to destination and H_t at relay is also added.

ETR comparison of all schemes in Fig. 12 shows that, AHH-VBF and AHH-VBF-B have minimum energy consumption. Since, in these schemes the node with the

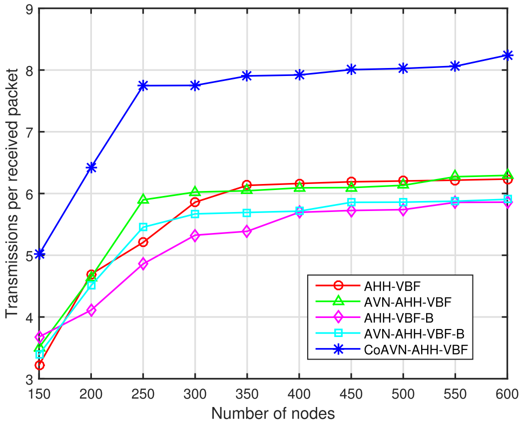


FIGURE 13. **Per packet transmissions comparison.**

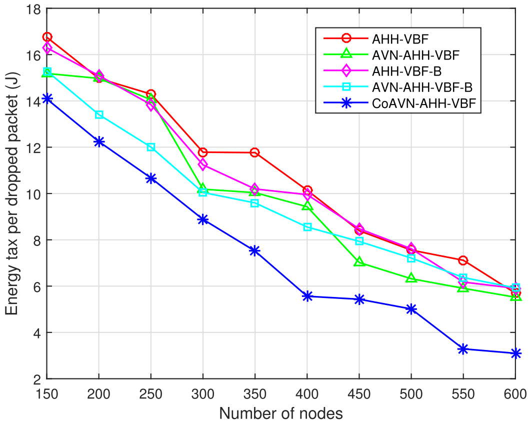


FIGURE 14. **Energy waste comparison.**

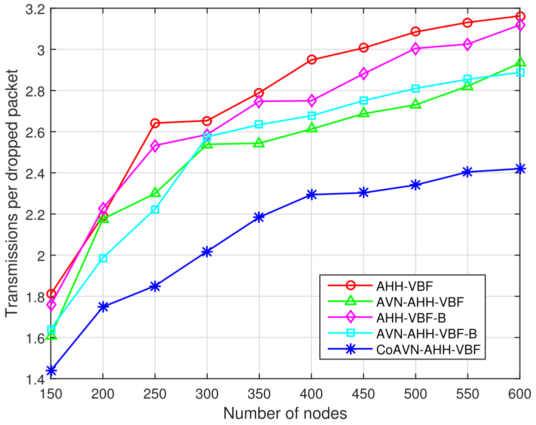


FIGURE 15. **Transmissions on dropped packet comparison.**

minimum value for Eq. (6) forwards the data packet. There is no consideration of number of neighbors and number of hop counts (traversed) in h_{tr}. On the contrary, in AVN-AHH-VBF and AVN-AHH-VBF-B, forwarding is based on the value of H_t calculated by Eq. (9) which also considers the number of traversed hops and number of neighbors. Due to this reason, the routing path from source node to destination (sink) is changed as compared to AHH-VBF and AHH-VBF-B schemes. This new forwarding criterion may result in a longer path (with more hops) towards the sink. From Fig. 13, it is clear that the average transmissions per successful packet are more for AVN-AHH-VBF and AVN-AHH-VBF-B as compared to the counterpart techniques AHH-VBF and AHH-VBF-B, respectively.

CoAVN-AHH-VBF consumes high energy per received packet as compared to the non-cooperative schemes because the packet is transmitted multiple times as compared to the non cooperative schemes. It can be seen clearly that the difference in energy consumption is more in sparse conditions. When network is sparse, distance between nodes is large and the value of SNR is low which in turn, increases BER. That is why, in such sparse network, number of retransmissions are more which ultimately increases energy consumption in the network. On the other hand, with number of nodes increasing in the network, SNR value at receiver is maximum due to shorter distance between nodes. This gives minimum BER which in turn avoids retransmissions. Less number of retransmissions leads to decreased energy consumption in CoAVN-AHH-VBF.

Fig. 14 shows comparison of proposed and existing schemes in terms of ETD in the network. Clearly, CoAVN-AHH-VBF performs better than others schemes under this metric. Though, AVN-AHH-VBF has one hop avoidance of void holes, but does not have any proper mechanism like the mechanisms in CoAVN-AHH-VBF. Fig. 14 shows predecessor technique due to which AHH-VBF wastes energy on every dropped packet because it does not have any void region avoidance mechanism. CoAVN-AHH-VBF uses void region avoidance technique to minimize the number of transmissions on every dropped packet in the network than all other techniques. This trend can be seen in Fig. 15 too. If we either eliminate cooperative routing or decrease BER, the number of retransmissions will be further decreased but at the cost of drastic decrease in DR.

As depicted in Fig. 16, our proposed scheme AVN-AHH-VBF outperforms its counterpart technique AHH-VBF in both scenarios; (*i*) when data is dropped on SNR basis and (*ii*) when BER based implementation is done for both schemes. In AHH-VBF and AVN-AHH-VBF, packet is accepted when the SNR meets the minimum threshold, thus successful delivery is more for these two schemes. In actual implementation of protocol in underwater harsh environment, only SNR does not ensure reliability at receiver. Thus, BER is implemented for both schemes. We see that DR of AHH-VBF-B is less than AHH-VBF. Similar trend can be seen for AVN-AHH-VBF scheme. It is obvious from Fig. 16 that AVN-AHH-VBF outperforms AHH-VBF. In the same manner, DR of AVN-AHH-VBF-B is more than AHH-VBF-B because of efficient forwarder selection in AVN-AHH-VBF-B. CoAVN-AHH-VBF outperforms all the other techniques whenever a data packet is dropped because of the BER threshold but CoAVN-AHH-VBF relay retransmits the same

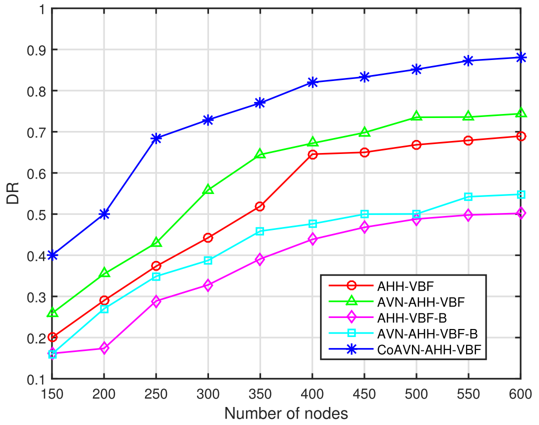


FIGURE 16. DR comparison of both schemes.

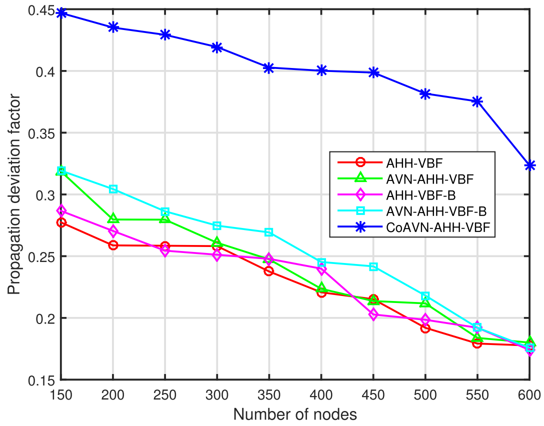


FIGURE 17. Comparing propagation deviation factor.

data packet. Thus, the packet is not dropped when threshold does not meet minimum threshold for BER. We observe from Fig. 16 that due to cooperation, high DR is achieved even at low node densities.

Fig. 17 shows the comparison of all schemes in terms of PDF. It can be seen that PDF of both schemes AVN-AHH-VBF and AVN-AHH-VBF is larger than AHH-VBF and AHH-VBF-B. These results validate the correctness of our modification in the holding time equation. A forwarder of the data packet can be selected with a farther location from the virtual vector between source and the sink. Thus, the impact of Eq. (9) on each hop results in extra deviation of the data packets from path along the virtual vector. In case of CoAVN-AHH-VBF, due to retransmissions from the relay, distance from source to destination is added in T_{pd} for a data packet. Also, distance from source to relay and relay to destination is added in T_{pd} in case of retransmission from relay. Because of this strategy, CoAVN-AHH-VBF has higher PDF in sparse and also in dense scenarios. However, PDF for CoAVN-AHH-VBF starts decreasing when density of the nodes in the network is increased. Since dense networks have more neighbors available to each source node, relay is selected near the virtual vector. In such cases, packet's deviation is minimum even when there is retransmissions from relay. Hence, PDF value is lower for CoAVN-AHH-VBF when node density is high.

TABLE 3. Performance trade-offs made by the protocols.

Protocol	Achieved parameter	Figure	Compromised parameter	Figure
AHH-VBF	ETR	Figure 12	DR	Figure 16
AHH-VBF	ETR	Figure 12	E2E delay	Figure 11
AVN-AHH-VBF	E2E delay	Figure 11	PDF	Figure 17
AVN-AHH-VBF	E2E delay	Figure 11	DR	Figure 16
CoAVN-AHH-VBF	DR	Figure 16	ETR	Figure 12
CoAVN-AHH-VBF	DR	Figure 16	E2E delay	Figure 11
CoAVN-AHH-VBF	DR	Figure 16	PDF	Figure 17
CoAVN-AHH-VBF	ETD	Figure 14	ETR	Figure 12
AHH-VBF	PDF	Figure 17	DR	Figure 16

B. PERFORMANCE TRADE-OFFS

A summary of the trade-offs made by our proposed and selected existing protocols is given in table 3. Proposed scheme AVN-AHH-VBF, minimizes holding time at the cost of PDF. Holding time Eq. (9) varies when the number of neighbors are varied, thus, neighbors located far from the virtual vector can forward data packets because node near the virtual vector may not have enough neighbors. The aforementioned strategy, in turn, deviates data packets from original path slightly as shown in Fig. 17. E2ED is directly proportional to holding time that is why, AVN-AHH-VBF pays cost in terms of PDF to achieve E2ED. In AHH-VBF, data packets do not deviate from the path, so they move towards sink along the virtual vector. As a result, data packets are forwarded on each hop towards sink even when there is a void node near the sink. Hence, large amounts of energy is wasted on a data packet (dropped by a void node) from source node till the void node. CoAVN-AHH-VBF achieves good DR at the cost of more energy consumption and E2ED. There are also retransmissions from relays when BER threshold is not met. Thus, number of retransmissions are high for each received packet.

VII. CONCLUSION

In this work, we have proposed two new schemes for underwater wireless sensor networks (UWSNs): avoiding void node adaptive hop-by-hop vector based forwarding (AVN-AHH-VBF) and cooperation based CoAVN-AHH-VBF (CoAVN-AHH-VBF). More specifically, this paper contributed in three aspects: energy efficient forwarder selection while avoiding void regions in the network, proper holding time calculation, and bit error rate BER minimization. Our forwarder selection technique resulted in high delivery ratio (DR) even in sparse network conditions. The holding time is minimized per successful packet by using our formulated Eq. (9). Simulation results show that both schemes are efficient in terms of energy consumption cost per dropped packet, delay and DR. Though, the energy expenditure of CoAVN-AHH-VBF is relative per received packet, this has been compensated by saving energy on every dropped packet.

The proposed non-cooperative scheme is relatively efficient in terms of delay and energy expenditure, and the proposed cooperative scheme is relatively efficient in terms of energy expenditure and DR.

REFERENCES

[1] E. Felemban, F. K. Shaikh, U. M. Qureshi, A. A. Sheikh, and S. B. Qaisar, ''Underwater sensor network applications: A comprehensive survey,'' *Int. J. Distrib. Sensor Netw.*, vol. 2015, Sep. 2015, Art. no. 896832.

[2] R. W. Coutinho, A. Boukerche, L. F. Vieira, and A. A. Loureiro, ''Geographic and opportunistic routing for underwater sensor networks,'' *IEEE Trans. Comput.*, vol. 65, no. 2, pp. 548–561, Feb. 2016.

[3] K. Latif, N. Javaid, A. Ahmad, Z. A. Khan, N. Alrajeh, and M. I. Khan, ''On energy hole and coverage hole avoidance in underwater wireless sensor networks,'' *IEEE Sensors J.*, vol. 16, no. 11, pp. 4431–4442, Jun. 2016.

[4] S. Ahmed *et al.*, ''Co-UWSN: Cooperative energy-efficient protocol for underwater WSNs,'' *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 4, Sep. 2015, Art. no. 891410.

[5] P. Xie, J. Cui, and L. Lao, ''VBF: Vector-based forwarding protocol for underwater sensor networks,'' in *Proc. Int. Conf. Res. Netw.*, 2006, pp. 1216–1221.

[6] N. Sun, G. Han, T. Wu, J. Jiang, and L. Shu, ''A reliable and energy efficient VBF-improved cross-layer protocol for underwater acoustic sensor network,'' in *Proc. 11th Int. Conf. Heterogeneous Netw. Quality Rel.*, Sep. 2015, pp. 44–49.

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

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

[9] T. Hafeez, N. Javaid, A. R. Hameed, A. Sher, Z. A. Khan, and U. Qasim, ''AVN-AHH-VBF: Avoiding void node with adaptive hop-by-hop vector based forwarding for underwater wireless sensor networks,'' in *Proc. 10th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput. (IMIS)*, Fukuoka, Japan, Sep. 2016, pp. 49–56, doi: 10.1109/IMIS.2016.131.

[10] A. Wahid, S. Lee, H.-J. Jeong, and D. Kim, ''Eedbr: Energy-efficient depth-based routing protocol for underwater wireless sensor networks,'' in *Proc. Adv. Comput. Sci. Informat. Technol.*, Sep. 2011, pp. 223–234.

[11] J. Khan and H. Cho, ''A distributed data-gathering protocol using AUV in underwater sensor networks,'' *Sensors*, vol. 15, no. 8, pp. 19331–19350, Sep. 2015.

[12] A. Wahid and K. Dongkyun, ''Analyzing routing protocols for underwater wireless sensor networks,'' *Int. J. Commun. Netw. Inf. Secur.*, vol. 2, no. 3, p. 253, 2010.

[13] K. Hao, Z. Jin, H. Shen, and Y. Wang, ''An efficient and reliable geographic routing protocol based on partial network coding for underwater sensor networks,'' *Sensors*, vol. 15, no. 6, pp. 12720–12735, 2015.

[14] 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, Sep. 2015.

[15] H. Yu, N. Yao, T. Wang, G. Li, Z. Gao, and G. Tan, ''WDFAD-DBR: Weighting depth and forwarding area division DBR routing protocol for UASNs,'' *Ad Hoc Netw.*, vol. 37, pp. 256–282, Sep. 2016.

[16] N. Javaid *et al.*, ''Delay-sensitive routing schemes for underwater acoustic sensor networks,'' *Int. J. Distrib. Sensor Netw.*, vol. 11, Mar. 2015, Art. no. 532676.

[17] N. Nowsheen, G. Karmakar, and J. Kamruzzaman, ''An adaptive approach to opportunistic data forwarding in underwater acoustic sensor networks,'' in *Proc. IEEE 13th Int. Symp. Netw. Comput. Appl. (NCA)*, Apr. 2014, pp. 229–236.

[18] T. Ali, L. T. Jung, and I. Faye, ''End-to-end delay and energy efficient routing protocol for underwater wireless sensor networks,'' *Wireless Pers. Commun.*, vol. 79, no. 1, pp. 339–361, Nov. 2014.

[19] W. Bai, H. Wang, X. Shen, R. Zhao, and Y. Zhang, ''Minimum delay multipath routing based on TDMA for underwater acoustic sensor network,'' *Int. J. Distrib. Sensor Netw.*, vol. 2016, Apr. 2016, Art. no. 1394340.

[20] M. Akbar, N. Javaid, A. H. Khan, M. Imran, M. Shoaib, and A. Vasilakos, ''Efficient data gathering in 3D linear underwater wireless sensor networks using sink mobility,'' *Sensors*, vol. 16, Sep. 2016, Art. no. 404.

[21] Z. Li, N. Yao, and Q. Gao, ''Relative distance based forwarding protocol for underwater wireless networks,'' *Int. J. Distrib. Sensor Netw.*, vol. 2014, Mar. 2014, Art. no. 173089.

[22] M. Ayaz and A. Abdullah, ''Hop-by-hop dynamic addressing based (H2-DAB) routing protocol for underwater wireless sensor networks,'' in *Proc. IEEE Int. Conf. Inf. Multimedia Technol. (ICIMT)*, Sep. 2009, pp. 436–441.

[23] S. Yoon, A. K. Azad, H. Oh, and S. Kim, ''AURP: An AUV-aided underwater routing protocol for underwater acoustic sensor networks,'' *Sensors*, vol. 12, no. 2, pp. 1827–1845, 2012.

[24] Y.-W. Hong and A. Scaglione, ''Energy-efficient broadcasting with cooperative transmissions in wireless sensor networks,'' *IEEE Trans. Wireless Commun.*, vol. 5, no. 10, pp. 2844–2855, Oct. 2006.

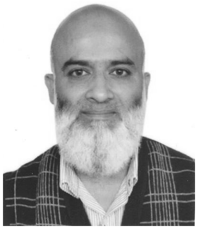
[25] J. Habibi, A. Ghrayeb, and A. G. Aghdam, ''Energy-efficient cooperative routing in wireless sensor networks: A mixed-integer optimization framework and explicit solution,'' *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3424–3437, Aug. 2013.

[26] A. uz Zaman and H. Y. Kong, ''Energy efficient cooperative LEACH protocol for wireless sensor networks,'' *J. Commun. Netw.*, vol. 12, no. 4, pp. 358–365, Aug. 2010.

[27] F. Mansourkiaie and M. H. Ahmed, ''Optimal and near-optimal cooperative routing and power allocation for collision minimization in wireless sensor networks,'' *IEEE Sensors J.*, vol. 16, no. 5, pp. 1398–1411, Mar. 2016.

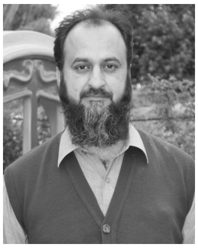
[28] M. Stojanovic, ''On the relationship between capacity and distance in an underwater acoustic communication channel,'' *ACM SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 11, no. 4, pp. 34–43, 2007.

[29] K. El-Darymli, ''Amplify-and-forward cooperative relaying for a linear wireless sensor network,'' in *Proc. IEEE Int. Conf. Syst. Man (SMC)*, Oct. 2010, pp. 106–112.



NADEEM JAVAID (S'08–M'11–SM'16) received the master's degree in electronics from Quid-I-Azam University, Islamabad, Pakistan, in 1999, and the Ph.D. degree from the University of Paris-Est, France, in 2010. He has supervised seven Ph.D. and 70 M.S. theses. He is currently an Associate Professor, and the founding Head of the ComSens (Communications over Sensors) Research Group with the Department of Computer Science, COMSATS Institute of Information Technology, Islamabad. He has authored or co-authored 450+ papers in technical journals and international conferences. His research interests include wireless ad-hoc networks, wireless sensor networks, and energy optimization in smart grids.

TAIMUR HAFEEZ received the B.S. degree in telecommunication and networking from the Department of Computer Science, COMSATS Institute of Information Technology, Islamabad, Pakistan, in 2016, under the supervision of N. Javaid. He is currently pursuing the M.S. degree in information and technology with the National University of Sciences and Technology, Islamabad. His research interests include wireless networking; especially underwater acoustic communication, datacenter networking, and software-defined networks.



ZAHID WADUD received the B.Sc. degree in electrical engineering and the M.Sc. degree in computer information system engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 1999 and 2003, respectively. He is currently pursuing the Ph.D. degree with the Capital University of Science and Technology, Islamabad, under the supervision of N. Javaid. He is also an Assistant Professor with the Department of Computer System Engineering, University of Engineering and Technology. His research interests include wireless sensor network, energy efficient networks and subsystems, mathematical modeling of wireless channels, embedded systems and sensors interface.

NABIL ALRAJEH received the Ph.D. degree in biomedical informatics engineering from Vanderbilt University, USA. He was a Senior Advisor for the Ministry of Higher Education, where he was involved in implementing development programs, including educational affairs, health information Systems, strategic planning, and research and innovation. He is currently a Professor of Health Informatics with the Biomedical Technology Department, King Saud University. His research interests include E-health applications, hospital information systems, telemedicine, intelligent tutoring systems, energy management in smart grids, and wireless sensor networks.

MOHAMAD SOUHEIL ALABED is currently an Associate Professor with the Biomedical Technology Department, College of Applied Medical Sciences, King Saud University, Riyadh, Saudi Arabia.

NADRA GUIZANI is currently pursuing the Ph.D. degree from Purdue University. Her thesis was in Prediction and Access Control of Disease Spread Data on Dynamic Network Topologies. She is a Graduate Lecturer with Purdue University. Her research interests include machine learning, mobile networking, large data analysis and prediction techniques. She is Active Member in both the Women in Engineering Program and the Computing Research Association for Women.

• • •