Experiment report

1. **Experiment time:** July 30th, 2015
2. **Experiment location**: receiving Node (MID3) was placed at Pocock rowing center and two source nodes (MID1, MID2) were setup in APL location.

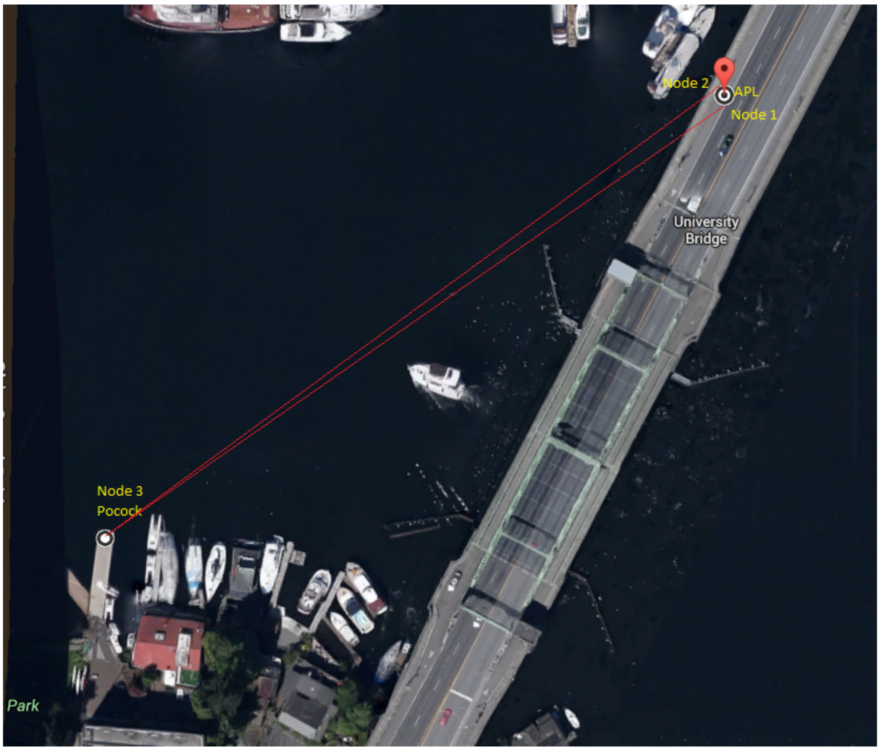

Figure 1: Deployment location

3. **Experiment purposes**:
   a. Test and validate Channel Impulse Response (CIR) in the lake.
   b. Test the performance of underwater network MAC protocol UW-Aloha with newly added back off scheme.
4. **Performance metrics and measurements:**
   a. Delay spread of impulse response
   b. Measuring packets sent, received, and dropped in order to analyze the performance of UW-Aloha protocol including throughput and loss rate.
5. **Experimenters**: Noshad Bagha, Yanling Yin, and Joseph Nuroho.
6. **Experiment procedure**:
   a. CIR procedure: Transmitting m-sequence signals from node 1 to 3 then node 2 to 3, before and after each trial. For longer experiment, we have taken one additional CIR in between trials.
   b. Back-off procedure
      i. Node 1: set packet length to 400 payload + 162 header in bytes, tx-rate=0.05, 0.08, 0.1, 0.15 packet/ sec.
      ii. Node 2: set packet length to 400 payload + 162 header in bytes, tx-rate=0.05, 0.08, 0.1, 0.15 packet/ sec (Table 1)

Table 1: Random Back off procedure

Trial	Transmission power(All modems)	Packet Size(Payload + Header) (bytes)	Transmission rate(pkt/sec)	Test time(mins)	Comments
1	-4 dB	562	0.05	34	3 CIR measurements
2	-4 dB	562	0.08	37	3 CIR meas.
3	-4 dB	562	0.1	15	2 CIR meas.
4	-4 dB	562	0.15	18	2 CIR meas.

7. Experiment environment:

Node 3 was moved from Pocock dock to an adjacent dock after 0.08 pkt/sec trial. CIR readings show similar delay spreads between these two docks. Table 2 is the distance between each node plus water depth.

Table 2: Distance and depth

water depth at each site	Node1	Node2	Node3
	4.9m	4.9m	5.4
node1 depth (sender1)	3m		
node 2 depth (sender2):	3m		
node3 depth (receiver):	3.5m		
distance between node1 and node3:	189m|206m		
distance between node2 and node3:	188m|205m		
distance between node1 and node2:	2m		

According to Table 2, we can consider the testing side as shallow water due to short distance between modems and both bottom and surface of the lake. In addition, lake Union's bottom at the testing location is classified as hard bottom. Both these conditions should increase the multipath effect and delay spread in compare to sea testing (Ref. 1.)

Figure 2 shows a top view of the experiment topology. The Pocock dock is shown in red dot and second dock is shown in a green dot.

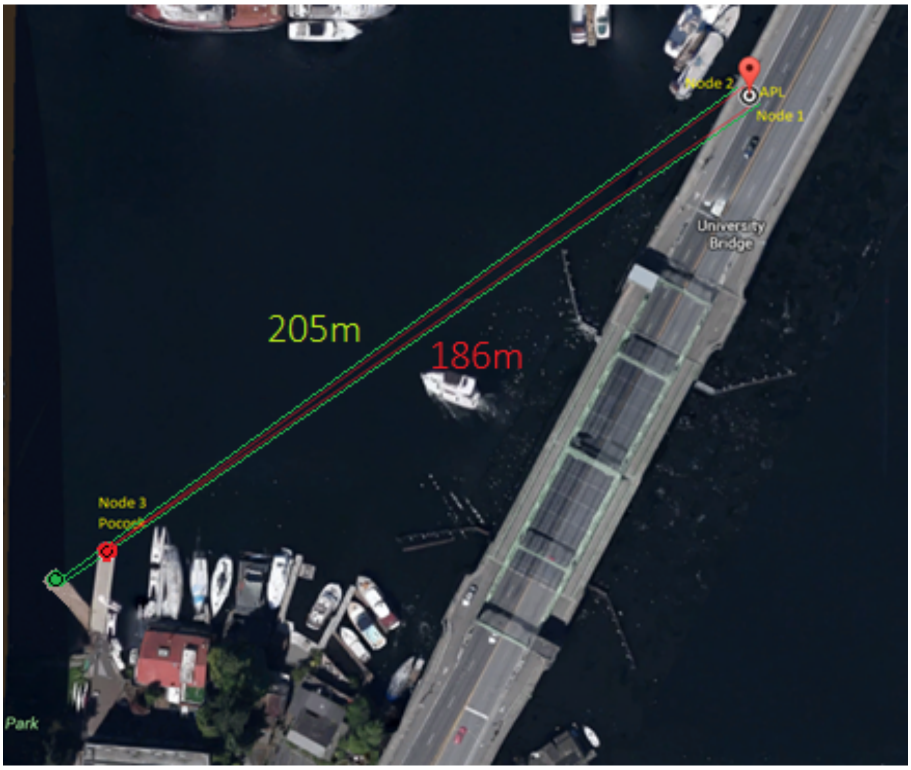

Figure 2: Top view of topology

Figure 3 is side view of experiment topology denoting the depth of each modem compared to the lake depth.

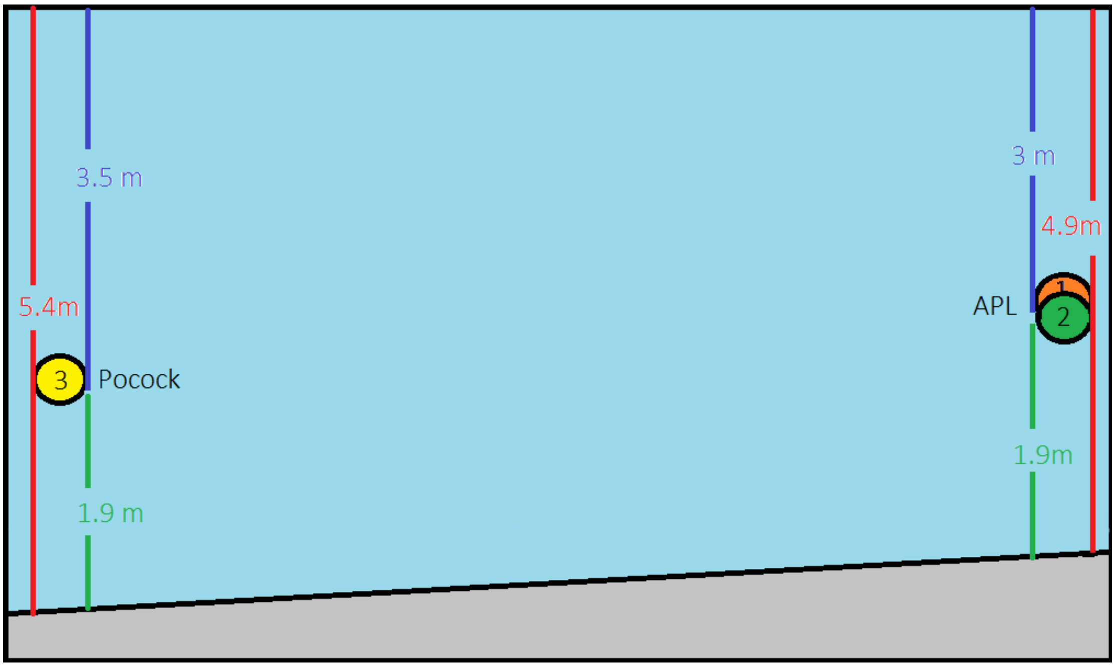

Figure 3: Side view of topology

Moderate boat traffic was observed during trials.

8. Back-off Scheme Algorithm

We have modified traditional binary exponential back-off scheme to make it suitable for underwater channel conditions. Back-off time slot is determined by N = 2^C -1 where N is number of Back-off units for Cth collision, where C= [1-3] inclusive.

Total transmission time is the time data is send to the time ACK is received. TTT is calculated by:

TTT= RTT + processing time 30% RTT

The 30% of total RTT will be added for additional processing delays and other unexpected delays. Each one TTT is considered as one unit of back-off. The back-off time will be a number between zero to N*TTT (Figure 4.)

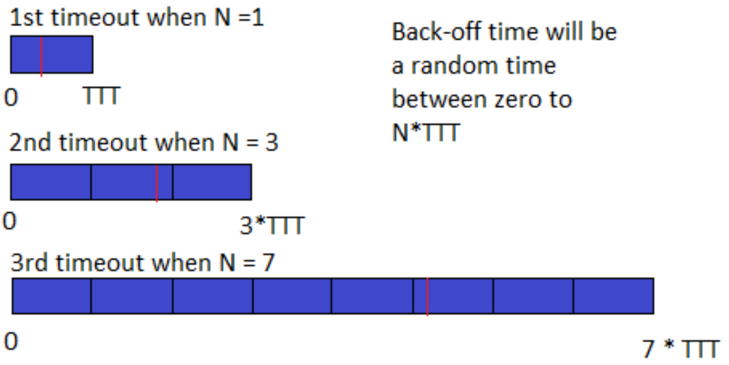

Figure 4: Back-off Algorithm

After some debugging, it was realized there is a need for sequence number. When an ACK timeout occurs and back off time is zero, modem will re-transmit immediately. Let's assume ACK from pervious failed transmission arrives one second after retransmission (Figure 5) without sequence number, program considers the ACK is coming from the most recent retransmission and will set TTT to one seconds. Since ACK timeout is equal 1.3 *TTT, it will set timeout to be 1.3 seconds which causes perpetual re-transmission and drop. By adding sequence number this issue is resolved. When such issue occurs, last ACK timeout time is increased by 30% again to prevent premature ACK timeout.

Figure 5: Without seq #, pervious ACK received will erroneously change TTT to few seconds.

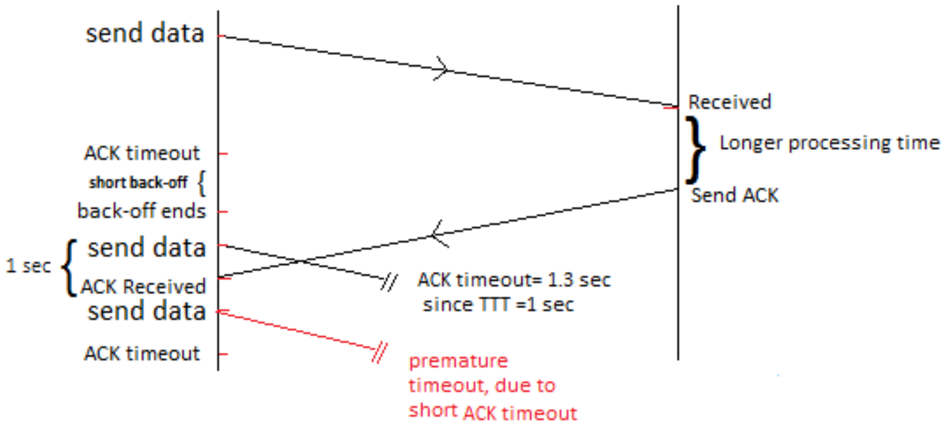

Figure 5 below

is the overview of Aloha Protocol plus modifications made for this experiment.

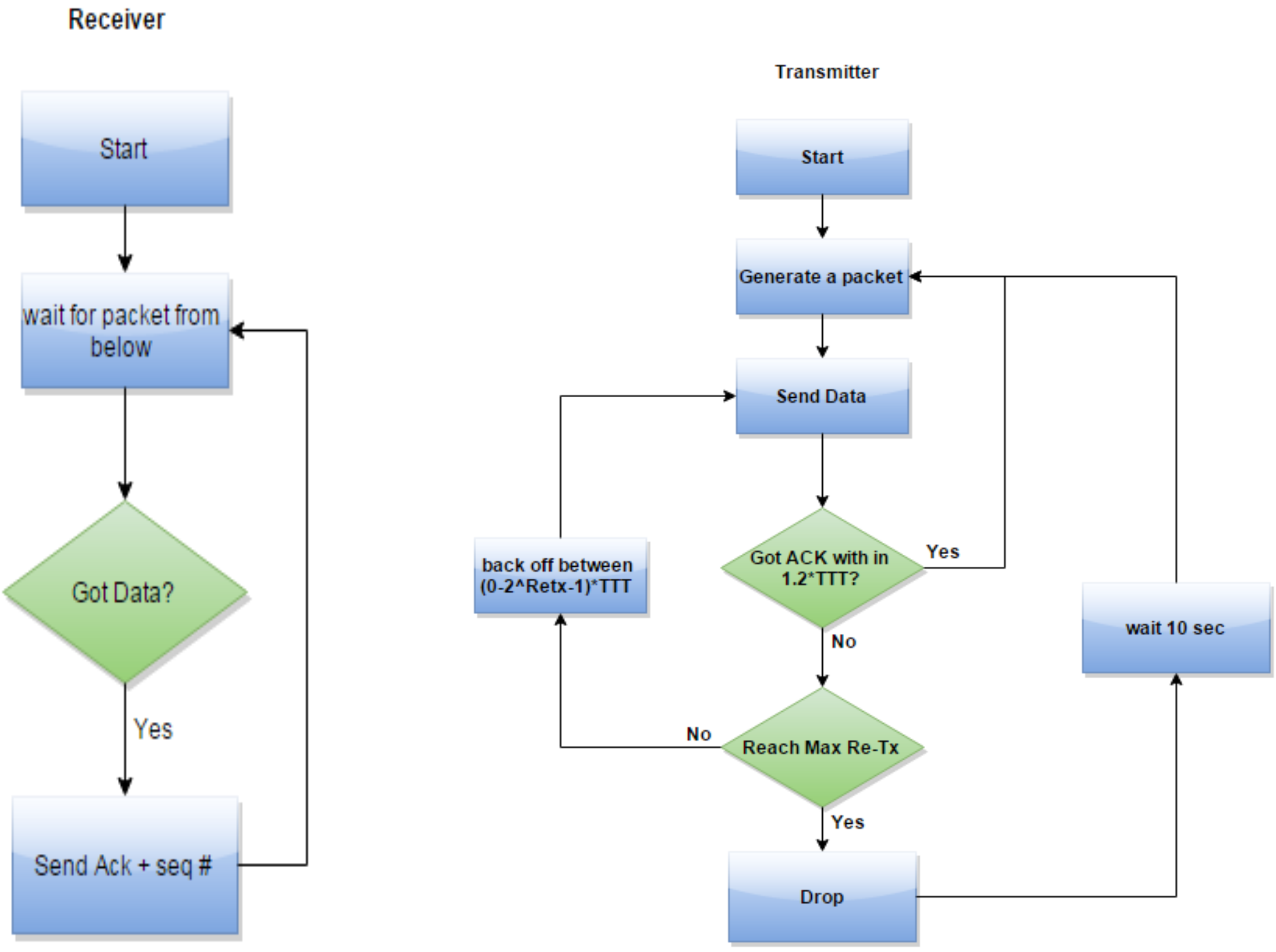

Figure 6: Receiver and Transmitter Algorithm

9. Field Experiment Data

Test duration considered for each tx-rate were determined so both nodes can have a chance to transmit at least 100 packets (Table 3.)

Table 3: Total packets send by MID and MID2

Tx-rate (pkt/sec)	Total Send Packets (MID1+MID2)
0.05	159
0.08	230
0.1	109
0.15	131

Table 4: Data for 3 modems for each tx-rate

Modem ID	rate(pkt/sec)	SEND	REC	RETX	DROP	Test Duration(min)
1	0.05	37	36	18	0	33.65
1	0.08	60	58	41	2	38.03
1	0.1	29	29	15	1	15.82
1	0.15	38	38	23	0	18.97
2	0.05	45	41	18	1	33.65
2	0.08	56	56	48	1	38.03
2	0.1	26	25	19	0	15.82
2	0.15	29	26	24	3	18.97
3	0.05	104	104	NA	NA	33.65
3	0.08	164	164	NA	NA	38.03
3	0.1	76	76	NA	NA	15.82
3	0.15	94	94	NA	NA	18.97

10. Field Experiment Results

The new back-off algorithm has shown better performance in compared to pure Aloha. Figure 7 shows throughput improvement of back-off in compared to prior field experiment based on pure Aloha.

$$Throughput = \frac{Packet\ size\ * \#\ ACK\ recived}{Test\ Duration}$$

Where packet size is a constant 562 Bytes.

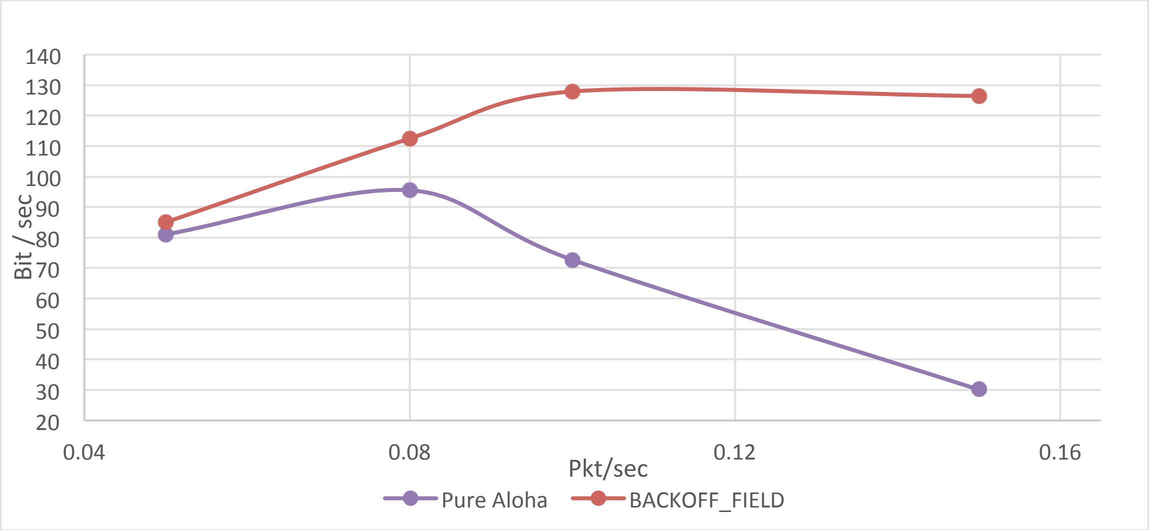

Figure 7: Throughput comparison between pure Aloha with no back-off and the new back-off scheme

Table 2 shows improved packet loss rate in the new algorithm.

$$Loss\ Rate = \frac{\#Packets\ Transmitted - \#\ ACK\ recived}{\#packets\ Transmitted}$$

Table 5: Packet Loss Rate Percentage

TX_Rate	Back-off (%)	Pure Aloha(%)
0.05	31	48
0.08	44	47
0.10	39	60
0.15	44	84

AquaSent modems have four channel hydrophone receivers. Figure 8 depicts CIR waveform received by each channel prior to the 0.05 tx-rate trial. All ten CIR results consistently show maximum delay spread of less than 50ms. This means for future lake experiments, we can set time guard to 50ms, which increases transmission rate to 1.38 Kbps.

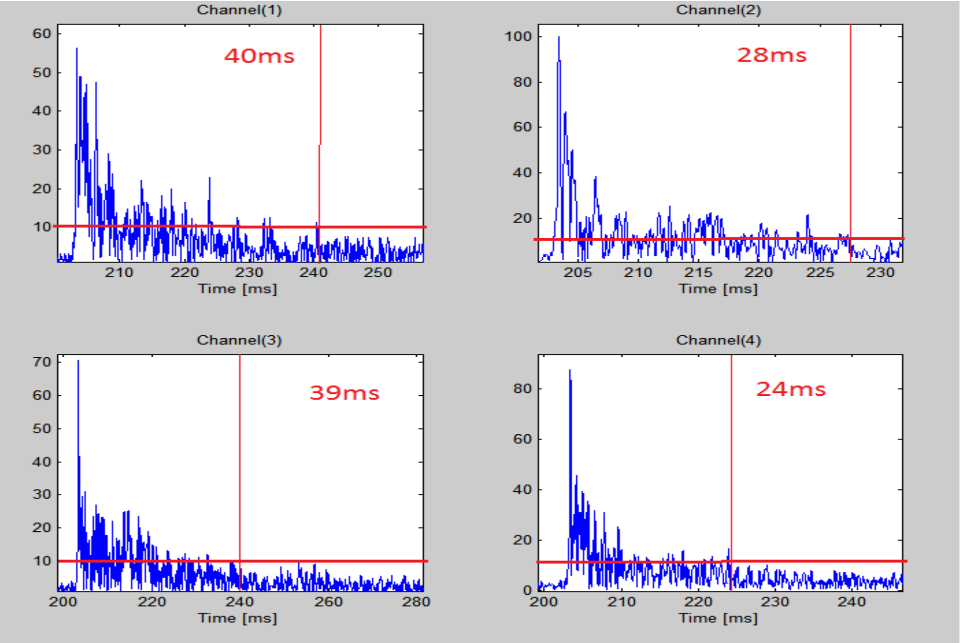

Figure 8: CIR taken before 0.05 tx-rate trial

11. Analysis

We have constructed a time-bar for the 0.1 packet/sec tx-rate. This trial ran for 950 seconds with Mode 1, which has transmission rate (R) of 1.38 kb/s. However, in Ref.2, 1.38 kb/s is calculated for time guard (Tg) = 50ms. Since nature of delay spread for Lake Union was unknown to us, we have set Tg =150ms for this experiment. Recalculating R for 150 ms time guard yields:

$$R = \frac{(rc\,.\,Kd\,.\,\log2\,(M))}{Ts+Tg} = 0.94\text{ kb/s}$$

Where coding rate rc = ½ , # data subcarriers Kd = 672, Modulation M = BPSK , and symbol duration Ts = 170.7 ms (Ref. 2.)

Considering 0.94 kb/s transmission rate, transmission time for 562 bytes of data is **4.8** seconds and for 162 bytes of ACK is **1.4** seconds. We have confirmed this timing empirically in the lab settings.

Table 6 is a color map for the time-bars in Figure 9-13.

Table 6: Time-bar color map

Description	MID 1	MID2
Successful Transmission	🟦	🟧
Data packet was received by MID3 but ACK was lost	🟦	🟧
Data packet was lost without getting to MID3	🟦	🟫

Since showing the time-bar plot for all 950 seconds of trial is difficult to read, only two ~ 200 seconds section has been chosen for this analysis. The full plot can be seen in Excel format here.

Figure 9 shows the time-bar from time 0 to 180 seconds. The first and second rows correspond to data sent by MID1 and MID2 and last row is the ACK sent by MID3 (Hub) to either MID1 or MID2.

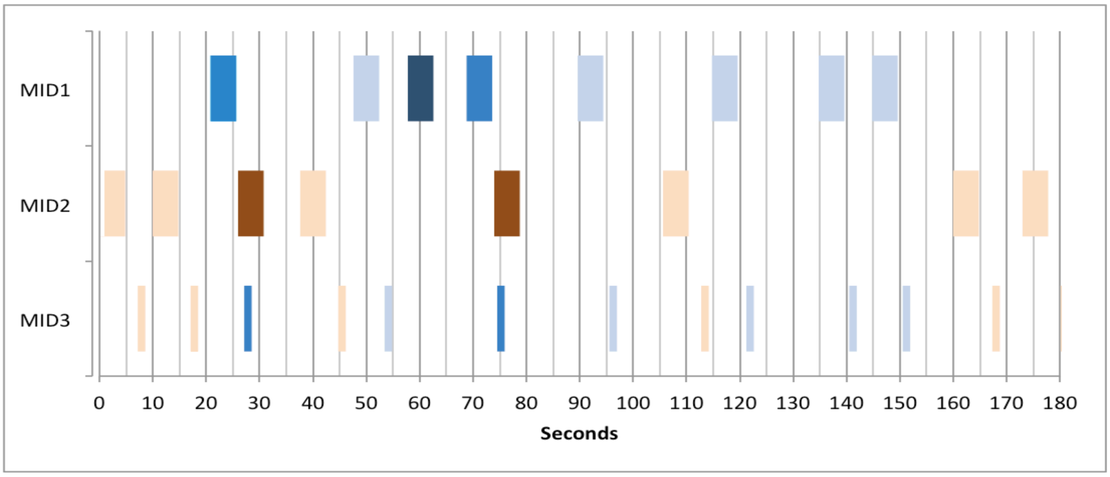

Figure 9: Time bar from 0 to 180 seconds

Table 7: Packet Loss Explanation (Figure 9)

Time (s)	Behavior	Explanation
27 and 75	ACK packet (MID3) overlapping with MID2 data packet. Both packets failed.	Packet loss due to overlapping.
59	Lost packet, no signal overlap	Bad channel conditions

12. Problems

Time Synchronization:

Figure 9 depicted ordinary behavior when two packets are overlapping. However, **Error! Reference source not found.**, below, shows some interesting behavior where non-overlapping signals are failing to. The 590 to 810 seconds interval has several instances that make it very interesting to study.

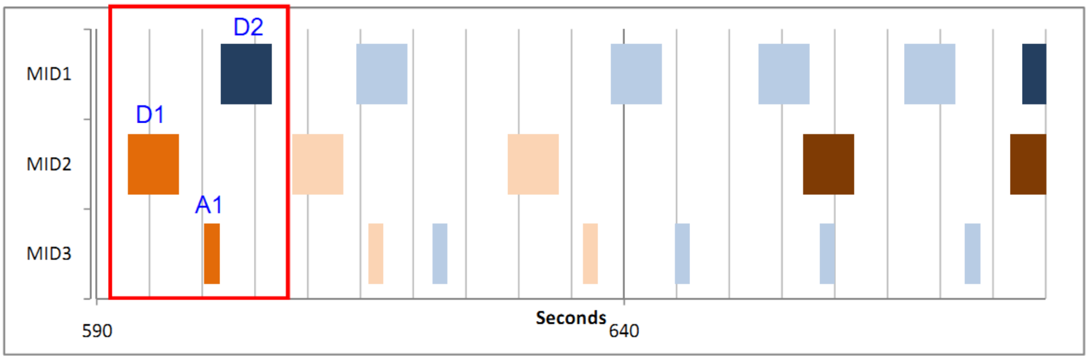

Figure 10: No overlap between A1 and D2, but both are lost

First, let's look at the transmission time and demodulation time for both Data packet and ACK when transmissions are successful. Table 8 shows the time duration for transmitting a data packet and ACK and each row corresponds to the numbered time bar in Figure 11.

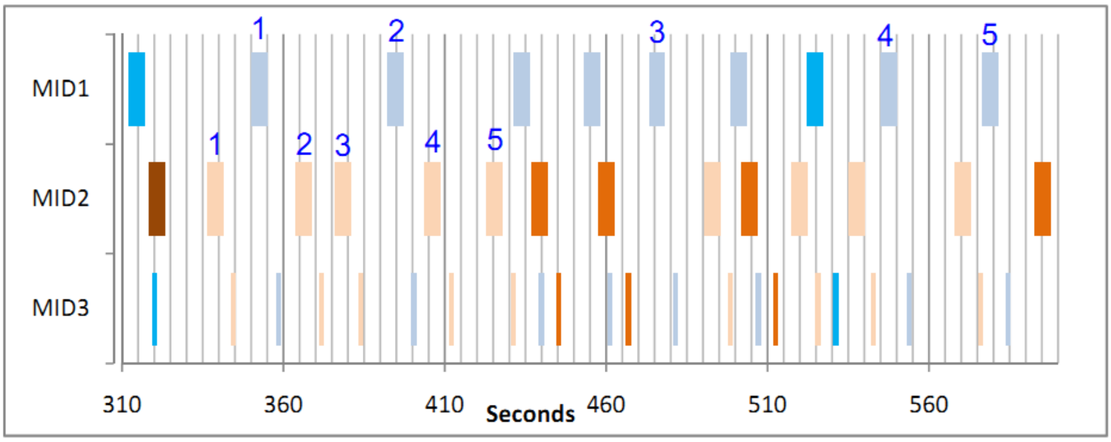

Figure 11: timeline for successful transmission, used in calculating the time consumption in table 1.

Table 8 Definitions

MID1-MID3 Data packet: from the time data packet sent from node1 to the time data packet decoded by node3.

MID3-MID1 ACK: from the time ACK sent from node3 to the time ACK decoded by node1.

MID1-MID3 TTT: total transmission time from node1 to node3 for successfully transmitting a packet including the ACK, transmission delay and processing time.

Table 8: Time duration for successful transmission (no overlap, see Fig.11)

Packet Num	MID1-MID3 Data (pkt/s)	MID3-MID1 ACK/s	MID1-MID3 TTT/s	MID2-MID3 Data pkt/s	MID3-MID2 ACK/s	MID2-MID3 TTT/s
1	6.14	3.85	9.99	7.12	2.46	9.58
2	5.94	3.86	9.80	7.17	2.50	9.67
3	6.00	3.84	9.84	7.33	2.46	9.79
4	6.43	3.83	10.36	7.35	2.47	9.82
5	5.86	3.82	9.68	7.41	2.40	9.81
mean	**6.074**	**3.84**	**9.934**	**7.276**	**2.458**	**9.734**
	6.07+1.29=7.36	**3.84-1.29=2.55**	**7.36+2.55=9.93**			

Assumption: node1's clock is 1.292s behind from node 2' clock (the exact time shift should be estimated by calculating more data, so 1.292s is just an approximate estimation, for example estimations calculated for Figure 12 packets is 1.366s.) Taking into account the 1.292s lag, TTTs between node1 and 2 become comparable.

As mentioned before, source nodes (node1 and node2) are only 2m apart and packet sizes are identical. So packet transmission time for both nodes should be very close. But from table 8, time duration of node1 for transmitting data packets are shorter than node2 and ACK packets are longer. However, TTT is the same. We can safely assume system clock for three nodes (computer time) is not synchronized and node1's clock is behind from the other two nodes. The time duration difference between node1 and node2 is **1.366**s. If we adjust node1's clock and make it synchronized with the other two nodes, the results in Figure10 will make sense, Figure 12.

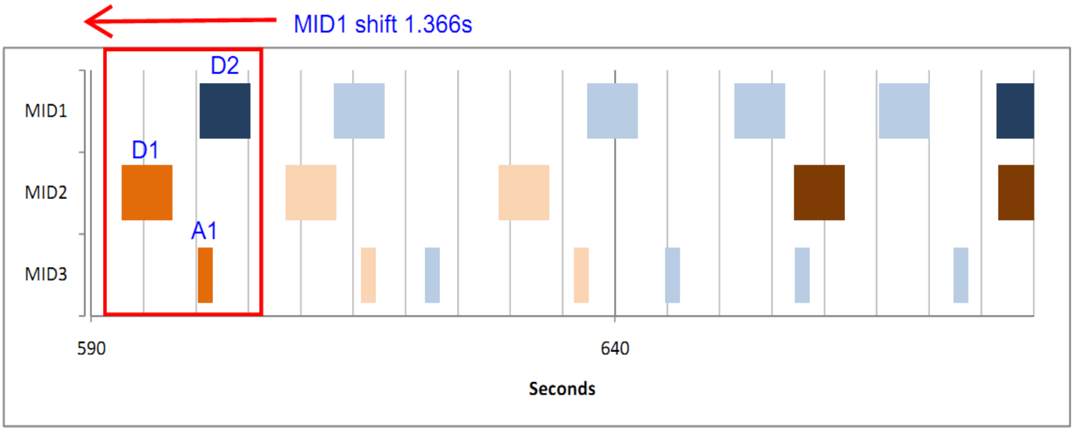

Figure 12: Shift node1's clock to make three nodes' timer be synchronized

ACK Loss without packets overlapping:

ACK loss should be an unlikely event due to small packet size. Figure 13 shows when two packets partially overlap, both packets are decoded successfully. But only the node, which first sends the data packet, gets the ACK and the 2nd node's ACK is lost. For example, lets look at red box1 in Figure 13 (group1). The blue data packet from MID1 (at 700s) overlaps with light orange ACK sent from MID3. When look at the log file (Figure 14,) we find that it has taken **6.28**s (=712.53-706.25) to transmit the ACK from node3 to node2. However, as it was determine in Table 8, the mean transmission time for ACK transmission is **2.47**s.

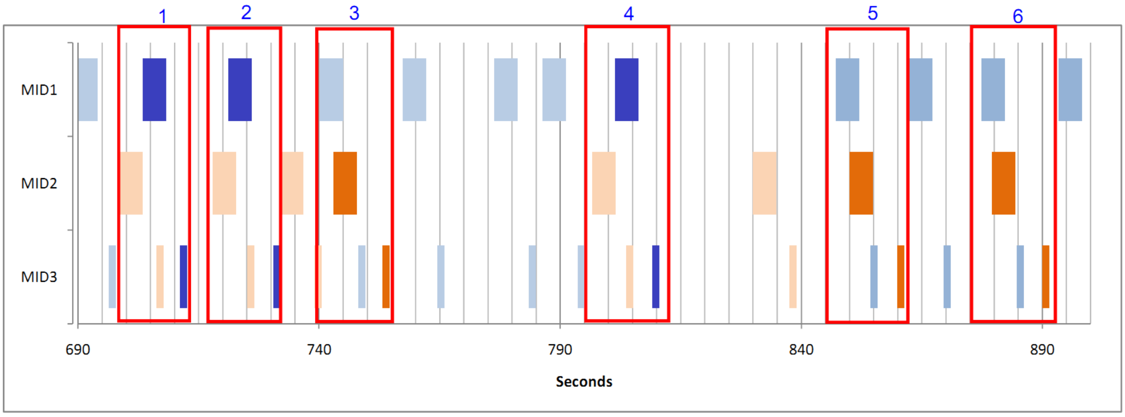

Figure 13: when two packets partially overlap, only the first arrival packet gets the ACK and the ACK for second packet is lost.

```
1      1438309365  704.78 SEND    D      1>562>3  --     Data    packet  sent
3      1438309367  706.25 RECV    D      2>562>3  --     Got     a       data    packet
3      1438309367  706.25 SEND    C      3>162>2  --     ACK     sent
3      1438309372  711.24 RECV    D      1>562>3  --     Got     a       data    packet
3      1438309372  711.24 SEND    C      3>162>1  --     ACK     sent
2      1438309373  712.53 RECV    C      3>162>2  --     Got     an      ACK
```

Figure 14: Log file for group1 in Figure 13. 1st blue bar shows node3 send an ACK to node2.2nd blue bar shows node2 receives an ACK from node3.

Note: *The start point of each packet in Log files and timebar plots is the time that MAC layer issues a transmission command and not necessarily the actual transmission time.*

Table 9 shows the time duration when two packets overlap. Comparing Table 9 with Table8, we can find that the time duration for **data** packet transmissions are similar, however, ACK transmissions take about 3 times longer to get to the destination when two packets overlap.

Table 9: Time duration for successful transmission when two packets partially overlap. Shown in Figure 13.

Groups	MID1-MID3 Data packet/s	MID1-MID3 ACK/s	MID1-MID3 TTT/s	MID2-MID3 Data packet/s	MID2-MID3 ACK/s	MID2-MID3 TTT/s
1	8.25	6.73	14.98	7.65	6.28	13.93
2	7.18	6.78	13.96	7.12	6.85	13.97
3	7.93	6.27	14.2	7.12	6.81	13.93
Table9 Mean	**7.78**	**6.59**	**14.38**	**7.29**	**6.64**	**13.94**
Table8 Mean	**7.22**	**2.47**	**9.7**	**7.22**	**2.47**	**9.7**

This issue occurs when **Data** packets are less than 2 seconds apart or partially overlapping. After first data packet transmission is complete MAC layer will issue an ACK transmission command to the PHY layer. However since PHY layer is receiving the second data packet (coming from a different node,) it will not switch to transmission mode until the second packet is received and decoded. Naturally, MAC layer will issue a second ACK transmission command upon receiving the second data packet. But for some reason, PHY layer only sends the first issued ACK from MAC layer and forgets about the second ACK.

From above section, we can conclude these points:

1. There was time synchronization issue among nodes during the experiment.
2. When two data packet are partially overlapped, there is still a good chance to successfully decode both packets.
3. The receiver won't switch to the transmitting mode if it detects continuous (less than 2 seconds apart) packets.
4. When the receiver gets more than 1 command to send the ACK, it will only remember the 1st command and only sends one ACK (which needs to be confirmed.)

13. References

[1] Stojanovic, M., "Underwater Acoustic Communications: Design Considerations on the Physical Layer," *Wireless on Demand Network Systems and Services, 2008.*

[2] Wan, Lei, et al. "Adaptive modulation and coding for underwater acoustic OFDM." Oceanic Engineering, IEEE Journal of 40.2 (2015): 327-336.

APPENDIX A

SNRs obtained from CIR read

0.04 TX-RATE

```
CPSYNC:SRC:1,DST:0,TYPE:64,MODE:1,BLOCK:12,GUARDT:150,TSTAMP:5015.14307s
EFFSNR:6.1
INSNR:20.3,21.2,20.7,22.8,
SIG/NOISE RMS:4.460251/0.041286,5.414592/0.040370,4.301922/0.035935,5.859414/0.030542,
CPSYNC:SRC:2,DST:0,TYPE:64,MODE:1,BLOCK:12,GUARDT:150,TSTAMP:5059.18604s
EFFSNR:7.5
INSNR:24.6,24.6,24.5,23.2,
SIG/NOISE RMS:5.050523/0.017622,8.022511/0.027940,6.203158/0.021712,6.442964/0.030489,
```

0.08 TX-RATE

```
CPSYNC:SRC:1,DST:0,TYPE:64,MODE:1,BLOCK:12,GUARDT:150,TSTAMP:3573.83716s
EFFSNR:7.1
INSNR:30.9,31.7,30.9,31.5,
SIG/NOISE RMS:3.974781/0.003237,5.815815/0.003938,4.736566/0.003807,4.660584/0.003321,
CPSYNC:SRC:2,DST:0,TYPE:64,MODE:1,BLOCK:12,GUARDT:150,TSTAMP:3538.93579s
EFFSNR:7.6
INSNR:32.4,35.8,34.6,35.0,
SIG/NOISE RMS:3.906591/0.002230,6.894738/0.001799,6.946907/0.002391,5.063342/0.001601,
```

0.1 TX-RATE

```
CPSYNC:SRC:1,DST:0,TYPE:64,MODE:0,BLOCK:0,GUARDT:150,TSTAMP:342.15714s
EFFSNR:7.4
INSNR:24.2,26.1,25.1,24.0,
SIG/NOISE RMS:3.376958/0.012918,3.902325/0.009599,4.469622/0.013892,3.187811/0.012775,
CPSYNC:SRC:2,DST:0,TYPE:64,MODE:0,BLOCK:0,GUARDT:150,TSTAMP:382.19983s
EFFSNR:4.3
INSNR:32.7,34.2,33.4,34.3,
SIG/NOISE RMS:4.851365/0.002606,5.603095/0.002120,5.026196/0.002282,5.792457/0.002148,
```

0.15 TX-RATE

```
CPSYNC:SRC:1,DST:0,TYPE:64,MODE:1,BLOCK:0,GUARDT:150,TSTAMP:1846.77209s
EFFSNR:5.9
INSNR:27.0,27.5,26.4,24.9,
SIG/NOISE RMS:3.295273/0.006529,6.330852/0.011114,4.781174/0.010809,3.159257/0.010102,
CPSYNC:SRC:2,DST:0,TYPE:64,MODE:1,BLOCK:0,GUARDT:150,TSTAMP:1892.72412s
EFFSNR:8.4
INSNR:32.6,38.1,35.5,34.9,
SIG/NOISE RMS:4.859767/0.002654,14.492626/0.002241,9.928327/0.002793,8.269522/0.002704,
```