An Enhancing VBF Protocol for AUVs: Integrating Uncertainty Management and Energy Efficiency

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I. Introduction

Autonomous Underwater Vehicles (AUVs) play a crucial role in applications such as deep-sea exploration and military operations. However, variations in temperature, salinity, and depth affect the speed of sound, leading to communication delays and signal degradation. These environmental factors introduce uncertainties that complicate effective communication and may increase energy consumption as AUVs sometimes need to expend additional power to maintain connectivity due to the position drift.

Current solutions primarily focus on improving energy efficiency but overlook the impact of these environmental uncertainties on underwater communication. For instance, VBF (Vector-Based Forwarding) creates a virtual directional pipeline from the source to the sink, with relay nodes forwarding messages after a holding period based on their proximity to the destination [2]. LE-VBF (Localization-Based Enhanced VBF) refines this process by adjusting the virtual pipe's dimensions according to node locations, aiming to minimize deviations [1]. DBR (Depth-Based Routing) simplifies routing by using the depth information of each node to direct packets upward towards surface sinks [3]. However, these protocols are designed mainly for static network and do not address the inaccuracies in node localization, leading to sub-optimal routing decisions and increased energy consumption in dynamic underwater settings.

To address these challenges, our research introduces an enhancement to the VBF protocol by incorporating an energy factor into the waiting time calculations and using an optimization tool, Gurobi, to fine-tune the calculation. This enhancement allows nodes to account for their residual energy, optimizing the timing of message relays to balance energy consumption and communication efficiency. Our approach finds the worst case of the network scenario with uncertainties and leverages the Gurobi to find the optimal output of the waiting time calculation formula, ensuring efficient data transmission while minimizing energy usage. Our goal is to extend the network's lifetime and enhance the reliability of underwater communications.

The effectiveness of our methods is validated through metrics such as network lifetime, packet delivery ratio, energy consumption distribution, and end-to-end delay. These improvements demonstrate the potential of our enhanced VBF protocol to address the dynamic challenges inherent in underwater communication, providing a more robust and energy-efficient solution.

II. System Model

This section introduces an enhanced VBF protocol, which is designed to manage uncertainties and improve energy efficiency. Initially, we describe the original VBF protocol and its workflow. Subsequently, we incorporate uncertainties into the VBF protocol to better reflect actual operational conditions. Next, an energy factor is integrated into the waiting time calculation equation to optimize energy usage. Lastly, we employ the Gurobi optimization tool to derive the optimal waiting times, taking into account both energy conservation and the uncertainties.

A. Background of VBF Routing Protocol

The network model includes a source node (o) at the ocean's bottom and a sink node (t) at the surface, connected by nine intermediate relay nodes, which is shown in Figure 1. Each relay has a defined communication range (R) and participates in data transmission within a virtual pipe of width W. Relay nodes within this pipe actively engage in forwarding messages, calculating their waiting time based on the projection (p), the distance to the previous node (d), and the angle (θ). The waiting time formula is given by:

$$\text{WaitingTime} = \left(\frac{p}{W}\right) + \left(\frac{R - d \cdot \cos(\theta)}{R}\right). \tag{1}$$

B. Incorporating Uncertainty into VBF

We enhance the VBF protocol by introducing uncertainties within a defined noise range $pos.x \pm \Delta$, $pos.y \pm \Delta$, and $pos.z \pm \Delta$. These adjustments impact node coordinates, altering subsequent calculations to reflect more realistic operational conditions.

C. Waiting Time Calculation with Uncertainty

1) Calculation of Projection: The projection p measures the perpendicular distance from a node to the line from the source (o) to the sink (t), critical for routing:

$$p = \frac{\sqrt{(v_y w_z - v_z w_y)^2 + (v_z w_x - v_x w_z)^2 + (v_x w_y - v_y w_x)^2}}{\sqrt{(t.x - o.x)^2 + (t.y - o.y)^2 + (t.z - o.z)^2}}, \tag{2}$$

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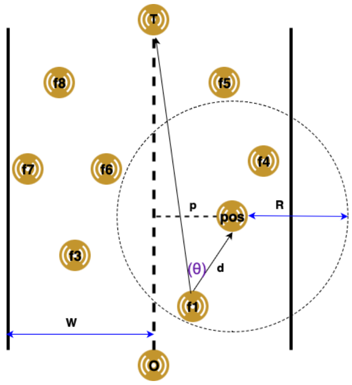


Fig. 1: Overview of the Network Model

where $\vec{w}$ is the vector from o to t, and $\vec{v}$ is the vector from the node position to o.

2) Distance and Angle Calculation: We calculate the distance d and the cosine of the angle θ to aid in routing decisions:

$$d = \sqrt{(pos.x - f.x)^2 + (pos.y - f.y)^2 + (pos.z - f.z)^2}, \tag{3}$$

$$\cos(\theta) = \frac{dx \cdot dtx + dy \cdot dty + dz \cdot dtz}{d \cdot \sqrt{dtx^2 + dty^2 + dtz^2}}. \tag{4}$$

3) Waiting Time Calculation: Compared to Equation 1, our equation consider the energy factor and use Gurobi to optimize the waiting times:

$$\text{WaitingTime}_i = \left(\frac{p_i}{W}\right) + \left(\frac{R - d_i \cdot \cos(\theta_i)}{R}\right) + \frac{e_{c_i}}{e_{i_i}}. \tag{5}$$

Constraints: Positional uncertainties within the noise range Δ are accounted for to ensure robust communication:

$$\mathbf{pos}_i - \Delta \leq \mathbf{pos}_i \leq \mathbf{pos}_i + \Delta. \tag{6}$$

Optimization Procedure: We apply Gurobi's quadratic programming to refine waiting times, enhancing the efficiency and reliability of communications under dynamic conditions.

III. Initial Results and Ongoing Work

This section outlines the preliminary results of our enhancements to the VBF protocol, focusing on the integration of a fixed noise model into node locations to understand its impact on network performance, including energy consumption and end-to-end delay. The experiments, conducted using the Aqua-sim NG simulator, show key points into the behavior of the network under varying conditions and set the stage for ongoing efforts to handle the uncertainties by using optimization tool.

A. Experiment Setup

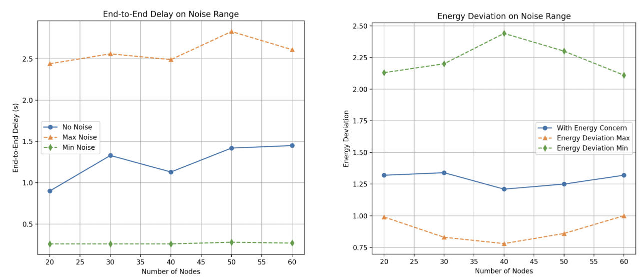
The simulations were conducted using the Aqua-sim NG simulator. Node is uniformly generated in a 100*100 area and counts ranged from 10 to 60. The power settings were 2 watts for transmission, 0.75 watts for reception, and 0.008 watts in idle mode. We utilized the AquaSim-Broadcast MAC protocol, and the Thorp attenuation model was employed for signal degradation.

B. Energy Consumption Distribution

From Figure 2b, it is evident that with the maximized waiting time for each node, the energy consumption across the network tends to be more uniform, and the rate of energy reduction is slower. In contrast, when minimizing the waiting time for each node, nodes located closer to the sink tend to lose their energy more rapidly, resulting in an uneven distribution of energy consumption.

C. End-to-end delay

From Figure 2a, it shows that in a noise-free environment, the delay remains consistently low regardless of the number of nodes, whereas in noisy conditions, especially at maximum noise, the delay peaks with increasing node density. This highlights how noise impacts network performance, with minimal noise allowing for more efficient data transmission even as the network scales up.



(a) End-to-End Delay on Noise Range

(b) Energy Consumption by Node

Fig. 2: Performance Metrics

D. Ongoing Work

We have already incorporated an energy factor into the waiting time calculations to account for energy consumption. Moving forward, we plan to use Gurobi to optimize the objective function, aiming to determine the optimal waiting times for each node under conditions of uncertainty.

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