Enhancing the Vector-Based Forwarding Routing Protocol for Underwater Wireless Sensor Networks: A Clustering Approach

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Abstract— **Underwater Wireless Sensor Networks (UWSNs) have an important role in different applications, such as offshore exploration and ocean monitoring. The networks consist of a considerably large number of sensor nodes deployed at different depths. Many routing protocols have been proposed in order to discover an efficient route between the sources and the sink. In this paper, we propose an algorithm to improve the performance of the Vector-Based Forwarding (VBF) protocol which we call a Clustering Vector-Based Forwarding algorithm (CVBF). In the proposed algorithm, the space volume of the network is divided into a number of clusters where one virtual sink is assigned to each cluster. Then, the nodes inside each cluster are allowed to communicate with themselves just to reach its virtual sink node, which in turn sends the packets to the main sink in the network. Simulation results demonstrate that the proposed algorithm reduces the energy consumption especially in dense networks, increases the packet delivery ratio especially in sparse networks, and decreases the average end-to-end delay in both sparse and dense networks. These advantages are emphasized when the algorithm is compared with four other powerful routing algorithms: VBF, Hop-by-Hop VBF (HH-VBF), Vector-Based Void Avoidance (VBVA), and Energy-Saving VBF (ES-VBF) routing protocols.**

Keywords-wireless networks; underwater sensor networks; multiple clusters; routing protocols.

I. INTRODUCTION

At the end of the twentieth century, wireless sensor networks became a hot research area. At the beginning, these networks covered only terrestrial applications. However, the earth is known to be a water planet, with 70 % of its surface being covered with water (principally oceans). With the increasing role of oceans in human life, discovering all of the ocean parts became of prime importance. On one side, traditional approaches formerly used for underwater monitoring missions have several drawbacks [1] and on the other side, these harsh environments are not feasible for human presence as unpredictable underwater activities, high water pressure, predatory fish and vast areas are major reasons for un-manned exploration. Due to these reasons, Underwater Wireless Sensor Networks (UWSNs) attract the interest of many researchers lately, especially those working on terrestrial sensor networks [2]. Over the last three decades, significant contribution has been made in the area of scientific, commercial, and military applications [3]. In particular, highly precise real-time continuous-monitoring systems are essential for vital operations such as off-shore oil field monitoring, pollution detection, disaster prevention, assisted navigation, mine reconnaissance, and oceanographic data collection. All these significant applications call for building UWSNs. The work done by Akylidiz et al. [4] is considered as the pioneering effort towards the deployment of sensor nodes for underwater environments.

Though there exist many network protocols for terrestrial wireless sensor networks, the underwater acoustic communication channel has its unique characteristics, such as limited bandwidth capacity and high delays, which require new efficient and reliable data communication protocols [5]. Major challenges in the design of underwater wireless sensor networks are: i) the limited bandwidth; ii) the underwater channel is severely impaired, especially due to multipath and fading problems; iii) high propagation delay in underwater which is five orders of magnitude higher than in Radio Frequency (RF) terrestrial channels; iv) high energy consumption due to longer distances; v) battery power is limited and usually batteries cannot be recharged, also because solar energy cannot be exploited underwater; vi) underwater sensor nodes are prone to failures due to fouling and corrosion. All the factors mentioned above, especially limited energy, would make designing a routing protocol for UWSN an enormous challenge.

Routing is a fundamental issue for any network, and routing protocols are considered to be in charge of discovering and maintaining the routes [2]. Most of the research works concerning UWSNs have been on the issues related to the physical layer, while issues related to the network layer such as routing techniques are a relatively new area. Thus, an efficient routing algorithm is to be provided. Although underwater acoustic networks have been studied for decades, underwater networking and routing protocols are still at the infant stage of research.

A review of underwater network protocols till the year 2000 can be found in [1]. Several routing protocols have been proposed for underwater sensor networks. A good survey until year 2012 about underwater wireless sensor routing techniques is presented in [2]. Here, Ayaz et al. introduced an overview of the state of the art of routing protocols in UWSNs and thoroughly highlighted the advantages, functionalities, weaknesses and performance issues for each technique. Based on network architecture, UWSNs routing protocols are classified into: location-based, flat, and hierarchical routing protocols. Vector-Based Forwarding (VBF) protocol has been suggested in order to solve the problem of high error probability in dense networks [6]. It is a location-based routing protocol. Here an idea of a virtual routing pipe from the source to the destination is proposed, and all the flooding data packets are carried out through this pipe. An enhanced version of VBF called Hop-by-Hop VBF (HH-VBF) has been proposed [7]. They use the same concept of virtual routing pipe as used by VBF, but instead of using a single pipe from source to destination, HH-VBF defines per hop virtual pipe for each forwarder [8]. Another extension of VBF protocol is introduced in [9] called Vector-Based Void Avoidance (VBVA) routing protocol which extends the VBF routing protocol. It addresses the routing void problem in underwater sensor networks. VBVA assumes two mechanisms, vector-shift and back-pressure, to handle voids. In [10], an energy-aware routing algorithm, called Energy-Saving Vector Based Protocol (ES-VBF), is proposed. In this protocol, Bo et al. put forward an energy-aware routing algorithm to save network energy. It takes both residual energy and location information into consideration, which shows a promising performance in balancing network energy consumption and packet reception ratio.

Other UWSNs routing protocols, such as Dynamic Source Routing (DSR), Time division Multiple Access (TDMA), Focused beam Routing (FBR), Directional Flooding-Based (DFR), and Depth-Based Routing (DBR) are found in [2][8][11][12].

The remainder of this paper is organized as follows. In Section II, the functionality and performance issues of VBF, HH-VBF, VBVA, and ES-VBF location-based routing protocols which will be used in a comparison with our algorithm are discussed. Section III presents the details of the proposed algorithm. In Section IV, we show the performance results of the proposed algorithm. Finally, we draw the main conclusions in Section V.

II. Review of Location-Based Routing Protocols

In this section, we discuss in brief four location-based routing protocols which we will choose to compare our algorithm with. These protocols are:

A. *Vector-Based Forwarding (VBF) Routing Protocol*

VBF is a location-based routing approach for UWSNs proposed by Xie et al. [6]. In this protocol, state information of the sensor nodes is not required since only a small number of nodes are involved during packet forwarding. Data packets are forwarded along redundant and interleaved paths from the source to the sink, which helps handling the problem of packet losses and node failures. It is assumed that every node previously knows its location, and each packet carries the location of all the nodes involved including the source, forwarding nodes, and final destination. The forwarding path is specified by the routing vector from the sender to the target. As soon as a packet is received, the node computes its relative position with respect to the forwarder. Recursively, all the nodes receiving the packet compute their positions. If a node determines that it is close enough to the routing vector, it puts its own computed position in the packet and continues forwarding the packet; else, it simply discards the packet. In this way, all the packet forwarders in the sensor network form a "routing pipe", the sensor nodes in this pipe are eligible for packet forwarding, and those which are not close to the routing vector do not forward. Fig. 1 illustrates the basic idea of VBF. In this figure, node S_1 is the source, and node S_0 is the sink. The routing vector is specified by S_1S_0. Data packets are forwarded from S_1 to S_0. Forwarders along the routing vector form a routing pipe with a pre-controlled radius, W.

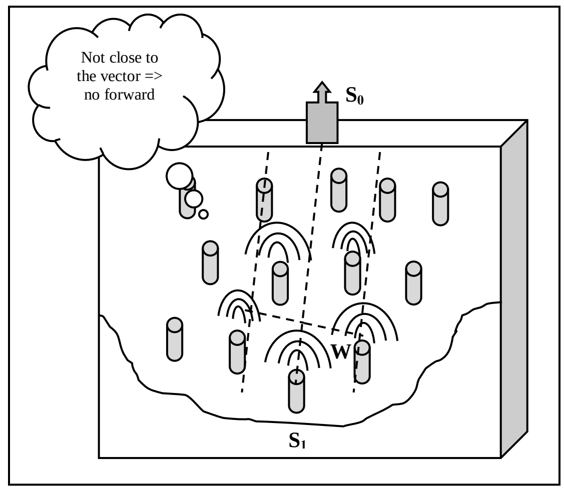


Figure 1. VBF routing protocol for UWSNs.

Additionally, a localized and distributed self-adaptation algorithm is developed to enhance the performance of VBF [6]. The self-adaptation algorithm allows each node to estimate the density in its neighborhood and forward packets adaptively. This algorithm is based on the definition of a desirableness factor, α [6]. This factor measures the suitability of a node to forward packets. Given a routing vector S_1S_0 and forwarder F, the desirableness factor of a node A is:

$$\propto = \frac{P}{W} + \frac{R - d \times \cos\theta}{R} \tag{1}$$

where P is the projection length of A onto the routing vector S_1S_0, d is the distance between node A and node F, θ is the angle between vector FS_0 and vector FA, R is the transmission range, and W is the radius of the routing pipe.

Fig. 2 represents the different parameters used in the definition of the desirableness factor [6]. From the definition, we see that for any node close enough to the routing vector, i.e., inside the pipe ($0 \leq P \leq W$), the desirableness factor of this node is in the range of [0, 3] depending on position of node A.

 ISBN: 978-1-61208-347-6

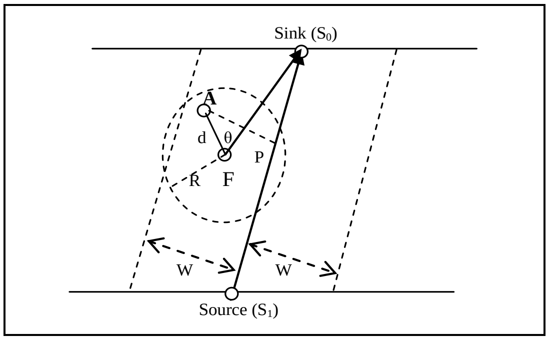


Figure 2. Desirableness factor in self-adaptation algorithm.

In this algorithm, when a node receives a packet, it first determines if it is eligible for packet forwarding (i.e., close enough to the routing vector) [6][7]. If yes, the node then holds the packet for a time period, $T_{adaptation}$, related to its desirableness factor and other network parameters (2). In other words, each qualified node delays forwarding the packet by a time interval calculated as follows:

$$T_{adaptation} = \sqrt{\propto} \times T_{delay} + \frac{R-d}{v_0} \qquad (2)$$

where T_{delay} is a pre-defined maximum delay, $v0$ is the propagation speed of acoustic signals in water, i.e., 1500m/s, and d is the distance between this node and the forwarder [7]. Principally, this self-adaptation algorithm gives higher priority to the desirable node to continue forwarding the packet. The theoretical analysis can be found in [6].

VBF has many essential drawbacks. First, using a virtual routing pipe from source to destination can affect the routing efficiency of the network with different node densities. In some spaces, if node deployment is sparser or become sparse due to some node movement, then it is possible that very few or even no node will lie within that virtual pipe, which is responsible for the data forwarding; even it is possible that some paths may exist outside the pipe. Eventually, this will result in small data deliveries in sparse spaces. Second, VBF is very sensitive about the routing pipe radius threshold, and this threshold can affect the routing performance significantly; such feature may not be desirable in the real protocol developments. Furthermore, some nodes along the routing pipe are used again and again in order to forward the data packets from sources to the sink, which can exhaust their battery power.

B. HH-VBF Routing Protocol

The need to overcome two problems encountered by the VBF, i.e., small data delivery ratio in sparse networks, and sensitivity to the routing pipe's radius, the HH-VBF (hop-by-hop VBF) is proposed by Nicolaou et al. [7]. HH-VBF forms the routing pipe in a hop-by-hop method, enhancing the packet delivery ratio significantly. Although it is based on the same concept of routing vector as VBF, instead of using a single virtual pipe from the source to the sink, it defines a different virtual pipe around the per-hop vector from each forwarder to the sink. In this protocol, each node can adaptively make packet forwarding decisions based on its current location. This design can directly bring the following two benefits: First, since each node has its own routing pipe, the maximum pipe radius is the transmission range. Second, in sparse networks, HH-VBF can find a data delivery path even so the number of eligible nodes may be small, as long as there exists one in the network.

In HH-VBF, the routing virtual pipe is redefined to be a per-hop virtual pipe, instead of a unique pipe from the source to the sink [7]. When some areas of the network are not occupied with nodes, for example there exist "voids" in the network, even a self-adaptation algorithm may not be able to route the packets. In such a case, a forwarder is unable to reach any node other than the previous hop. Although simulation results show that HH-VBF considerably produces better results for packet delivery ratio, but still it has an inherent problem of routing pipe radius threshold, which can affect its performance. Moreover, due to its hop-by-hop nature, HH-VBF is not able to add a feedback mechanism to detect and avoid voids in the network and energy efficiency is still low compared to VBF [7].

C. VBVA Routing Protocol

Xie et al. [9] introduce a Vector-Based Void Avoidance (VBVA) routing protocol, which extends the VBF routing protocol to handle the routing void problem in UWSNs. VBVA assumes two mechanisms, vector-shift and back-pressure. The vector-shift mechanism is used to route data packets along the boundary of a void. The back-pressure mechanism routes data packets backward to bypass a concave void. VBVA handles the routing void problem on demand and thus does not need to know network topology and void information in advance. Hence, it is very robust to cope with mobile voids in mobile networks. Simulation results in [9] show that VBVA can handle both concave and convex voids effectively and efficiently in mobile underwater sensor networks only when these voids are inside the forwarding pipe, while the voids outside the forwarding pipe is not solved by VBVA.

D. ES-VBF Routing Protocol

To solve the energy problem in UWSN, Bo et al. [10] put forward an energy-aware routing algorithm, called Energy-Saving Vector-Based Protocol (ES-VBF). The main purpose of this routing protocol is saving energy. ES-VBF takes both residual energy and localization-based information into consideration while calculating the desirableness factor as in (3), which allows nodes to weigh the benefit for forwarding packets. The ES-VBF algorithm modifies the calculation of the desirableness factor of (1) for VBF protocol to be calculated if the node residual energy is smaller than 60% of initial energy as:

$$\propto = 0.5 \times \left(1 - \frac{energy}{initialenergy}\right) + \left(\frac{P}{W}\right) + \left(\frac{R - d \times \cos\theta}{R}\right) \quad (3)$$

where *energy* is the residual energy of nodes and *initialenergy* is the initial energy of nodes. By simulation results in [10], it is shown that the performance is promising in balancing network energy consumption and packet reception ratio. This means that the ES-VBF protocol saves energy in an efficient manner. At the same time, there is a small falling in packet reception ratio, which needs further research aiming at finding a better solution not only reducing energy consumption but also achieving high packet reception ratio.

III. Clustering VBF Routing Algorithm: The Proposed Algorithm

In this paper, we propose an algorithm for UWSNs which we call a Clustering Vector-Based Forwarding algorithm (CVBF). The objective of the proposed routing algorithm is to reduce energy consumption, increase the packet delivery ratio, and decrease the average end-to-end delay. This is emphasized through comparison with VBF, HH-VBF, VBVA, and ES-VBF routing protocols.

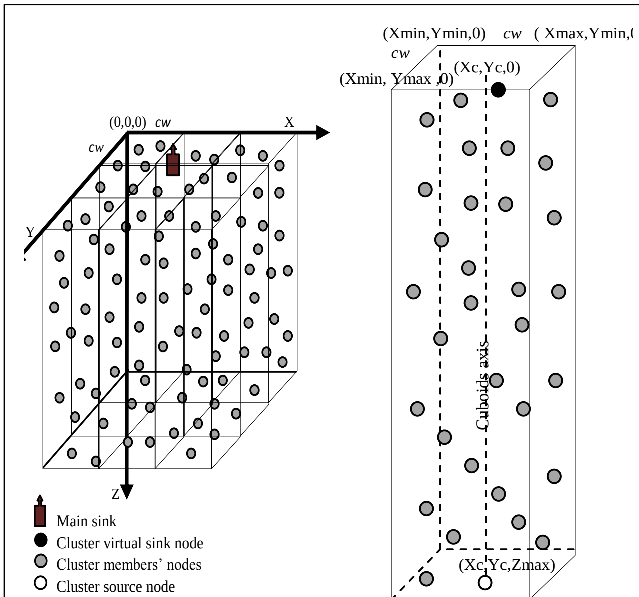
According to our approach, the whole network is divided into a predefined number of clusters. All sensor nodes are assigned to the clusters on the basis of their geographic location, and then one node at the top of each cluster is selected as a *virtual sink* for that cluster. The rest of nodes in each cluster transmit the data packets to their respective cluster virtual sink. The routing inside each cluster follows the VBF routing protocol discussed in Section II. This implies that the concept of using one virtual routing pipe for all network nodes in VBF is replaced by defining one virtual routing pipe for each cluster to forward the packets from any node in the cluster to its virtual sink in that cluster. We assume that the routing pipe radius is equal to the transmission range of a node. Each intermediate node in any cluster selects the next hop to a node inside its cluster. In this way, the network will have many virtual routing pipes, one pipe per cluster, which guarantees forwarding the packets in the upward direction instead of forwarding the packets widely across the network nodes in the VBF algorithm. It is well expected that this will decrease the average end-to-end delay node and reduce the number of hops to reach the virtual sink node which will enhance the network performance. In addition, CVBF avoid voids in the network because each node belongs to a specific cluster.

Also, if a small number of nodes are available in the neighborhood, CVBF can still find a data delivery path. After receiving the data packets from cluster sensor nodes, cluster virtual sinks perform an aggregation function on the received data, and transmit them towards the main sink node using single-hop routing. Cluster virtual sink nodes are responsible for coordinating their cluster members and communicating with the main sink node.

The proposed algorithm is stated in the following steps:

Step1: Clustering the Nodes

This step involves dividing the network into groups of nodes according to their geographic location producing non-overlapping clusters excluding the main network sink which is allocated on the water surface. The following values are given: the network space X×Y×Z, node transmission range, routing pipe width, and the node speed. We divide the network space into equal space volumes; in the form of cuboids (each cuboid has four rectangular sides and two square ones). The division is based on the values of X and Y coordinates, and the cluster width, *cw*, as shown in Fig. 3 (a).



(a) Network area with 9 clusters (b) One cluster and its virtual sink

Figure 3. A CVBF network area: (a) Network area with 9 clusters, (b) One cluster and its virtual sink

Choosing the best number of clusters is proposed as:

$$N = \frac{X \times Y}{(cw)^2} \tag{4}$$

where $X \times Y$ is the total surface area of the network and $(cw)^2$ is the area of the cluster surface. The cluster width is thus calculated as:

$$cw = \sqrt{\left(\frac{X \times Y}{N}\right)} \tag{5}$$

It is given that the surface area is square; therefore, we choose *N* as a number raised to the power of two: 2^2, 3^2, 4^2, or 5^2. Here, we choose N that gives the value of *cw* as near as possible to $\sqrt{2}$R in order to make sure that the virtual pipe of the cluster includes all the nodes inside that cluster, as shown in Fig. 4.

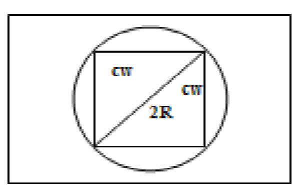


Figure 4. A horizontal section of cluster virtual pipe.

As an extreme case, if we choose one cluster (N=1) only, then our algorithm reduces to the VBF protocol. In other words, our algorithm is a good generalization to VBF protocol.

 ISBN: 978-1-61208-347-6

Step2: Selecting the Cluster Virtual Sink

For each cluster (cuboid) which has a space volume cw×cw×Z, we choose the nearest node to the main sink to be a cluster virtual sink. As shown in Fig. 3 (b), the surface corner coordinates of the cluster are: (Xmin, Ymin, 0), (Xmax, Ymin, 0), (Xmin, Ymax, 0), and (Xmax, Ymax, 0).

All other nodes can send data to their corresponding virtual sink following the mechanism of VBF and depending on the value of its desirableness factor α. If more than one node have the same depth position, we choose the nearest node to the cuboid axis, in which its surface point coordinates is the point (Xc, Yc, 0). The source node of the cluster is fixed at the position (Xc, Yc, Zmax).

Step3: Calculating the Cluster's Maintenance Time

This step takes into consideration the node mobility that affects network topology and performance, thus necessitating a cluster maintenance algorithm. For a correct network operation, the maintenance algorithm should be executed simultaneously in all clusters. In this step, we propose a suitable periodical time which we call *maintenance time, Tm.* This time is enough to move a node from its cluster to another cluster according to speed and maximum distance of the node. Each node in the cluster checks its belonging to that cluster after the periodical time *Tm*. If a node belonging to a cluster moves away from that cluster, it naturally has two choices. The first choice is to enter another neighboring cluster, and so we transfer this node from the old cluster to the new cluster. The second choice is that it exits from all the network space, and so we leave this node in the old cluster. To calculate *Tm*, we divide the known maximum distance of a node movement, *dmax*, by the current speed of the node, *S*:

$$Tm = \frac{dmax}{S} \tag{6}$$

In other words, all the nodes with positions near the cluster boundaries are prone to exit from their own cluster and enter to other clusters. To avoid exiting a node from the network space, we suggest to carefully choose the node positions to be far from the network space boundaries.
The proposed algorithm is summarized in the Pseudocode of Fig.5:

Pseudocode

Step 1: Clustering the nodes
1. Given network space X x Y x Z and node transmission range R.
2. Calculate cw=$\sqrt{(X \times Y)/N}$ where N=2^2, 3^2, 4^2, or 5^2, and cluster space = cw×cw×Z
3. For each cluster, i=1 to N with step 1
   3.1. Given Xi takes values from Ximin to Ximax, and Yi takes values from Yimin to Yimax
   3.2. Ki is the number of nodes in the space Xi×Yi×Z

Step 2: Selecting the cluster virtual sink
1. Sort the nodes, Ki, according to the values of their Z coordinate to determine the minimum value of Z and call it Zmin.
2. Count the number of nodes, Kiz, in which their Z coordinate equal Zmin.
3. If (Kiz=1)
   Then
      This node is the *virtual sink* of cluster i
   Else
      (a) Calculate Xc=[(Ximax-Ximin)/2], and Yc=[Yimax-Yimin)/2] to get the points of the cluster axis, (Xc,Yc,Zmin) and (Xc,Yc,Z)
      (b) Calculate the nearest node to point (Xc,Yc,Zmin) from the given Kiz to become *virtual sink* of cluster i

Step 3: Calculating the cluster's maintenance time
1. If a node is near to the cluster axis and its mobility does not cause exit this node from that cluster or If a node moves outside the whole network space
   Then
      This node is still belongs to its original cluster
   Else
      If a nodes exits from the cluster
      Then
         (a)Given the node speed, S, and the maximum distance of any node, *dmax,*
         (b) Calculate Tm=*dmax*/S
         (c) For J=0 to Simulation time with step Tm
            For each node in the cluster i and has coordinates (Xi,Yi,Z)
               If (Ximin>=Xi>=Ximax and Yimin>=Yi>=Yimax)
               Then
                  This node is still in the cluster
               Else
                  Remove this node from cluster i and enter it to the suitable neighboring cluster
2. All the nodes in cluster i forward the packets to its virtual sink following the mechanism of VBF routing algorithm
3. All the virtual sinks forward the packets to the main sink

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Figure 5. Pseudocode of the proposed routing protocol CVBF.

IV. PERFORMANCE EVALUATION

Performance is quantified through measures of energy consumption, packet delivery ratio, and average end-to-end delay [10]. The success rate is the ratio of the number of packets successfully received by the sink to the number of packets generated by the source. The energy consumption is the total energy consumed by the sensor network nodes. The average delay is the average end-to-end delay for each packet received by the sink.

Simulation is performed by the underwater package Aqua-Sim of ns-2 [13][14]. In all our simulations, we set the parameters similar to UWM1000 LinkQuest Underwater Acoustic Modem [15]. The bit rate is 10 kbps, and the transmission range R is 100 m. The energy consumption on

 ISBN: 978-1-61208-347-6

the sending mode, receiving mode, and idle mode are 0.6J, 0.3J, and 0.01J, respectively. The data packet size is 76 bytes and control packet is 32 bytes. The pipe radius in each cluster is 100 m. In all simulation experiments, sensor nodes are randomly distributed in a space volume of 600 m ×600 m ×600 m. They can move in a two-dimensional space, i.e., in the X-Y plane (the most common mobility pattern in underwater applications) with the medium node speed S in the range (2m/s-5m/s). The maximum distance of a node movement *dmax* is 5m. The number of clusters N used is 9 clusters (it is found in our experiments that the number N=9 give better performance than that for N=1, 4, 16, 25). The cluster width cw is $\sqrt{(600 \times 600)/9} = 200$ m. We have one data source, one main sink, and 9 virtual sinks. For each setting, the results are averaged over 30 runs with a randomly generated topology. The total simulation time for each run is 1000 s. The simulation results are plotted in Figures 6, 7, and 8.

Fig. 6 depicts the total energy consumption as the number of sensor nodes varies. The energy consumption increases with the number of nodes since more nodes are involved in packet forwarding. On the other hand, this figure shows that the energy consumption for the proposed algorithm is less than that in VBF and HH-VBF routing protocol only on dense networks, when the number of nodes is greater than 300 nodes, indicating that the CVBF algorithm can save more energy with high node density, as shown in Table I, extracted for Fig. 6.

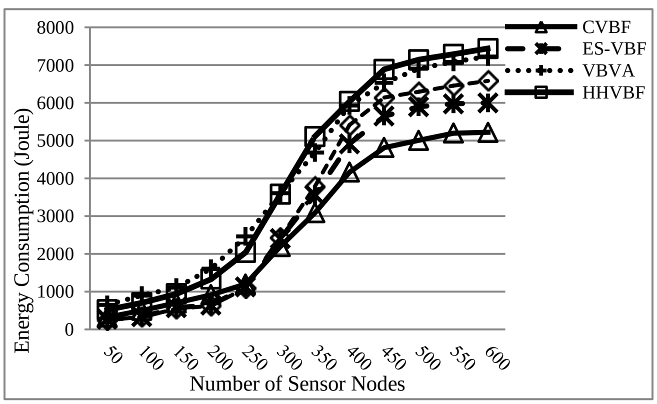

Figure 6. CVBF energy consumption *vs.* number of sensor nodes.

TABLE I. REDUCTION IN TOTAL ENERGY CONSUMPTION

No. of Nodes	Total Energy Consumption(Joule)					
	VBF	***HH-VBF***	***VBVA***	***ES-VBF***	***Proposed CVBF***	***Reduction percentage***
50	250.12	515.37	646.71	260.72	**320.65**	-28%
150	550.53	939.98	1103.65	570.23	**698.97**	-26%
300	2424.16	3578.32	3604	2400.91	**2190**.86	8.7%
450	6142.81	6890.6	6532.1	5646.4	**4816.87**	14%
600	6589.39	7440.6	7231.9	6000.03	**5220.02**	13%

Fig. 7 shows the packet delivery ratio with the number of sensor nodes. It is seen that the packet delivery ratio increases with the increase of the number of nodes. When more than 200 nodes are deployed in the space, the packet delivery ratio remains above 90% for both ES-VBF routing protocol and CVBF algorithm. Table II, extracted from Fig. 7, shows that our algorithm gives better results in packet delivery ratio than VBF, HHVBF, VBVA, and ES-VBF protocols.

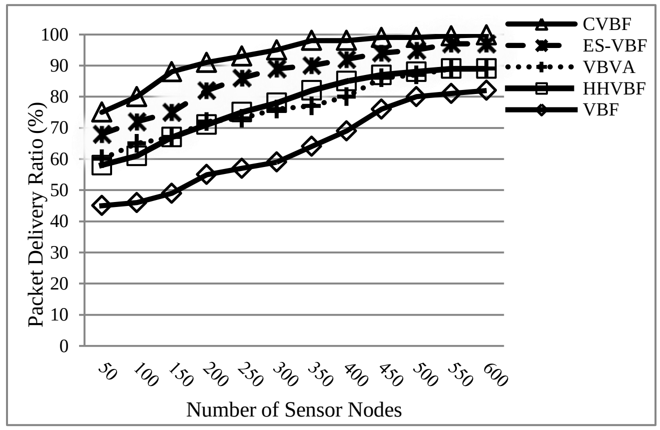

Figure 7. CVBF packet delivery ratio *vs.* number of sensor nodes.

TABLE II. INCREASE IN PACKET DELIVERY RATIO

No. of Nodes	Packet Delivery Ratio (%)					
	VBF	***HH-VBF***	***VBVA***	***ES-VBF***	***Proposed CVBF***	***Increasing percentage***
50	45	58	60	68	**75**	10%
150	49	67	67	75	**88**	17%
300	59	78	76	89	**95**	6.7%
450	76	87	86	94	**99**	5.3%
600	82	89	89	99	**99.8**	0.08%

Fig. 8 describes the average end-to-end delay with the number of sensor nodes. It is seen that the average end-to-end delay decreases with the increase of node density in the network. When the number of sensor nodes increases, the paths from the source to the sink are closer to the optimal path (α=0); therefore, the average end-to-end delay decreases, as shown in Table III, extracted from Fig. 8.

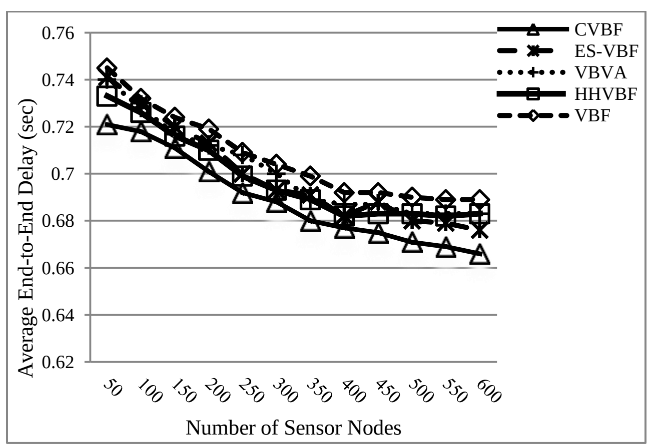

Figure 8. CVBF average end-to-end delay *vs.* number of sensor nodes.

TABLE III. REDUCTION IN AVERAGE END-TO-END DELAY

No. of Nodes	Average End-to-End Delay(sec)					
	VBF	***HH-VBF***	***VBVA***	***ES-VBF***	***Proposed CVBF***	***Reduction percentage***
50	0.745	0.733	0.74	0.741	**0.721**	1.6%
150	0.724	0.716	0.717	0.72	**0.711**	0.7%
300	0.704	0.693	0.7	0.693	**0.688**	0.7%
450	0.692	0.683	0.687	0.688	**0.675**	1.2%
600	0.689	0.683	0.683	0.676	**0.666**	1.5%

We evaluate the performance of CVBF under various network scenarios. The simulation results show that CVBF significantly exhibits a better performance than VBF, HH-VBF, VBVA, and ES-VBF protocols since it has: lower energy consumption, higher packet delivery ratio, and lower average end-to-end delay.

Calculating the cluster width *cw* depends on two parameters: the surface area of the network X×Y and choosing the number of clusters *N*. We choose a value of *N* for which the cluster width is nearest to the value of $\sqrt{2}$R. We conclude this after examining different values of *N*. This is because each node can transmit the data packets only to the neighbors allocated in its transmission range.

V. CONCLUSIONS

In this paper, we propose a clustering vector-based forwarding algorithm to improve the performance of the location-based routing protocol in underwater wireless sensor networks. In the proposed approach, the space area of the network is divided into clusters where one virtual sink is assigned to each cluster. Choosing the number of clusters depends on the value of the network surface area and the transmission range of the sensor node. The nodes inside each cluster are allowed to communicate with themselves following the concept of VBF protocol only to reach its virtual sink node, which sends the packets to the main sink node in the network. Due to node mobility, some nodes may move outside their cluster and enter another cluster. Therefore, we check the node position periodically as a maintenance step to allocate each node to its suitable cluster.

Simulation results demonstrate that the proposed algorithm efficiently reduces energy consumption especially in dense networks, increases the packet delivery ratio especially in sparse networks, and decreases the average end-to-end delay in both sparse and dense networks, in comparison with the four routing algorithms VBF, HH-VBF, VBVA, and ES-VBF. It is interesting to note that our multiple-cluster algorithm is a good generalization to the VBF protocol. The VBF results from our algorithm by adopting the special case of single-cluster manipulation.

ACKNOWLEDGMENT

We would like to thank the (anonymous) reviewers for their helpful comments.

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