PERFORMANCE EVALUATION OF AD HOC PROTOCOLS FOR UNDERWATER NETWORKS

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Abstract – *Underwater networking is a recently evolving technology which promises to provide the required infrastructure that will further cooperation amongst Unmanned Underwater Vehicles (UUVs). Underwater networks face extreme challenges of low bandwidth, high latency, and minimal energy resources. AUSI team has made its initial efforts to address the issues of underwater networks and as a result developed two protocols namely, Controlled Flooding for Small Networks (COFSNET) and Autonomous Undersea Systems Network (AUSNET) [1]. Both the protocols are tailored versions of existing protocols developed for Mobile Ad hoc Networks (MANET) [2]. The goal of this study is to analyze the performance and effectiveness of these protocols in various network topology scenarios and with different types of traffic load.*

1.0 INTRODUCTION

The purpose of this paper is two fold; firstly, it introduces a novel application of an existing networking concept, secondly, a performance study of the existing ad hoc underwater networking protocols. Underwater networking is a recently evolving technology which promises to provide the required infrastructure that will further cooperation amongst Unmanned Underwater Vehicles (UUVs). Underwater networks face extreme challenges of low bandwidth, high latency, and minimal energy resources. AUSI team has made its initial efforts to address the issues of underwater networks and as a result developed two protocols namely, Controlled Flooding for Small Networks (COFSNET) and Autonomous Undersea Systems Network (AUSNET) [1]. Both the protocols are tailored versions of existing protocols developed for Mobile Ad hoc Networks (MANET) [2]. COFSNET uses the concept of a controlled flood technique to facilitate multi-hop communication. This is the bare minimum protocol that is required to facilitate multi-hop communication for a dynamic network. The AUSNET effort builds upon emerging ad-hoc (self-forming, self-maintaining) network protocol Dynamic Source Routing (DSR) [3]. AUSNET adds second personality to DSR called Dead Reckoning (DR). AUSNET design anticipates that the movement of underwater vehicles is not random and that it can be predicted or it is known beforehand. The DR component of DSR tries to make use of the movement information by making an estimation of the current network topology based on the trajectory of each vehicle. Once the network topology is determined, a spanning tree algorithm provides the shortest path to the destination, thus reducing the overhead of route discovery in DSR. The goal of this study is to analyze the performance and effectiveness of these protocols in various network topology scenarios and with different types of traffic load.

The emphasis of the study is primarily on understanding the underwater networks. The focus is on two specific aspects of underwater networks: (1) the network topology of a fleet of UUVs deployed to achieve a common task, (2) the characteristics of traffic of such a network. For this purpose, several real underwater scenarios are simulated. The selection criteria were based on the generality and simplicity of the scenario. Scenarios such as follow the leader, role swapping, and geometrical formation are studied. For each scenario different types of traffic (including regular status packets (vehicle health), sensor data, control commands, and coordination (and/or) cooperation packets) were used in simulation.

A simulator that was developed in-house to test AUSNET and COFSNET was further enhanced to support this study. The scope of the development of the simulator was limited to understanding the performance of the protocols with respect to latency, throughput, energy consumption, and protocol overhead. For the purpose of this study latency is defined as the time delay between when the packet is originated at the source node and when it reached the destination node successfully. Throughput is calculated as the amount of useful information delivered per unit of time. Energy consumption measures the amount of energy required to deliver a unit of data. Overhead is defined as the difference between the amount of traffic generated during the scenario and the actual payload data communicated.

The goal of this study at the general level is to study the effectiveness of two existing protocols. The focus is not only on obtaining direct results but also on the development of a general evaluation methodology. The results will be utilized in further development of the protocols and as a guide for evaluation of any future protocols in this area.

The rest of this section is intended for the audience with minimum networking background to help understand some basic networking terminology that is used throughout this paper. The functionality of the communications section of any system participating in a multi-node shared media network can be categorized into three layers also called the network or protocol stack. The layers are: network layer, data link layer, and physical layer. The network layer provides address assignment, and packet's forwarding methods. Protocol Data Unit [PDU] is called a Packet at this layer. The data link layer provides Frame format, Transmitting frames over the net [additional bit/byte stuffing, start / stop flags, checksum, and CRC]. Different network and protocol characteristics are defined by different data link layer specifications. The Data Link layer is subdivided into the Media Access Control (MAC) which controls access and encodes data into a valid signaling format for the physical layer, and the Logical Link Control (LLC), which provides the link to the network [for the Network layer] Protocol Data Unit [PDU] is called a Frame at this layer. The physical layer defines the physical [hardware] implementation and the electrical [signal level] implementation; network cabling, connector type, pin-out, physical data rates, maximum transmission distances, and data transmission encoding. At this layer information is placed on the physical network medium.

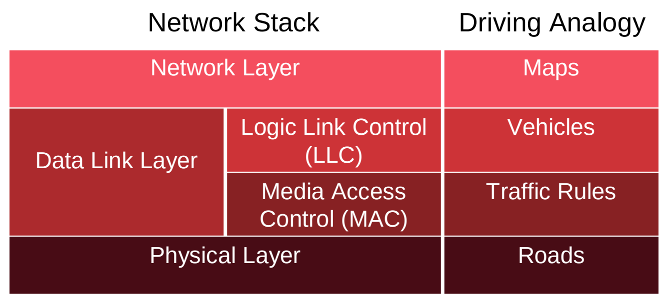


Figure 1: Network Stack mapping to driving analogy

To understand the role of each layer at a very conceptual level lets consider the Driving Analogy, let's consider that a delivery boy needs to deliver a box from the store to a destination address. This is very similar to a source node trying to send a packet to a destination node, the box being the packet and store and destination address being the source and destination nodes respectively. First, the delivery boy needs to figure out the way to the destination address. There are two broad methods he can use: first is to look at a map, and second is to ask someone for directions. This functionality of finding the way (route discovery) is provided by the network layer. Depending on the protocol used the network layer either has a map built into it or it builds its own map. The newly evolving ad hoc on-demand routing protocols do not use a map but ask someone (node) for the route. Sometimes this someone could be the destination node itself. This is like the delivery boy calling the destination address and asking for directions to the place.

Once the delivery boy figures out the route, he needs some form of transportation to get to the destination. Assume he drives his car; he will have to follow the traffic rules to avoid accidents. The media access control sub layer of the data link layer provides the functionality of the traffic rules to avoid packet collisions in a shared media. The functionality of the car itself is provided by the logic link control sub-layer of the data link layer.

Finally the delivery boy depends on the road system to get to the destination. This functionality is provided by the physical layer. Just like different roads have different speed limits, the data rates will be different for different physical media used.

The rest of this paper is organized as follows: the first section describes the goal of the paper and also introduces some basic network vocabulary. The second section outlines the existing work done in the field of underwater networking. The third section introduces a new protocol called COFSNET. The fourth section describes briefly the AUSNET protocol. The fifth section outlines the simulator that was used to generate the simulation results. The sixth section presents the simulation and In-water testing results. Finally the paper concludes in the seventh section.

2.0 BACKGROUND

Two major groups are currently working in the area of Acoustic Underwater Networks. One of them is the Woods Hole Oceanographic Institute (WHOI) and the other is the SeaWeb project. From a network layer point of view the WHOI group has implemented a micro modem that satisfies or fits into the functional classification of physical layer and the data link layer. The SeaWeb project concentrates more on the data link layer and network layer. Under SeaWeb project Benthos Inc. worked closely to provide the physical layer of the acoustic modems.

In the past there has been a lot of research done to understand the acoustic channel and characterize it. One of the programs that capitalized on this work and addresses some of the networking issues is the Seaweb program [5]. Research under the Seaweb program focused on the physical layer and the data link layer of the networking protocol stack. The physical layer developments address the physical layer issues such as the power management, multi-paths propagation, and coding techniques. Seaweb technology uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method that is also used in the IEEE 802.11 wireless standard for link layer design. This kind of media access scheme is known to work well in the IEEE 802.11 wireless networks where bursty traffic is the most common kind of traffic. The CA scheme used has introduces overhead and increases latency. It is questionable whether such a scheme is the best solution for the underwater operations where the per-bit costs are high and the nature of traffic is more periodic and less bursty. To enable ad hoc routing Seaweb makes use of a server (located on land) and some fixed inexpensive infrastructure. All the routes are monitored and controlled from the central server. This architecture does not reflect the self-forming and self-maintaining nature of the ad-hoc networks. To support more dynamic networks such as the underwater network of fleet of AUVs we need reactive routing protocols such as DSR and AODV which are capable of self-forming and self-maintaining.

The WHOI Micro Modem can be used in two modes Master-slave mode or the Autonomous mode. While in master-slave mode, the master node triggers using a Cycle Initialization command to send or request data to or from other nodes in the network. In the Autonomous mode, the modem is essentially only a physical layer device.

Figure 2 outlines activities of the above mentioned teams in each of the layers of the protocol stack

Network Stack	AUSI Team	Seaweb	WHOI
Network Layer	COFSNet & AUSNet Dynamic Routing	Static Routing	Star Network Topology for packet forwarding (no routing)
Data Link Layer	Frames No MAC	No Frames MAC: CSMA/CA	No Frames MAC: TDMA
Physical Layer	Benthos Acoustic Modems	Benthos Acoustic Modems with enhanced features	WHOI Micro Modem

Figure 2: Network Stack mapping to existing efforts

3.0 COFSNET

Controlled Flooding is a comparatively primitive networking protocol that is either used in one of the phases of the more advanced networking protocols of today or considered inefficient in most land applications. Underwater applications differ widely from that of wireless applications. We have discovered that in many of the present underwater applications controlled flooding may be the most efficient networking protocol contradicting the performance evaluations done in the wireless environment.

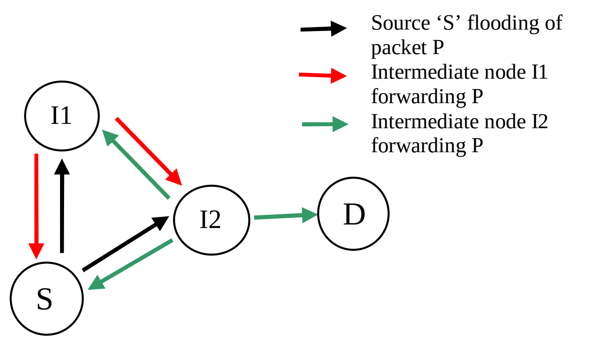


Figure 3: Flooding in COFSNET

Controlled flooding is a mechanism in which a source node that needs to send a packet to a destination node simply floods the network with the packet, which is addressed to the destination and with a Time To Live (TTL) for that packet. An intermediate node that receives this packet will decrement the TTL and will forward it. The packet will be absorbed when the TTL has expired. When the destination receives this packet it decodes it to obtain the content of the packet. This kind of flooding can quickly swamp the network with re-forwarding of the same packet. For example consider the network topology shown in Figure 3

Table 1 shows the connectivity of the network. Let us look at the sequence of events that occur when the Source node 'S' is sending a packet to Destination node 'D'. To begin, 'S' transmits the packet (indicated by black arrows in figure 3) and is received by nodes 'I1' and 'I2'. Nodes 'I1' and 'I2' decode the header and realize that the packet is destined for 'D' and not for themselves. Hence, they forward the packet by transmitting the same packet with the TTL decremented (indicated by the red and the green arrows). The forwarding of the packet by node 'I1' will be received by node 'I2' and vise versa, this really is a duplicate packet and hence using the unique combination of the source address and sequence number (SQ#) present in the packet header, nodes 'I1' and 'I2' suppress this duplicate packet thus, controlling the flooding. When node 'D' receives the packet that is forwarded by node 'I2' it then consumes the packet.

	S	I1	I2	D
S		C	C	N
I1	C		C	N
I2	C	C		C
D	N	N	C	

Table 1: Communication range connectivity; C-connected, N-not connected

Figure 4 shows the description of the COFSNET header. The data goes in the payload section and its length is represented by the length field. Src ID and Dest ID represent the source and the destination ID's of the nodes respectively.

1 Byte	1 Byte	12 bits	4 bits	2 Bytes	64Kb
Src ID	Dest ID	SQ#	TTL	Length	Payload

Figure 4: COFSNET Header description

4.0 AUSNET

The other protocol that is under research currently is Autonomous Undersea Systems Network (AUSNET). AUSNET is a National Science Foundation (NSF) funded STTR Phase 2B program addressing network protocols for underwater communications. This joint effort is being performed by TSI and AUSI. The goal of AUSNET is to enable expanded networking services specially tailored to the acoustic environment and AUV operational scenarios. This effort builds upon emerging ad-hoc (self-forming, self-maintaining) network protocol Dynamic Source Routing (DSR). DSR works with the help of two mechanisms: Route Discovery and Route Maintenance. DSR allows nodes to discover routes to arbitrary destinations and to maintain them. The DSR protocol allows the network to be completely self-forming and self-maintaining. The protocol is specially designed for use in multi-hop wireless mobile ad hoc networks. Modifications and enhancements have been done to DSR under the AUSNET program to make it suitable for the underwater communication. The major enhancements include the Dead Reckoning algorithm and the reduction on the host address size. Under the dead reckoning algorithm, AUSNET utilizes the AUV fleet mission information to estimate the network topology. Once the estimated topology is computed a spanning tree algorithm is used to find routes to a destination. If the dead reckoning is unsuccessful, AUSNET falls back on DSR's Route Discovery mechanism. AUSNET is implemented as a C++ library and also has been tested under simulation. Table 2 highlights some key differences between COFSNET and AUSNET.

AUSNET	COFSNET
Based on DSR	Based on Flooding
DSR highly evolved protocol	The most basic protocol
Good for frequent long duration communications	Good for shot duration in-frequent communication
Header size overhead	Minimum required header
Better performance in medium node density	Best for very low node density
Robustness is achieved with the help of control messaging	Robustness is achieved by redundancy
To start it uses Flooding	No latency at all

Table 2: Comparison of AUSNET and COFSNET

5.0 SIMULATOR

The TSI Mobile Ad-Hoc Undersea Network Simulator was used for all simulation based testing. The simulator was developed under the AUSNET program to facilitate further testing and optimization. Its modular design leads to an easy integration of the

COFSNET protocol as well. The simulator is designed to allow for modeling of both mobile AUVs traversing the area with set waypoints and simultaneously model the movement of the message through the transmission medium. Via access to the simulated medium's physical constraints, the simulator allows for alterations of the transmission range and signal propagation speed as well as alterations of AUSNET constants such as timeout length and number of retries. The simulator is also designed to keep track of numerous statistical qualities, and provides a mechanism to send packets at regular intervals, both to random or specified hosts. Figure 5 shows a snapshot of the simulator with 3 nodes.

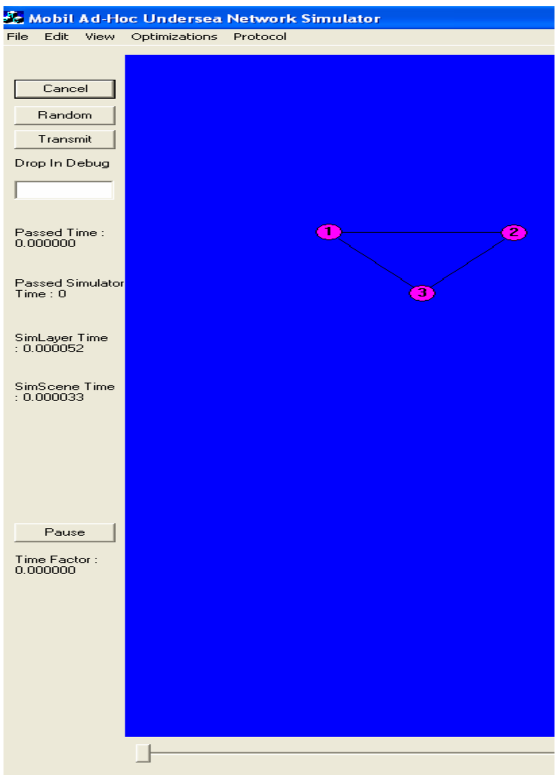


Figure 5: Simulator user interface

6.0 RESULTS

The section presents two sets of results, first some simulation results and second In-water testing summary performed at locations on two different occasions.

6.1 Simulation Experiments

The initial goal was to study the underwater protocols in various scenarios under different kinds of traffic. The following are the scenarios conducted so far and this is still a work in progress.

Scenario 1: A three node network with the nodes places in a triangular formation. Node 3 (destination node) starts to move away from node 1 (source node) such that it is forced to use node 2 as the intermediate hop. The goal of this scenario was to look at the overhead involved with route discovery with AUSNET.

Scenario 2: Similar to scenario 1 but the number of nodes in the network was 5 and node 3 moves away until it is forced to use the remaining nodes as intermediate nodes.

Scenario 3: Similar to scenario 1 but the number of nodes in the network was 7 and node 3 moves away until it is forced to use the remaining nodes as intermediate nodes.

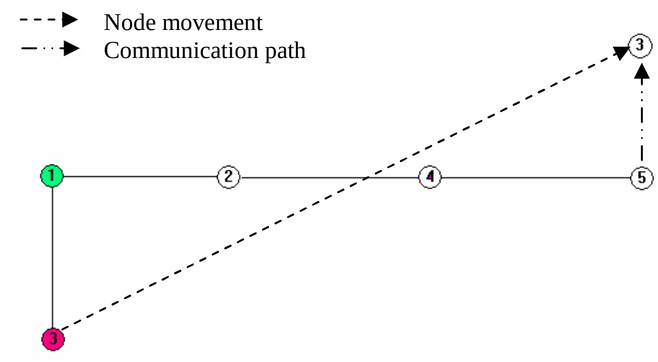
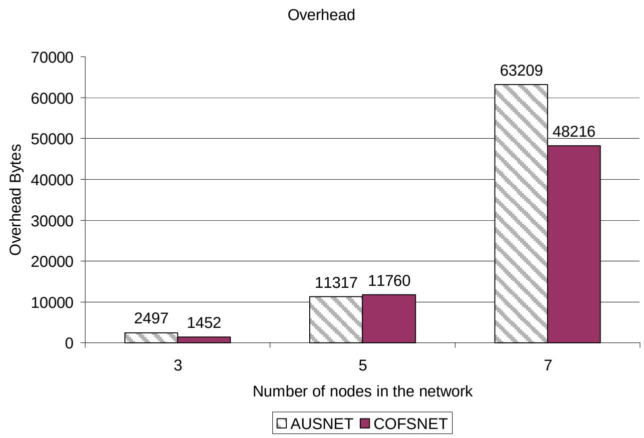


Figure 6: Node topology in scenario 2

The results of the three scenarios have been represented in the following graphs. The first one shows the overhead (different between the total number of bytes transmitted in the network and the actual data bytes delivered) associated with both the protocols. Clearly COFSNET shows lesser overhead in scenarios 1 and 3 and slightly grater in scenario 5. The AUSNET overhead is due to the discover route packets and header size.

The second graph shows the average latency (difference between the time of transmitting the packet by the source node and time it was successfully received by the destination node). Clearly again COFSNET performed better with relatively much lesser latency in all the cases. This again is due to the initial delay in AUSNET with Route Discovery process.



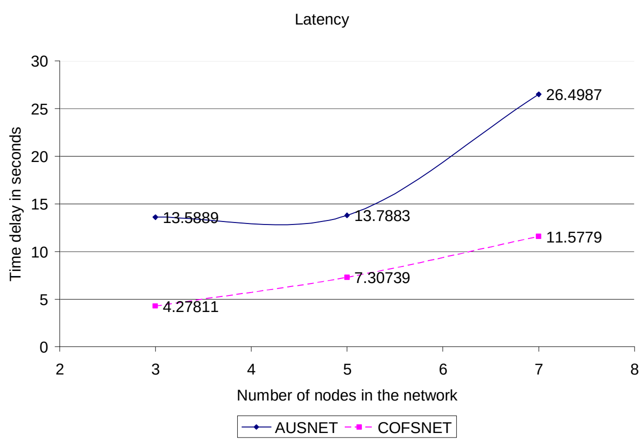


Figure 7: Protocol overhead and message latency comparison of AUSNET and COFSNET

6.2 In-water Testing

In-water testing of the protocols was done on two occasions in the following locations

- Lake George, Bolton landing, NY.
- AUV Fest 2005 Hood Canal, Keyport, WA.

Lake George Test Summary

The Objectives of the AUSNET testing were to

- Demonstrate basic AUSNET connectivity in water
- Demonstrate basic 3-node connectivity in water
- Demonstrate network reconfiguration with 3 nodes in water
- Demonstrate 4-node network node failure with recovery

The experiment was moved north to the Dollar islands within Lake George (Figure 8). The idea was to use the island to break acoustic connectivity rather than have to extend the equipment long distances due to the excellent acoustic range. First we setup the buoys so that they would initially be networked together with AUSNET. We then proceeded to move one buoy to the other side of the island, cutting off the acoustic communications thus simulating an AUV moving out of range. We then situated the chase boat in a location north of the Island so that the chase boat node would become the relay node between the Gateways. The AUSNET software was able to reconfigure itself to relay through the chase boat node. We then moved one buoy within line of sight of the first buoy, so that both buoys could again talk to each other. When we sent a message, the AUSNET protocol reconfigured itself again to properly optimize the network path. This took the relay node out of the communication path. A series of tests were then conducted to verify that AUSNET does work in the water with real modems, and correctly reconfigures the network route to changing conditions.

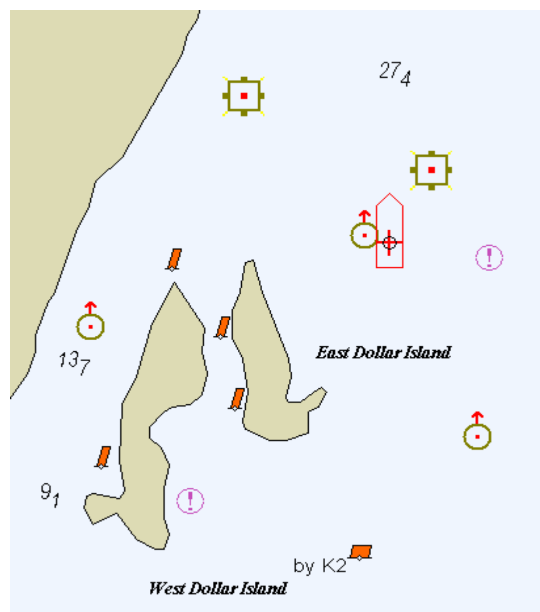


Figure 8: AUSNET Test setup for Friday Oct 22nd 2004. Circles represent location of Gateway buoys. Square icons represent locations used to test communications.

From this series of tests, we demonstrated basic AUSNET connectivity, basic 3-node AUSNET connectivity, and AUSNET network reconfiguration with 3 nodes in the water. Since we were out of time and had to depart the test location, we were not able to perform the 4-node objective.

With the nodes located as shown in Figure 8, buoys 1 and 2 were not able to communicate directly between each other acoustically due to the island between them. This was verified through a separate test using modem ranging, as well as during the AUSNET testing which preceded this experiment

The same setup was used to test COFSNET protocol. Six separate experiments were carried out, whereby a short ASCII message was sent from an origin node to a destination node(s). All nodes were part of the same group. The experiment conditions are summarized in Table 3.

Experiment	Origin	Destination
1	Boat	All nodes
2	Boat	Buoy 1
3	Boat	Buoy 2
4	Buoy 1	Buoy 2
5	Buoy 1	All nodes
6	Buoy 1	Boat

Table 3: Message origin and destination for COFSNET tests.

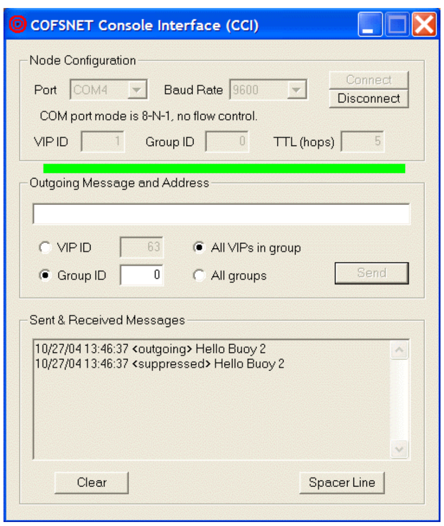


Figure 9: COFSNET Console Interface terminal application

For each of these experiments, the COFSNET protocol performed as predicted [6]. Figure 9 shows the GUI tool used to interface with the COFSNET library.

AUV Fest 2005 Test summary

The COFSNET protocol was used during SAUV/MARV operations at AUVFest to provide a network layer for transmission of vehicle commands and status between the operator and the AUVs. The COFSNET network consisted of 2 SAUVs, one MARV and the operator console. Two gateway buoys provided spatial acoustic communication coverage of the working area, which was a rectangle 1.3 mi x 0.4 mi, allowing the operator console to be connected via RF to the buoys. Both buoys used the same ID and were represented conceptually as a single node in the network.

COFSNET performed well during the testing, successfully filtering and forwarding messages as appropriate. This demonstration showed that COFSNET worked well within a 5 node network [7].

The AUSNET protocol testing was conducted on June 15, 2005 in the same network. The results of these tests were less than acceptable, due to the issues described below. One buoy is in need of troubleshooting due to a firmware upload failure. It appears that this buoy was put into a state of programming, and was interrupted during the programming of the firmware. Further debugging is necessary to determine the operational state of this buoy.

The acoustic conditions within the Hood Canal operating area led to serious operational issues within the AUSNET Routing System. The conditions changed rapidly leading to quickly shifting routes and mono-directional communication. These changes to the physical medium led to interruptions of AUSNET Communication. This was alleviated to some extent via changes to the transmission settings of the Benthos Acoustic Telemetry Modems including lowering baud rate and transmission power.

AUSNET communications were further hampered greatly by the lack of access control to the physical medium, leading to significant signal interference and packet loss. An attempt to remedy this using the frequency-hopped modem firmware from Benthos was unsuccessful due to failure of loading Benthos software over RF modems. Further testing with the new Benthos Acoustic Firmware is required to determine if this will have the desired effect on signal collision.

7.0 CONCLUSION

The two protocols are designed for different requirements, and hence show varying behaviors in different applications. COFSNET was designed to provide a very simple protocol for low density networks and provides no guarantee of packet delivery (best effort service). AUSNET on the other hand was designed to guarantee packet delivery and also to support medium sized networks. Hence we have seen that in small networks, COFSNET has performed better in simulation and also in practical experiments. One key issue that was the highlight of the practical experiments was that fact that COFSNET was insensitive to asymmetric links where as AUSNET was sensitive, which degraded the performance of AUSNET further.

This is just the beginning of the study and a much more simulation work has to be done to completely understand the behaviors of both the protocols. AUSNET definitely holds the promise for future medium sized networks that require guaranteed service. COFSNET has consistently proven to provide the required connectivity in various best effort applications.

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