Adaptive hop-by-hop cone vector-based forwarding protocol for underwater wireless sensor networks

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Abstract
In the recent past, a significant increase has been observed in the use of underwater wireless sensor networks for aquatic applications. However, underwater wireless sensor networks face several challenges including large propagation delays, high mobility, limited bandwidth, three-dimensional deployments, expensive manufacturing, and energy constraints. It is crucial for underwater wireless sensor networks to mitigate all these limitations primarily caused by the harsh underwater environment. To address some of the pertinent challenges, adaptive hop-by-hop cone vector-based forwarding routing protocol is proposed in this article which is based on the adaptive hop-by-hop vector-based forwarding. The novelty of adaptive hop-by-hop cone vector-based forwarding includes increasing the transmission reliability in sparse sensor regions by changing the base angle of the cone according to the network structure. The number of duplicate packets and end-to-end delay is also reduced because of the reduced base angle and a smart selection criterion for the potential forwarder node. The proposed routing protocol adaptively tunes the height and opening of the cone based on the network structure to effectively improve the performance of the network. Conclusively, this approach significantly reduces energy tax, end-to-end delay, and packet delivery ratio.

Keywords
Underwater wireless sensor networks, conic potential forwarding nodes, packet delivery ratio, end-to-end delay

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Introduction
Underwater wireless sensor networks (UWSNs) are a robust application of the wireless sensor networks (WSNs) that are mainly used for examining the oceanic environment. UWSNs have many applications, for example, pollution examining, mines exploration,1 and coastline protection, as shown in Figure 1.2

The acoustic sensors collect the data and use a routing scheme to relay it toward the sink. The basic architecture of a UWSN consists of acoustic wireless sensors with one or more sinks that are deployed on the sea surface or underwater, as shown in Figure 2. Unlike sink nodes, the sensor nodes suffer from the limitation of energy along with other constraints.3 The role of the
sink on a sea surface is to collect information and forward it through radio links to the fusion centers for further processing. Sinks are equipped with sound and radio modems along with GPS modules. The communication means used for UWSNs are entirely different from the terrestrial WSNs. Radio frequencies cannot be used for signaling as they are significantly attenuated in water. However, these frequencies can still be utilized for the link between surface-deployed sinks and offshore station(s) as they offer attractive features like low bit error rate, reliability, and significant bandwidth. Using optical signals for communication in UWSNs is also not feasible due to the reason that it needs an accurate line of sight among the nodes. However, because of the dynamicity of the underwater channel, the nodes are hardly placed at the line of sight all the time, frequently altering the optical link. Therefore, using acoustic signals instead is the most feasible and widely adopted method in UWSNs. The effect of the channel is less severe on these signals as compared to the electromagnetic and optical waves. Despite the feasibility of the acoustic signal in the underwater environment, it faces intrinsic challenges that include low propagation speed (1500 m/s), multi-path fading, and high bit error rate varying at different depths.

Several routing schemes have been designed for UWSNs, for example, vector-based\(^4\) and depth-based.\(^5\) However, various associated issues with such schemes have been pointed out by subsequent research. One of the main issues in vector-based routing schemes is the redundant transmissions of packets. For resolving this issue, the holding time mechanism is proposed in the adaptive hop-by-hop vector-based forwarding (AHH-VBF)\(^6\) scheme that considers various parameters to estimate the packet’s holding time. In addition, the potential forwarding node is selected by considering the distances from sink, virtual vector, and source node. Such distance calculation in this scheme helps to reduce the end-to-end delay (E2ED); however, the duplicate packets are not reduced which results in high energy consumption.

**Contributions**

In this article, we address the issue of duplicate packet transmission in AHH-VBF by proposing a new protocol called adaptive hop-by-hop cone vector-based forwarding (AHHC-VBF), where we divide the hemispheric forwarding region into smaller portions. These smaller portions are called conic forwarding regions and only the nodes inside these regions are able to forward a particular packet. Due to the smaller forwarding region, a lower number of duplicate packets are transmitted due to which the total energy consumption is lower. In particular, the following are the main contributions of our work:

1. We have performed an in-depth investigation of the limitations of AHH-VBF protocol;
2. We have proposed a new protocol, AHHC-VBF, to increase the transmission reliability in sparse sensor regions in UWSNs by selecting the optimized route for packet transmission via constructing a cone type directional structure;
3. Our proposed scheme increases energy efficiency by selecting the appropriate height/opening of the cone to adjust the optimal transmission power of a node;
4. We introduce a new parameter “desirableness factor” in the previous scheme (AHH-VBF) to
assign priorities to conic potential forwarding nodes (CPFNs);
5. Our proposed protocol addresses the void hole and traffic congestion problem by adjusting the base angle of the cone based on the neighbor’s information;
6. Our proposed protocol reduces the duplicate packets as well as energy consumption with the help of holding time calculation which makes the node having the least number of forwarders forward the packet;
7. We have performed an extensive evaluation of our proposed scheme to measure the performance of the network in terms of packet delivery ratio (PDR), ETX, energy consumption, E2ED, and accumulated propagation distance (APD).

The remaining article is organized into the following sections. The related work is described in section “Related work.” Section “Channel model” describes the channel model and preliminaries (basic terminologies used in the article). Section “Proposed approach (AHHC-VBF protocol)” describes our proposed approach of AHHC-VBF including the method of finding CPFNs, holding time calculations, desirability factor, and various types of packets. Section “Experimental setup” describes the experimental setup for our simulations. The results and discussions are provided in section “Results and discussions,” where a detailed performance comparison of our proposed AHHC-VBF protocol with the AHH-VBF is performed. Finally, section “Conclusion and future work” concludes our work and gives future recommendations.

**Related work**

The existing protocols proposed for UWSNs are described in this section. Several routing strategies are proposed including vector-based,4,7,8 depth-based,5,9-11 cluster based,12,13 and AUV-based,14-16 as summarized in Table 1.

Networking in UWSNs is the facilitation of technology for various applications inside water. There exist many applications of UWSNs, for example, oceanographic data gathering, pollution monitoring, strategic surveillance applications, disaster management and control, ocean exposure, and offshore surveying. We have classified the previous work into the following segments: the research challenges, a brief survey of the UWSNs routing protocols, energy-efficient routing protocols, depth-based routing protocols, and location-based routing protocols. Akyildiz et al.17 describe various research challenges in UWSNs including several central aspects of underwater acoustic communication, that is:

- Different architectures of UWSNs for two- and three-dimensional scenarios;
- Cross-layer method and channel characteristics;
- Network topology and valuable cost of devices for UWSNs;
- Comparison of terrestrial sensor networks and UWSNs.

With the expansion of the research in UWSNs, researchers also recognize the more prominent issues in this field, for example, large propagation delay, repeated loss of connectivity during communication, control on energy sources causing the damage of the whole network, and low communication bandwidth.

Jornet et al.18 presented a protocol for increasing the network’s lifetime and reducing the consumption of energy. The protocol is named as focused beam routing (FBR) protocol, and it uses a continuous power level instead of the variable for constraining the flooding. This protocol utilizes the location information to forward packets, that is, the location of sensor nodes and the destinations. The duplicate packets and flooding are reduced; however, more duplicate packets result in increasing the E2ED.

Another protocol, called directional flooding-based routing (DFR), for reducing energy consumption is proposed by Hwang and Kim.19 This protocol is based on the approach of bounding the flooding region with the base angle several nodes, that is, source and destination nodes as well at the node which forwarded the packet previously. The base angle is determined by the node’s density and the link. However, the current angle is based on the source and destination. When a packet is broadcasted by the source node, it is received only by
the nodes lying in the range of the base angle while rejected by the ones lying outside the range. This protocol results in lower energy consumption; however, a higher power level is used. Also, finding the potential forwarding nodes is difficult in a sparse network and may result in void hole.

Dhongdi et al.\textsuperscript{20} discuss energy efficiency, sources of energy, constraint, and the routing protocol in detail. They describe several harvesters that produce energy from various sources via different harvesting devices to convert electrical and mechanical energy into energy for powering the sensors. In addition, the different routing paths used by the sensors for carrying their data to the destination result in higher energy consumption. The protocols using the most prominent paths are the ones with compromised energy. Rani et al.\textsuperscript{21} reviewed different types of routing protocols and classified them in accordance to their routing strategy and characteristics. The classification is based on the technique on which the UWSN routing protocol is established. These classifications are as follows: algorithm based, and cross- and non-cross-layer policy

| Protocol | Strategy | Advantage | Flaw |
|----------|----------|-----------|------|
| FBR\textsuperscript{18} | Flooding-based routing | Reduced unnecessary flooding | Increased E2ED due to RTS and CTS |
| DFR\textsuperscript{19} | Flooding-based routing | Limit the energy consumption | No strategy for void hole in sparse networks |
| VBF\textsuperscript{7} | Vector-based routing | Limiting the direction and forwarding range | Cause duplicate packets in dense network and void holes in sparse network |
| HH-VBF\textsuperscript{8} | Vector-based routing | Improved PDR | Fails to provide energy fairness and void hole avoidance |
| AHH-VBF\textsuperscript{6} | Vector-based routing | Energy efficiency is achieved due to transmission power adjustment | Imbalanced energy consumption |
| EBVBF\textsuperscript{26} | Vector-based routing | Increased network lifetime due to balanced energy consumption | Computation complexity is increased |
| ESEVB\textsuperscript{24} | Vector-based routing | Increased network lifetime by the even consumption of network energy | PDR is not improved due to high suppression |
| DBR\textsuperscript{5} | Depth-based routing | Increasing the PDR in dense area network | Degradation in network performance in sparse area network |
| WDFAD-DBR\textsuperscript{9} | Forwarder node selection is based on depth difference between two hops | Network lifetime increases with less energy consumption | E2ED is increased |
| GEDAR\textsuperscript{27} | Geographic and opportunistic routing | Move void node to new depth to recover from void hole | High network energy consumption due to void node motion and high network overhead |
| AUR\textsuperscript{15} | AUV-based data collection | Decreased energy consumption | High E2ED |
| LiMAH\textsuperscript{28} | Sector-based routing | Alleviate void holes to maximize the network life time and balanced data transmission over an intermediate node in heterogeneous network deployment | E2ED level is worst due to number of calculations involved in selecting the forwarder nodes |
| QELAR\textsuperscript{23} | Q-learning-based routing | High energy efficiency and PDR | Processing complexity is increased |
| EBERR\textsuperscript{5} | Depth- and energy-based routing | High energy efficiency and PDR due to balanced network energy consumption and detecting void hole | High E2ED for the lack of complete greedy approach |

UWSN: underwater wireless sensor network; FBR: focused beam routing; DFR: directional flooding-based routing; VBF: vector-based forwarding; HH-VBF: hop-by-hop VBF; AHH-VBF: adaptive HH-VBF; EBVBF: energy-balanced VBF; ESEVB: energy-scaled and expanded VBF; DBR: depth-based routing; WDFAD-DBR: weighting depth and forwarding area division DBR; GEDAR: GEographic and opportunistic routing with Depth Adjustment-based topology control for communication Recovery; AUR: AUV-aided underwater routing protocol; QELAR: Q-learning-based energy-efficient and lifetime-aware routing; EBERR: energy balanced efficient and reliable routing; E2ED: end-to-end delay; PDR: packet delivery ratio; RTS: request to send; CTS: clear to send.
based. The authors discuss several types of algorithms including the ones that are more prominent and attractive in UWSN routing. On one hand, in cross-layer routing protocol, one layer can depend on another for receiving information. On the other hand, in a non-cross-layer protocol, each layer is independent and operated on their specific function provided by the lower layer. Therefore, in a non-cross-layer protocol, each lower layer is interfaced with the upper layer; however, the function of each layer is different.

UWSNs use acoustic signals because of the higher attenuation of radio signals. This results in high E2ED and imbalanced consumption of energy during the communication of sensors and sink nodes. In particular, the imbalances in the energy of the nodes near to the sink nodes are weak because of load sharing between sensors and sink nodes. In this regard, Cheng and Li have approached these imbalances of energy and long delay times in networks using two different methods. The first method uses the autonomous underwater vehicle (AUV), while the second one utilizes the multi-hop transmission. In the previous research, it is pointed out that the AUV is used to collect a higher amount of data from the traveling path to minimize the routing time. In addition, the multi-hop transmission is discussed in several routing protocols which depend on the architecture of the network. First, they classify the data level based on its importance and then collect the data using AUV. Importance levels of data are based on the difference of nodes measured from the collected data, that is, when the node is more distant from each other, the difference is large compared to the other nodes.

An adaptive energy-efficient as well as lifetime-aware routing scheme has been proposed by Hu and Fei. This protocol uses machine-learning approach of reinforcement learning, called Q-learning-based energy-efficient and lifetime-aware routing (QELAR), for increasing network’s lifetime by even distribution of the node’s residual energy. According to the authors, no extra devices or downlink communication/location information are needed for this protocol and therefore it can be effectively used for mobile UWSNs. Wadud et al. proposed a protocol named energy-scaled and expanded vector-based forwarding (ESEVBF) for reducing the energy consumption and duplicate packets. Their approach is based on expanding the holding time difference on the basis of several factors such as residual energy and the pipeline’s width. The authors claim to achieve a longer network lifetime with their approach because fewer number of nodes expire in the given time interval. However, the packet delivery rate (PDR) is not improved because of the suppression of more nodes due to the forwarding scheme. For this reason, they proposed another protocol to stretch the holding time difference that is basically a more enhanced version of ESEVBF protocol. In this protocol, the technique of holding time calculation is extended from the first to the second hop forwarder to determine the best path. The authors also claim a reduction of void holes’ occurrences due to this strategy. However, due to the more control packets in this protocol, overhead is increased. Similarly, for increasing the network’s lifetime, Abbas et al. proposed another protocol called energy-balanced vector-based forwarding (EBVBF). This protocol aims to balance the energy of nodes and get rid of network’s zones for avoiding the potential disturbances in communication in nodes and their sinks. For energy balancing, another protocol called “Energy Balanced and Reliable Routing (EBERR)” has been proposed by Wadud et al. In this protocol, the expected next hop is considered for finding the potential forwarders. In addition, two embedded sinks are deployed that increase the packet delivery. Overall, this protocol achieves a longer network lifetime; however, the corresponding E2ED is also increased because of avoiding a complete greedy approach. In addition, the cost is a bit increased due to the communication of the embedded sinks via high-speed fiber medium.

Coutinho et al. proposed GEDAR (GEographic and opportunistic routing with Depth Adjustment-based topology control for communication Recovery) routing protocol in which different phenomena are discussed. They describe the depth adjustment of a node in case of a void hole occurrence and use a winch-based apparatus or bouncy-based apparatus to recover from the void hole. If there is no void hole created in the communication, the GEDAR uses the greedy forwarding strategy. In a WSN, two types of holes can occur. The first type is the one which occurs because forwarder nodes are not available. The second type is the energy hole that results because of the lack of balanced data traffic. The performance of the network is adversely affected when void hole is created. Wadud et al. proposed a protocol that focuses on alleviating the hole for prolonging the network lifetime. Their approach aims at balancing energy dissipation by dividing the number of transmissions evenly in various network areas. They focus on the forwarding nodes and the transmission region for communication. They divided the whole communication region into small areas, that is, small cubes. In addition, the choice of the next-hop forwarding node is also made based on the nodes present in the same cube nodes. The vector-based forwarding (VBF) and hop-by-hop vector-based forwarding (HH-VBF) routing protocols are proposed in the literature. The VBF protocol guides the network through a vector virtually drawn from a source node to a sink node, that is, the destination node. The VBF protocol is efficient in dense sensor networks, while the HH-VBF protocol in sparse sensor networks. In both protocols, a pipeline is made according to the node distribution of the network and
the sensor node advances their packets based on the pipeline. In VBF, the forwarding area and the direction of the pipeline of a source node remain constant for the entire communication, while in HH-VBF it changes at each hop, as a result, the PDR is improved.

Yu et al.\textsuperscript{9} presented a novel approach, called AHH-VBF, for enhancing the performance of HH-VBF. The AHH-VBF differs from HH-VBF in the following areas: first, in AHH-VBF, the direction and radius of the pipeline are changed at each hop according to the network structure in sparse and dense networks. This further restricts the next-hop forwarding region of the current forwarder node. In contrast, the HH-VBF merely focuses on changing the pipeline’s direction. Second, in AHH-VBF, the transmission power is changed adaptively at each hop based on the distribution of the node saving transmission energy. However, the transmission power of the source node remains constant in HH-VBF. Third, the AHH-VBF changes its holding time phenomena of the packet at each node, while in HH-VBF, several distances are considered for calculating the holding time, for example, source node and last-hop forwarder, virtual vector and forwarder. AHH-VBF searches for the node that is closer to the destination node and assigns it a high priority which is eventually selected as the forwarder.

For avoiding void holes in UWSNs, a protocol based on proactive strategy is proposed in Khan et al.\textsuperscript{29} This protocol considers the type of network (e.g. dense, sparse network) and adjusts the communication methodology accordingly. For dense or partially dense areas in the network, a vertical inter-transmission technique is used, while clusters are formed for the sparse regions. Another protocol named energy-efficient multi-level clustering protocol for underwater wireless sensor networks\textsuperscript{30} is proposed where the residual energy is used for making the clusters or logical levels. The same level is assigned to nodes which have similar energy and the cluster heads of the clusters or logical levels. The same level is assigned to nodes which have similar energy and the cluster heads of the clusters or logical levels. The existing routing protocols for UWSNs are summarized in Table 1.

### Channel model

The underwater acoustic channel is often considered a difficult medium of communication due to its limited transmission bandwidth and poor quality of communication. Designing a reliable communication strategy is often challenging because of the highly frequency-selective and time-varying nature of the channel. There are various parameters that affect the nature of acoustic channel such as salinity, temperature, and water depth. Figure 3\textsuperscript{31} shows the relation between acoustic speed and water depth using thermoclines. Mathematically, the speed of acoustic signal can be represented using equation (1)\textsuperscript{32}

\[
c = 1446.96 + 4.591T - 5.305 \times 10^{-2}T^2 \\
+ 2.374 \times 10^{-2}T^3 + 1.340(S - 35) + 1.63 \\
\times 10^{-1}D + 1.675 \times 10^{-7}D^2 - 1.025 \times 10^{-2} \\
T(S - 35) - 7.139 \times 10^{-13}TD^3
\]

where \(c\) represents the speed of acoustic signals, \(T\) denotes the temperature in degree Celsius (\(0^\circ C \leq T \leq 30^\circ C\)), \(S\) represents the salinity in parts per thousand (\(30 \leq S \leq 40\) PPT), and \(D\) is the depth of water in meters (\(0 \leq D \leq 8000\) m).

The acoustic channel is attenuated in underwater sensor networks over a distance \(d\) and is shown in equation (2)\textsuperscript{33}

\[
10\log A(d,f) = k.10\log d + d.10\log a(f)
\]

where \(k\) is the spreading coefficient. The possible values of \(k\) are 1, 1.5, and 2. These values are used to represent the propagation, that is, the value of 1 for \(k\) represents cylindrical spreading in shallow water region. Similarly, the value of 1.5 represents the practical spreading, while \(k = 2\) means a spherical spreading in deep region of water. \(a(f)\) represents the propagation model and can be expressed by equation (3)\textsuperscript{34}

\[
10\log a(f) = \frac{0.1f^2}{1 + f^2} + \frac{40f^2}{4100 + f^2} + \frac{2.75f^2}{10^4} + 0.003\text{ (dB/km)}
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\]
Equation (3) is suitable for high frequencies, while for lower frequencies, equation (4) may be used

$$10 \log \alpha(f) = \frac{0.11 f^2}{1 + f^2} + 0.001 f^2 + 0.002$$  \hspace{1cm} (4)

The underwater noise can be expressed by the formula given in equation (5)

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)$$  \hspace{1cm} (5)

where $N_t(f)$, $N_s(f)$, $N_w(f)$, and $N_{th}(f)$ represent turbulence, shipping, waves, and thermal noise, respectively.

The signal-to-noise ratio (SNR) for frequency $f$ and distance $d$ is represented by equation (6)

$$\text{SNR}(f, d) = P(f) - A(d, f) - N(f) + DI$$  \hspace{1cm} (6)

where $P(f)$ refers to the transmission power, $A(d, f)$ represents the attenuation, and $N(f)$ is the noise. The directivity index is represented by DI, that is, the quality of the node for avoiding the noise through redirecting its hydrophone.

In addition to the above parameters, acoustic modems are also an integral part of the acoustic channel and have an impact on communication. They are categorized as commercial acoustic modems and research acoustic modems. Table 2 presents the properties of some of the commercial acoustic modems designed for UWSNs.

### Table 2. Properties of commercial acoustic modems for UWSNs.

| Modem  | Frequency band (KHz) | Bit rate (kbps) | Max depth (km) | Range (km) | Tx (W) | Rx (W) | Sleep (mW) | Bit error rate |
|--------|----------------------|-----------------|----------------|------------|--------|--------|------------|----------------|
| UWM1000| 26.77–44.62          | 17.8            | 0.2            | 0.35       | 2      | 0.75   | 8          | $<10^{-9}$     |
| UWM2000| 26.77–44.62          | 17.8            | 4              | 1.5        | 8      | 0.8    | 8          | $<10^{-9}$     |
| UWM2200| 53.55–89.25          | 35.7            | 2              | 1          | 6      | 1      | 12         | $<10^{-9}$     |
| S2CM   | 18–34                | 13.9            | 2              | 3.5        | 35     | 0.8    | 2.5        | $<10^{-10}$    |
| 18/34  |                      |                 |                |            |        |        |            |                |
| S2CR   | 48–78                | 31.2            | 2              | 1          | 18     | 1.1    | 2.5        | $<10^{-10}$    |
| 48/78  |                      |                 |                |            |        |        |            |                |
| S2CR   | 38–64                | 27.7            | 2              | 2          | 18     | 1.1    | 2.5        | $<10^{-10}$    |
| 40/80  |                      |                 |                |            |        |        |            |                |
| S2CR   | 42–65                | 31.2            | 2              | 1          | 18     | 1.1    | 2.5        | $<10^{-10}$    |
| 42/65  |                      |                 |                |            |        |        |            |                |

UWSN: underwater wireless sensor network.

Figure 3. Schematic diagram of sound speed profile in (a) winter, with a mixed layer to a depth of 200 m, and (b) summer, when solar heating creates a seasonal thermocline (depth axes not to scale).
Definition 1. Contestant nodes (CNi): the node i lying inside the source node’s transmission range. Let N be a set of nodes in a network and can be expressed as shown in equation (7)

\[ N = \{n_1, n_2, n_3, \ldots, n_k\} \] (7)

The CNi can be expressed according to equation (8) as \( CN_i \subseteq N \).

\[ CN_i = \{j \in N \land dist_j \leq TR_i\} \] (8)

where

\[ dist_j = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \]

\( dist_j \) is the distance between node i \((x_i, y_i, z_i)\) and node j \((x_j, y_j, z_j)\) in three-dimensional Euclidean space and \( TR_i \) is the transmission range of node i.

Definition 2. Eligible neighbor nodes (ENNi): the node i which is present inside the transmission range of a source node, but located at a lesser distance to the surface sink than the source node. Let \( D_i \) and \( D_j \) be the depth of node i and node j, respectively. So, the ENNi can be expressed according to equation (9) as \( ENN_i \subseteq CN_i \)

\[ ENN_i = \{j \in CN_i \land D_j < D_i\} \] (9)

Definition 3. Region toward destination (RTD): the region of the transmission range where all the nodes are closer to the destination than the current one is called RTD. Let \( N(x_N, y_N, z_N) \) and \( S(x_S, y_S, z_S) \) be a coordinate of the neighbor and source node (the current node), respectively, so any point RTD \((x, y, z)\) is present in RTD region if it satisfies equations (9) and (10)

\[ \sqrt{(x_N - x)^2 + (y_N - y)^2 + (z_N - z)^2} \leq TR_s \] (10)

Proposed approach (AHHC-VBF protocol)

This section describes our proposed protocol called AHHC-VBF based on AHH-VBF. In AHHC-VBF, the transmission region (forwarding region of the source node) is adjusted to achieve the following goals:

1. Save energy of the entire network efficiently for the prolonged existence of the whole network;
2. Decrease the E2ED of the packet, that is, increasing the throughput of the network;
3. Guarantee reliability in communication.

High mobility and non-uniform distribution of the sensor nodes occur in UWSNs due to water currents; in some regions, the network becomes dense (density of the node is high) while in others it becomes sparse (density of the node is low). Therefore, we propose AHHC-VBF, in which we adaptively monitor the next-hop forwarding region by constructing a cone (three-dimensional geometric shape) forwarding structure so that we adaptively adjust the height and radius (opening) of the cone according to the node distribution. According to the definition, the opening (upper region of the cone), as shown in Figure 5, is defined on the basis of the base angle \( 2\theta \) of the cone. If we define a large base angle \( 2\theta \) for a cone, the cone opening will increase and more forwarding region will be covered, that is, more chances of forwarding nodes to send the source node’s packet. However, if we define a small base angle \( 2\theta \), the opening of a cone will be small and less forwarding region will be covered by the cone, that is, lower chances of forwarding nodes to send the source node’s packet. Setting up of the base angle \( 2\theta \) of the cone and the next-hop forwarding node is based on the nodes present in the RTD of the source node, that is, we adaptively monitor the ENNs that exist in the origin’s RTD (source node). On the basis of such network structure, the size of the base angle \( 2\theta \) is redefined. The base angle of a cone should be in the range \( 30^\circ \leq 2\theta \leq 150^\circ \).

We start from the small base angle \( 2\theta \), that is, \( 30^\circ \) and adjust it according to the network structure (sparse or dense network), that is, we configure the base angle. Next, we select the most preferable CPFNs present inside the cone. As discussed in section “Desirableness factor,” the desirableness factor \( \alpha \) for a node is
configured according to the node distribution in the neighbor region of the source node.

Let us consider the example shown in Figure 5; there are transmission regions R1 (node S region) and R2 (node F region), a current source node S, and a sink node G which is the desired destination node. TR is the transmission range of the source node and also the height of the cone. The packet needs to be transmitted from the source node (S) to the destination node (G). During the analysis of the network topology, we found the status of the network. In region R1, we have a dense region in the RTD of the existing source node and therefore we have to set up a small base angle for a cone, that is, the small opening of a cone to achieve a small number of CPFNs inside the cone which are eligible for next forwarding.

The nodes that are in the range of the forwarding node are known as the contestant nodes. Therefore, the nodes, for example, “A, B, C, D, E, F, I, H” existing in region R1 are the contesting nodes to collect the packet sent by a source node S. When a received packet at the source node S is forwarded, all the contestant nodes (i.e. “A, B, C, D, E, F, I, H”) inside region R1 collect the packet and send it to the next forwarder. However, nodes I and H are the suppressed nodes (i.e. the depth is greater than S) and they simply drop the received packet. In addition, nodes E and D present in the RTD of the source node are the ENNs (not the CPFNs) and they also discard the packet after calculating their respective positions. The nodes that are present inside the CPFNs are the appropriately selected nodes for the next forwarding of the received packet from the current source node S. The node F is the best forwarder as it first sends the packet due to its shorter holding time as compared to the other CPFNs A, B, and C present inside the cone. When the holding time of the CPFNs A, B, and C expires, it will also transmit the packets. However, before transmitting, they will observe that the packets have been forwarded by node F (the best forwarder node); therefore, the CPFNs A, B, and C will also discard the packets. In region R2, there is a sparse region of the network, that is, a smaller number of ENNs are present in this region. We started according to equation (12) from a small base angle of the cone and gradually increased the setup of the base angle according to the node distribution in the RTD of the source nodes. Therefore, the cone opens up, that is, there is more probability of the CPFNs being present inside the cone, which also minimizes the creation of void hole for further forwarding of the packets. For the sparse region, the smaller size of the base angle may create a void hole. However, when we gradually increase the size of the base angle of the cone, the opening of the cone is increased and there are chances of the CPFNs of the source node. Also, as we increase the size, that is, the base angle of the cone, then the upper region, which is the opening region of the cone, is spread more than the lower region. Therefore, the probability of finding the best CPFN nodes is increased. In R2 nodes, K and N are the ENNs nearer to the source node but they are not CPFNs, therefore it is not the candidate’s nodes for forwarding the packet. In this way, the redundancy of the packet is also minimized. Node M is the best next-hop forwarder CPFN, and it will forward the packets received from node F. In addition, we have the transmission ranges for UWSNs which depend on the transmission power. The transmission ranges also increase with the increase in transmission power. Unlike terrestrial sensor networks, energy constraint is important in UWSNs. Therefore, to reduce the overall energy consumption in AHHC-VBF, the node’s distribution should be considered to adaptively adjust the transmission/forwarding power hop-by-hop. Algorithm 1 and Figure 6 describe the details of the forwarding technique used in AHHC-VBF. In addition, the proposed scheme uses the technique presented in Algorithm 2 in case of a void hole. The packet type and IDs are given in Table 3.

**Finding CPFNs in AHHC-VBF**

This section describes the method of finding whether a node is inside the cone of a source node or not. We discuss this search process of CPFNs. The candidate nodes...
(the ones lying inside the cone of node S) either transmit the packet to the destination node (sink) if it is located within the range or to the next-hop forwarding nodes. When the nodes are present inside the cone, we also consider the priority of CPFNs using equation (13). The search process of CPFNs is as follows: first, the distances of the ENN from the source node and the nodes from the virtual vector are calculated, that is, the horizontal length (distance) from the virtual vector of the source node for each ENNs present in the RTD of the source node. Let us consider an example where we have an ENN A as shown in Figure 7 having coordinate \(A(x_A, y_A, z_A)\) and let the coordinate of the source node S is \(S(x_s, y_s, z_s)\). Therefore, the distance \(SA\) between the nodes S and A can be calculated by using equation (11)

\[
SA = \sqrt{(x_s - x_A)^2 + (y_s - y_A)^2 + (z_s - z_A)^2}
\]
Using equation (11), we find the distance of all ENNs node present in the RTD of the node S. Similarly, we can find the distance of each node from the virtual vector SG. Next, we find the CPFNs of the node which are present in the RTD. Consider node A, we have a horizontal distance P from SG, that is, from the virtual vector to node A, and the distance between nodes S and A using equation (11). Therefore, we can find the angle $\phi_1$ of the node A made with the virtual vector SG using equation (12)

$$\sin(\phi_1) = \frac{P}{SA}$$

Similarly, we can find the angles $\phi_2$ and $\phi_3$ for nodes B and K, respectively, using equation (12). We compare the calculated angle with half-angle of the pre-defined angle 2$\theta$ of the cone. In case the cone’s half-angle is greater than the calculated one, it shows that the node is inside the cone otherwise the node is outside the cone. For example, if the defined angle for a cone is 2$\theta = 90^\circ$, its half is $\theta = 90^\circ/2$, and the node is called CPFN if its angle is located in the range of $0 \leq \phi \leq 90^\circ/2$. As shown in Figure 7, the angle of nodes K and A lies in the defined range of angle of a cone, but node B lies outside the range. In this way, we find the CPFNs of the source node in order to do a reliable communication.

**Holding time calculation for AHHC-VBF**

Holding time is calculated to overcome packet redundancy and enhance the network’s performance. During this calculation, every next-hop forwarding node (that

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**Algorithm 1:** Algorithm for packet forwarding.

1. **Step 1:** Node, hears a transmission from node $j$
2. **Step 2:** Get_typeID(packet)
   - If typeID = 1 then
     - Packet is NR
     - Get Region of node($Node_i(x, y, z)$, $Node_j(x, y, z)$)
     - If $Node_j$ is in suppress region then
       - Update suppressed neighbor table
     - Else if $Node_j$ is inside the cone then
       - Reply with CPFN_ID
     - Else
       - Reply with PFN_ID
   - Else if typeID = 2 then
     - Update PFN_neighbor table
   - Else if typeID = 3 then
     - Update CPFN_neighbor table
   - Else
     - Go to Step 3
3. **Step 3:** Get PID
4. **Step 4:** Get Region of node($Node_i(x, y, z)$, $Node_j(x, y, z)$)
   - If $Node_j$ is inside the cone then
     - Go to Step 5
   - Else
     - Go to Step 3
5. **Step 5:** Calculate $H_{time}$ and set a timer
   - While timer $\neq 0$
     - If Transmission is heard then
       - Drop the packet
     - Break
     - Decrement timer

---

**Algorithm 2:** Treatment of void hole.

1. **Step 1:** Node, broadcasts NR
   - All neighbor receive it
2. **Step 2:** All neighbors reply with Ack
   - If No Ack is received from upper region then
     - Void hole detected
     - Go to Step 3
   - End
3. **Step 3:** Increase the cone angle by 15°
   - Go to Step 1
   - Continue until Ack is heard from upper hemisphere

---

Note:

- $\phi$ → angle of individual node with SG
- $\theta$ → cone half angle
- $\Phi$ → CPFN

**Figure 7.** Method of finding CPFNs.
exists in the source node’s range) forwards the packet only after waiting for a specified amount of time, to avoid forwarding by the other close by nodes to the destination. If every node inside a cone or within the RTD of a source node forwards the packet, there will be a lot of redundancy at the receiver end and numerous duplicate packets will be created in the network. Due to the duplicate packets, the following complex situation may occur. First, as the bandwidth of the acoustic communication is much lower than the terrestrial communication, the collision probability is increased at the receiver end. Second, the lifetime of the network will be reduced because of the additional consumption of energy while transmitting or receiving the packet. Therefore, to reduce the cost caused by the duplicate packets, the holding time concept is proposed in UWSNs. As shown in Figure 8, the formula for a node to hold the packet $H_{time}$ (holding time) is written as equation (13)\(^6\)

$$H_{time} = \frac{1}{2} \times \alpha \times t_{delay} + \frac{(TR - S\overrightarrow{F})}{V_{sound}}$$

(13)

where

$$\alpha = \left(\frac{P}{TR} \times \sin (\theta) + \beta \times \cos (\gamma)\right) \left(1 - e^{-hops}\right)$$

and

$$\beta = 1 - \frac{SF \cos \phi}{TR}$$

$$\gamma = 90 - \sin^{-1}\left(\frac{|ENN_i|}{|CN_i|}\right)$$

$$|CN_i| \in [0, N]$$

$$|ENN_i| \in [0, |CN_i|]$$

$$i = 1, \ldots, |ENN_i|$$

$$V_{sound} \approx 1500 \text{ m/s}$$

where S is the forwarding node of the last hop and G is the sink node at the water’s surface. TR is the transmission range of the last-hop forwarding node. To reduce the power consumption, the node’s distribution in the network is used to adaptively adjust the TR. $t_{delay}$ is the pre-defined delay for each node. $\alpha$ is the AHHC-VBF desirableness factor as discussed in section “Desirableness factor,” $V_{sound}$ represents the signal’s speed, and $hops$ denotes the number of hops the CPFNs have from the destination. Upon receiving a node, it forwards it to the next node, however, before forwarding, the holding time ($H_{time}$) of the collected packet is calculated first via equation (13). Next, a timer value is configured by the node with the finishing time $H_{time}$. Upon expiry of the time, the packet is forwarded if no duplicate packet is received by the node, otherwise it is dropped.

### Desirableness factor

Desirableness factor represents the “suitability” of forwarding a packet by a node. Let us consider the example in Figure 8, the virtual vector $SG$ where S represents the source node, G is the desired destination node, P denoted the horizontal distance from virtual vector $SG$ to node F, and $\theta$ is the angle which is equal to the half of the pre-defined angle of the cone. $W = R \sin \phi$ is the radius of the cone as the pre-defined angle of the cone is changed at each hop according to the network structure, so W is also adjusted hop by hop. $\phi$ is the included angle between $SF$ and $SG$, and TR is the transmission range of the last-hop forwarding node adjusted adaptively. Desirableness factor of AHHC-VBF gives priority to the node having the minimum hops from the sink, for reducing E2ED in the network. In addition to the closeness of a node to virtual vector, $\gamma$ makes $\alpha$ more suitable for selecting the node having fewer forwarders, so that probability of duplicate packets can be reduced.

From the definition of the desirableness factor, it is proven that the range of $\alpha$ is [0, 2]. During the transmission of packets, the decision of finding the next best forwarder is taken from the computation of the desirableness factors. If a node has a high desirableness
factor, the node should continue to forward the packet. Therefore, based on the values of $\alpha$, for the nodes inside the cone of the source node (i.e. the CPFNs), we give different priorities to them. The following ranges of the desirableness factor specify the position of the next forwarder nodes present in the range of source node. Their ranges are given in Table 4.

We give priority to the next forwarder based on the value of the desirableness factor. Their priorities are given in the following condition:

- Best forwarder $> \text{Good forwarder} > \text{Normal forwarder} > \text{Worst forwarder}$

Those CPFNs will transmit the packet in the next-hop forwarding nodes which are more distant from the source node and have a minimum distance from the virtual vector. The node is known as optimal node and its position is also good, that is, the node is suitable for forwarding for which the desirableness factor value is smallest, that is, $\alpha$ of the node is closer to 0. For node $F$, the desirableness factor should be less among all other calculated desirableness factors $(\alpha_0, \alpha_1, \alpha_2, \ldots, \alpha_n)$ for the nodes lying in the cone of the source node, that is, CPFNs. Its horizontal distance from the virtual vector is small and it is more distant from the current source node $S$ (its distance is equal to the TR of the source S node approximately), and nearer to the sink $G$ node. However, nodes $K$ and $L$ are not the best nodes for forwarding the packet, also, they have a larger value of $\alpha$ than $F$. In equation (13), the desirableness factor $\alpha$ represents the node distance from the virtual vector and shows the distance of a node from the sink node and source node. When $SF \cos \theta$ is equal to TR, the range of the source node and $P$ is equal to 0 (nodes are located on the virtual vector), then $\alpha$ is equal to 0 (its minimum value) and the node will forward the packet without any delay. However, when $SF \cos \theta$ is equal to 0 and $P$ is equal to $Rsin\theta$, then $\alpha$ is equal to 2 (its maximum value), the node will be at the worst position, and it will wait for a longer period compared to the other CPFNs of source node. According to equation (13) and from the above discussion of the holding time, we can conclude that when a node is near to the sink node and virtual vector, and away from the source node, the waiting time is short. On the contrary, in case of more distance of the node from the sink node and closer to the source node, there will be more waiting time.

### Packet type, neighbor table, and packet queue

In our proposed scheme, each node has to advance or collect the three types of packets, that is, NR, ACK, and DATA. NR represented by NR (refer to Table 11) is used to find the competent neighbor nodes. The NR packet format is a string of (typeID, SID, Depth, X-axis, Y-axis, Z-axis). The typeID field is used to recognize the packet type. The typeID field value for NR packet is “1.” The SID and Depth contain the address and depth of the current source node (forwarder node), respectively. X-axis, Y-axis, and Z-axis denote the position of a node in terms of x, y, and z coordinates, with respect to the source node. The ACK packet is the reply of the nodes, receiving the NR packet. The string of the ACK packet is (typeID, SID, Depth, Angle-info, Ax, Ay, Az). The value of typeID field for the ACK packet is “2” or “3” depending on the region of the node as shown in Table 3. If a particular node is inside the cone, then the typeID is “2” and “3” if it is outside the cone. SID contains the address of the source node and Depth contains the depth of nodes sending ACK. Angle-info denotes the angle information of the neighbor node constructing with the virtual vector of the source node. Ax, Ay, and Az denote the x, y, and z coordinates, respectively, of the node sending ACK packets. The DATA packet contains the desired information for which the whole protocol is designed, that is, the information intended to be sent to the destination (sink node). The header of the DATA packet is a string of (typeID, SID, DID, Dy, Dy, Dz, TR). The value of typeID field for the DATA packet is “4.” SID contains the address of the node sending the data packet. The sequence number of the data packet is denoted by PID, while the address of the destination node (CPFN) is represented by DID. X-axis, Y-axis, and Z-axis denote the position of a node sending DATA packet along x, y, and z coordinates. $D_x$, $D_y$, and $D_z$ denote the position of a node along x, y, and z, respectively, coordinate of the node to which the DATA packet is sent. TR denotes the transmission range and height of the cone of the forwarder node which is adaptively adjusted.

In some scenarios, when more than one node generates the same packet, a duplicate packet is encountered at the receiver’s end resulting in extra energy consumption. Also, when the node collects the information of the neighbor node, it sends NR every time resulting in increased E2ED as well as higher energy consumption. Therefore, to avoid this, the packet queue and neighbor table are established at each node. The neighbor table is a string of (NEIGHID, DISTANCE, DEPTH,
NEIGHX, NEIGHY, NEIGHZ, TIMESTAMP), where NEIGHID denotes the neighbor node address, DISTANCE denotes the separation of two neighbor nodes, and DEPTH is the neighbor nodes depth. NEIGHX, NEIGHY, and NEIGHZ denote the x, y, and z coordinate of the contestant node, respectively. TIMESTAMP shows the time after which we update the neighbor entry. The packet queue (established to avoid duplicate packet) format is shown as tuple (SID, PACKID, FLAG), where SID is the source node address and PACKID is the PID of the packet. FLAG is a one-bit Boolean number which will be either true or false, the flag value of “1” (true) means the corresponding packet has been forwarded.

**Experimental setup**

We performed an extensive simulation to evaluate the performance of AHHC-VBF. We have used the Pure Aloha MAC protocol as it has also been used in AHH-VBF. In addition, all experiments of our work have been performed using MATLAB as a simulator tool. The overall experimental setup of our proposed scheme is summarized in Table 5. We deploy 100–500 nodes in the region of 10 km × 10 km 10 km (length × width × height) for simulation purpose, the average volume covered by each node varies from 10 to 2 km³ and a total of nine sinks are deployed which are fixed at the water surface. Data header size is 11 bytes, while the size of payload (data) is 72 bytes and the data rate is 16 kbps. The size of both NR and ACK packet is 50 bits. The experiments are run over 100 times in each round, while in each round trip, a random network topology is generated. To confirm the reliability of communication, one packet should be generated approximately in 5 s. The initial energy of a node is 100 J. The transmission and receiving power are 50 W and 158 mW, respectively, for a packet. Also, due to water currents, the sensor nodes move randomly. To restrict the sensor nodes’ movement from getting outside the node deploying region, the Random Walk 2D mobility model is used. The nodes change their direction of movement every 2 s at the speed of 1–3 m/s. The Random Walk 2D mobility model enables movement of sensor nodes in horizontal direction, that is, in a two-dimensional X-Y plane (common mobility in the underwater wireless environment). However, this may not be the case in reality as there is usually some slight movement of nodes in vertical direction also.

**Metrics**

The proposed system is evaluated using the following metrics: PDR, ETX, E2ED, and APD.

PDR can be defined as “the ratio of the number of packets that successfully reach a destination node to the number of packets sent by source node.” Mathematically, PDR can be expressed as shown in equation (14)

$$PDR = \frac{\text{Packets successfully received}}{\text{Packet sent}}$$

ETX is defined as “the sum of average energy consumption of each node when a packet reaches to the sink node successfully.” It contains several types of energies such as ETX (transmission energy for a packet), ERX (receiving energy for a packet), IDLE (energy for the idle state of a node), and the energy for CTRL (energy for sending control packet). Mathematically, ETX can be expressed as shown in equation (15)

$$ETX = \frac{\text{Total energy}}{N \times \text{packets}}$$

where N represents the nodes in the network.

E2ED is stated as “the total time taken by a packet to get it delivered from the source node to the destination node.” It contains several types of delays such as transmission delay, propagation delay, holding time, and processing delay. In addition, the packets may be received by more than one sink node as we have multiple-sink (nine sinks) network, therefore in such cases, the shortest E2ED will be considered.

Average APD is the average distance that a packet covers during passing through many hops and reaching successfully from source to sink node. Also, because of the multiple sinks (nine), the shortest APD is considered as the final APD. The APD can be calculated using the formula given in equation (16)
where $P$ represents the total packets reached to the sink node, $\text{hop}$ is the hop number of the packet from the source node to sink, and $\text{distance}_{ij}$ is the distance of the $i$th hop of the $j$th packet.

**Results and discussions**

We compare the AHHC-VBF against AHH-VBF in terms of the metrics defined, that is, APD, ETX, E2ED, energy consumption, and PDR. Each comparison is discussed in the following subsections.

**PDR comparison**

The PDR increases with the increase in the number of nodes in both protocols AHHC-VBF and AHH-VBF. The reason is that due to the increase in nodes, the creation of holes is decreased resulting in increased PDR as shown in Figure 9. Routing protocols have two kinds of associated holes' occurrences. One hole occurs when there is no potential forwarding node in the range of a source node which is called coverage hole and the other one is called energy hole which is due to lack of energy with the current source node, that is, the source node not having sufficient threshold energy (50 mW). When the number of nodes reaches 500, the effective neighbor nodes achieve their maximum number. However, the collision rate of packets is increased, that is, the success rate of the packets is decreased with the increased node density. When the probability of a successfully forwarded packet is higher, there is a higher average number of neighbors per node. In AHH-VBF, PDR also increased with the increase in nodes but it is lower than AHHC-VBF. The main reasons are as follows: when we limit the forwarding region to the cone, a smaller number of nodes forward the packet and there is a high probability that no or negligible amount of collisions take place at the receiver side. In contrast, AHH-VBF uses a large forwarding region (pipeline) due to which a relatively higher number of nodes forward the packet, therefore the collision probability is higher at the receiver resulting in a higher number of lost packets. Also, AHHC-VBF tries to maximize the reliability by adaptively adjusting the height and opening of the cone if a node does not find CPFNs. Increased reliability means a lower packet loss and improved PDR.

**E2ED comparison**

The comparison of the E2ED between AHH-VBF and AHHC-VBF is shown in Figure 10(a). The E2ED is reduced with increasing nodes for both AHH-VBF and AHHC-VBF. This is because, within the given range of the pipeline and the cone, the number of qualified forwarding nodes increases. Furthermore, the E2ED reduces for both, with increasing transmission range as the number of hops covered by a packet to reach the sink decreases. The E2ED of AHHC-VBF is lower than AHH-VBF because the opening (base angle) and height of the cone are adaptively adjusted according to the distribution of the nodes. In addition, we select the node which is closer to the destination node and virtual vector of the source node to forward the packet. Figure 10(b) shows the performance of AHHC-VBF in comparison with AHH-VBF on different node densities with varying transmission range. We observe that for a given node density, the percentage improvement decreases with the increasing transmission range because both AHHC-VBF and AHH-VBF can easily find the best forwarders nearer to the sink.

Furthermore, for a given transmission range, the percentage improvement decreases with the increasing number of nodes in the network as shown in Table 6 because for a larger number of nodes, both protocols are equally probable to find optimal forwarder. Furthermore, for a given transmission range, the percentage improvement decreases with the increasing number of nodes in the network because for larger number of nodes, both protocols are equally probable to find optimal forwarder.

**ETX comparison**

ETX is defined as the total average energy consumption of each node when a packet is reached to the sink node successfully. The comparison of ETX between AHH-VBF and AHHC-VBF is shown in Figure 11. The ETX is reduced with an increasing number of nodes. This is because, with the increasing node density, the number
of successful packets increases reducing the ETX. The energy of a node is wasted in different scenarios, such as when the next-hop forwarding node is not found in some region due to the void hole (sparse region) and when duplicate packets are transmitted due to poor design of holding time. ETX of AHHC-VBF is lesser than the average ETX of AHH-VBF because of the following factors: first, we adjust the height and spreading region of the cone up to a very immense amount that the creation of the duplicate packets is controlled effectively in this region. Second, energy is efficiently consumed by adaptively changing the source power of transmission, according to the distance from the farthest forwarding node (CPFN).

Third, the size of the REQUEST and ACK packets is very small as compared to the sizes used in AHH-VBF, therefore the energy required for a REQUEST and ACK is much less, while the information is received by more than one neighbor node via one neighbor request. In addition, the energy consumption of the AHHC-VBF is very small in the range of 340–500 nodes, that is, it almost reached to idle energy as compared to AHH-VBF. This is because, we only consider the CPFNs present in the RTD of the source node, that is, we consider those CPFNs that are more nearer to the sink node (located in the range of the source node) and virtual vectors of the source node.

**APD comparison**

The APD is defined as the total average distance accumulated by a packet when it passes through many hops.
and reaches successfully from the source node to a sink node. The APD comparison between AHH-VBF and AHHC-VBF is shown in Figure 12. The APD of AHHC-VBF is less than AHH-VBF for all densities of the network. This is due to the fact that AHHC-VBF considers the number of hops to sink, in addition to the other parameters in calculating the value for alpha. It further searches for a CPFN having the shortest link toward the sink resulting in a smaller number of hops covered by the packet from source to sink, and therefore eventually decreasing the APD. However, in AHH-VBF, the number of hops is not considered when calculating the value of alpha for a forwarding node. This results in a higher probability for the packet to reach the sink after passing through a relatively large number of hops and therefore resulting in a higher value of APD. This is because, when there is a sparse region of the network, more opening of the cone is required to decrease the transmission failure of the packet and as a result, the APD is increased. As we adjust the base angle of the cone at each node (at each hop), the opening region of the cone is restricted with the increasing nodes resulting in a more directional communication and decreased APD.

**Analysis on various node densities and transmission ranges**

We further performed simulations on different transmission ranges to verify the validity of AHHC-VBF. For a given number of nodes in a network, the increase in transmission range results in more area covered by a node. In other words, more number of nodes will come in the transmission range of the particular node. The node will have a high probability to find CPFNs nearer to the sink resulting in decreased E2ED as shown in Figure 13(a).

The E2ED of AHHC-VBF is less than AHH-VBF for a given node density and transmission range. This happens because in AHHC-VBF, if a node does not have CPFNs, it quickly increases the opening of the cone. However, in AHH-VBF, in case of non-availability of CPFNs for a node, the transmission range is increased which requires high computation time. We also observed that the percentage improvement in E2ED decreases from low to high network density as well as from small to large transmission range, as shown in Table 7. This is because, for dense network scenarios, both are equally probable to find best forwarders. For large transmission ranges, both have a large number of nodes residing in their range that increases the probability of finding a forwarder node near the sink. Figure 13(a) and (b) shows that the
E2ED is high for low network density and low transmission range because for a sparse network scenario, the node mostly fails to find the forwarder in the direction of the sink and the packet reaches the node through a long path. Similarly, the E2ED is high for small transmission range because the packet passes through a large number of hops to reach the sink node. Figure 14(a) and (b) shows the change in the number of forwarded copies of data packets with varying node densities and transmission ranges. For sparse network scenarios and small transmission ranges, fewer data packets are forwarded. The reason for this is that most of the packets cannot reach the next-hop forwarder. As the network becomes denser, the source node can easily find next forwarder, therefore the forwarded copies of data increase.

For large transmission range in a sparse network scenario, the total number of forwarded copies of data is large as compared to a small transmission range. This is because, for a large transmission range, the probability is high that a node will have CPFNs.

We observe that with increasing transmission range and node density, the total forwarded copies of data reduce. This happens because, in case of large transmission range and high network density, the probability of packet collision is high, resulting in a large number of packet loss. We also observe that the total forwarding copies of AHH-VBF are larger than those of AHHC-VBF for a given transmission range and node density because the forwarding area in AHHC-VBF is smaller than that of the AHH-VBF due to which lesser number of nodes are selected for forwarding as compared to AHH-VBF. In addition, we analyzed that percentage improvement increases with the number of nodes. Furthermore, average percentage improvement decreases with the increasing transmission range, as shown in Table 8.

We further analyzed AHHC-VBF for the total energy consumption of the network. Network energy consumption occurs due to many factors, for example, packet transmission and receiving, processing and control packets transmission and receiving. Among all these factors, packet transmission majorly contributes to the total energy consumption of the network. Figure 15(a) and (b) shows the total network energy consumption of the network with varying transmission ranges and node densities. These figures show that AHHC-VBF consumes lower energy compared to AHH-VBF due to the lower number forwarded packets in the former. The total energy consumption is very low in sparse network scenarios due to the following reasons: first, for a sparse network scenario, most of the data packets
fail to go upstream; second, only few duplicate packets are transmitted; and third, due to low network density, fewer nodes receive the data packet. In contrast, for a dense network, the total energy consumption is high as compared to that of a sparse network. In addition, we analyzed that percentage energy consumption increases with number of nodes in the network and decreases with transmission range as shown in Table 9. There are a number of reasons for this: first, due to a large number of successful packets, high energy is consumed; second, a large number of nodes receive the data packets; and third, the higher number of duplicate packets’ transmission also results in higher energy consumption.

**Conclusion and future work**

A routing protocol called adoptive hop-by-hop cone vector-based forwarding (AHHC-VBF) for underwater acoustic sensor networks (UWSNs) is proposed in this article. It enhances the performance of the state-of-the-art counterpart routing protocol, that is, AHH-VBF. In particular, our proposed protocol aims to reduce ETX and total energy consumption, improve PDR, and reduce E2ED. Extensive simulations have been performed to verify the validity of the proposed protocol. Our results demonstrate that AHHC-VBF improves PDR by 11.87% and ETX by 19.18%. Overall, the total energy consumption reduces by 9.16% and E2ED by 4.23% against the state-of-the-art counterpart as shown in Table 10. However, some performance trade-offs have been observed due to the setting of the cone angle on the basis of the neighboring nodes’ information. In future, the performance of AHHC-VBF can be improved by reducing duplicate packets and balancing energy among the neighbors when the cone angle is increased.

### Table 8. Percentage improvement in total forwarded copies of data.

| Node numbers | 200 | 250 | 300 | 350 | 400 | 450 | Average improvement |
|--------------|-----|-----|-----|-----|-----|-----|---------------------|
| $T_r = 1000$ m | 5.1% | 5.4% | 6.8% | 11.87% | 15.8% | 16.2% | 10.19% |
| $T_r = 1200$ m | 5% | 5.1% | 9.09% | 12.17% | 11.4% | 12% | 9.12% |
| $T_r = 1400$ m | 4.8% | 4.9% | 4.92% | 7.1% | 6.9% | 6.5% | 5.85% |

### Table 9. Percentage improvement in energy consumption.

| Node numbers | 200 | 250 | 300 | 350 | 400 | 450 | Average improvement |
|--------------|-----|-----|-----|-----|-----|-----|---------------------|
| $T_r = 1000$ m | 6.25% | 5.71% | 10% | 12% | 15.9% | 15.7% | 11.92% |
| $T_r = 1200$ m | 6% | 6.1% | 8.47% | 9.67% | 12.8% | 12.68% | 9.28% |
| $T_r = 1400$ m | 5.9% | 5.88% | 5.92% | 9.6% | 9.09% | 7.31% | 7.28% |

![Figure 15. (a) Total energy consumption versus network size (nodes); (b) total energy consumption versus transmission range (m).](a) (b)
The acronyms used in the article are defined in Table 11.

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**References**

1. Felemban E, Shaikh FK, Qureshi UM, et al. Underwater sensor network applications: a comprehensive survey. *Int J Distrib Sens N* 2015; 11(11): 896832.
2. Wadud Z, Ismail M, Qazi AB, et al. An energy balanced efficient and reliable routing protocol for underwater wireless sensor networks. *IEEE Access* 2019; 7: 175980–175999.
3. Ahmed M, Salleh M and Channa MI. Routing protocols based on node mobility for Underwater Wireless Sensor Network (UWSN): a survey. *J Netw Comp Appl* 2017; 78: 242–252.
4. Xie P, Zhou Z, Nicolaou N, et al. Efficient vector-based forwarding for underwater sensor networks. *EURASIP J Wirel Comm* 2010; 2010: 1–3.
5. Yan H, Shi ZJ and Cui JH. DBR: depth-based routing for underwater sensor networks. In: *International conference on research in networking*, Singapore, 5–9 May 2008, pp.72–86. Berlin; Heidelberg: Springer.
6. Yu H, Yao N and Liu J. An adaptive routing protocol in underwater sparse acoustic sensor networks. *Ad Hoc Netw* 2015; 34: 121–143.
7. Xie P, Cui JH and Lao L. VBF: vector-based forwarding protocol for underwater wireless sensor networks. In: *International conference on research in networking*, Coimbra, 15–19 May 2006, pp.1216–1221. Berlin; Heidelberg: Springer.
8. Nicolaou N, See A, Xie P, et al. Improving the robustness of location-based routing for underwater sensor networks. In: *Oceans 2007- Europe 2007*, Aberdeen, 18–21 June 2007, pp.1–6. New York: IEEE.
9. Yu H, Yao N, Wang T, et al. WDFAD-DBR: weighting depth and forwarding area division DBR routing protocol for UASNs. *Ad Hoc Netw* 2016; 37: 256–282.
10. Wadud Z, Ullah K, Hussain S, et al. DOW-PR Dolphine and whale pods routing protocol for underwater sensor networks. *Wirel Pers Commun* 2011; 51(4): 607–627.
11. Ismail M, Islam M, Ahmad I, et al. Reliable path selection and opportunistic routing protocol for underwater wireless sensor networks. *IEEE Access* 2020; 8: 100346–100364.
12. Domingo MC. A distributed energy-aware routing protocol for underwater wireless sensor networks. *Wirel Pers Commun* 2011; 51(4): 607–627.
13. Wang P, Li C and Zheng J. Distributed minimum-cost clustering protocol for underwater sensor networks (UWSNs). In: *2007 IEEE international conference on..."
14. Magistretti E, Kong J, Lee U, et al. A mobile delay-tolerant approach to long-term energy-efficient underwater sensor networking. In: 2007 IEEE wireless communications and networking conference, Kowloon, China, 11–15 March 2007, pp.2866–2871. New York: IEEE.

15. Yoon S, Azad AK, Oh H, et al. AURP: an AUV-aided underwater routing protocol for underwater acoustic sensor networks. Sensors 2012; 12(2): 1827–1845.

16. Cayirpunar O, Kadioglu-Urtis E and Tavli B. Optimal base station mobility patterns for wireless sensor network lifetime maximization. IEEE Sens J 2015; 15(11): 6592–6603.

17. Akyildiz IF, Pompili D and Melodia T. Underwater acoustic sensor networks: research challenges. Ad Hoc Netw 2005; 3(3): 257–279.

18. Jornet JM, Stojanovic M and Zorzi M. Focused beam routing protocol for underwater acoustic networks. In: Proceedings of the third ACM international workshop on underwater networks, San Francisco, CA, 15 September 2008, pp.75–82. New York: ACM.

19. Hwang D and Kim D. DFR: directional flooding-based routing protocol for underwater sensor networks. In: OCEANS 2008, Quebec City, QC, Canada, 15–18 September 2008, pp.1–7. New York: IEEE.

20. Dhongdi SC, Nahar P, Sethunathan R, et al. Cross-layer protocol stack development for three-dimensional underwater Acoustic Sensor Network. J Netw Comp Appl 2017; 92: 3–19.

21. Rani S, Ahmed SH, Malhotra J, et al. Energy efficient chain based routing protocol for underwater wireless sensor networks. J Netw Comp Appl 2017; 92: 42–50.

22. Cheng CF and Li LH. Data gathering problem with the data importance consideration in underwater wireless sensor networks. J Netw Comp Appl 2017; 78: 300–312.

23. Hu T and Fei Y. QELAR: a machine-learning-based adaptive routing protocol for energy-efficient and lifetime-extended underwater sensor networks. IEEE T Mob Comp 2010; 9(6): 796–809.

24. Wadud Z, Hussain S, Javaid N, et al. An energy scaled and expanded vector-based forwarding scheme for industrial underwater acoustic sensor networks with sink mobility. Sensors 2017; 17(10): 2251.

25. Wadud Z, Ullah K, Quzi AB, et al. An efficient routing protocol based on stretched holding time difference for underwater wireless sensor networks. Sensors 2019; 19(24): 5557.

26. Abbas CJ, Montandon R, Orozco AL, et al. EBVBF: energy balanced vector based forwarding protocol. IEEE Access 2019; 7: 54273–54284.

27. Coutinho RW, Boukerche A, Vieira LF, et al. Geographic and opportunistic routing for underwater sensor networks. IEEE Trans Comp 2015; 65(2): 548–561.

28. Wadud Z, Javaid N, Khan MA, et al. Lifetime maximization via hole alleviation in IoT enabling heterogeneous wireless sensor networks. Sensors 2017; 17(7): 1677.

29. Khan ZA, Awais M, Alghamdi TA, et al. Region aware proactive routing approaches exploiting energy efficient paths for void hole avoidance in underwater WSNs. IEEE Access 2019; 7: 140703–140722.

30. Bansal R, Maheshwari S and Awwal P. Energy-efficient multilevel clustering protocol for underwater wireless sensor networks. In: 2019 9th international conference on cloud computing, data science engineering (confluence), Noida, India, 10–11 January 2019, pp.107–113. New York: IEEE.

31. https://www.sciencedirect.com/topics/physics-and-astronomy/thermoclines

32. Climent S, Sanchez A, Capella JV, et al. Underwater acoustic wireless sensor networks: advances and future trends in physical, MAC and routing layers. Sensors 2014; 14(1): 795–833.

33. Stojanovic M. On the relationship between capacity and distance in an underwater acoustic communication channel. ACM SIGMOBILE Mob Comp Commun Rev 2007; 11(4): 34–43.

34. Jouhari M, Ibrahimi K, Tembine H, et al. Underwater wireless sensor networks: a survey on enabling technologies, localization protocols, and internet of underwater things. IEEE Access 2019; 7: 96879–96899.

35. Al-Salti F and Alzeidi N. State-of-the-art of the physical layer in underwater wireless sensor networks. In: International journal of wireless & mobile networks, vol. 11, December 2019. DOI: 10.5121/ijwmn.2019.111602.