Performance Analysis of Two Data Delivery Schemes for Underwater Sensor Networks

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ABSTRACT

Underwater Sensor Networks (UWSNs) comprise sensor nodes that communicate over multiple wireless hops to perform collaborative tasks such as environmental monitoring, military surveillance, and oceanic exploration. Acoustic waves are used for underwater transmission, resulting in a communication channel that suffers from limited bandwidth, high delay, and high transmission loss. Existing data delivery schemes designed for terrestrial sensor networks are unsuitable for use in the underwater environment; several new schemes have been proposed for underwater use. In this paper, we provide an analysis of two data delivery schemes: Vector Based Forwarding and the Multipath Virtual Sink architecture, observing performance under varying network size, network density, and traffic load, and conclude by highlighting characteristics from each scheme that are helpful in Underwater Sensor Networks.

1. INTRODUCTION

The beautiful and mystical ocean remains one of the most unexplored and inaccessible regions on earth. Underwater Sensor Networks (UWSNs) are proposed as a means for oceanic observation, offering new capabilities such as real time monitoring, remote configuration, and improved robustness. An UWSN comprises sensor nodes — mounted on underwater vehicles, attached to surface buoys, or anchored to the seabed — which communicate wirelessly and collaborate to observe physical conditions such as temperature, motion, or pollutant levels. UWSNs have a wide variety of useful applications: early warning systems for natural disasters, environmental monitoring, oil rigging, military surveillance, and scientific oceanic research.

Underwater networking research is still in its infancy, with a few data delivery schemes proposed for underwater use, and no single scheme accepted as the standard. In this paper, we provide an analysis of two proposed data delivery schemes: the Multipath Virtual Sink architecture (Seah & Tan, 2006) and Vector Based Forwarding (Xie, Cui, & Li, 2005). We observe various performance metrics — reliability, delay, and energy consumption — under varying network size, network density, and traffic load, concluding with a summary of the features desirable in an UWSN data delivery scheme.

This paper is organised as follows. In Section 2, we discuss challenges faced in underwater networks. In Section 3, we study two data delivery schemes, providing a comparative analysis in Section 4; finally, we conclude in Section 6 by summarising key ideas in each scheme which prove effective for underwater data delivery.

2. CHALLENGES IN UNDERWATER NETWORKING

Propagation of radio waves underwater suffers from high attenuation; hence, acoustic waves are used for communication instead (Stojanovic, 2003), causing UWSNs to have radically different features from terrestrial sensor networks (Akyildiz, Pompili, & Melodia, 2005):

- **Limited bandwidth and low transmission rates.** Water absorbs energy from acoustic waves, causing bandwidth to be extremely limited in the underwater channel, with transmission typically on the order of tens of kbps.

- **High transmission loss.** Acoustic links experience severe transmission loss due to multi-path, signal attenuation, and geometric spreading. Noise is unpredictable and bursty, coming from marine life, human aquatic activity, and natural phenomena such as storms. These conditions give birth to a harsh environment characterized by high signal loss, fluctuating link quality, and intermittent link connectivity.

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- **High latency.** Acoustic waves propagate underwater at about 1500 m/s, five orders of magnitude slower than radio waves, possibly traveling along curved, irregular paths as well. This results in high transmission delays and delay variance.

- **Sparse and three-dimensional deployment.** Underwater sensor nodes are waterproof, resistant to corrosion, and can withstand high water pressures, making them costly and more likely to be deployed in sparse topologies. Furthermore, applications which monitor an ocean column require three-dimensional deployment.

Existing data delivery schemes designed for use in terrestrial sensor networks cannot cope with such harsh conditions, thus compeling the development of new schemes.

3. UNDERWATER DATA DELIVERY

Data delivery schemes are designed to tackle the problem of relaying data from sensors to sinks. A few data delivery schemes have been proposed for use in UWSNs. We present two schemes: the Multipath Virtual Sink architecture, and Vector Based Forwarding, with a focus on the data delivery aspect — how data packets journey from sources to the sink — and omit details such as route discovery and query processing.
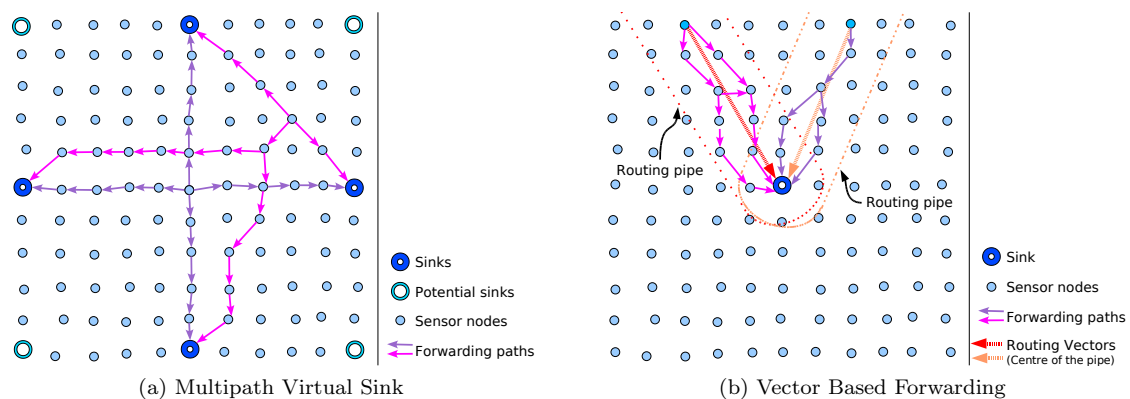

(a) Multipath Virtual Sink (b) Vector Based Forwarding

Figure 1: Two Data Delivery Schemes

3.1. Multipath Virtual Sink Architecture

The Multipath Virtual Sink Architecture (MVS), illustrated in Figure 1a, offers two key ideas: spatially diverse sinks, and simultaneous retransmission. Key features of MVS include:

Multi-path forwarding to spatially diverse sinks. Traffic from sensor nodes typically converge toward a sink, causing congestion in the area around the sink. To resolve this, MVS places sinks at network boundaries, spaced equally apart from one another, and connected to some centralized control via high-speed wired links. This forms a *virtual sink*. Sensor nodes will then have to deliver data to at least one of the sinks; data flows through multiple diverging paths, reducing contention at sinks, and allowing packets to avoid congested regions.

Fixed-path forwarding. A simple reverse-path forwarding mechanism is used to deliver data from source to sink. All nodes maintain a routing table with the next hop for each sink, using number of hops as the forwarding metric. An initialization period takes care of path setup. Forwarding paths remain permanently fixed throughout the network lifetime.

Simultaneous retransmission. Harsh channel conditions provide packets a dismal chance of survival over multiple hops. In radio frequency networks, ARQ techniques are used to improve reliability at the link layer, but high and fluctuating delays underwater make re-transmissions grossly inefficient. MVS proposes a novel solution: sources transmit packets *simultaneously* instead of sequentially, to provide reliability and yet avoid delay and signaling overheads.

3.2. Vector Based Forwarding

Vector Based Forwarding (VBF), illustrated in Figure 1b, can be described as a position-based scheme which employs controlled flooding, with the following features:

Localization. A key assumption made in VBF is that sensor nodes are capable of measuring both the distance travelled by a signal, and its angle of arrival. With this information, nodes can calculate their position relative to the signal source, without global localization information.

Multi-path forwarding within a routing pipe. VBF uses a *routing pipe*, a cylindrical region centred around a straight line from source to sink, to deliver data along multiple paths. Only nodes within the routing pipe can forward packets. To achieve this, the pipe's centre is attached to packets as a *routing vector*, specifying coordinates of source, sink, and previous hop (all coordinates are relative to the source). The *optimal path* comprises a chain of nodes situated along the routing vector and on the fringe of each others' transmission range.

Variable-path forwarding. Unlike MVS, forwarding paths are not fixed. Rather, every packet transmitted by a node can potentially spawn new paths within the routing pipe.

Adapting to network density. As flooding within the routing pipe may cause contention, VBF attempts to estimate local node density and to limit the number of nodes which actually forward packets. Upon receiving a packet, a node calculates its deviation, or *desirableness factor*, from the optimal path, as a measure of its suitability for forwarding that packet. Nodes nearer to the routing vector and further away from the previous hop are considered more suitable than those further from the routing vector and nearer to the previous hop. The packet is buffered for some time before being forwarded; this time interval, or *adaptation delay*, is proportional to the desirableness factor, with zero delay for nodes on the optimal path. During this time, the node may overhear neighboring nodes forward the same packet. It may be useless to forward the packet again, thus requiring the node to compare its desirableness factor relative to its neighbours and to decide whether to forward or drop the packet.

4. SIMULATIONS AND ANALYSIS

In this section, we study and compare MVS and VBF through simulations, using the Qualnet simulator[3]. To model the underwater channel, we change several parameters in our simulator: signal propagation speed is set to 1500 m/s, the speed of sound in water; spherical spreading and Rayleigh fading are used to model transmission losses and multi-path effects (Etter, 2003). We model our nodes after the LinkQuest UWM1000 underwater acoustic modem, having a bitrate of $7kbps$ and transmission range of $200m$[4]. To avoid drifting away with the currents, underwater sensor nodes must be anchored to the seabed. Consequently, we consider stationary nodes deployed uniformly across a rectangular area.

In our simulations, we assume that paths to the sinks are set up, i.e. the initialization phase for MVS completes successfully, and all sources under VBF are aware of the sink coordinates. We also assume that a signal's angle-of-arrival and distance travelled are accurately available to nodes. For MVS, sinks are placed along the network boundaries at equal distances from each other; for VBF, a single sink is placed at the centre. Some nodes are selected as sources, evenly distributed inside the deployment area, sending 50 packets to the sink. Packets are 128 bytes long. Each source starts transmitting at a random time within $200s$ of the simulation start time. A simple CSMA scheme is used at the MAC layer, and all results are averaged over 30 trials.

MVS and VBF have configurable parameters. For MVS, we can change the number of sinks; for VBF, the desirableness modifier a_c and adaptation delay modifier T_{delay}. A lower value for a_c means that nodes must be closer to the optimal path before they will forward packets, and a lower value for T_{delay} reduces the buffer time. In our simulations, we choose parameters as given in the original papers, with a few variants. Altogether, three variants are chosen for VBF (denoted as $VBF_{a_c,T_{delay}}$): $VBF_{0.5,200}$, $VBF_{1.5,200}$ and $VBF_{1.5,600}$, and two variants for MVS: MVS_4 with 4 sinks, and MVS_8 with 8 sinks. $VBF_{1.5,200}$ and MVS_4 are from the original papers.

4.1. Performance Metrics

In our simulations, each packet generated by the sources is assigned a unique sequence number. Since MVS and VBF both employ multi-path forwarding, several copies of a given packet may arrive at the sink. We

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[3]Qualnet Simulator from Scalable Networks, Inc. http://www.scalable-networks.com
[4]LinkQuest Inc., UWM1000 Acoustic Modem, http://www.link-quest.com/html/uwm1000.htm

refer to the first copy of a packet arriving at the sink as a *distinct* packet, and subsequent copies as *duplicate* packets.

Furthermore, when evaluating MVS, we regard all sinks as collectively forming a single virtual sink, and a packet is considered as being delivered successfully to the virtual sink when its *first* copy arrives at any one of the physical sinks. We study and evaluate performance of the various schemes using the following set of metrics:

- **Packet Delivery Ratio (PDR).** PDR is the prime measure of reliability. We define PDR to be the number of distinct packets received successfully at the sink, as a fraction of the total number of packets produced by source nodes.

- **Average end-to-end delay.** The average end-to-end delay is given by the average time taken for a packet to reach the sink.

- **Total number of transmissions.** The total number of transmissions at the physical layer by all nodes provides an estimate of power consumption. This metric should be viewed in relation to PDR, since there is often a tradeoff between energy consumption and reliability.

We observe these metrics under varying network density, network size, packet interval, and number of sources.

4.2. Results: Varying Network Size

In this experiment, we investigate the scalability of both schemes with respect to network size. We vary the number of nodes from 36 to 400, keeping the distance between nodes at $125m$, and scaling the area of deployment proportionately, from $0.625km \times 0.625km$ to $2.625km \times 2.625km$. 25% of nodes are chosen as sources, sending packets at $180s$ intervals. Results are shown in Figure 2.

(a) Packet Delivery Ratio vs Network Size

(b) End-to-End Delay vs Network Size

(c) Transmissions vs Network Size
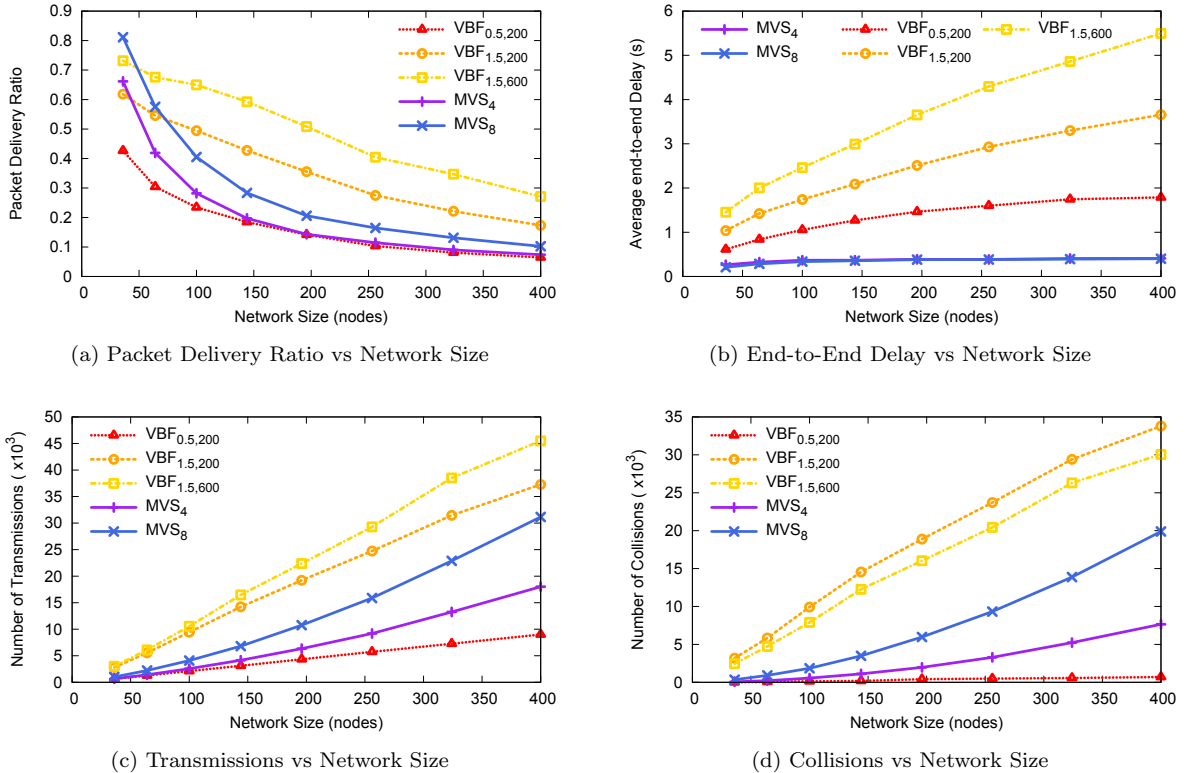
(d) Collisions vs Network Size

Figure 2: Performance Under Varying Network Size

Figure 2a shows the Packet Delivery Ratio for the network. Both MVS schemes show a rapidly decreasing PDR, due to the use of fixed-path forwarding. Packets traversing a fixed path are highly vulnerable to link

breaks: the probability of successful delivery decreases exponentially with the number of hops, and a single transmission failure between any two hops stops packet delivery along that path totally. VBF has a slower rate of decrease of PDR because forwarding paths may vary, and a transmitted packet, when received successfully by neighboring nodes, may cause each neighboring node to spawn a new path toward the sink, keeping the packet alive for a longer time.

Figure 2b shows average end-to-end delay. Delay increases under the VBF schemes because distance to the sink is increased for nodes on the edge of the deployment area, and a fair number of packets from these nodes are still able to reach the sink. For MVS, packets from the centre of the network are furthest from the virtual sink and incur the longest delay, but they are also least likely to arrive at the sink; majority of packets are then received from areas near the sink, giving MVS a low and constant delay. Both MVS schemes have similar delay because the additional 4 sinks in MVS_8 are placed at the corners and a packet is more likely to reach sinks along the sides first, rather than sinks at the corners.

The number of physical-layer transmissions is shown in Figure 2c. It increases for all schemes due to more hops being traversed by each packet. On average, $VBF_{0.5,200}$ expends less power than MVS_4, yet is able to match the PDR of MVS_4 at network sizes beyond 150 nodes. Comparing the schemes with highest reliability, we find that on average, $VBF_{1.5,600}$ requires 2.2 times as much power as MVS_8 to deliver twice as many packets.

4.3. Results: Varying Network Density

In this experiment, we observe the impact of network density on performance. We vary the number of nodes from 36 to 400, confined within a $1km \times 1km$ area. 25% of nodes are chosen as sources, sending at $180s$ intervals. Our results are shown in Figure 3.
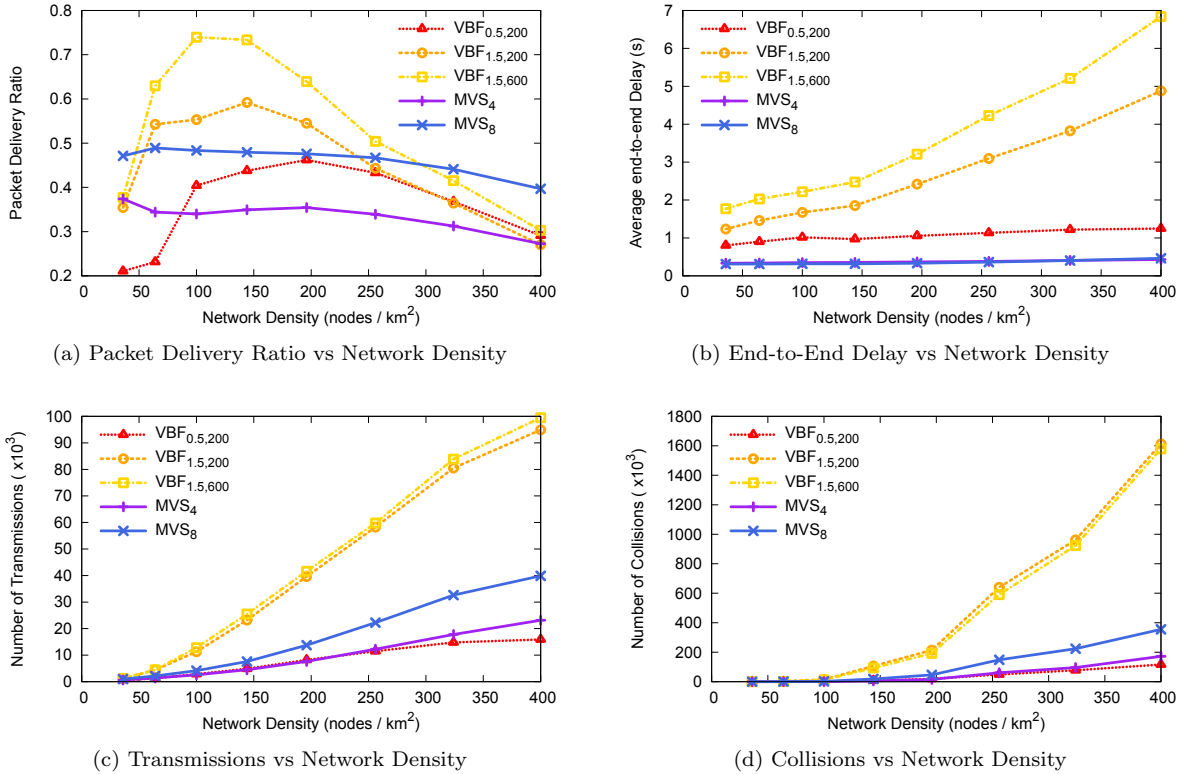

(a) Packet Delivery Ratio vs Network Density

(b) End-to-End Delay vs Network Density

(c) Transmissions vs Network Density

(d) Collisions vs Network Density

Figure 3: Performance Under Varying Network Density

For all VBF schemes, PDR increases with network density, up to about 150 nodes/km^2, because more nodes aid in the delivery process. Unfortunately, as shown in Figure 3d, collisions in the network show a great increase, eventually causing a decline in PDR. The problem stems from VBF's density adaptation mechanism: nodes closer to the optimal path can forward more packets and enjoy low adaptation delay; at

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high node densities, there are too many such nodes which forward packets eagerly, increasing the number of collisions. Due to collisions, neighboring nodes fail to overhear other copies of packets; thinking that no nodes in the vicinity are transmitting, they proceed to forward their own buffered packets, worsening congestion in the area. MVS schemes also have a problem with collisions at higher node densities, but by using diverging paths, collisions increase at a far slower rate and PDR decreases slowly as well.

In the VBF paper, delay decreases with increasing node density, but this is achieved by using a high bitrate of $500kbps$, which incurs a drastically lower collision rate. This is not the case in our simulations. Under VBF, congestion along the pipe's centre causes successfully delivered packets to be forwarded by nodes near the edge of the routing pipe or closer to the previous hop. Packets are buffered with a longer adaptation delay at these nodes; moreover, increased network density puts more intermediate nodes between source and sink, so packets route through more hops before reaching the sink. As a result, delay increases for $VBF_{0.5,200}$ and $VBF_{1.5,600}$. MVS does not buffer packets and attempts to take the shortest path to each sink, therefore both MVS schemes incur much lower delay, fairly independent of network density.

On average, $VBF_{1.5,600}$ consumes about 2.6 times as much power than MVS and delivers 1.2 times as many packets. $VBF_{0.5,200}$ is remarkably different from the other VBF schemes: compared to MVS_4, it consumes similar amounts of energy, but attains higher PDR, comparable delay, and causes a low number of collisions as well.

4.4. Results: Varying Packet Interval

In this experiment, we observe the effect of packet interval on performance. 100 nodes are deployed in a $1km \times 1km$ area, with 25 sources sending at intervals between $5s$ to $180s$. Results are shown in Figure 4, using a reversed x-axis.

(a) Packet Delivery Ratio vs Packet Interval

(b) End-to-End Delay vs Packet Interval

(c) Transmissions vs Packet Interval

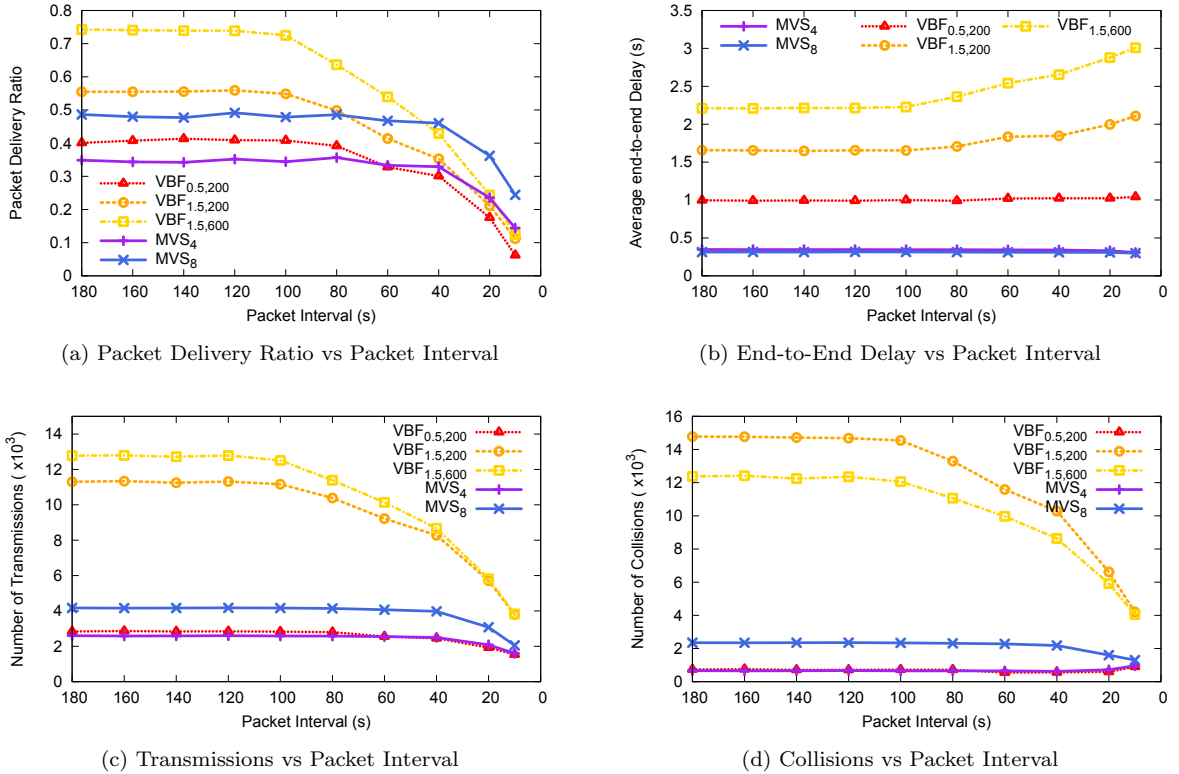(d) Collisions vs Packet Interval

Figure 4: Performance Under Varying Packet Interval

Sending data at smaller intervals introduces congestion into the network. VBF's forwarding paths converge at the sink, making it more vulnerable to congestion than MVS, which uses diverse paths; consequently, VBF starts to see a decline in PDR from $100s$, while MVS can cope better at low packet intervals, enjoying a stable PDR up to $40s$.

Under congestion, packets in VBF tend to traverse sub-optimal paths, causing average end-to-end delay to increase. MVS continues to deliver packets with low delay.

When PDR is stable, $VBF_{1.5,600}$ consumes 3 times as much power as MVS_8 to deliver 1.5 as many packets. On average, $VBF_{1.5,600}$ consumes 2.6 times as much power as MVS_8 to deliver 1.2 times as many packets. $VBF_{0.5,200}$ expends the same amount of power as MVS_4, yet provides higher reliability for intervals greater than $60s$.

4.5. Results: Varying Number of Sources

In this experiment, we observe performance under a varying number of sources. 100 nodes are deployed in a $1km \times 1km$ area, with between 10 to 100 sources sending at $180s$ intervals. We present the results in Figure 5.

(a) Packet Delivery Ratio vs Number of Sources

(b) End-to-End Delay vs Number of Sources

(c) Transmissions vs Number of Sources

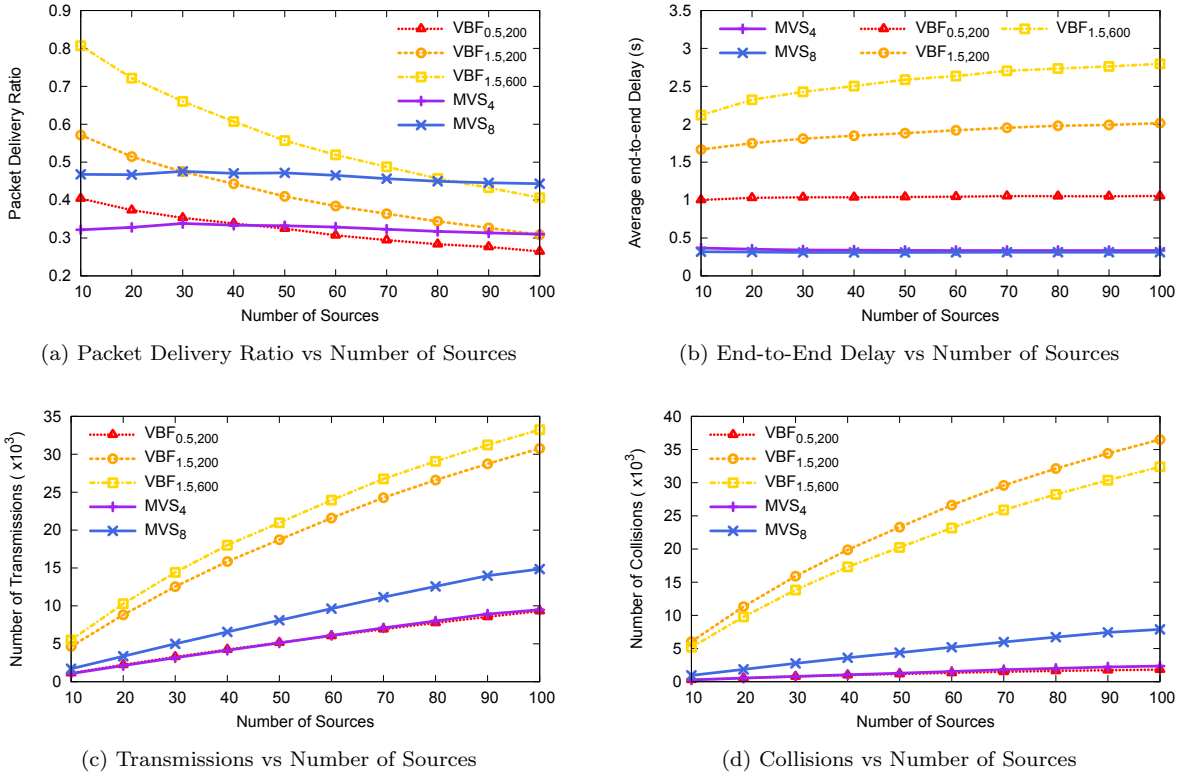(d) Collisions vs Number of Sources

Figure 5: Performance Under Varying Number of Sources

As the number of sources increases, PDR decreases under VBF. It appears that as more nodes transmit, their routing pipes begin to overlap and interfere with each other. The adaptation algorithm was designed for a single routing pipe and is unable to reduce the number of transmissions in the face of increased congestion. Moreover, converging packets cause high contention near the sink. In contrast, MVS maintains a stable PDR. By routing packets through diverse paths, some packets are able to avoid congested areas.

Average end-to-end delay increases slightly in VBF since more sources are further away from the sink. MVS maintains a low and stable delay. On average, $VBF_{1.5,600}$ consumes 2.6 times as much power as MVS_8 to deliver 1.2 times as many packets.

5. OVERALL ANALYSIS

In general, we see that VBF attains higher reliability than MVS, at the cost of higher energy consumption. Under a fixed network size of $1km \times 1km$, $VBF_{1.5,600}$ consistently outperforms MVS_8 in PDR by a factor of 1.2 on average and requires 2.6 times as many transmissions. MVS is more scalable with respect to network density, packet interval and number of traffic sources; VBF is more scalable with respect to network size. MVS consistently incurs low delay, while VBF experiences increasing delay in most scenarios.

Given the adverse underwater conditions, some redundant forwarding mechanism can help to improve reliability, but this aggravates the problem of congestion. MVS and VBF both choose to forward packets through multiple paths. VBF chooses to forward packets through paths near to each other, resulting in more congestion along forwarding paths and high contention at the sink. The approach adopted by MVS — forwarding through spatially diverse paths — proves more effective in avoiding congestion.

Fixed-path forwarding, employed in MVS, is rigid and vulnerable to the intermittent link connectivity underwater. Along each of the paths to the virtual sink, a single link break between two hops completely stops packet traversal along that path. VBF achieves higher reliability because the forwarding path can vary; nodes clustered along the forwarding path aid the delivery process, supporting packets on their way to the sink, and attaining higher reliability.

Re-transmissions provide a remedy for high transmission losses underwater. Considering that sequential re-transmission incurs unacceptable overheads, simultaneous re-transmission is used in MVS to improve reliability and minimize delay, at the cost of higher energy consumption. This is shown in the simulations, with MVS_8 consistently having a higher PDR and number of transmissions than MVS_4.

Buffering packets can improve reliability with a tradeoff in higher delay. $VBF_{1.5,600}$ attains highest PDR across all VBF schemes because it buffers packets for a longer time, allowing the underwater channel to recover before transmitting.

6. CONCLUSION AND FUTURE WORK

Underwater Sensor Networks can aid mankind's efforts in unravelling the secret mysteries of the ocean. Much work needs to be done to address data delivery issues and limitations inherent in underwater acoustic technology. In this paper, we have compared two data delivery schemes and noted interesting points for future research.

The Multipath Virtual Sink architecture presents a simple yet effective approach. To further optimize performance, it may be beneficial for sources to choose only a few paths among those available, rotating between different paths so as to avoid any collisions among spatially diverse but interleaving paths. The main drawback to MVS lies in its fixed-path forwarding method. Fortunately, MVS is versatile and other forwarding mechanisms can be used easily with MVS.

Vector Based Forwarding offers a location-based scheme that is built upon a considerably strong assumption: that nodes are equipped with signal distance and angle-of-arrival detection capabilities. In particular, accurate angle-of-arrival is difficult to achieve in a real scenario even with directional hydrophones, and in the presence of multi-path fading. It will be interesting to observe the effects of relaxing this assumption, i.e. in the presence of errors in the angle-of-arrival information, how much will the performance degradation be. To enhance VBF, optimal values for the desirableness constant, adaptation delay, and routing pipe radius might be dynamically changed to suit network conditions; the adaptation algorithm should also mitigate the effect of overlapping routing pipes.

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