On the Performance of Delay–Tolerant Routing Protocols in Underwater Networks

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***Abstract*—The underwater acoustic channel features long and variable propagation delay, high bit error rate and limited bandwidth. Moreover, underwater mobile networks consisting of Autonomous Underwater Vehicles (AUVs) for surveillance and monitoring applications often suffer from intermittent connectivity as nodes move around the area of operations. Therefore, this scenario is appropriately modeled as a Delay-Tolerant Network (DTN). In this paper, we investigate two classes of DTN routing protocols: Spray-and-Wait (SNW) and the Resource Allocation Protocol for Intentional DTN (RAPID), together with a standard flooding protocol for underwater mobile networks, and their performance is analyzed in terms of packet delivery ratio, average end-to-end delivery delay and throughput, in different load conditions across various node mobility scenarios. Our results show that RAPID performs better than other DTN routing protocols in terms of packet delivery ratio at higher load conditions irrespective of node mobility, whereas the Binary version of SNW has the best performance in terms of average delivery delay.**

***Index Terms*—Underwater mobile networks; delay-tolerant networking; routing; ns2-Miracle; performance evaluation; mobility**

I. Introduction and Related Work

Delay- and Disruption-Tolerant Networks, commonly known as DTNs, are characterized by their lack of connectivity due to node mobility and typically sparse topologies, very long and variable propagation delay, and high bit error rate of the communication channels. These conditions likely result in the lack of an instantaneous end-to-end path from source to destination. In such critical environments, well-known ad hoc routing protocols such as AODV [1] and DSR [2] fail to establish routes, as they require a route to be discovered and set up before data packets are actually forwarded. In fact, DTNs feature intermittent connectivity and temporarily broken links, which may hamper the functionality of common ad hoc routing protocols. When instantaneous end-to-end paths do not exist, the routing protocols must adhere to the "store-carry-and-forward" approach, which exploits the mobility of nodes to route data. In this approach, data is moved from the source to the next available node and stored there, waiting for an opportunity to forward the data. If present, mobile nodes can carry the stored data while moving, and look for opportunities to forward the data to other nodes towards the destination. Overall, these techniques provide eventual data delivery with a certain probability [3]–[5]. A common technique to maximize the delivery probability of the packets is to replicate them to different nodes so that at least one of the copies will successfully reach its destination with high probability [6]. Routing protocols that behave this way are called replication-based. Instead, DTN protocols that do not replicate packets are called forwarding-based [7], [8].

Mobile underwater networks consisting of Autonomous Underwater Vehicles (AUVs) for surveillance and monitoring applications often suffer from intermittent connectivity. In addition, the mobility patterns of the AUVs are usually governed by their task or mission rather than by communication requirements. The Delay-Tolerant Network (DTN) paradigm is, therefore, appropriate to model this scenario. In this paper, we will present an evaluation of DTN routing protocols as applied to underwater mobile networks, with focus on the Spray-and-Wait (SNW) [9] and the Resource Allocation Protocol for Intentional DTN (RAPID) [10] routing protocols. In particular, SNW is a replication-based protocol: its Vanilla and Binary flavors (both considered in the forthcoming evaluation) differ in how packet replicas are passed to other nodes as they are met. RAPID also replicates packets in a controlled flooding fashion, and its behavior can be tuned towards the optimization of a single metric, such as the average end-to-end delay, the number of missed deadlines or the maximum delay allowed. In particular, the recipients of packet replicas are chosen in terms of how much they can contribute to the metric to be optimized (e.g., decreasing the average delivery delay by replicating packets to nodes having more frequent meetings with the final destination). In our simulations, we compared the two versions of SNW with two instances of RAPID, which focus on the optimization of average delay and maximum delay, respectively. For a better comparison, we also show the performance of a standard flooding protocol, which plainly forwards a copy of every data packet to every node.

The concept of Delay-Tolerant Network (DTN) was introduced by Kevin Fall in [11], which outlines the architecture of a DTN (characterized by very high propagation delay and frequent network partitions due to intermittent connectivity). Routing issues in DTN are quite challenging as there is no continuous path from source to destination, and hence ad hoc routing protocols usually fail. Routing protocols for DTN follow the "store-carry-and-forward" approach. Representative of this approach is Epidemic routing [6], which forwards each copy of the messages (not common among the nodes in contact) to each node. This approach is flooding-based in nature, and is exhaustive of network resources. To limit the utilization of network resources, Spryropoulos et al. proposed Spray-and-Wait [9], in which only a limited number of message copies are replicated among nodes. The Probabilistic ROuting Protocol using History of Encounters and Transitivity (PROPHET) [12] attempts to exploit the likelihood of real-world encounters by maintaining a set of probabilities for successful delivery to known destinations in the DTN, and replicating messages during opportunistic encounters only if the mobile node in contact that does not possess the message appears to have a better chance of delivering it to the destination. MaxProp [3], which is a vehicular DTN routing protocol, not only prioritizes to which node to forward the message replicas, but also puts emphasis on which message to forward. The refinements brought about by MaxProp lie in determining which messages should be replicated first, and which should be dropped in case of buffer overflow at a node. Balasubramanian et al. proposed the Resource Allocation Protocol for Intentional DTN (RAPID) [10] to intentionally optimize a single routing metric, such as average end-to-end delivery delay, missed delivery deadlines or maximum delivery delay, as opposed to other DTN routing protocols that tend to incidentally affect the performance metrics as claimed by the authors. So far, the DTN routing protocols pointed out here are all multi-copy or replication-based protocols developed for terrestrial DTNs. In [13], the authors proposed a single-copy or forwarding based DTN routing protocol termed as Prediction Assisted Single-copy Routing (PASR) for underwater acoustic sensor networks, and demonstrated performance improvements over multi-copy routing in a resource constraint underwater network scenario.

Our contribution in this paper is to evaluate the performance of two DTN routing protocols, Spray-and-Wait and RAPID, in mobile underwater acoustic networks, which feature a different propagation model than the radio networks the original DTN protocols have been designed for. In particular, due to both the lower propagation speed of acoustic waves and the limited movement speed of underwater mobiles, the duration of contacts has different statistics, which in turn have an impact, e.g., on the probability that messages are delivered or not.

II. Description of Spray-and-Wait and RAPID

In this section, we give a brief overview on the taxonomy of DTN routing protocols, and summarize the design of the Spray-and-Wait and the RAPID protocols.

DTN routing protocols are classified according to many different criteria: however, one of the most common ones is whether or not the protocol creates message replicas. Routing protocols that do not replicate a message are called forwarding-based, whereas the protocols that replicate messages are called replication-based. There are pros and cons to both approaches, and which approach is preferable depends on the application scenario. Forwarding-based routing approaches are generally much less wasteful of network resources, as only a single copy of a message exists in the network at any given time [7], [8]. Therefore, when the destination receives that copy of the message, no other node has a copy. This eliminates the need for the destination to provide feedback to the network (except for an acknowledgement to the current sender) to indicate that other copies of the message can be discarded, as is the case instead in replication-based approaches. However, forwarding-based approaches usually do not provide sufficiently high message delivery ratios in many DTN scenarios [9]. On the other hand, replication-based routing protocols achieve higher message delivery ratios [3], since multiple copies of messages exist in the network, and at least one must reach the destination. Therefore, a typical tradeoff here is found between the two approaches, whereby the former spends less resources but may provide low probability of correct delivery, whereas the latter tends to spend more resources but also provides better delivery ratios [14]. Moreover, many of the flooding-based protocols are inherently not scalable. A class of replication-based schemes, such as Spray-and-Wait [9], attempts to find a good working point on this tradeoff by limiting the number of replicas of a given message.

The standard flooding protocol that we investigate as a base for underwater mobile network scenario works as follows: the source node, which possesses messages or message replicas in its buffer, broadcasts a PING message to initiate the neighbor discovery process. The mobile nodes which receive the PING message send back an ACKP message in unicast mode, and remain ready to receive the DATA message transmitted by the source node. Upon receiving the ACKP messages, the source node creates a neighborhood list, and starts transmitting first those messages whose final destinations are in the neighborhood list. The remaining messages are replicated to each node in the list according to the order of reception of ACKP messages. The protocol does not care whether the messages are successfully received by the neighbors or not, as there is no mechanism for acknowledging the successful deliveries. The neighborhood discovery process of the standard flooding protocol is also the same for both Spray-and-Wait and RAPID routing protocols.

Spray-and-Wait [9] is a DTN routing protocol that attempts to gain the delivery ratio benefit of replication-based routing while keeping resource utilization low as in forwarding-based routing. SNW achieves resource efficiency by setting an upper bound on the number of copies per message allowed in the network. The SNW protocol is composed of two phases, namely, the spray phase and the wait phase. When a new message is generated, the protocol assigns a number L which is attached to that message, indicating the maximum allowable copies of the message throughout the network. During the spray phase, the source of the message "sprays," or transfers, one copy to L distinct relays. When a relay receives the copy, it enters the wait phase, whereby it simply stores that particular copy of the message until the final destination of the message is encountered for direct delivery. There are two main versions of the SNW routing protocol, respectively known as Vanilla and Binary. The two versions differ in the mechanism employed to "spray" the L copies of a message. The simplest way to achieve this, called Vanilla, is to transmit a single copy of the message from the source to the first L distinct nodes it encounters after the message is generated. The second version, referred to as Binary SNW, works as follows: the source node starts with L copies of the message. It transfers $L/2$ of the copies to the first node it encounters. Each node then transfers half of its copies to future nodes they meet that have no copy of the message. When a node eventually gives away all of its copies, except for one, it switches to the wait phase where it waits for a direct transmission opportunity with the final destination of the message. The advantage of the Binary version is that messages are disseminated much faster than in the Vanilla version.

RAPID [10] stands for Resource Allocation Protocol for Intentional DTN. The goal of RAPID is to intentionally optimize a single routing metric: average delay, missed deadlines, or maximum delay. The core of the RAPID protocol is based on the concept of a utility function. The utility function assigns a utility value, depending on the routing metric to be optimized. The utility is defined as the expected contribution of the packet to the routing metric. RAPID replicates first those packets that locally result in the highest increase in the utility function. RAPID is flooding-based in nature, and will therefore attempt to replicate all packets if network resources such as storage and bandwidth allow. The overall protocol is comprised of the following steps: i) metadata is exchanged between nodes in contact to help estimate the packet utilities; ii) direct delivery, as packets destined to neighboring final destinations are immediately transmitted; iii) replication, as packets are replicated based on the marginal utility, that is the change in utility over the size of the packet; and iv) termination, as the protocol ends when contacts break or all packets have been replicated.

III. Simulation Results

In this paper, we focus on the performance analysis of flooding as well as of the SNW and RAPID routing protocols in an underwater acoustic mobile network. All routing protocols are simulated using ns2-Miracle [15]. For SNW, we consider both the Vanilla and the Binary versions. We also focus on two different instances of RAPID, each pursuing the optimization of a different objective: the first focuses on the minimization of the average delay, whereas the second minimizes the maximum delivery delay. These versions of RAPID have been chosen to model the case a DTN must strive to keep the delivery delay within acceptable limits, while still forwarding data in a best-effort fashion.

Given that the network is fully mobile, we account for power losses due to propagation via a simple path loss model [16], [17]. The usage of more accurate propagation modeling software (e.g., based on ray tracing as in [18]) is hardly an option in this case, due to the very high computational complexity that would result. Noise is also accounted for via the empirical equations in [16], [17].

The network is composed of 10 mobile AUVs, 5 sources and 5 destination nodes. All AUVs navigate at a given average speed within a shallow-water area of $5\,\mathrm{km} \times 5\,\mathrm{km}$. The transmissions are performed at a bit rate of $4800\,\mathrm{bps}$ over a bandwidth of $5\,\mathrm{kHz}$ at a center frequency of $11.5\,\mathrm{kHz}$, using the Binary Phase-Shift Keying (BPSK) modulation. Upon the preliminary exchange of PING and ACKP packets, the transmitter node estimates the distance between itself and the destination from the round-trip time, and sets its transmit power to match a target packet transmission success rate of 90%. The power budget is computed according to the empirical equations for path loss and noise cited above. In any event, the transmit power never exceeds $190\,\mathrm{dB}\,\mathrm{re}\,\mu\mathrm{Pa}$.

The average speed has been fixed to span various movement paces. The movement is randomized via a Gauss-Markov mobility model [19]. According to this model, each node randomly chooses a movement speed and direction and keeps it constant for a given time (also random). After this time has expired, a new velocity vector is generated. Unlike a completely random waypoint model, the Gauss-Markov model prescribes that every future random choice is correlated to the previous one according to a correlation parameter $0 \le \alpha \le 1$, where $\alpha = 0$ means a fully random waypoint selection, whereas $\alpha = 1$ is a fully correlated (i.e., linear) movement. If nodes reach the boundaries of the network area, they are automatically bounced off the border.

The source nodes generate messages at a rate of 0.25 to 3 packets per minute per node. The overall duration of the simulation is 6 hours, even though one more hour is allowed after the completion of every run, in order to complete the delivery of messages which are still being propagated. All results are averaged over 30 different simulation runs.

We start our evaluation from Figs. 1 to 3, where we respectively report the average packet delivery ratio in the network (defined as the ratio of the number of packets correctly delivered end-to-end to the number of generated packets), the end-to-end delivery delay (i.e., the time elapsed from when a packet is generated by its source to when it is received by its intended destination), and the average normalized throughput (defined as the number of packets per packet transmission time that are delivered to their destination). The average movement speed of the nodes is set to $2\,\mathrm{m/s}$ here. From Fig. 1, we observe that the Binary version of SNW performs better than the Vanilla version, as could be expected from the discussions in [9]: other than to the specific underwater scenario, this result is mainly due to the way Vanilla SNW operates, i.e., by not allowing recipients of a copy to replicate it further. On the contrary, Binary SNW allows replication so long as a node has not "exhausted" all of its available copies of the message. Flooding ranks slightly worse than Binary SNW, but still much better than Vanilla: in fact, flooding poses no limit on the number of copies of a message that can be simultaneously circulated at any given time, but on the other hand it performs no check on whether it is convenient or not to actually transmit a packet. On the contrary, both instances of RAPID perform well, and achieve a delivery ratio of roughly 0.8 even at high packet generation rates. This good result is due to RAPID's more focused replica forwarding scheme,

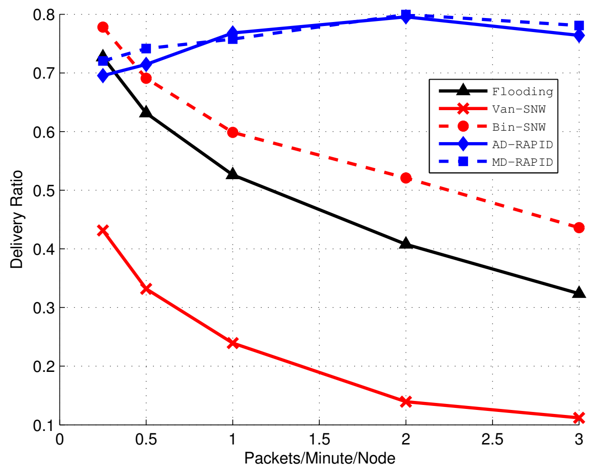

Figure 1. Delivery ratio as a function of the packet generation rate per node at an average node speed of $2\,\mathrm{m/s}$.

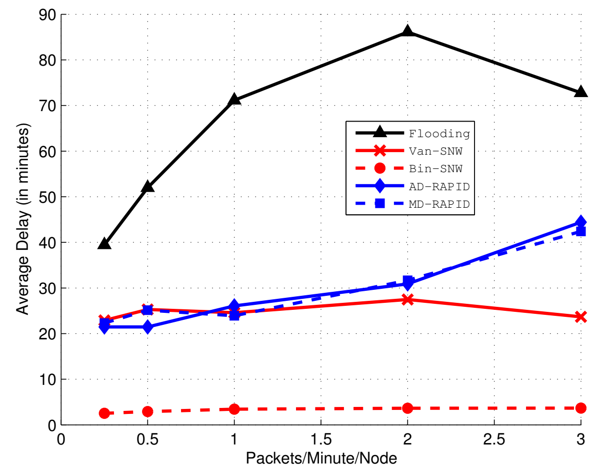

Figure 2. Average delivery delay as a function of the packet generation rate per node at an average node speed of $2\,\mathrm{m/s}$.

which chooses whether or not to forward a replica to a given node based on the contribution of that node to the metric to be optimized. While avoiding to transmit replicas may seem disadvantageous in general, it actually allows to save time, which can then be dedicated to replicating those messages which exhibit a better chance to meet the delay minimization objectives.

In Fig. 2, we observe that Binary SNW provides better average delay than both RAPID instances, which may sound counterintuitive, given that RAPID has been configured to minimize the average or maximum delay. However, we recall that the average delay is computed only across the packets that have been actually delivered to the destination: hence the higher delay incurred with RAPID is a consequence of its better delivery ratio and of local decisions made by each forwarder, which are also driven by the chance that a node will meet the final destination of a certain packet in the future. In fact, a node may avoid forwarding some replicas in order to wait for a different node, which offers a better chance of delivery. On the contrary, Binary SNW spreads packet copies in a way that is oblivious of the chance that receivers actually meet the destination: this reduces the delay before packets are delivered, but also increases the chance that a packet never finds its final recipient (after a certain number of replications, a node is no longer allowed to create further replicas, and can forward the packet only to the final destination upon meeting it). We remark that, unlike DTN protocols, plain flooding yields the highest delay instead, because it does not enforce any particular rule as to how a replica is forwarded, nor does it assign any priority to the replication of the usually many packets in the queue. The noticeable decrease in the average delay for a packet generation rate of $3\,\mathrm{pkts/min/node}$ in Fig. 2 is again explained by considering that the average delay is computed only across actually delivered packets: the higher traffic rate makes it in fact more likely that when two nodes meet, one of those is the final destination of one or more of the packets in the sender's queue.

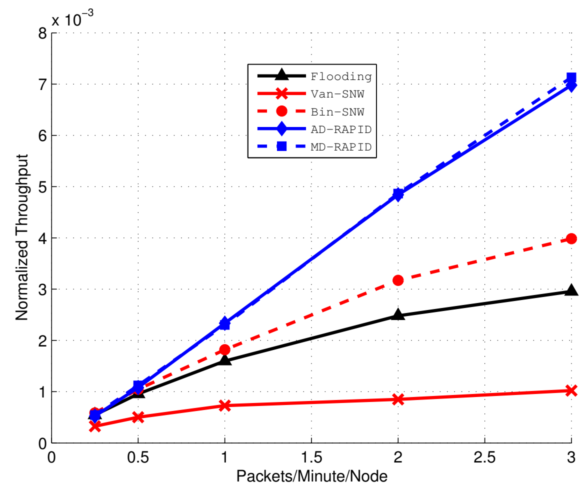

Figure 3. Normalized throughput as a function of the packet generation rate per node at an average node speed of $2\,\mathrm{m/s}$.

For reference, we conclude this first part by noting that the normalized network throughput (Fig. 3) reflects the information provided by the delivery ratio in Fig. 1: namely, RAPID provides very good performance, Vanilla SNW delivers the least traffic, Binary SNW ranks in between and flooding does slightly worse. Due to the similarity to the behavior of the success ratio, the throughput pictures will therefore be omitted in what follows.

It is common wisdom that the speed of mobility should influence network metrics in DTNs. In fact, a higher average speed implies two main effects: i) nodes experience more meetings on average and ii) meetings tend to have a shorter duration. The second effect is to be taken greater care of in underwater networks employing limited transmission bit rates, where it is very important to choose which packets to transmit

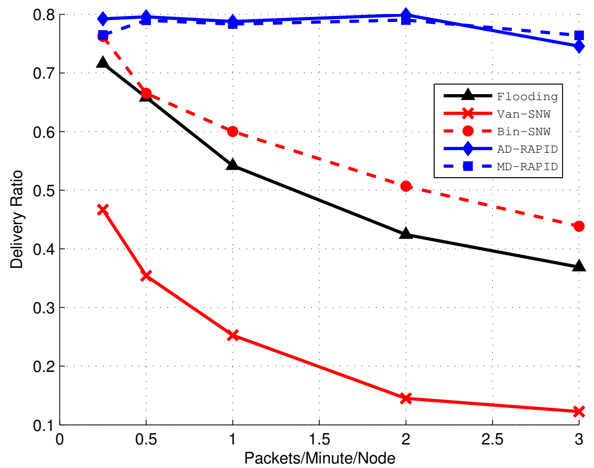

Figure 4. Delivery ratio as a function of the packet generation rate per node at an average node speed of $6\,\mathrm{m/s}$.

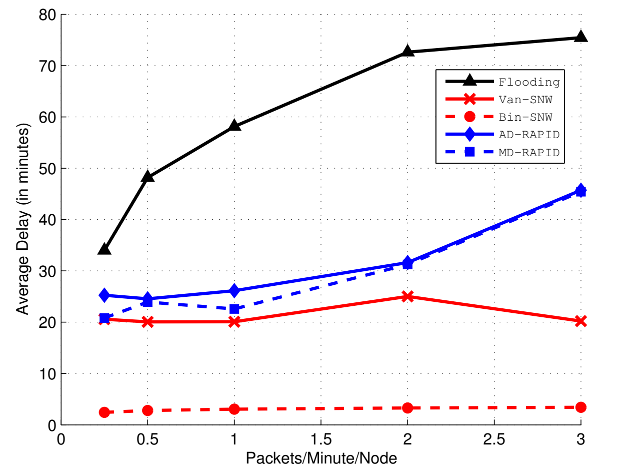

Figure 5. Average delivery delay as a function of the packet generation rate per node at an average node speed of $6\,\mathrm{m/s}$.

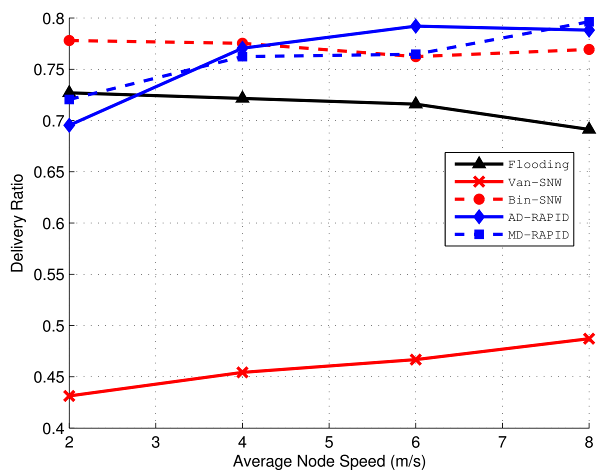

Figure 6. Delivery ratio as a function of the average node speed at a packet generation rate of $0.25\,\mathrm{pkts/min/node}$ (low load).

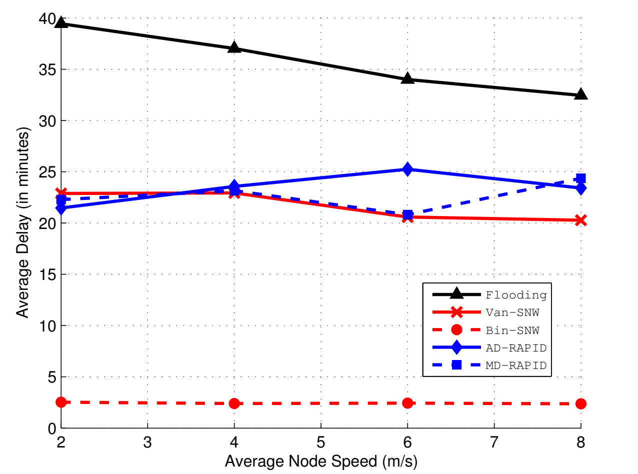

Figure 7. Average delivery delay as a function of the average node speed at a packet generation rate of $0.25\,\mathrm{pkts/min/node}$ (low load).

within the limited window allowed by the meeting time.

In order to investigate the impact of node mobility, we varied the average node speed from $2\,\mathrm{m/s}$ to $8\,\mathrm{m/s}$. While we acknowledge that a speed above $4\,\mathrm{m/s}$ is unlikely for AUVs, we report the related results nevertheless, as this allows to understand whether faster AUVs are beneficial or not in terms of network performance. Figs. 4 and 5 respectively show the delivery ratio and delay performance for an average node speed of $6\,\mathrm{m/s}$. The general message is that the performance of the network in fact improves. In particular, flooding shows a slightly higher delivery ratio and a 10% lower delivery delay overall: in fact flooding does not control how conveniently the packets are replicated, hence its performance improves with higher node speed, and does not suffer any particular disadvantage because of the shorter encounter durations. RAPID also benefits from faster movement, especially at low traffic generation rate, thanks to the greater chance to meet the destination of generated packets.

To achieve a better understanding of the impact of node mobility on the performance metrics of the routing protocols, we report the delivery ratio and delivery delay as a function of the average node speed for different load conditions (i.e., low and high packet generation rates). From Figure 6, we can see that at low load Binary SNW performs better than both instances of RAPID in terms of delivery ratio at an average node speed of $2\,\mathrm{m/s}$, but as node mobility increases RAPID outperforms all other protocols. This is because faster mobility makes node meetings more frequent, allowing RAPID a better estimation of inter-meeting times between different pairs of nodes. In turn, the better estimates allow the fine-tuning of the packet replication strategy, whose ultimate effect is a higher packet delivery ratio.

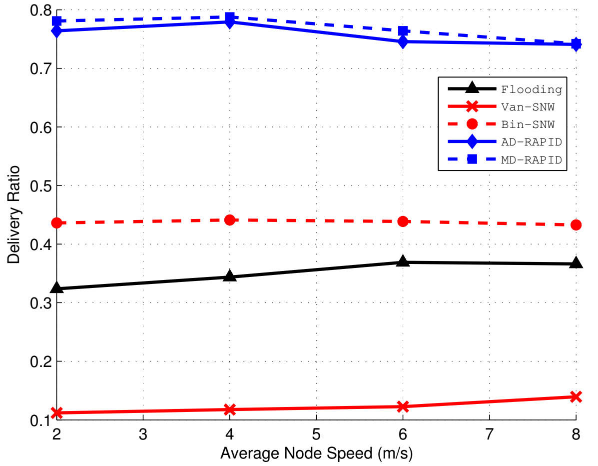

Figure 8. Delivery ratio as a function of the average node speed at a packet generation rate of $3\,\mathrm{pkts/min/node}$ (high load).

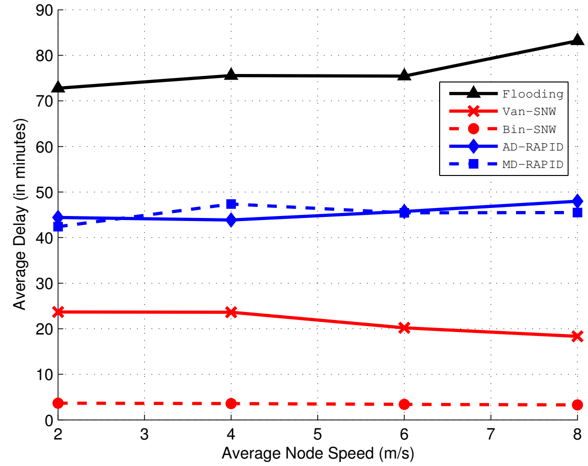

Figure 9. Average delivery delay as a function of the average node speed at a packet generation rate of $3\,\mathrm{pkts/min/node}$ (high load).

Also, Vanilla SNW achieves a slightly higher delivery ratio as node mobility increases, since it finds more opportunities to spread packet replicas throughout the network or to deliver them directly to destinations, thanks again to the higher node meeting rate. Both flooding and Vanilla SNW enjoy benefits due to increased node mobility in terms of average end-to-end delivery delay, as frequent node meetings contribute to quicker packet delivery to destination, as can be seen from Fig. 7.

For high load conditions (see Figs. 8 and 9), the observed benefits of increased node mobility on delivery ratio at low load conditions are more limited, as even though the nodes are meeting more frequently for increasing mobility, the contact duration is not sufficient for exchanging all required packets. This is also the reason why the average delay increases with respect to the low traffic case.

To complete our evaluation of mobility, we now turn our attention to the correlation parameter α of the Gauss-Markov mobility model, which can be tuned to control the smoothness among the patterns of the AUVs. We recall that the value of α can be varied from 0 to 1, where $\alpha = 0$ denotes fully random movement, and $\alpha = 1$ translates into a fully correlated, linear movement. Studying the impact of α on the network performance may help design AUV behaviors in terms of how smooth their movement should be in order to favor networking when doing missions over a certain area.

In Figures 10 and 11, we respectively present the delivery ratio and average end-to-end delay as a function of the packet generation rate per node for $\alpha = 0.5$ (moderately correlated node movements) and $\alpha = 0.9$ (highly correlated node movements), at an average node speed of $2\,\mathrm{m/s}$. We see from the results that an increased correlation in the mobility patterns of the mobile nodes enables all the routing protocols to successfully deliver more packets to their destinations with lower average end-to-end delays. However, for Binary SNW, the improvement in terms of delivery ratio and average delivery delay due to correlated mobility is not as significant as for other routing protocols, which may be explained as follows.

Correlated mobility provides a group of the mobile nodes the opportunity to be in contact with one another more frequently. Flooding and Vanilla SNW benefit from this, and deliver more packets successfully to their destinations more quickly, compared to the case of random node movements. Both versions of RAPID also utilize the frequent contacts with mobile nodes to fine tune their target metrics, and thereby quickly deliver more packets to their destinations. However, Binary SNW receives a limited benefit from highly correlated mobility, and such benefit mainly comes from a higher chance that packets are generated (and directly delivered) to the destination while the contact with that specific destination is still active.

IV. Conclusions

In this paper, we investigated the performance of DTN routing protocols in underwater mobile networks. Vanilla and Binary Spray-and-Wait as well as two versions of RAPID were considered, and compared to a baseline flooding protocol. The results have been generated for various load conditions and node mobility parameters. From these results we conclude that the two best candidates are Binary Spray-and-Wait and RAPID, for different reasons. Binary Spray-and-Wait is a simple and effective policy, and performs well in terms of delay, even though its success ratio tends to decrease at high network load. RAPID is more complex, but its structure allows to decrease the number of useless replica transmissions by focusing on those that have a better chance to minimize delay. As an additional advantage, this improves the probability that a packet is actually delivered to the final destination.

The impact of node mobility is largely as expected, in that a higher average movement speed induces more frequent contacts and therefore increases the probability of delivering a packet and reduces the delay. However, this improvement

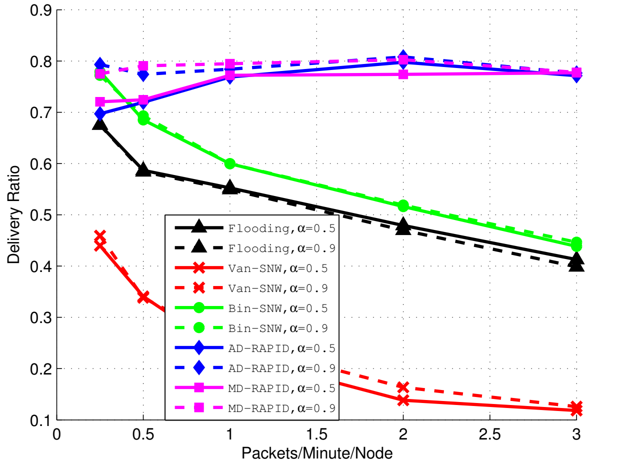

Figure 10. Delivery ratio as a function of the packet generation rate per node for $\alpha = 0.5$ and $\alpha = 0.9$. The average node speed is $2\,\mathrm{m/s}$.

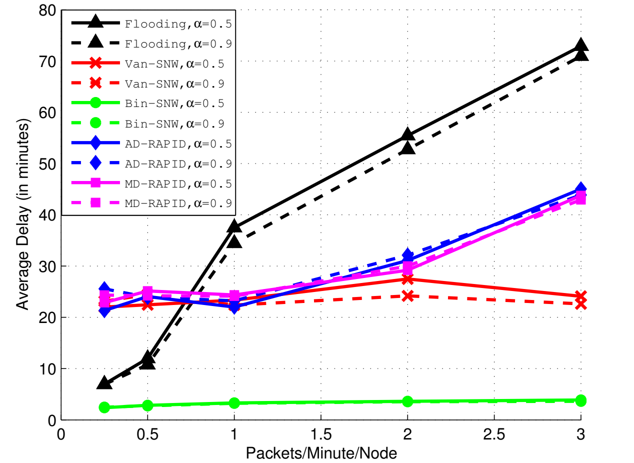

Figure 11. Average delivery delay as a function of the packet generation rate per node for $\alpha = 0.5$ and $\alpha = 0.9$. The average node speed is $2\,\mathrm{m/s}$.

is not substantial enough to advocate the improvement of underwater mobile networking via faster nodes. On the other hand, a smooth node movement pattern is beneficial to the network, especially to RAPID, which is based on the statistics of previous node meetings, and thus works best if such statistics are more stable.

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