VBF: Vector-Based Forwarding Protocol for Underwater Sensor Networks

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Abstract. In this paper, we tackle one fundamental problem in Underwater Sensor Networks (UWSNs): robust, scalable and energy efficient routing. UWSNs are significantly different from terrestrial sensor networks in the following aspects: low bandwidth, high latency, node float mobility (resulting in high network dynamics), high error probability, and 3-dimensional space. These new features bring many challenges to the network protocol design of UWSNs. In this paper, we propose a novel routing protocol, called vector-based forwarding (VBF), to provide robust, scalable and energy efficient routing. VBF is essentially a position-based routing approach: nodes close to the "vector" from the source to the destination will forward the message. In this way, only a small fraction of the nodes are involved in routing. VBF also adopts a localized and distributed self-adaptation algorithm which allows nodes to weigh the benefit of forwarding packets and thus reduce energy consumption by discarding the low benefit packets. Through simulation experiments, we show the promising performance of VBF.

1 Introduction

Recently, sensor networks have emerged as a very powerful technique for many applications, including monitoring, measurement, surveillance and control. The idea of applying sensor networks in underwater environments (i.e., forming underwater sensor networks (UWSNs)) has been advocated by many researchers [1, 4, 2]. Even though underwater sensor networks (UWSNs) share some common properties with terrestrial sensor networks, such as dense deployment and limited energy, UWSNs are significantly different from terrestrial sensor networks in many aspects: low bandwidth, high latency, node float mobility (resulting in high network dynamics), high error probability, and 3-dimensional space [2]. These new features bring many challenges to the protocol design of UWSNs. In this paper, we tackle one fundamental problem in UWSNs: robust, scalable and energy efficient routing.

Routing Challenges in UWSNs Same as in terrestrial sensor networks, saving energy is a major concern in UWSNs. At the same time, UWSN routing should be able to handle node mobility. This requirement makes most existing energy-efficient routing protocols unsuitable for UWSNs. Most routing protocols proposed for terrestrial sensor networks are mainly designed for stationary networks or networks with limited mobility of the sinks. They usually employ query flooding as a powerful method to discover data delivery paths. In UWSNs, however, most sensor nodes are mobile, and the network topology changes very rapidly even with small displacements due to strong multipath. The frequent maintenance and recovery of forwarding paths is very expensive in high dynamic networks, and even more expensive in dense 3-dimensional UWSNs. Thus, to provide scalable and efficient routing in UWSNs, we have to seek for new solutions. In this paper, we investigate this challenging routing problem in UWSNs, with scalability and energy efficiency as the design objectives. Moreover, robustness is also an important concern due to the high node failure rate and error-prone channels in UWSNs.

Contributions In this paper, we propose a novel routing protocol, called vector-based forwarding (VBF), to address the routing problem in UWSNs. VBF is robust, scalable and energy efficient. It is essentially a location-based routing approach. No state information is required on the sensor nodes and only a small fraction of the nodes are involved in routing. Moreover, in VBF, packets are forwarded along redundant and interleaved paths from a source to a destination, thus VBF is robust against packet loss and node failure. Further, we develop a localized and distributed self-adaptation algorithm to enhance the performance of VBF. The self-adaptation algorithm allows nodes to weigh the benefit of forwarding packets and thus reduce energy consumption by discarding low benefit packets. We evaluate the performance of VBF through extensive simulations. Our experiment results show that for networks with small or medium node mobility (1 m/s-3 m/s), VBF can effectively achieve the goals of robustness, energy efficiency, and high success of data delivery.

2 Vector-Based Forwarding Protocol (VBF)

2.1 Overview of VBF

Vector-Based Forwarding (VBF) protocol addresses the node mobility issue in a scalable and energy-efficient way. In VBF, each packet carries the positions of the sender, the target and the forwarder (i.e., the node which forwards this packet). The forwarding path is specified by the routing vector from the sender to the target. Upon receiving a packet, a node computes its relative position to the forwarder by measuring its distance to the forwarder and the angle of arrival (AOA) of the signal[3]. Recursively, all the nodes receiving the packet compute

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[3] We assume that sensor nodes in UWSNs are armed with some devices that can measure the distance and the angle of arrival (AOA) of the signal. This assumption is justified by the fact that acoustic directional antennae are of much smaller size than RF directional antennae due to the extremely small wavelength of sound. Moreover, underwater sensor nodes are usually larger than land-based sensors, and they have room for such devices [8].

their positions. If a node determines that it is close to the routing vector enough (e.g., less than a predefined distance threshold), it puts its own computed position in the packet and continues forwarding the packet; otherwise, it simply discards the packet. Therefore, the forwarding path is virtually a routing “pipe” from the source to the target: the sensor nodes inside this pipe are eligible for packet forwarding, and those outside the pipe do not forward.

2.2 The Basic VBF Protocol

In VBF, each packet carries positions of the sender, the target and the forwarder in three fields, represented by **SP**, **TP** and **FP** respectively. In order to handle node mobility, each packet contains a **RANGE** field. When a packet reaches the area specified by its TP, this packet is flooded in an area controlled by the **RANGE** field. The routing pipe is define by the vector from the sender (with position SP) to the target (with position TP) and the radius of the pipe is defined in the **RADIUS** field. Routing in VBF is initiated by query packets. VBF routes different queries in different ways:

(1) Sink_Initiated Query There are two types of such queries: one is location-dependent query in which the sink is interested in some specific area and knows the location of the area; another is location-independent query in which the sink wants to know some specific type of data regardless of its location. For a location-dependent query, the sink issues an **INTEREST** query packet, which carries the coordinates of the sink and the target in the sink-based coordinate system, i.e., it has the information of SP and TP. This query is then directed to the targeted area following the pipe defined by SP and TP. For a location-independent query, the TP field of the INTEREST packet is invalid, and this query will be *flooded* to the target nodes. Upon receiving such query, the intended nodes can compute their locations in the sink-based coordinate system and then direct the subsequent data packets to the sink.

(2) Source_Initiated Query If a source initiates a transmission, it first sets up a coordinate system originated at itself and floods **DATA_READY** packet into the network. Therefore, each node (including sink) can compute its location in the source-based coordinate system. The sink transforms the position of the source into its own coordinate system, and sends a location-dependent INTEREST packet to the source to allow the source to compute its position in the sink-based coordinate system for the subsequent communication.

2.3 The Self-Adaptation Algorithm

In the basic VBF protocol, all the nodes inside the routing pipe are qualified to forward packets. This is not necessary in a dense network. To save energy, it is desirable to adjust the forwarding policy based on the local node density. Due to the mobility of the nodes in the network, it is infeasible to determine the global node density. Moreover, it is inappropriate to measure the density at the transmission ends (i.e., the sender and the target) because of the low propagation speed of acoustic signals. We propose a self-adaptation algorithm for VBF to allow each node to estimate the density in its neighborhood (based on local information) and adjust its forwarding accordingly.

Desirableness Factor We introduce the notion of **desirableness factor** to measure the "suitableness" of a node to forward packets.

Definition 1. *Given a routing vector* $\overrightarrow{S_1S_0}$*, where* S_1 *is the source and* S_0 *is the sink, for forwarder* F*, the* **desirableness factor***,* α*, of a node* A*, is defined as* $\alpha = \frac{p}{W} + \frac{(R - d \times cos\theta)}{R}$*, where* p *is the projection of* A *to the routing vector* $\overrightarrow{S_1S_0}$*,* d *is the distance between node* A *and node* F*, and* θ *is the angle between vector* $\overrightarrow{FS_0}$ *and vector* $\overrightarrow{FA}$*.* R *is the transmission range and* W *is the radius of the "routing pipe".*

For a node, if its desirableness factor is large, then it is not desirable for this node to continue forwarding the packet. If the desirableness factor of a node is 0, then this node is on both the routing vector and the edge of the transmission range of the forwarder. We call this node as the **optimal node**, and its position as the **best position**. For any forwarder, there is at most one optimal node and one best position. If the desirableness factor of a node is close to 0, it means this node is close to the best position.

The Algorithm When a node receives a packet, it first computes its position and determines if it is in the routing pipe. If yes, the node then holds the packet for a time interval $T_{adaptation}$ calculated as follows:

$$T_{adaptation} = \sqrt{\alpha} \times T_{delay} + \frac{R - d}{v_0}, \tag{1}$$

where T_{delay} is a pre-defined maximum delay, v_0 is the propagation speed of acoustic signals in water, i.e., 1500m/s, and d is the distance between this node and the forwarder. In the equation, the first term reflects the waiting time based on the node's desirableness factor: the more desirable (i.e., the smaller the desirableness factor), the less time to wait. The second term represents the additional time needed for all the nodes in the forwarder's transmission range to receive the acoustic signal from the forwarder. When two nodes are very close to the best position, Equation 1 can enlarge the delay time interval between these two nodes. During the delayed time period $T_{adaptation}$, if a node receives duplicate packets from n other nodes, then this node has to compute its desirableness factors relative to the original forwarder and these nodes $\alpha_0, \alpha_1, \ldots, \alpha_n$. If $min(\alpha_0, \alpha_1, \ldots, \alpha_n) < \alpha_c/2^n$, where α_c is a pre-defined initial value of desirableness factor ($0 \leq \alpha_c \leq 3$), then this node forwards the packet; otherwise, it discards the packet. The theoretical analysis can be found in [8].

2.4 Performance Evaluation

We evaluate the performance of VBF through extensive simulations. We define three metrics to quantify the performance of VBF: success rate, energy consumption and average delay. 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 approximated by *communication time*, which is measured by the total time spent in communication, including transmission time and receiving time of all nodes in networks. The *average delay* is the average end-to-end delay for each packet received by the sink.

In our simulations, sensor nodes are deployed uniformly in a space of 100 × 100 × 100. They can move in horizontal two-dimensional space, i.e., in the X-Y plane (which is the most common mobility pattern in underwater applications). The transmission range is set to 20 meters. In order to have a bigger number of hops, the source and the sink are fixed at (90,90,100) and (10,10,0), respectively. All other nodes in the network are mobile with the same movement pattern (random walk) unless specified otherwise. The source sends data packets at the rate of 2 packets per second. The data packet size is 76 bytes and control packet is 32 bytes. The total simulation time is 200 seconds.

We first investigate the impact of node density and mobility. In this set of experiments, all the mobile nodes have the same speed. The routing pipe radius is fixed at 20 meters. We vary the mobility speed of each node from 0 m/s to 5 m/s and the number of nodes from 500 to 1500. The simulation results are plotted in the Fig. 1, Fig. 2 and Fig. 3. This set of simulation experiments have shown that in VBF, node speed has little impact on success rate, energy consumption and average delay. It demonstrates that VBF could handle node mobility very effectively.

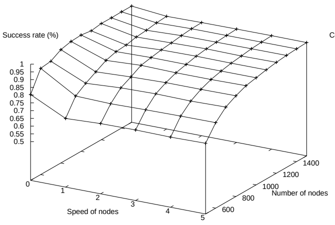

Fig. 1. Impact on success rate

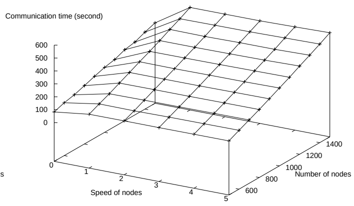

Fig. 2. Impact on comm. time

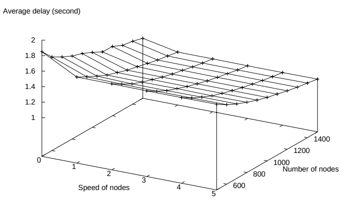

Fig. 3. Impact on average delay

We have also conducted simulations to show the impact of the routing pipe radius, the effectiveness of the self-adaptation algorithm, and the robustness of VBF. Due to space limit, we will not show the results in this paper. Interested readers can refer to our technical report [8].

3 Related Work and Conclusion Remarks

VBF is essentially a geographic routing protocol. To our best knowledge, VBF is the first effort to apply the geo-routing approach in underwater sensor networks. In the literature, there are many geographic routing protocols [6, 5, 3, 7, 9], in which location information of nodes is used to determine the forwarding route. Compared with VBF, these protocols assume that the location service (i.e., positioning the nodes) is available. Thus, they do not address how to position nodes in a highly dynamic network, which in fact is the foundation of the VBF protocol. Moreover, in order to save energy, VBF adopts a self-adaptation algorithm to allow nodes to weigh the benefit of forwarding packets. This idea shares some similarity with the timer-based contention algorithm in CBF protocol [3]. The major differences between these two algorithms are two-fold: (1) the timer-based contention algorithm is designed for 2-dimensional space, not for 3-dimensional UWSNs; (2) the timer-based contention algorithm can not suppress the duplicate packets from nodes close to the optimal position.

In summary, VBF is a novel protocol designed to address the routing challenges in UWSNs. It is scalable, robust and energy efficient. Through extensive simulations, we demonstrated that for networks with small or medium node mobility (1 m/s-3 m/s), VBF can effectively achieve the goals of robustness, energy efficiency, and high success of data delivery.

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