

Table II
PACKET DELIVER RATIO ALONG THE PATH

(Bold black - reliable one-hop communication, Bold blue - reliable multi-hop communication, Red - unreliable one-hop communication).

Sender ID	Successful Reception Ratio								
	N1 (%)	N2 (%)	N3 (%)	N4 (%)	N5 (%)	N6 (%)	N7 (%)	N8 (%)	N9 (%)
N1	—	40.6	22.3	6.9	1.7	0.0	0.0	0.0	0.0
N2	67.0	—	20.5	0.8	1.7	0.0	0.0	0.0	0.0
N3	60.2	92.9	—	56.1	25.5	0.0	0.0	13.3	6.1
N4	20.4	32.6	80.1	—	50.3	5.0	0.6	45.9	48.6
N5	6.0	16.5	14.7	66.2	—	28.1	7.2	66.2	44.3
N6	0.0	0.0	4.6	2.3	35.6	—	56.8	47.7	12.1
N7	0.0	0.0	0.0	0.0	6.0	67.2	—	85.1	16.4
N8	0.0	0.0	2.0	2.0	2.0	2.0	81.6	—	100.0
N9	0.0	0.0	8.3	22.9	16.7	14.6	22.9	100.0	—

Spatial communication range uncertainty emerges in two aspects. 1) The communication ranges of different nodes vary significantly. As shown in Table II, $N1$ and $N2$ are only able to communicate with each other with reception ratios higher than $1/3$, which means the communication range for both of them is only one hop. However, $N5$ is able to reach $N9$ with 44.3% reception ratio, indicating that its communication range is a 4-hop distance. Even if all nodes operate at same power, frequency band and baud rate, the network has heterogenous communication reliability, which challenges the MAC design and protocol evaluation for UANs. 2) When one sender transmit, receivers at different locations have evidentially variant reliability. There exists a possibility that closer receivers have much worse communication than the nodes further away, which is observed when $N4$ and $N5$ transmitted. In MAC protocol design, collision handling and transmission scheduling tightly depend on the communication ranges. When the actual neighborhood does not match the designed model, its performance will be significantly reduced.

The communication range not only varies spatially, but also shows dynamic nature in temporal dimension. Owing to the time varying feature of wind, current, marine mammal noise and man made activities, the link reliability feature changes with time. We divide the total 3 hours test into 30 equivalent time segments and record the communication range (in hops) for each time period. The communication range varied significantly on both forward and backward links in the experiment. Fig. 6 illustrates the dynamic communication range when $N5$ (in Table II) sent packets. No packets could be reliably delivered to any nodes in several periods. On the contrary, in the rest of time $N5$ had good communication reliability for transmissions in both directions.

C. Delayed Data Transmission

The purpose of medium access control is to handle the interference in a shared medium by scheduling transmissions of multiple devices. Zero or negligible delay between the actual data transmission time on acoustic modems and scheduled sending time by the MAC protocol is expected to guarantee

the functionality of MAC protocols. However, in our field experiments, we discovered considerable delays between the scheduled transmission time and the actual modem sending time. The major reason for extra delays might be the busy terminal problem of acoustic modems [11], [16].

In current acoustic modem design, the actions of packet transmission and reception cannot be interrupted once they get started. This implies that the modem has to receive the whole packet forcibly without dropping out halfway, even if it is overhearing a packet *not to it*. This phenomenon is called busy terminal problem. If the modem is busy with either sending, receiving or overhearing at a scheduled packet transmission time, the outgoing packet pushed into the modem can not be processed immediately as the MAC protocol has scheduled. The packet transmission will be postponed until the modem comes out of busy state. This busy terminal problem is aggravated by the long transmission time in acoustic networks. In our experiments, the packet of 200 bytes lasted for 7.4 seconds when Benthos modems operated at 300 bps.

We calculate the interval between modem sending time and MAC scheduling time and display the delays in Fig. 7. When the packet transmissions were not interfered by the busy terminal problem, the modem sending delays were randomly distributed from 0 to 200 ms. Among these 48 packet receptions in Fig. 7, four significant delays were observed in one test. This means the delayed modem transmission is not a rare situation. The highest delay was up to 1.8 seconds, which implies that the actual data sending time was 1.8 seconds later than the MAC scheduled transmission. These four modem sending delays were considerable even compared with the 0.7 seconds propagation delay and could make the collision avoidance mechanism futile. The delays introduced by the busy terminal problem are impulsive and unpredictable events and therefore pose grand challenges to MAC protocol design.

D. Summary

To summarize, we observed high packet loss rate and significant channel asymmetry, spatial and temporal communication range uncertainty and delayed data transmission on acoustic

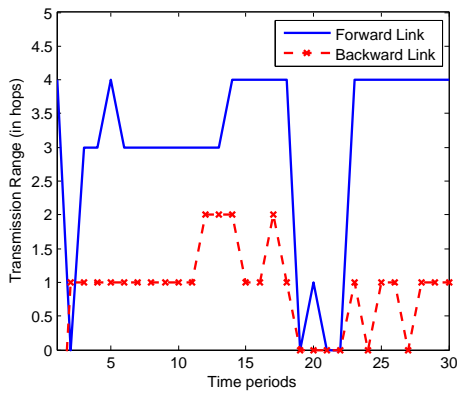


Figure 6. Transmission range changes with time.

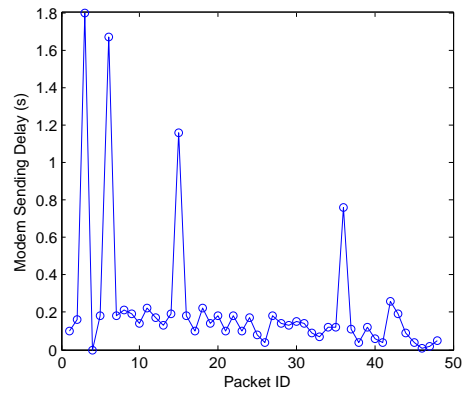


Figure 7. Delays before modem transmission.

modems, from real filed experiments.

Dealing with high packet loss rates becomes a challenging task for MAC protocol design, as packet losses could dramatically degrade the MAC performance from all aspects. Significant channel asymmetry becomes another challenge faced by MAC protocols with two-way handshaking or acknowledgement mechanisms. Collision avoidance handling, transmission scheduling and MAC performance analyzing rely on neighborhood information which suffers a lot uncertainty on the communication range in both spacial and temporal dimensions. Unexpected sending delays on acoustic modems are critical due to the busy terminal problem. Especially in dense networks where nodes experience heavy overhearing, delayed packet transmissions would cause significant collision avoidance failures. In the next section, we discuss the impact of aforementioned features on underwater MAC protocols in details.

V. EXPERIMENT RESULTS AND ANALYSIS

The mechanisms of UW-Aloha, SASHA and PTMAC have been introduced in Section II. In this section, we analyze and compare the performance of three representative MAC protocols in terms of packet behavior, node level behavior and end-to-end performances. The packet behavior we are going to analyze includes hop-by-hop packet delivery delays and delivery ratio. In Section V-B, we define load balancing as a critical factor to evaluate node level behavior of the three MAC protocols. The end-to-end performance metrics we compare include throughput, delay and delivery ratio. Next we discuss each performance in details.

A. Packet Behavior

First we are going to study the packet behavior of the three MAC protocols, which includes the hop-by-hop delay and delivery ratio of data packets. These two packet level performance measures serve as the foundation to analyze the overall end-to-end protocol performance and meanwhile provide insights to pinpoint the problems within the design of the protocols. The hop-by-hop delay and delivery ratio of the three protocols are presented in Fig. 8 and Fig. 9. Hop-by-hop delay is defined to be the interval between the time when the

packet arrives at the sender and the time when the packet is delivered to the receiver. Hop-by-hop delivery ratio is defined to be the percentage of the packets received by the receiver at a given hop.

UW-Aloha achieved much lower delays than the handshaking SASHA and scheduling based PTMAC, benefiting from the simple nature of the protocol. UW-Aloha is designed to transmit packets immediately as long as the node is in idle state. Even when it suffered huge packet losses, packets were dropped after a certain number of retries, which enabled senders to process new packets after short delays. The downside of this packet dropping mechanism is that it leads to a low packet delivery ratio. For instance, Link 5 had a much higher packet loss rate than other links and therefore discarded a substantial amount of packets, leading to a sharp delivery ratio drop.

SASHA and PTMAC showed comparable hop-by-hop delays, as both protocols introduce extra delays for data packet transmission. For SASHA, the two-way handshaking process is time consuming, which was 13.1 seconds in the experiment, including the long preamble, high propagation delay and guard time. If the packet loss rate is as significant as in Fig. 5, drastically long delays will be imposed on handshaking processes and retransmissions. Therefore, SASHA had larger delays than UW-Aloha and PTMAC on most links. In particular, the peak delay on Link 5 was caused by the huge packet losses and retransmissions. Regarding the packet delivery ratio, on Link 5, SASHA had a sharp drop similar to UW-Aloha, but due to a different reason. Unlike UW-Aloha, SASHA retransmits until all packets are delivered. With this scheme, a large amount of packets were queued on Link 5, which had a bad link quality.

Nodes running PTMAC take turns to send packets. Each cycle took about 32.9 seconds in our experiment. If retransmission is needed, it has to wait 32.9 seconds for a new transmission cycle regardless whether its neighbor nodes have sending task in the assigned slots. The significant amount of packet losses and retransmissions on Link 5 caused a remarkable peak in packet delivery delay. This is a limitation of statistic scheduling design. On the other hand, since the whole running time was used for data packet transmissions in PTMAC, nodes had more transmission opportunities than

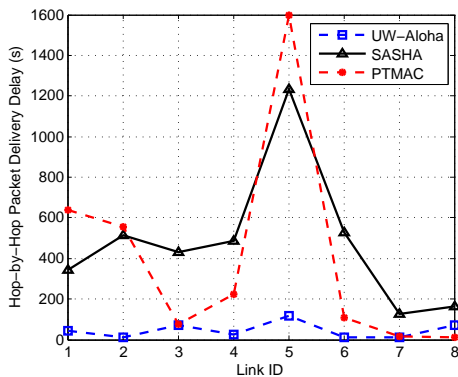


Figure 8. Hop-by-hop packet delivery delays.

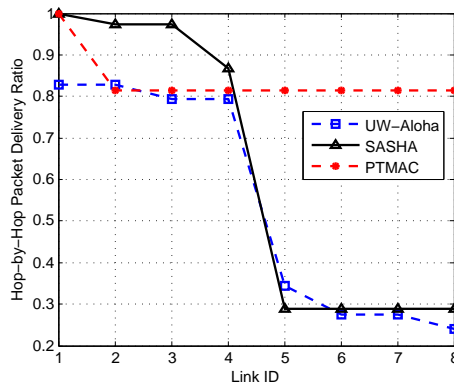


Figure 9. Hop-by-hop packet delivery ratios.

nodes in SASHA, and therefore achieved appealing delivery ratios on all hops along the path.

B. Node Behavior

In the node behavior analysis, we compare the data sending and receiving behaviors of each node among the three MAC protocols. We list the number of packets sent and received in a two and half hours test in Table III. We define load balancing factor in Equation (1).

$$F_B = \frac{(\sum_{i=1}^n N_i)^2}{n \sum_{i=1}^n N_i^2}, \quad (1)$$

where n is the number of nodes and N_i is the number of packets processed at node i . It is a different metrics from fairness [17], which is defined as an equal share of bottleneck. Load balancing refers to the balanced sending or receiving actions among nodes in the multi-hop network. Load balancing is a preferred feature in a network when all nodes have same traffic load, which was true in our experiment.

Table III lists the balancing factor of three MAC protocols. Transmission balancing plays an important role in determining the network lifetime. Balanced transmission can help to avoid the early depletion of a node because of unbalanced heavy load, thus enhance network connectivity. Reception balancing, on the other hand, can help to avoid over-crowded region in the network. This feature is crucial for MAC protocol performance since the collision probability relies on the traffic rates. Severe interference would happen in the over-crowded region.

UW-Aloha had poor balance on both sending and receiving events, since nodes closer to the source had more packets to receive and transmit than nodes closer to the sink, especially when a large amount of packets were dropped on Link 5. SASHA had better transmission balancing benefiting from the handshaking mechanism. Data packets could be sent out only when reservation is successful, which reduces unnecessary data transmissions. However, receiving balancing factor is still low due to the severe packet losses. Similar to UW-Aloha, much fewer packets traveled through Link 5, due to the time consuming two-way handshaking and retransmissions. For PTMAC, on the contrary, all nodes in the network have equal slots to transmit. Unbalanced sending was caused by

retransmissions. Since PTMAC is designed to be collision free, more significant packet losses and retransmissions than UW-Aloha and SASHA in the test was possibly caused by the transmission range dynamics. PTMAC is based on the assumption that nodes two hops away are unable to reach each other and therefore allowed to send simultaneously, which should be the truth in the field. However, due to the communication range uncertainty, packets can reach nodes further than two hops, leading to unexpected collisions. Another serious problem for scheduling based MAC is the delayed modem transmission. When a packet is failed to be pushed out at scheduled time due to the busy terminal problem, unexpected collisions also occur. The receiving process, on the other hand, achieved high balancing rate in PTMAC. Nodes almost received similar number of packets along the path and led to a higher end-to-end throughput than the other two protocols, which will be discussed in Section V-C.

C. End-to-End Performance

The end-to-end performance metrics we focus on in the comparison are throughput, packet delivery ratio, and delays.

1) *End-to-End Throughput*: End-to-end throughput is the most direct metric to evaluate the network performance. As shown in Fig. 10(a), UW-Aloha got the lowest throughput even at ultra low traffic rate. Because of time limitation, we did not get chance to conduct further test for UW-Aloha. The low throughput was a result of the packet drop mechanism. As revealed in Table III, a large number of packets failed to reach N_6 , since UW-Aloha is designed to simply drop packet after several retries. This leads to much lower end-to-end throughput and delivery ratio performance for UW-Aloha. SASHA achieved similar throughput performance with UW-Aloha at low traffic rate. SASHA handles data packet interference better than UW-Aloha using RTS/CTS reservation, but with a penalty incurred by high handshaking delays. The throughput of SASHA increased when the network had higher traffic rates. However, SASHA significantly underperformed PTMAC. Since the whole time in PTMAC was assigned for data transmission, the throughput performance linearly grew with the increasing network load before the PTMAC saturated. The highest throughput for PTMAC only depends on the

Table III
NUMBER OF PACKETS SEND AND RECEIVED ALONG THE PATH

Sender ID		Number of Data Packets									F_B (%)
		N1	N2	N3	N4	N5	N6	N7	N8	N9	
UW-Aloha	Send	96	90	81	73	163	77	37	35	\	82.6
	Recv	59	49	49	47	47	20	16	16	14	80.9
SASHA	Send	66	75	56	47	46	49	30	29	\	90.0
	Recv	59	52	51	51	45	15	15	15	15	79.5
PTMAC	Send	175	239	98	181	334	132	67	49	\	76.4
	Recv	59	59	48	48	48	48	48	48	48	99.2

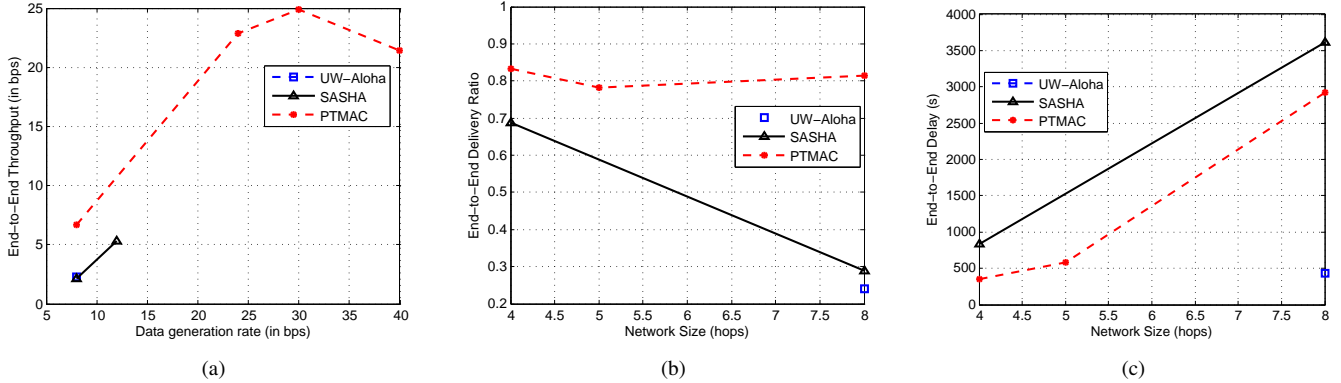


Figure 10. End-to-end performance comparison. (a) Throughput, (b) Delivery ratio, (c) Delay.

modem transmission rate and channel quality. Due to the pipelined scheme, the hop with worst channel performs as the bottleneck.

2) *End-to-End Delivery Ratio*: End-to-end delivery ratio is an important metric related to the network reliability. Due to the high cost of transport layer retransmission in UANs, link level reliability becomes an essential feature for MAC protocols. In Fig. 10(b), we compare three MAC protocols in terms of delivery ratio performance. End-to-end packet delivery ratio relies on the network size. With a larger number of hops along the path, packets are more vulnerable to losses.

UW-Aloha had as much as 75% packets loss along the path after a limited number of retransmissions. The huge packet losses were caused by collisions and bad channel quality. When the network was as small as 4-hops, SASHA successfully delivered 70% of packets generated. However, when the network size increased to 8-hops, the delivery ratio drastically reduced to 28%. As Link 5 was very unstable in the 8-hop network, a quite large number of packets were stuck in the middle of network. Even though SASHA is designed to be able to avoid data packet interference, the time consuming handshaking process and high packet losses lead to low capacity on data packet delivery, which is the main reason for the low delivery ratio in the 8-hop network. PTMAC, on the other hand, achieved the highest end-to-end reliability. Benefiting from the scheduling mechanism, nodes had time to process more packets since no contention or reservation delays were introduced in PTMAC.

3) *End-to-End Delay*: End-to-end delay grows with the increase of network size, since longer time would be required to reach the destination if the sink is further away. Fig. 10(c) shows the delay performance of the three MAC protocols.

According to the design of UW-Aloha, packets are pushed out with minimum delays. Even though superfluous packets were lost in the middle of network, the delivered packets were able to reach the destination with small end-to-end delays, as shown in Fig 10(c). SASHA and PTMAC had much more significant end-to-end delays than UW-Aloha. This conclusion is consistent with the results of hop-by-hop delays in Fig. 8. Since both protocols are designed to deliver all packets with unlimited retries. When one link (Link 5) was bad, the substantial retransmissions led to dramatic delays. Delays of both SASHA and PTMAC linearly increase with the network size according to our test results. Similar to the throughput performance, SASHA was inferior to PTMAC on delay performance. This is also caused by the time consuming handshaking process considering the low sound speed and long preamble in acoustic modems.

VI. DISCUSSION

In Section IV, we discussed three facts we observed about real system features, namely, high packet loss rate and significant channel asymmetry, communication range uncertainty and delayed data transmissions. The impact of these facts on three representative MAC protocols was analyzed in Section V. In this section, we discuss how these real system features affect

general MAC protocols and provide some suggestions on how to address the observed issues in underwater MAC protocol design.

The high packet loss rate brings grand challenges to underwater MAC protocol design. Even though most MAC protocols employ retransmission mechanism to deal with packet losses, it becomes inefficient if we consider the long preamble length, high propagation delays and high energy consumption with retransmissions in real systems. In this case, network coding technique [18] becomes a promising technique because of the broadcast nature of UANs. The communication reliability could be improved to some extent benefiting from the error recovery capacity of network coding. However, the time-varying feature of UANs requires dynamic coding rate, which is still an open issue.

On another hand, the significant channel asymmetry might degrade the performance of the ARQ based MAC protocols, since both the data packet and the ACK packet losses will lead to data packet retransmitting. This implies that the number of retransmissions is determined by the worse channel between the data transmission channel (forward link) and the feedback channel (backward link). To counter the negative effect of channel asymmetry, one viable solution is to employ independent coding rates for channels with different link qualities. However, this introduce further complexity for MAC protocol design.

The spatial and temporal communication range uncertainty changes the interference area in real experiments, which is generally assumed to be fixed and homogenous in theoretical and simulation studies. This results a gap between simulation results and the real performance in sea experiments. This gap could be mitigated by introducing the communication range randomness in the simulator. For scheduling based MAC protocols, the communication range uncertainty can also incur undesired interference to nodes that are multi-hop away if they fail to consider the dynamic neighborhood issue. Dynamic scheduling might help but is difficult to implement in real underwater networks, where the negotiation throughout the network is slow and inefficient even if a common control center exists.

The delayed data transmission on acoustic modems could make the collision avoidance mechanism futile. Especially in the network where nodes experience heavy overhearing, the data transmissions might behave in totally unexpected ways. Adding large guard time could reduce the chance of collisions when the data transmission is undesirably postponed due to the busy terminal problem, however, with a penalty of increased network latency.

VII. CONCLUSION

In this work, we conducted multi-hop string network experiments at Atlantic Ocean. In the field results, we observed high packet loss rate and significant channel asymmetry, spatial and temporal communication range uncertainty and delayed data transmission caused by the busy terminal problem, which have evidential effect on MAC protocol performance. We also analyzed and compared the random access based UW-Aloha,

handshaking based SASHA and scheduling based PTMAC with different network scenarios. Based on the field test results, we studied the advantages, shortcomings and limitations of three MAC protocols and how they work in real systems. The end-to-end metrics we compared are throughput, delivery ratio and delays. Following this, we discussed the impact of observed system features on general underwater MAC protocols and provided some inspirations to address these specific problems in MAC design for real multi-hop networks.

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