Testbed-based Performance Evaluation of Handshake-free MAC Protocols for Underwater Acoustic Sensor Networks

Yashar M. Aval, Yu Han, Andrew Tu, Stefano Basagni, Milica Stojanovic and Yunsi Fei
Department of Electrical and Computer Engineering
Northeastern University, Boston, MA 02115

***Abstract*—This paper concerns the experimental performance evaluation of three protocols for channel access in underwater acoustic sensor networks. In particular, we consider *handshake-free* protocols, i.e., solutions for accessing the acoustic channel without mechanisms of pre-emptive channel reservation, aiming at obtaining lower packet latencies while maintaining high throughput. Two of the protocols that we consider, namely, the Traffic-Adaptive Receiver-Synchronized (TARS) protocol, and the Lightweight Stochastic Scheduling (LiSS) protocol, are based on a utility-optimization framework for computing the optimal transmission strategy dynamically. We benchmark the performance of TARS and LiSS to that of ALOHA, which is the exemplary handshake-free protocol. Our experimental evaluation is based on a testbed of four Teledyne Benthos acoustic modems deployed in an outdoor pool filled with water from the ocean. Our results show that the optimization framework of protocols such as TARS and LiSS achieves remarkable performance both in terms of packet delivery ratio, because of a noticeable reduction of interference, and of end-to-end latency, because of considerable shortening of the slot duration.**

I. Introduction

Underwater acoustic networking is emerging as a concrete answer to the many application challenges for which underwater cabling is costly, impractical or too time consuming to deploy. Typical applications include surveillance of areas such as ports, harbors and coastlines, or monitoring of fisheries and excavation sites (e.g., oil wells, trenches, archaeological sites) [1]. For these networks, a wealth of solutions at all layers of the protocol stack are being proposed, all addressing the concerns and challenges of the underwater channel and the strict requirements of acoustic communications [2]. In particular, designing and implementing efficient medium access control (MAC) for underwater acoustic sensor networks (UASNs) is challenging due to the long propagation delays of the underwater acoustic channel and its unique spatial-temporal variability. MAC protocols successfully used for terrestrial networks are not as effective for accessing the underwater channel because of the many differences between the radio channel and its acoustic underwater counterpart. Many radio protocols based on channel reservation through a "handshake" between the sender and the receiver, such as an RTS/CTS exchange à la IEEE 802.11, incur overhead and disproportionate delays underwater. In fact, many protocols notoriously inefficient for radio access, such as ALOHA-like approaches, become effective ways of accessing the underwater channel because of little overhead and higher channel utilization. In other words, protocols that avoid the overhead of channel reservation mechanisms ("handshake-free" protocols) result in good channel access, allowing robust packet communication even at higher traffic loads.

In this paper we investigate the performance of handshake-free MAC protocols for underwater communications, where overhead and higher delays are avoided by transmitting packets without previous channel reservation. In particular, we investigate the performance of solutions where interferences are reduced, and throughput increased, by some form of probabilistic channel access. The protocols we consider are recently proposed, state-of-the-art solutions, namely, the Traffic-Adaptive Receiver-Synchronized (TARS) protocol by Han and Fei [3], and the Lightweight Stochastic Scheduling (LiSS) protocol proposed by Marinakis et al. [4]. TARS combines the low overhead of handshake-free protocols with a receiver-synchronized approach that adjusts the packet transmission time in a slot to align packet receptions for collision reduction. A queue-aware utility-optimization framework is formulated to dynamically determine the optimal transmission strategy that maximizes the network throughput, which takes both packet interference and data queue status into consideration. Such optimal transmission strategy is traffic-adaptive and can be achieved in a distributed manner, thus being suitable for actual implementation in multi-hop UASNs. Similar to TARS, LiSS is also a stochastic MAC protocol targeting network-wide optimization. Scheduling packet transmission for optimized throughput is determined by the network topology, without explicitly considering traffic. To demonstrate the effectiveness of handshake-free protocols for channel access, we compare the performance of TARS and LiSS to that of ALOHA, which is the exemplary handshake-free protocol. As TARS and LiSS assume that nodes are synchronized, we consider the slotted version of the ALOHA protocol [5].

Our comparison is based on a testbed of four Teledyne Benthos (TB) smart acoustic modems, SM-975 [6], which we deployed in an outdoor pool located at the Marine Science Center of Northeastern University in Nahant, MA. Each modem has been endowed with a basic protocol stack that we developed using Matlab, which include traffic generation, MAC protocol implementation and interaction with the API of the TB SM-975, acting as physical layer. We investigated fundamental metrics such as the packet delivery ratio (PDR) and the end-to-end latency of packets exchanged among the modems configured in a single-hop topology. Our results show that the adaptive optimization framework of protocols such as TARS and LiSS achieves remarkable performance both in terms of PDR, because of a noticeable reduction of interference, and of end-to-end latency, because of considerable shortening of the slot duration.

The rest of the paper is organized as follows. In the following section we survey related works on the implementation and testing of MAC protocols for UASNs. Section III gives details on the three protocols that we have investigated, namely, TARS, LiSS and Slotted ALOHA. In Section IV we provide a description of our testbed along with the results from our experimentation. Finally, Section V concludes the paper.

II. Related Work

In this section we provide an overview of MAC protocols specifically designed for long-delay UASNs.

There have been significant efforts in the past decade on the design of underwater MAC protocols to cope with the adverse features of underwater acoustic communications [4], [7]–[17]. These solutions can be divided into contention-free and contention-based MAC protocols. Contention-free protocols, such as ST-MAC [7] and STUMP [8], require centralized scheduling, leading to either excessive control overhead or sluggish responses to network dynamics.

Contention-based MAC protocols are more suitable for (mobile) UASNs because of their higher flexibility and responsiveness to varying traffic loads and changing network topologies. This type of solutions can be further classified into two categories: handshake-based and handshake-free solutions. Most existing handshake-based solutions are variants of those originally proposed for terrestrial wireless networks [9]–[12]. In order to improve channel utilization in UASNs, some protocols schedule concurrent transmissions by leveraging long propagation delays, such as DOTS [10] and M-FAMA [11]. Other works reduce the one-way handshake delay through a receiver initiated approach, an example being provided by DSH-MAC [12]. However, the handshake procedure inherently exacerbates the already large propagation overhead, resulting in limited improvement on channel utilization.

Light-weight handshake-free protocols, including ALOHA [18], become therefore attractive for UASNs because of their lower overhead and potentially higher channel efficiency. However, due to the lack of prior channel coordination and to the spatial-temporal uncertainty typical of UASNs, this type of solutions may suffer from high packet collisions [13]. To reduce collisions, some ALOHA variants have been proposed [13]–[16]. The work in [13] adds a guard band in the time slot to alleviate collisions, which only works well in short-range networks. The work in [14] uses an advance notification control packet for collision reduction. However, the idle time spent in overhearing is a waste of channel bandwidth, with detrimental consequences also on packet latency. In [15] and [16], a receiver-synchronized approach is used to reduce collisions in Slotted ALOHA. However, both solutions suffer from low throughput in heavy traffic conditions.

More recently, several handshake-free solutions have been proposed that use a stochastic approach to find the best transmission strategy for improving network throughput [3], [4], [17], [19]. In [17], a stochastic random access method is proposed based on interference characterization. Its performance relies heavily on the accuracy of packet interference estimation, which in general is not trivial to obtain in time-varying UASNs. In [19], a Delay-Aware Probability-based MAC protocol (DAP-MAC) is proposed for high channel utilization, by leveraging the long acoustic propagation delay for concurrent transmission. Its utility-optimal transmission strategy is obtained by considering the difference in node sending success. However, a long time slot is required to accommodate concurrent sending, which incurs wasting the limited channel bandwidth. The work in [4] proposes a Lightweight Stochastic Scheduling (LiSS) protocol, targeting network-wide optimization. The utility formulation considers packet interference within a node's two-hop neighborhood. However, it does not consider the packet collisions caused by cross-slot receptions, which may result in increased packet collisions in large UASNs. In [3], a Traffic- Adaptive Receiver-Synchronized protocol (TARS) is proposed with a queue-aware utility-optimal framework. It improves network throughput by reducing packet collisions using a receiver-synchronized scheme, and including the data queue status in the utility formulation to make the optimal transmission strategy adaptive to traffic loads. Simulation results have shown that TARS is able to achieve higher throughput and lower packet delay than LiSS. As LiSS and TARS are among the best performing handshake-free solutions, we selected them for comparison in this paper.

III. TARS, LiSS, and Slotted ALOHA

In this section, we describe the three representative handshake-free protocols considered in this paper, namely, TARS, LiSS, and Slotted ALOHA.

A. TARS

The Traffic-Adaptive Receiver-Synchronized (TARS) protocol is a stochastic handshake-free random access protocol targeting network-wide throughput optimization [3]. TARS uses a receiver-synchronization approach to solve the spatial uncertainty issue in UASNs caused by the varying and low sound propagation speed and by the sender-receiver distance difference. It sets the receiver as the synchronization reference rather than the sender, to reduce collisions. A sender transmits a packet only at the transmission phase in a slot, which is sender-receiver distance dependent, to align packet receptions in single slots. As seen from Fig. 1, where packets from senders i and k are transmitted with different transmission phases and are received at j in single slots, by aligning packet receptions within single slots, the spatial uncertainty caused by the sender-receiver distance difference is eliminated.

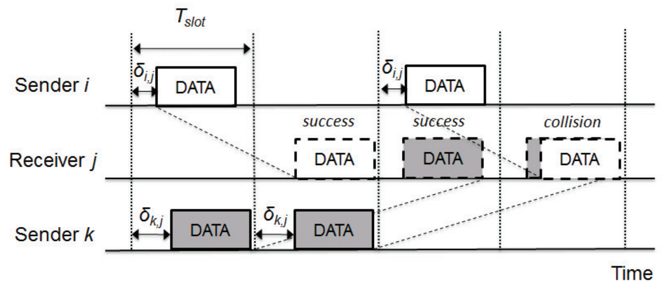

Fig. 1: Receiver synchronization in TARS: Packets from senders i and k are transmitted with different transmission phases ($\delta_{i,j}$ and $\delta_{k,j}$) and are received at receiver j in single slots, where T_{slot} is the slot size.

In TARS, a node is allowed to send a packet in any slot with its pre-calculated transmission phase to the receiver of the packet. The decision of whether to send a packet in a slot as well as which packet to send are made at the beginning of each slot, according to the optimal transmission strategy, which is dynamically obtained in a utility-optimization framework for throughput maximization across all network links. The utility-optimization framework is queue-aware, taking into account both packet interference and data queue status, represented by an estimated empty queue probability. (Details on the definition of the strategy can be found in [3].) Thus, the optimal transmission strategy in TARS can adapt to traffic loads, which is very suitable for mobile and traffic-varying UASNs.

B. LiSS

The Lightweight Stochastic Scheduling (LiSS) protocol is also a stochastic handshake-free protocol for network-wide throughput optimization [4]. Unlike TARS, it uses the traditional transmitter-synchronization approach, where a node can only send a packet at the beginning of a slot. Such approach works well for a network with reduced distances, where the longest propagation delay is about the same or smaller than the slot size, guaranteeing in-slot packet receptions. However, for a large network, due to varying propagation delays for packets on different links, cross-slot packet receptions may occur, leading to increased packet collisions.

Similarly to TARS, the LiSS optimal transmission strategy is obtained by solving a utility-optimization problem (for whose details the reader is referred to [4]). The optimization problem considers the packet interference range within a node two-hop neighborhood, making the optimal transmission strategy adaptive to network topology, i.e., the number of one-hop and two-hop neighboring nodes. Therefore, once the network topology is fixed, the optimal transmission strategy for network nodes keeps unchanged. However, the optimal transmission strategy in LiSS does not adapt to traffic loads. It always chooses the same sending probability (the one under saturated data loads, as in TARS) for all data loads, which may be too conservative for channel utilization, especially under scarce packet generation conditions, where the sending probability could be much higher without hurting the network throughput.

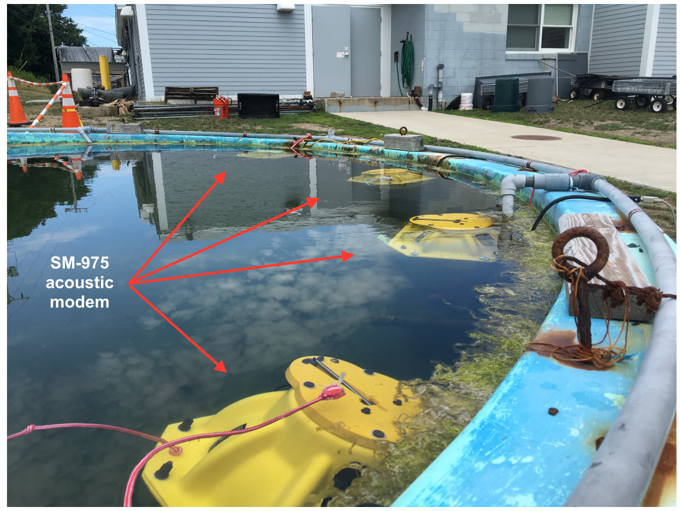

Fig. 2: Four TB SM-975 acoustic modems in the outdoor salt water pool at the NU Marine Science Center in Nahant, MA.

C. Slotted ALOHA

The ALOHA protocol is one of the earliest and most basic random access protocols proposed for wireless broadcast channels [18]. In the slotted version of this protocol, a node awaits for the beginning of a time slot and then sends the first packet in its data queue in its entirety to its intended recipient. An acknowledgment packet (ACK) is sent back to the sending node to confirm the successful delivery of the packet. In the event of packet loss (e.g., for interference with other transmissions), the sending node will attempt to retransmit the packet in the following slot with probability p, opting to remain silent in that slot with probability $1-p$. The randomness in packet retransmission decreases the probability of repeated collisions, increasing channel utilization [5]. Nodes will attempt to retransmit a packet for a pre-set total of times before discarding it.

IV. Experimental Results

A. Testbed settings

The four Teledyne Benthos SM-975 acoustic modems were submerged in an outdoor circular pool filled with saltwater from the nearby ocean. The pool is 1 meter tall and its diameter is 6 meters. The distance between two adjacent modems was about 2 meters (Fig. 2).

The transmit power of the modems can be set to values in the range from 169 dB to 190 dB.[1] For the experiments in the pool the transmit power of all units is set to its minimum (169 dB), as the modems are placed close to one another. Since there is insignificant fading and interference in the

[1] The mentioned source levels in dB are relative to 1 μPa measured 1 m distance from the source.

pool, packets are expected to be delivered successfully, unless collisions occur. The SM-975 modems have two modes of operation. They can use either multiple frequency-shift keying (MFSK) modulation with incoherent receiver, or phase-shift keying (PSK) modulation with coherent receiver. During this experiment, we use MFSK modulation with bit rate of 800 bps, over the frequency band between 9 kHz and 14 kHz.

We implemented the three protocols in Matlab, running on small-factor computers controlling the modems. The protocol stack of each of the modem consists of three layers: Application, for traffic generation, MAC for channel access, and an interface to the physical layer for controlling the modem. This simple architecture is shown in Fig. 3.

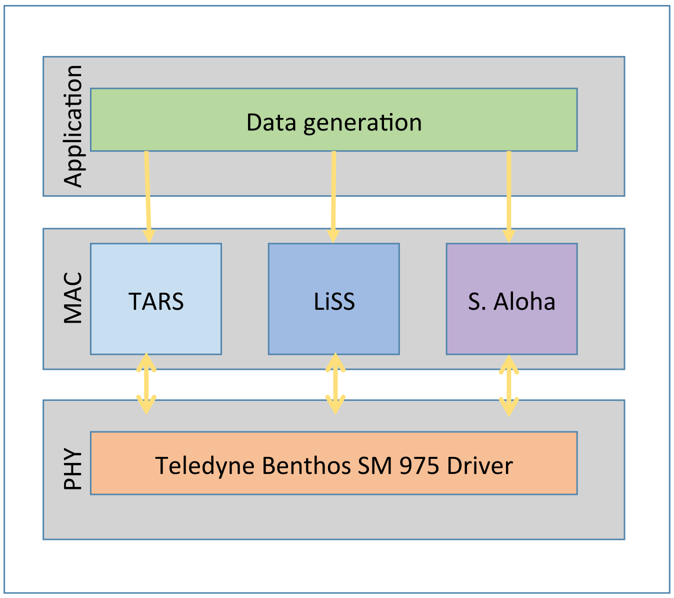

Fig. 3: The basic protocol stack for each modem. Data packets are generated according to a Poisson process of varying rate. They are then randomly assigned a destination and handled by the selected MAC protocol, using the Matlab-based interface to the SM-975 (PHY layer).

The top layer takes care of the packet generation function, which randomly generates data packets according to a Poisson distribution with a varying parameter, corresponding to low, medium and high traffic conditions. In particular, at low traffic on average, each node is given a packet to transmit every 45 to 90 seconds, which corresponds to a network-wide generation rate of 0.045 to 0.09 packets per second. At medium traffic, the network-wide generation rate grows to 0.135 to 0.18 packets per second. At high traffic each node generates a packet every 15 to 18 seconds, for a network-wide load of 0.23 to 0.27 packets per second. The corresponding packet generation rate is identical for all modems. The payload of each packet is 41 bytes, and the transmission of a packet including the packet header takes about 1.8 seconds. The middle layer implements channel access, i.e., it is either TARS, LiSS or Slotted ALOHA. The MAC transmit function reads the data packets from the queue and calls the function of the physical layer. The MAC layer also keeps track of the acknowledgments from the receiver, and upon time out (for packet loss) retransmits the packet. The receiver decodes and stores the received data packets. At the lowest level, we program the direct interface to the modem through a serial port connection. The combination of this interface and the modem acts as the physical layer.

Since the three protocols require node synchronization, we develop a scheme for time synchronization across the network nodes. As our topology configuration is a single-hop network, i.e., each node is in the transmission range of every other node, we designate a node to be the master, and use its clock as the reference clock for the network. Any other node receives the timing information from the master and adjusts its own clock accordingly. The synchronization process is depicted in Fig. 4.

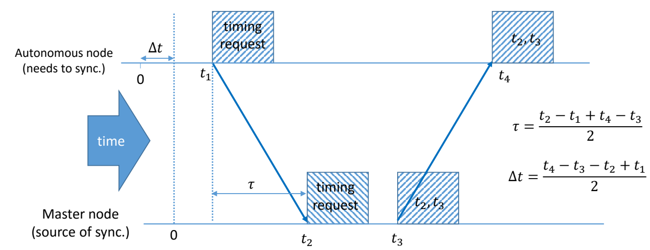

Fig. 4: Nodes synchronize their clocks with the master node by sending and receiving a packet with timestamps. When a node wants to synchronize its clock, it sends a packet to the master node, requesting timing information. The master node responds with a packet that contains the actual time of receiving the request, as well as the time when the response is transmitted. This information is sufficient for each node to estimate the propagation delay (denoted by τ) as well as the clock difference with the master node (denoted by Δt).

For Slotted ALOHA we dimension the slot duration to accommodate the transmission of the data packet, that of the ACK and twice the propagation delay. For this specific experiment, the slot duration was set to 3.2 seconds. If a node does not receive the ACK by the end of the slot, it will keep retransmitting the data packet in the following slots with probability p until either the packet is received successfully or the maximum allowable retransmissions threshold is reached. In the latter case, the packet is discarded. The threshold for maximum allowable retransmissions has been set to 3 for all three protocols. In other words, if after 4 attempts a packet is not correctly acknowledged, that packet is discarded. The probability p used in our experiments has been set to $1/4$. Because of their definition, the slot duration in both TARS and LiSS only needs to consider the packet transmission time. Given the packet duration of 1.8 seconds, the slot duration was set to 2 seconds for TARS and LiSS in this experiment, leaving a guard interval of 0.2 seconds for synchronization errors, delay spread, and propagation delay.

The TARS implementation includes three major differences compared to that of Slotted ALOHA. First, TARS uses a receiver synchronization approach, where nodes compensate for the propagation delay by sending data packets with transmission phases in a slot to guarantee no cross-slot packet receptions. Second, TARS uses an optimal adaptive transmission strategy (i.e., the optimal sending probability) that is dynamically determined by a throughput-optimization framework and changes with data loads and network topology to increase channel utilization while controlling packet collisions. Third, ACKs are not sent immediately after a successful packet delivery. In order to reduce overhead, ACKs are piggybacked to data packets. If a node does not have a data packet to send back to the sender of a packet in need to be acknowledged, it waits for 25 seconds, and if no packets is generated for that sender to send the ACK with, it transmits a dedicated ACK. If an ACK (either piggybacked or dedicated) is not received within 30 seconds, the sender retransmits the data packet.

The LiSS implementation differs from that of TARS in two ways. First, it uses the traditional transmitter synchronization approach as Slotted ALOHA, where packets are transmitted at the beginning of a slot. Second, its optimal transmission strategy is only determined by the network topology, without adapting to possible variation of the data traffic.

Experiments are conducted as follows. For each MAC protocol, and each traffic generation rate, we conduct three experiments and report the averaged results. Each experiment lasts for 35 minutes, where the first 5 minutes are not included in the analysis to allow to the network to reach steady state.

B. Investigated metrics

We compared the three protocols with respect to the following metrics.

1) **Packet delivery ratio (PDR)**, namely, the percentage of packets successfully delivered to their destinations.
2) **Packet end-to-end delay**, namely, the time that it takes to (successfully) deliver a packet. It includes the queuing delay, transmission delay, and propagation delay.
3) **Number of packet retransmissions**, namely, the number of packet retransmissions per successfully delivered packet.

C. Results

Packet delivery ratio. The average packet delivery ratio is shown in Fig. 5 as a function of the packet generation rate. At low to medium traffic, TARS and LiSS are capable of delivering almost all of the data packets as data packets are unlikely to suffer from four consecutive collisions and get dropped. TARS achieves the highest PDR because of its optimized transmission strategy.[2] LiSS shows lower PDR than TARS (especially at medium traffic) due to its inability of adapting to varying traffic.[3] Slotted ALOHA shows low PDR at all traffic rates because of the greater number of packet collisions and retransmissions, which leads to discarding many packets. Furthermore, since slotted ALOHA uses longer time slots, the amount of traffic that it can handle is further reduced.

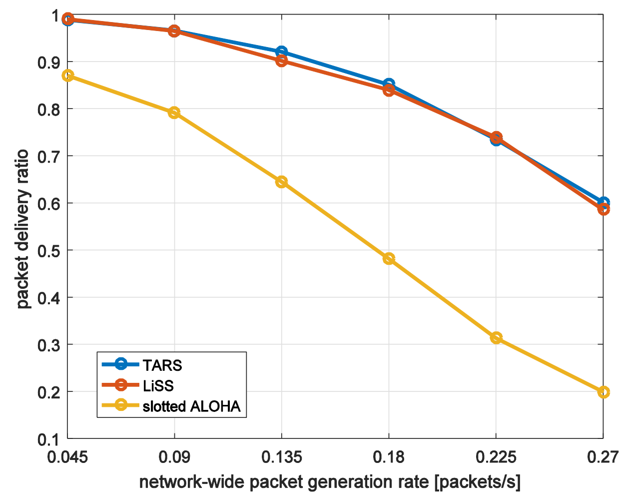

Fig. 5: Packet delivery ratio.

Packet end-to-end latency. Average delay results are shown in Fig. 6.

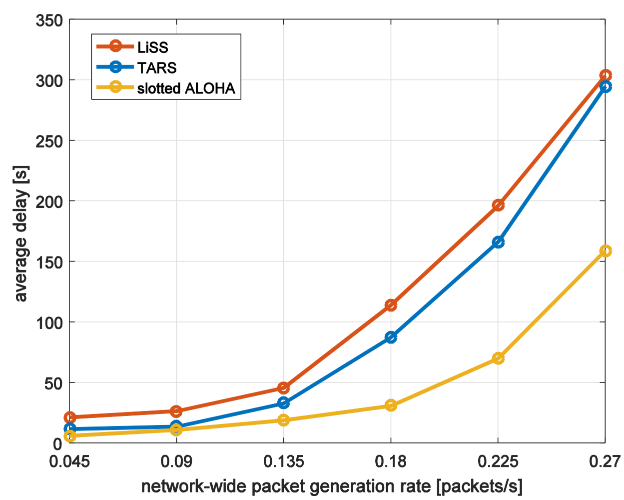

Fig. 6: Packet end-to-end latency.

TARS shows better performance than LiSS at low to medium traffic, because of its more aggressive transmissions with controlled packet collisions. Slotted ALOHA exhibits the smallest latency among the three protocols because of two reasons. First, latency is computed only over successfully delivered packets and we observed that the few packets delivered by Slotted ALOHA are often delivered at the first

[2] Due to the small nodal distances (and also small propagation delays), the throughput improvement contributed by interference alignment in TARS is not significant in this experiment.

[3] Note that in this experiment, the traffic is evenly distributed, i.e. all nodes have a similar traffic load. The difference between TARS and LiSS would be more pronounced in cases where traffic is not evenly distributed (e.g. when one node collects the data from all the other nodes).

attempts, i.e., with small delays. The other reason is that when a packet is transmitted in a slotted ALOHA network, an immediate ACK is expected. Therefore, retransmissions are attempted within few seconds, reducing the overall delay.[4] This is in contrast to TARS and LiSS, where a retransmission is attempted after 30 seconds.

Number of packet retransmissions. The average number of packet retransmissions is shown in Fig. 7.

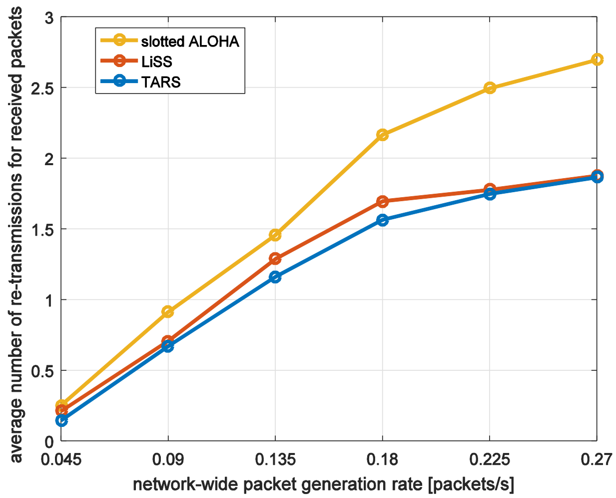

Fig. 7: Number of packet retransmissions for successfully received packets.

The number of packet retransmissions is an indicator of packet collisions. At low traffic, most packets can be successfully delivered on the first attempt, and therefore few retransmissions occur. As the network traffic increases, more collisions happen, resulting in increased retransmissions. Slotted ALOHA is the worst in terms of packet retransmissions, due to the lack of effective collision avoidance mechanism. TARS shows fewer packet retransmissions than LiSS, especially in medium traffic scenarios, because of its optimal transmission strategy specifically aimed at reducing packet collisions. It can be seen that at high traffic, Slotted ALOHA attempts the maximum number of retransmissions (three) for most of the delivered packets, while TARS and LiSS keep the number of retransmissions to less than two.

V. Conclusions and Future Work

This paper reports the results of a testbed-based comparative performance evaluation of three MAC protocols for underwater acoustic sensor networks. The three protocols, all handshake-free and synchronized, are TARS, LiSS, and Slotted ALOHA. We tested the protocols over a single-hop topology formed by four TB acoustic modems SM-975 submerged in a salt water pool. Our results show that the adaptive optimization framework of protocols such as TARS and LiSS achieves remarkable performance in terms of PDR, end-to-end latency, and number of packet retransmissions.

In the future, we plan to perform similar experiments in the ocean at the Northeastern University Marine Science Center in Nahant, MA, where we are developing the Northeastern University Marine Observatory NETwork (NU MONET) [20], a multi-hop underwater acoustic network. We plan to evaluate the performance of the three protocols in networks with up to 7 nodes with respect to packet delivery ratio, packet end-to-end delay, number of packet retransmissions, and power consumption.

[4] Our results are generated with an unlimited queue length. Limiting the queue length for each node, could have effect on the end-to-end latency of all three protocols.

Acknowledgments

This research was supported in part by the NSF and ONR through the grants CNS 1428567, NSF 1428567, and ONR N00014-15-1-2550. Andrew Tu and Stefano Basagni were also supported by NSF through a GENI SAVI travel grant. The work was performed under the sponsorship of the EU FP 7 ICT project SUNRISE "Sensing, monitoring and actuating on the UNderwater world through a federated Research InfraStructure Extending the Future Internet."

References

[1] J. Heidemann, M. Stojanovic, and M. Zorzi, "Underwater sensor networks: Applications, advances and challenges," *Philosophical Transactions of the Royal Society A*, vol. 370, pp. 158–175, Aug. 2012.

[2] T. Melodia, H. Kulhandjian, L.-C. Kuo, and E. Demirors, "Advances in underwater acoustic networking," in *Mobile Ad Hoc Networking: Cutting Edge Directions*, S. Basagni, M. Conti, S. Giordano, and I. Stojmenovic, Eds. Hoboken, NJ: John Wiley & Sons, Inc., Mar. 2013, ch. 23, pp. 804–852.

[3] Y. Han and Y. Fei, "TARS: A traffic-adaptive receiver-synchronized MAC protocol for underwater sensor networks," in *Proceedings of IEEE MASCOTS 2015*, Atlanta, GA, Oct. 2015, pp. 1–10.

[4] D. Marinakis, K. Wu, N. Ye, and S. Whitesides, "Network optimization for lightweight stochastic scheduling in underwater sensor networks," *IEEE Transactions on Wireless Communications*, vol. 11, no. 8, pp. 2786–2795, Aug. 2012.

[5] J. F. Kurose and K. W. Ross, *Computer Networking: A Top-down Approach*, 6th ed. Upper Saddle River, NJ: Pearson Education, Inc., 2013.

[6] "The Teledyne Benthos SMART product SM-975," http://www.benthos.com/index.php/product/ smart_products/sm-975.

[7] C.-C. Hsu, K.-F. Lai, C.-F. Chou, and K. Lin, "ST-MAC: Spatial-temporal MAC scheduling for underwater sensor networks," in *IEEE INFOCOM*, Apr. 2009, pp. 1827–1835.

[8] K. Kredo, P. Djukic, and P. Mohapatra, "STUMP: Exploiting position diversity in the staggered TDMA underwater MAC protocol," in *IEEE INFOCOM*, Apr. 2009, pp. 2961–2965.

[9] M. Molins and M. Stojanovic, "Slotted FAMA: A MAC protocol for underwater acoustic networks," in *IEEE OCEANS*, May 2006, pp. 1–7.

[10] Y. Noh, P. Wang, U. Lee, D. Torres, and M. Gerla, "DOTS: A propagation delay-aware opportunistic MAC protocol for underwater sensor networks," in *IEEE Int. Conf. on Network Protocols*, Oct. 2010, pp. 183–192.

[11] S. Han, Y. Noh, U. Lee, and M. Gerla, "M-FAMA: A multi-session MAC protocol for reliable underwater acoustic streams," in *IEEE INFOCOM*, Apr. 2013, pp. 665–673.

[12] T. Hu and Y. Fei, "DSH-MAC: Medium access control based on decoupled and suppressed handshaking for long-delay underwater acoustic sensor networks," in *IEEE Local Computer Networks Conf.*, Oct. 2013, pp. 523–531.

[13] A. A. Syed, W. Ye, J. Heidemann, and B. Krishnamachari, "Understanding spatio-temporal uncertainty in medium access with ALOHA protocols," in *ACM WUWNet*, 2007, pp. 41–48.

[14] N. Chirdchoo, W.-S. Soh, and K. C. Chua, “Aloha-based MAC protocols with collision avoidance for underwater acoustic networks,” in *IEEE INFOCOM*, May 2007, pp. 2271–2275.

[15] Y. Zhou, K. Chen, J. He, and H. Guan, “Enhanced slotted aloha protocols for underwater sensor networks with large propagation delay,” in *IEEE Vehicular Technology Conf. Spring*, May 2011, pp. 1–5.

[16] P. Mandal, S. De, and S. S. Chakraborty, “A receiver synchronized slotted Aloha for underwater wireless networks with imprecise propagation delay information,” *Ad Hoc Networks*, vol. 11, no. 4, pp. 1443–1455, 2013.

[17] Z. Guan, T. Melodia, and D. Yuan, “Stochastic channel access for underwater acoustic networks with spatial and temporal interference uncertainty,” in *ACM WUWNet*, Nov. 2012, pp. 18:1–18:8.

[18] N. Abramson, “The ALOHA System—Another alternative for computer communications,” in *Proceedings of AFIPS 1970, Fall Joint Computer Conference*, vol. 37, Houston, TX, Nov. 1970, pp. 281–285.

[19] Y. Han and Y. Fei, “A delay-aware probability-based MAC protocol for underwater acoustic sensor networks,” in *Computing, Networking and Communications (ICNC), 2015 International Conference on*, Feb. 2015, pp. 938–944.

[20] “Northeastern University Marine Observatory NETwork (NU MONET),” http://www.northeastern.edu/numonet/.