Sector-based Routing with Destination Location Prediction for Underwater Mobile Networks

(Invited Paper)

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Abstract

Unlike in terrestrial sensor networks where the locations of destination nodes are often assumed to be fixed and accurately known, such assumptions are usually not valid in underwater sensor networks where the destination nodes tend to be mobile inherently, either due to their self-propelling capability, or due to random motion caused by ocean currents. As a result, many existing location-based routing protocols do not work well in underwater environments. We propose a location-based routing protocol that is designed for mobile underwater acoustic sensor networks, called "Sector-based Routing with Destination Location Prediction (SBR-DLP)". While the SBR-DLP also assumes that a node knows its own location like many other location-based routing protocols, it predicts the location of the destination node, and therefore, relaxes the need for precise knowledge of the destination's location. Through simulations, the SBR-DLP is shown to enhance the packet delivery ratio significantly when all nodes are mobile.

1. Introduction

Underwater acoustic sensor networks have recently gained interest from researchers around the world due to their vast variety of possible applications, such as oceanographic data collection, marine pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance applications, etc. [1]. One of the current research directions is in the area of networking, especially in how to design efficient routing algorithms for underwater acoustic mobile networks. Despite several similarities to terrestrial sensor networks (e.g., ad-hoc in nature, energy constraint, bandwidth limitation, etc.), there are still many differences between terrestrial and underwater networks that bring challenges when designing suitable routing algorithms.

One of the major differences from terrestrial sensor networks is that, instead of using radio waves, the underwater sensor networks utilize acoustic signals for communications. The use of acoustic signals is the most suitable choice for underwater communications due to its much lower attenuation when compared with radio waves. However, it is characterized by low bandwidth, high propagation delay, and high bit error rate. The acoustic channel's bandwidth is both frequency and range dependent [2], [3]. Specifically, a long-range system that operates over tens of kilometers may have a bandwidth of only a few kilohertz, while a short-range system operating over tens of meters may have a hundred kilohertz of bandwidth [1]. The low speed of sound in underwater causes its propagation delay to be around 0.67 s/km; this is very high compared to that of radio waves in terrestrial networks, which is often assumed to be negligible. The acoustic channel may also experience "shadow zones", where there are high bit error rates and temporary losses in connectivity, due to the extreme characteristics of the underwater channel.

Another difference is that the node density in underwater sensor networks tends to be much lower when compared to the terrestrial networks, due to the high cost of underwater sensor nodes. The sparse deployment implies that the typical assumption of fully-connected network in terrestrial sensor networks is no longer valid. Moreover, underwater sensor nodes (both mobile and "static" nodes) experience random movement due to the unpredictable ocean current, which is approximately 3-6 km/hr [4]. Depending on its speed and direction, this may further exaggerate the problem of partial connectivity.

In order to design a good routing algorithm for mobile underwater acoustic networks, the abovementioned characteristics must be taken into account. In this paper, we propose the "Sector-based Routing with Destination Location Prediction (SBR-DLP)" algorithm for such networks. Specifically, the SBR-DLP is a location-based routing scheme coupled with location prediction capability, in order to help enhance the packet delivery rate. Although several location-based routing algorithms [5]–[7] have been previously proposed for mobile underwater networks, all of them assume that the destination node is fixed and its location is known to all other nodes, which may not be suitable for fully mobile networks. In this work, we are interested in how to route a packet in a fully mobile underwater acoustic network, where the destination node is also mobile.

The remainder of this paper is organized as follows. In the next section, we discuss in detail the existing location-based routing algorithms designed for underwater sensor networks. We then present in Section 3, the proposed SBR-DLP routing algorithm. Section 4 describes the simulations that we have carried out to evaluate the performance of the proposed algorithm, and finally, we conclude in Section 5.

2. Related Work

The recent studies on routing for underwater sensor networks have focused on location-based routing techniques, as they could achieve energy efficiency through a small amount of overhead. When network topology is unavailable, other non-location-based routing algorithms typically rely on some form of flooding mechanism. However, flooding should be seriously avoided in underwater because it is very expensive in terms of bandwidth and energy consumption. Location-based routing techniques, on the other hand, eliminates the need for flooding by using location information to find the direction in which the packets should be forwarded, thus saving energy and bandwidth.

Although some location-based routing schemes (e.g., BLR [8], GFG [9], GPSR [10]) have been proposed for terrestrial networks, none of them is suitable for underwater acoustic sensor networks, because they are designed with terrestrial network characteristics in mind (e.g., dense deployment, negligible propagation delay, etc.). Hence, new routing strategies are needed for underwater networks.

The first routing algorithm designed for mobile underwater sensor networks is the *vector-based forwarding (VBF)* protocol [5]. In VBF, each of the sender's neighboring nodes determines its candidacy to be the next relay node by first computing the distance between itself and a virtual vector from the sender (S) to the destination (D), denoted as "*routing vector* $\overline{SD}$". A predefined radius from the routing vector forms a "*routing pipe*". If the node is located within this routing pipe, it is a candidate to be the next relay node. Multiple candidates compete among themselves to be the next relay node using a *desirableness factor*, which tells each node how long it should hold the packet before attempting to relay the packet. Because the desirableness factor favors the node that is located nearest to the destination, it has a higher priority of becoming the next relay (its packet holding time is shorter than others). The VBF is extended to the HH-VBF (hop-by-hop VBF) in [6], in order to overcome two problems encountered by the VBF: small data delivery ratio in sparse networks, and sensitivity to the routing pipe's radius. Instead of using a single routing pipe from the source to the destination, the HH-VBF forms the routing pipe in a hop-by-hop fashion. As a result, it can enhance the packet delivery ratio significantly.

The proposed SBR-DLP is different from both VBF and HH-VBF; instead of allowing each candidate node to decide whether it should relay the packet, the SBR-DLP lets the sender determine its next hop using information received from the candidate nodes. This eliminates the problem of having multiple nodes acting as relay nodes, which is encountered in both VBF and HH-VBF. Moreover, because of the constant radius of the routing pipe in both VBF and HH-VBF, it is possible that there is no node within the routing pipe. Another important difference is that, the SBR-DLP does not assume that the location of the destination node is fixed and accurately known to the sender node.

Focused beam routing (FBR) has been recently proposed in [7]. It is a geographical routing algorithm integrated with an open loop power control mechanism that allows the sender to select its transmit power levels from P_1 to P_n. The FBR starts with the sender broadcasting a request-to-send (RTS) to its neighbors using a certain power level (e.g., say P_i). A node hearing this RTS will first determine its distance from the routing vector $\overline{SD}$ using the sender's and destination's locations included within the RTS, as well as its own current position. The node becomes a candidate relay node only if it is positioned within a cone of angle $\pm\theta$, referred to as a "transmitting cone". Only nodes that are candidate relay nodes respond with the clear-to-send (CTS), which carry their location information. Next, among all the candidate relay nodes, the sender selects the node that is located nearest to the destination. If there is no node within the transmitting cone, the sender increases its transmit power level from P_i to P_{i+1}, where $i+1 \leq n$. If there is still no neighboring node even after the sender has exhausted its maximum power level, P_n, it will shift its cone in either right or left direction to cover the entire vicinity.

Although the SBR-DLP shares some similarities with the FBR (e.g., letting the sender decide its next relay node), there are some important differences. The FBR assumes that the destination node is fixed and its location is accurately known, while the SBR-DLP does not. In addition, instead of using a single transmitting cone that covers only a fraction of the communication area, the SBR-DLP considers the entire communication circle to locate the candidate relay nodes. Furthermore, while the FBR needs to rebroadcast the RTS every time it cannot find a candidate node within its transmitting cone, the SBR-DLP does not need to do so. Note that, even if the FBR extends its transmitting cone to an angle width of 180°, due to the lack of a collision avoidance mechanism, the CTSs from different neighbors may collide easily, which degrade performance. This problem is highly pronounced in a dense network. In the SBR-DLP, the problem has been addressed in its design.

3. The SBR-DLP Algorithm

The SBR-DLP is a location-based routing algorithm in which a sensor node does not carry any information about its neighboring nodes nor the network topology. However, each node is assumed to know its own position, and the destination node's pre-planned movements. We are more interested in applications such as sea exploration and monitoring, etc., that may require the destination node to move along with the mobile network in order to cover the entire exploration/monitoring area. For such applications, the destination node acts as a moving sink, and its movement is usually predefined prior to launching the network. This is in contrast to some other applications, where the destination node can be fixed on the water surface acting as a gateway or a sink, and is in turn connected to a high speed backbone. The destination's fixed location can be made known to all other nodes without ambiguity; this presents a less challenging problem, but it has been the focus of existing location-based routing techniques described in Section 2. Although the SBR-DLP tackles the mobility issue of the destination node by assuming that its pre-planned movements (e.g., its waypoints and their corresponding schedule) are made known to all other nodes before launching, it is important to note that the destination node may still deviate from its schedule due to the ocean current. Also, the SBR-DLP does not assume the knowledge of all other nodes' movements. In order to avoid the need for flooding, it routes a packet to the destination in a hop-by-hop fashion, instead of finding the complete path before sending a packet. In the following sub-sections, we discuss the SBR-DLP operation in detail.

3.1. Finding the Next Relay Node

When a node, S, wishes to send a packet (either a new or relay packet) to the destination node D, it finds its next relay node by broadcasting a *Chk_Ngb* packet, which includes the sender's current position and the packet ID. Upon hearing the *Chk_Ngb*, each neighboring node x checks whether it is nearer to Node D than the distance between Nodes S and D, using the predicted location of Node D (we will explain how the destination location is predicted in Section 3.3). If the condition is met, Node x will have to respond to Node S by transmitting a *Chk_Ngb_Reply* packet.

In order to reduce possible collisions at Node S among the *Chk_Ngb_Reply* responses, each neighboring node first determines the sector that it is in, and then schedules the transmission time of its *Chk_Ngb_Reply* accordingly. For a given k-sector system, the node starts to locate the first sector by ensuring that the sector is bisected by the virtual vector $\overline{SD}$. The subsequent sectors are then labeled according to their priorities, which are determined using their angular differences from $\overline{SD}$. Figure 1 illustrates how a four-sector system is labeled. After determining the sector that it is in (say, j), a neighboring node writes into its *Chk_Ngb_Reply* the sector number j, its node ID, and its estimated distance from the predicted destination location. It then schedules the transmission to occur after an offset given by

$$t_{\text{offset},j} = \alpha(j-1)P_{\max}, \tag{1}$$

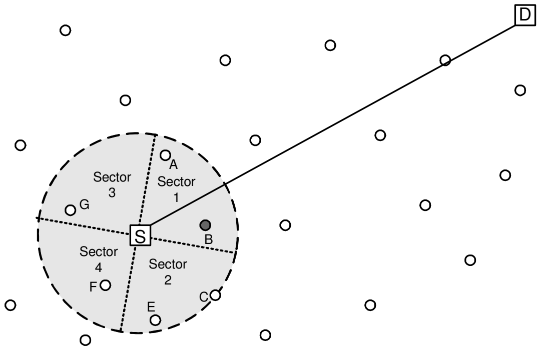

Figure 1. Forwarder selection at the sender.

Table 1. How Node S picks its next relay node.

Sector	Candidates	Distance to D	After Filtering
1	A, B	500, 480	A, B
2	C	550	
3	-	-	
4	-	-	
		Next relay node	B

where $0 \leq \alpha \leq 1$ and $P_{\max}$ is the maximum propagation delay. As a general guideline, α can be selected based on the number of sectors, k, such that if k is large, a small α would suffice because the probability of collisions from different sectors would also be small. This also helps shorten the duration that Node S needs to wait before acquiring all the responses from all the k sectors.

After gathering all the *Chk_Ngb_Reply* from its candidate neighbors, Node S filters out those nodes that might travel out of its range before being able to acknowledge the receipt of its packet. This is estimated using its propagation delay from each candidate node, the time at which it receives the Chk_Ngh_Reply, and the maximum possible relative velocity. Note that the filtering is necessary because the change in their relative distance may be quite significant over the long delay incurred, as a result of the slow propagation speed of underwater acoustic waves. Also, if a more accurate estimation of the candidate node's movement is desired, one may consider including the node's direction and speed in the *Chk_Ngb_Reply* to the sender. After performing the filtering, the remaining candidates are sorted according to their sector priorities. If there is more than one candidate having the same priority at the top of the list, the one that has the closest predicted distance to Node D will be picked. Table 1 illustrates how Node S picks Node B to be its relay node, based on the topology shown in Figure 1. After selecting its relay node, Node S transmits its data packet to this node. The relay node then acts as a sender using the same procedure above, until the packet reaches its destination.

Now, suppose that there is no response from any of the sender's neighboring nodes. The sender shall wait for a time interval of T_{wait} for the topology to change, before making another attempt. If the sender fails to find any neighbor for a number of n_{discard} times, it discards the packet.

3.2. Implicit/Explicit Acknowledgments

For a high error rate channel such as the underwater acoustic channel, the acknowledgment is preferably done in a hop-by-hop fashion, while leaving the end-to-end acknowledgment for the higher layers. Moreover, to achieve energy efficiency, the acknowledgment in the SBR-DLP is done implicitly through overhearing whenever possible. The sender assumes that the packet is successfully received if it overhears the *Chk_Ngb* packet from its relay node while the latter is trying to find the next relay node. An explicit acknowledgment (ACK) packet will be used in the case where the packet is received by its destination node. If a sender does not receive any acknowledgment after a certain timeout, it makes another transmission attempt by broadcasting the *Chk_Ngb* again. For the case where a relay node has successfully received the data packet but its acknowledgment fails to reach the sender, it will reply to the sender with an explicit ACK when it hears the sender's subsequent *Chk_Ngb* for the same packet ID.

3.3. Destination Location Prediction

As we have seen earlier in Section 3.1, destination location prediction is an important part of the SBR-DLP, because a sender tries to forward its data packet in the direction of the virtual vector $\overline{SD}$. If the prediction is way off, a packet may be routed through a path that is much longer than necessary, or it may not even reach the destination. Although the SBR-DLP does not require precise knowledge of the destination's location, it is expected that the larger the error in the destination location prediction, the lower the performance of the SBR-DLP. This problem becomes more pronounced in underwater mobile networks where the sensor nodes may experience mobility not only from its own propeller, but also from the ocean current. In general, an autonomous underwater vehicle's (AUV) movement is usually pre-planned, but the speed and direction of the ocean current depend on multiple factors and are usually random. Thus, even if the pre-planned movement of the destination node is available to all other nodes, the ocean current could still render this information inaccurate.

In order to help predict the destination location, the SBR-DLP requires the destination node to periodically broadcast a "*Notification (NTF)*" packet to notify its one-hop neighbors if it deviates from its schedule significantly. We choose to notify only its one-hop neighbors, rather than the entire network, because the long propagation delay can cause the *NTF* packet to become stale by the time it reaches a node that is several hops away. In addition, since the destination node itself is mobile, other nodes within the network may also hear its *NTF* packet at a different time. In order to trigger the *NTF* packet, the destination node checks if it has deviated from its schedule every time when it reaches a predefined waypoint. If it finds that the difference (Δ) between the current time (t_{NTF}) and the scheduled time (t_{expect}) is greater than a threshold ($\Delta_{\text{threshold}}$), it will broadcast the *NTF* packet, which contains the parameters t_{NTF} and Δ. Upon hearing the *NTF* packet, a node stores these parameters for later use.

Now, suppose that a node has just heard the *Chk_Ngb* packet from a sender at time t_{now}. It first checks if it has previously heard the *NTF* packet. If so, it will estimate the current location of the destination by looking at the destination's predefined movement at the time that is offset by $\hat{\Delta}$ from its schedule, where $\hat{\Delta}$ is the estimated time difference from the predefined schedule. The node uses the parameters t_{NTF}, Δ, and t_{now} to compute $\hat{\Delta}$ using

$$\hat{\Delta} = \frac{\Delta \cdot t_{\text{now}}}{t_{\text{NTF}}}. \tag{2}$$

4. Simulations and Results

4.1. Simulation Setup

In our simulation setup, there are N sensor nodes moving randomly within a 2D network of 1000 m by 1000 m. There is only one destination node, referred to as a SINK, which is moving with a pre-planned path. The SINK's pre-planned path is stored in each of the sensor nodes. However, due to the ocean current, the SINK deviates from its pre-planned path in such a way that, for any given pair of consecutive waypoints, X and Y, instead of moving from X to Y directly, the SINK travels from X to Z to Y. The position of point Z is d_{max} away perpendicularly from the midpoint of $\overline{XY}$. All nodes (including the SINK) are equipped with half-duplex and omnidirectional modems, which operate at a fixed data rate of 2400 bps, with a range of 300 m. We assume that the speed of sound in underwater is constant at 1500 m/s, while the speed of the sensor node is 2 m/s unless specified otherwise. The direction of each sensor node (including the SINK's pre-planned path) is randomly picked from the range of $[-45°, 45°]$ according to uniform distribution. Its direction remains constant for an exponentially distributed period of time with an average of 300 s, before it is randomly picked again. If a node reaches the boundary of the testing area, it is reflected by the boundary, back into the testing area. The *DATA* and control packets (i.e., *Chk_Ngb, Chk_Ngb_Reply, NTF, and ACK*) are 4800-bit and 32-bit long, respectively, while the other parameters used are: $n_{\text{discard}} = 3$, $\alpha = 0.5$, $\Delta_{\text{threshold}} = 30$ s, and $T_{\text{wait}}(n_{\text{fail}}) = 30n_{\text{fail}}$ s, where n_{fail} is the number of failed attempts to transmit a packet, and $1 \leq n_{\text{fail}} < n_{\text{discard}}$.

In order to easily interpret and understand the behavior of the SBR-DLP under different settings, we eliminate the effects of the MAC layer by allowing only one packet in the network at any instant. For each packet, the source node is selected randomly among the N nodes.

In our simulations, we evaluate the SBR-DLP's performance by varying the following parameters: sector size, node density, and node speed. The routing performance's metric that we have used is the packet delivery ratio (PDR), which is defined as the ratio of the number of unique *DATA* packets that are successfully received at the SINK to the total number of *DATA* packet transmissions.

4.2. Simulation Results

We choose to benchmark the SBR-DLP with the SBR, which is a replica of the SBR-DLP except that there is no destination location prediction mechanism. Thus, the SBR relies solely on the original pre-planned path of the destination node. This helps us understand the gain in performance resulting from the use of destination location prediction while keeping all other parameters the same.

Figure 2 shows that the performance of both the SBR-DLP and the SBR are rather independent of the number of sectors, as their PDR are quite stable with respect to the number of sectors. Note that the SBR-DLP and the SBR are equivalent when $d_{\max}$ is 0, because the destination node always conforms to its pre-planned path. From the figure, we can also see the improvement in PDR when location prediction is introduced. By comparing the plots from the SBR-DLP with the ones from the SBR, we can see that when the maximum deviation $d_{\max}$ is increased from 10 m to 100 m, the use of location prediction helps raise the PDR significantly for all $d_{\max}$. An interesting observation from the SBR's plots is that, although one may expect that a higher deviation $d_{\max}$ would result in a lower PDR, it is noted that the SBR's performance does not decrease further when $d_{\max}$ changes from 50 m to 100 m. This can be explained by focusing our attention on the movement of the SINK. Keeping in mind that $d_{\max}$ is the amount of the SINK's deviation from its pre-planned path. When the deviation is large enough to cause routing failure, increasing the deviation further would still result in the same routing failure, without causing much change to the PDR.

Next, we study the effects of node density on both the SBR-DLP and the SBR. As shown in Figure 3, both algorithms exhibit similar trends when the number of nodes in the network is varied from 10 to 40 nodes. Unsurprisingly, we notice that the PDR increases dramatically as the number of nodes increases in this range. For the SBR-DLP, the PDR starts to get saturated when the number of nodes exceeds 40 nodes, likely because network disconnectivity has now become rare. On the other hand, the SBR's performance degrades slightly when the number of nodes exceeds 40 nodes. Without destination location prediction, the SBR always relies on the SINK's pre-planned path, which is no longer accurate. However, a low density network may not be affected as much by the deviations in the SINK locations, compared to a high density network. This is because, for higher density networks, there are also higher chances that a sender would pick a relay node that is much closer to both the destination and the virtual vector $\overline{SD}$. Thus, for such networks, the effects of inaccurate SINK locations are naturally more pronounced. To support this claim, let us compare the SBR with the SBR-DLP for both low and high density regions in Figure 3. As can be seen, the performance gain from the use of destination location prediction is much more significant in the higher density region.

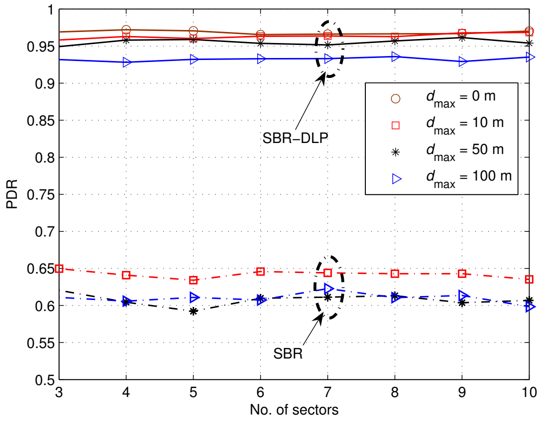

Figure 2. The effects of number of sectors in a 30-node network, for SBR (dashed) and SBR-DLP (solid).

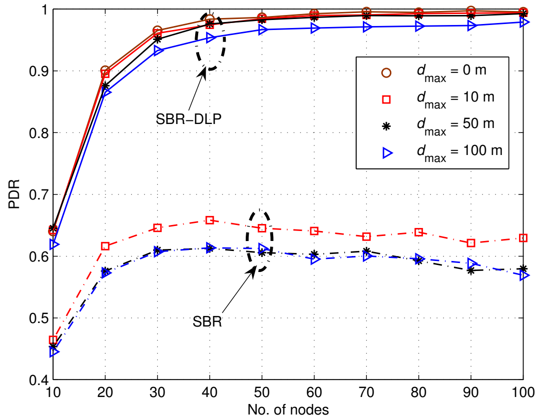

Figure 3. The effects of number of nodes in a 6-sector network, for SBR (dashed) and SBR-DLP (solid).

Now, let us look at Figure 4 to examine the effects of node speed on the performance of both the SBR-DLP and the SBR. Here, we only focus on the 30-node network, since it has been shown to be dense enough to illustrate the significant gains brought by destination location prediction. As expected, the SBR-DLP outperforms the SBR

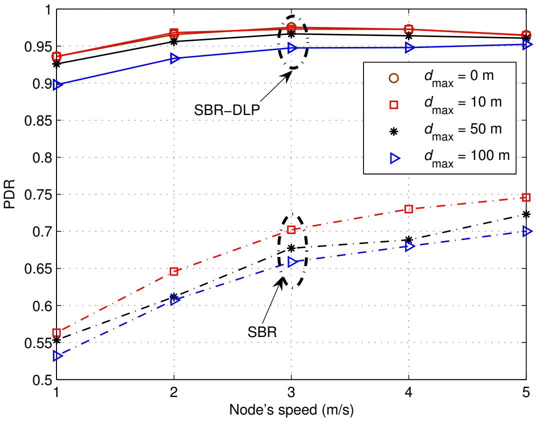

Figure 4. The effects of node speed in a 30-node and 6-sector network, for SBR (dashed) and SBR-DLP (solid).

significantly in all cases. It can also be seen that the PDR of both the SBR-DLP and the SBR improves as the node speed increases. In general, node mobility can be both advantageous and disadvantageous to routing protocols. On the one hand, the change in topology caused by node mobility may harmfully cause the network to be disconnected; on the other hand, it may beneficially allow the network to be reconnected. For those protocols that take node mobility into account adequately, they can make the advantages outweigh the disadvantages. In our case, both the SBR-DLP and the SBR take node mobility into account during the process of finding the next relay node. Thus, they benefit more from the change in topology caused by node mobility, which explains why their PDR increases with node speed.

Although the results shown above correspond to the use of the SBR and the SBR-DLP in 2D networks, similar trends also apply if they were to be implemented in 3D networks. In a 3D network, the communication circle and the sector become a communication sphere (assuming omni-directional antenna) and a spherical wedge, respectively. As long as a node can locate itself within 3D space, there is no burden scaling from 2D to 3D networks for these protocols.

5. Conclusion

In this paper, we have proposed the SBR-DLP, which is a multi-sector based routing algorithm coupled with destination location prediction. It is suitable for mobile underwater acoustic sensor networks where the destination nodes can also move along with other nodes in the network. Its design takes into consideration the unique characteristics of such networks, namely, long propagation delay, node mobility, high channel error rate, and low data rate.

We have shown through simulations that routing designs for fully mobile networks need to account for the mobility of the destination node. However, even a simple location prediction mechanism could help improve the packet delivery ratio significantly. In addition to its superior performance, the SBR-DLP is highly adaptive to network dynamics, such as nodes joining and leaving the network, because of its reactive hop-by-hop packet routing mechanism.

In our future work, we will integrate the SBR-DLP with several underwater MAC protocols, and investigate their relative performance. We also plan to relax the assumption that the SINK can lock back to its original "flight path" fairly quickly after a certain deviation, so as to create a more realistic mobility model.

Acknowledgment

The research reported in this paper was supported by the Ministry of Education of Singapore, AcRF Tier 1 funding, under Grant No. R-263-000-370-112.

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