

A SDN-Controlled Underwater MAC and Routing Testbed

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Abstract—Efficient data communication among autonomous under-water vehicles (AUVs) is difficult. Challenges include the long propagation delays arising with acoustic communication solutions, and line-of-sight requirements for optical transceivers. Existing multi-hop routing approaches are not always appropriate due to node mobility. This work presents a centralized approach to network control, exploiting the observation that AUV networks will have a bounded number of nodes. The paper describes a SDN realization of AUV networking, and documents the implementation of a small-scale replica of the system in our testbed, which can be accessed remotely via a web page and SSH. We then demonstrate the functionality of our implementation by evaluating the performances of two existing MAC protocols namely Slotted FAMA [11] and UW-Aloha [13], in a multi-hop, underwater scenario.

I. INTRODUCTION

Underwater Wireless Networking (UWN) has attracted special focus in recent times. The physical characteristics of the underwater channel have resulted in various Electro-Magnetic (EM), optical, and acoustic communication technologies being employed in UWN, and delivering different communication ranges [9]. EM waves have wide frequency bands and a fast propagating speed, but the conducting nature of sea water severely constrains the communication range. Underwater optical communication also has its advantages in bandwidth and propagating speed, yet its communication range is also limited by the absorption and backscatter in water, though not as much as EM waves. Acoustic waves have the longest transmitting range in underwater environment, but it remains challenging to communicate in the temporally and spatially varying underwater acoustic environment. The underwater acoustic channel presents challenges such as long propagation delays, limited available bandwidths, and high error rates. At the current time, acoustic and optical transmission modalities predominate for underwater communications, with the bulk of attention paid to acoustics because of its relative simplicity for modeling and implementation (it acts the same as EM in the air, except for long propagation delays). Optical signaling, on the other hand, requires a much more complicated implementation.

Aside from its short communication range, optical PHY typically requires line of sight for successful transmissions, is usually uni-directional, thus requiring relative localization among nodes. At the same time, these very same properties give optics the potential for covertness, since a lack of line of sight in optics can also prevent interceptions. The properties of these different propagation media present interesting trade off and optimization scenarios, with some combining methods to create a hybrid approach [7].

A further challenge associated with AUV communications is that encapsulated in the fundamental mobile ad-hoc routing problem. Allowing an arbitrary number of mobile nodes to communicate with one another is challenging, even on land. Yet the underwater networking environment is sufficiently different to that on land to encourage development of more environment-specific solutions. For example, in AUV communication, the number of mobile nodes is *not* arbitrary - it depends entirely on deployment decisions. Additionally, even the movements of each AUV is much more predictable than land vehicles, since their routes are generally pre-programmed, or have movement instructions amended in real time. These properties make having a centralized controller, like those in software defined networks, an obvious choice for handling communication behavior among AUVs.

Software defined networking (SDN) is a relatively new networking paradigm aimed at flexibility and simplicity through high level abstractions by decoupling the data plane, where actual data is transmitted, from the control plane, where meta-data related to network functionality is transmitted. This is done by utilizing a centralized network controller that defines network behavior among all the other nodes. A comprehensive survey of ongoing research in the SDN area is provided in [8].

This work proposes an under water SDN system, complete with a central network controller, that principally handles routing and movement decisions for each AUV. The control plane is separated from the data plane through use of separate channels, and the modularity of the system components allow for flexible replacements of technologies including, but not

limited to, propagation media and their associated MAC protocols, routing schemes, and applications depending on need. We implement a small-scale replica of our underwater SDN system in our remotely-accessible WaterCom [6] testbed and, using it, we compare the performance of two state-of-the-art acoustic MAC protocols, Slotted FAMA [11] and UW-Aloha [13] in a multi-hop scenario. Insofar as we know, this is the first comparison of underwater MAC protocols in a multi-hop scenario with physical modems.

The rest of the paper is organized as follows: section II gives an overview of the existing research efforts in the field of underwater communications and SDN. We then go on to present the details of our UW SDN design in section III. In section IV we describe the implementation of a simplified version of our system inside our testbed, and we use it to compare the performance of two MAC protocols in section V. Finally, we conclude with section VI.

II. RELATED WORK

Much work has been carried out on various aspects of underwater acoustic networks, such as the acoustic channel model, simulation software, protocol design, and localization algorithms. Due to limitations of acoustic channel based simulation [15], various lab and commercial underwater acoustic modems has been developed and evaluated in different underwater environments. A large amount of link layer, network layer, and transport layer protocols have been investigated for UWN, and it is also well-accepted that cross layer design should be adopted for underwater network protocol stacks [13]

Many have also proposed various architectures for an Underwater Wireless Network (UWN) system, some of which were implemented as experimental testbed for both UWN and oceanographic researchers. The Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing (SUNSET) provides a complete toolchain for UWN protocol developers to evaluate their protocol by simulation, in-lab emulation and field experiments [14]. The OCEAN-TUNE Long Island Sound testbed consists of an on shore control center, off shore surface nodes and bottom nodes with sensors, which can help collecting oceanographic data, as well as providing the UWN research community flexible and ubiquitous access to field experiment resources [16]. A typical architecture includes surface nodes as gateway nodes between UWN and Radio Frequency (RF) network, and stationary or mobile underwater nodes equipped with sensors or actuators.

Although these testbeds can provide practical solutions for UWN development, their architectural designs are inherently hardware-based and regrettably not flexible enough for satisfying the emerging needs of novel applications, such as implementing localization service for a UWN with AUV. Akyildiz, Wang, and Lin gave a detailed description of their concept of SDN for next generation underwater communication networks in [1] with no actual implementation. UANT, a SDN style research platform with the main goal of flexibility in implementing and comparing different protocols in the physical, MAC, and application layers was presented in [12], which was more on the scale of individual modems rather than a network system on the whole.

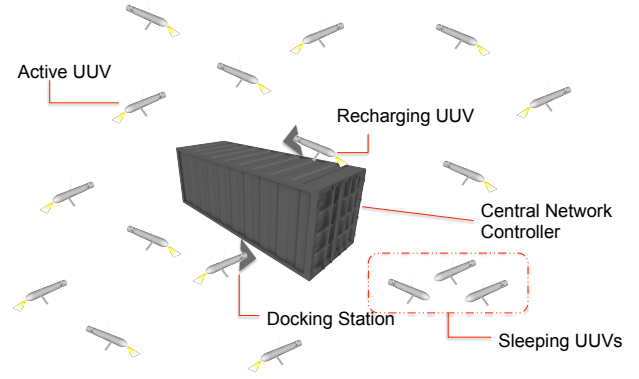


Fig. 1. A diagram of our under-water SDN system. The network controller controls every aspect of each AUV, including their movements and routing information

III. DESIGN

Our under-water SDN system is a network of mobile sensor nodes in the form of AUVs mainly confined to a specific area in the ocean where they will conduct their mission. At the center of the system is the static network controller doubling as a data sink for the mobile AUVs that can be placed on the ocean floor, close by or in the area of operation. This controller is charged with tasks such as controlling AUV movements to arrange the network topology, disseminating routing information, receiving exploration data collected locally by the AUVs, and acting as a recharge station for the AUVs. It may also act as a data gateway to the ocean surface through various means (wired link or other approaches).

A. Support for the acoustic PHY

One of the biggest challenges to any wireless sensor network is power conservation. The AUVs in our system, as mobile wireless sensors, are not exempt from this constraint. In order to save power, these AUVs can use lower-powered acoustic radios for transmission. However, this solution comes with trade-offs with respect to transmission range. While higher powered acoustic radios have transmission ranges in the kilometers, the power-saving radios that the AUVs have may only transmit at a range of hundreds of meters. As such, there is the need of multi-hop routing for both inter-AUV communication and AUV to data sink communication, to which we may apply SDN principles. The controller node, which supplies power to the AUVs, is able to use a higher powered acoustic radio that can reach all the AUVs with a single hop. Thus it can transmit control signals to all the AUVs to arrange the network topology, as well as disseminate routing information. To guarantee a high level of quality of service on the control plane, a specific acoustic channel is dedicated to these control signals so that there will be no interference from data packets. Once the AUVs receive these instructions they are able to arrange themselves and route data packets accordingly. With the controller knowing at all times the topology of the network and constantly updating all the AUVs with new routing information using long range acoustics, packets can be routed in the network as if the nodes are all stationary.

B. Support for the optical PHY

Our under-water SDN system is also capable of supporting the optical physical layer. Optical radios under water can transmit at data rates up to 2.28 Mbps [3], which is significantly faster than acoustic radios. Additionally, optical radios require less power and have very short propagation delay, since visible light travels at the speed of light. On the other hand, optical communications require line-of-sight between radios and are generally not omni-directional. This results in very short ranges of transmission, up to about 100 meters [4], which is comparable with the power-saving acoustic radios. The uni-directional property of optical radios require relative localization among radios, presenting challenges, but at the same time also making duplex communication a possibility (ie. radios can send and receive packets at the same time). Finally, the line-of-sight requirement, though mainly seen as a disadvantage, can be valuable when covertness is a requirement, making optical radios ideal for covert military operations.

The tasks of the network controller in the optical PHY case is nearly identical to those in the acoustic PHY case. Here, the control plane continues to use the acoustic channel, but the data plane has now been moved to the optical one. Due to the need for localization for optical transmissions, the controller's instructions regarding each node's whereabouts becomes even more crucial. Once each AUV receive both routing information as well as the network topology information, they are able to direct their transmission beams toward the correct direction.

C. Traffic control

Since the majority of nodes in our network are mobile, the controller must give movement instructions as well as network communication instructions to each AUV to avoid physical AUV collisions. Moreover, because AUVs can recharge themselves close by the controller, it must also schedule AUV arrivals so that AUVs with higher priorities (AUVs that are soon to run out of power) can be served first. Other AUVs awaiting service are directed to "parking spaces" on the ocean floor. These AUVs may turn off their radios for the most part to save power.

IV. IMPLEMENTATION

We implemented parts of the acoustic version of this system in our WaterCom [6] testbed. WaterCom allows anyone to set up and execute simple experiments remotely through our server reachable via the URL <apus.cs.ucla.edu>. Using a simple HTTP web interface, one may submit a large variety of under-water communications tests remotely, which the server executes automatically. More complicated experiments may also be executed remotely, though these require SSH access.

There are six OFDM acoustic modems in total in our testbed. Three of which are AquaSeNT AM-OFDM-13A models that can send out stronger signals whose communicate range is up to 5 km, and the rest are the educational version OFDM models that can communicate up 150m. Transducers and hydrophones of all modems are placed in a small tank as shown in Figure 2. Next, we lined the bottom and four

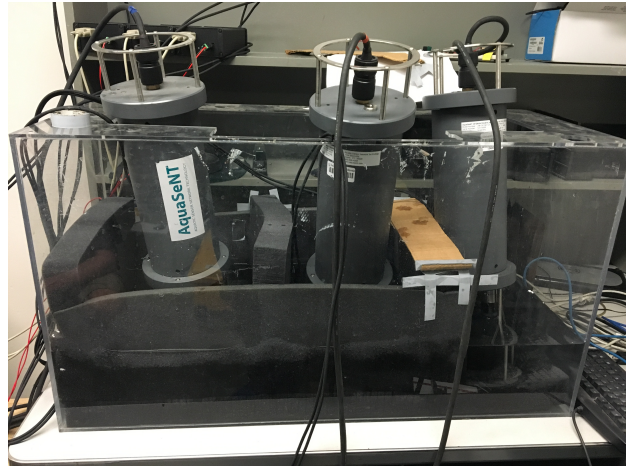


Fig. 2. Our implementation of the under-water SDN scenario in the improved WaterCom [6] testbed

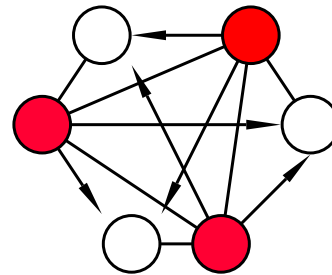


Fig. 3. The resulting network topology in the testbed; the colored nodes represent the 13A models; arrow lines mean single-direction links

sides of our water tank with foam to attenuate the acoustic waves propagating along the tank, as well as the reflections. Finally, using the same foam material, we divided the tank into three compartments with a pair of strong and weak modems in each compartment. By applying these foam material, acoustic wave could be attenuated faster than usual, which will help us to customize the link topology. This allows us to create a topology where the educational modems must go through at least one stronger radio to reach any of the other radios. The graphical topology layout is seen in Figure 3. The colored nodes represent the 13A models capable of transmitting stronger signals. Due to compartmentalization, each smaller modem can only be heard by the modem in the same compartment as itself, though they can hear all the stronger modems transmitting.

The six modems are connected with the WaterCom server, via which we remotely control the modems. The underwater protocol stack SeaLinx [10] is employed to provide the networking services for experiments. Different protocol modules can be loaded in transport layer, network layer and link layer of SeaLinx to compare their performances with different configurations.

In this configuration, the SDN controller is the server for simplicity's sake, which has a wired connection to each modem, representing the sensors. We justify this in that in a real deployment scenario, control packets are on a different

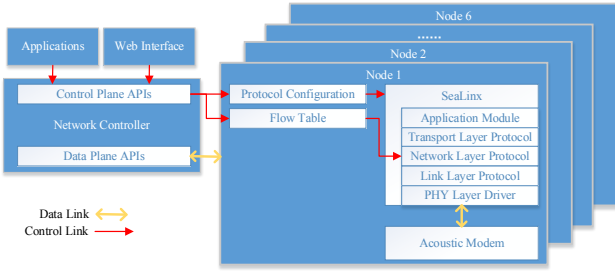


Fig. 4. A diagram of the testbed in SDN terms

channel with very little chances of losses due to interference. Thus the only real drawback is the failure to take into account the propagation time, which will not be manifest in a tank environment at any rate. The server as the network controller is still able to disseminate routing information to each node, direct AUV movements in a simulated fashion by adjusting the sending power of each acoustic modem, and even swap out any of the protocols as needed. Figure 4 presents the separation of all the different functions of each component in our implementation of the underwater SDN system.

V. COMPARING UNDER-WATER ACOUSTIC MAC PROTOCOLS IN THE UNDERWATER SDN TESTBED

With our under water SDN testbed, we compare the performance of two existing under water MAC protocols, Slotted FAMA [11] and UW-Aloha [13]. Slotted FAMA is a under-water MAC protocol based on the FAMA protocol [5], which allows for carrier sensing via sending long enough RTS and CTS packets. Slotted FAMA improves upon FAMA by slotting transmission times, eliminating the asynchronous nature of the protocols and thus decreasing the lengths of the RTS and CTS packets to save power.

UW-Aloha is based directly on the pure Aloha protocol, where each node sends packets whenever needed, and re-transmit collided packets later as required. However, the slow propagation speed of acoustics makes it impossible for nodes to determine whether a collision has occurred by the usual method of carrier sensing, especially when the transmission distances are long. UW-Aloha solves this problem by incorporating ACKs into the protocol to inform the senders of the transmission status.

We compare the two MAC protocols in an under-water multi-hop scenario using the physical setup from Section IV. To make things more interesting, we modify the network topology by omitting specific links from the topology by editing the routing table. First, we only use bi-directional links as potential routes, forcing each of the educational modems to both send and receive from the 13A model in the same compartment as itself. Next, we adjusted the transmission powers of the 13A models so that the ones on the ends of the tank cannot hear each other. The resulting topology is seen in Figure 5.

We dictate the far left educational modem to be the sending node, and the far right educational modem, the receiving node.

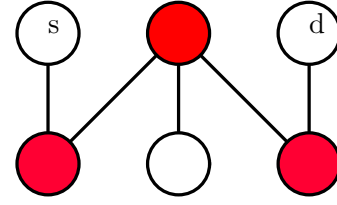


Fig. 5. The network topology as used in the experiment; s denotes the source node, while d denotes the destination

A packet from the source must thus travel four hops to reach the destination, and all along the way, there are possible interferences among adjacent nodes. Under this condition we compare the overall throughput and packet delivery ratio of Slotted FAMA and UW-Aloha. For reference, we also test a third “dummy” MAC protocol that simply checks to see whether a given packet is for its corresponding node, and sends out packets as it receives them.

For all three protocols we run 5-minute test cases; for each test case we vary the length of each packet between 100 and 900 Bytes, and the packet generation rates between 0.3 and 1.2 packets per second. In our experiment, we find that all packets with the length of 900 Bytes experienced no throughput regardless of the protocol, and realized that the data packets cannot be properly decoded when the packet length is at 900 Bytes.

A. Custom protocol parameters and their impacts

The Slotted FAMA and UW-Aloha protocols have custom parameters that can be varied. Slotted FAMA has the parameter “guard time” to account for clock drifts among the different nodes, while UW-Aloha can vary its ACK timeout length. For Slotted FAMA, we only found that having too short of a guard time can negatively impact the packet delivery ratio, but otherwise it has very limited impacts at levels of 1000 and above. The ACK timeout length for UW-Aloha, on the other hand, is a different story. We vary the timeout between 10 and 40 seconds, and we see a consistent trend of the overall throughput due to fewer packets being sent out. This makes sense since the protocol is spending more time waiting for confirmation of packets received than generating more packets to transmit. Additionally, this leads to a higher packet delivery ratio on the MAC layer because there are fewer transmissions in general, thus less of a chance for collisions. However, the amount of throughput sacrificed does not justify this slightly higher packet delivery ratio.

To compare the three protocols, we choose the best performing set of transmissions according to the custom protocol parameter for each protocol. For Slotted FAMA, we use the dataset generated with guard time = 1000; for UW-Aloha, we use the dataset generated with ACK timeout = 100.

B. Comparing the MAC protocols amongst one another

We compare the packet delivery ratios and overall throughputs of the MAC protocols. We define packet delivery ratio here to be the number of packets received to the number of

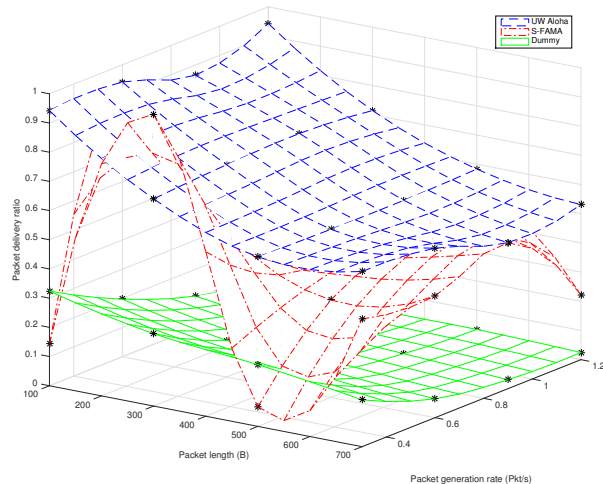


Fig. 6. The packet delivery ratio of Slotted FAMA, UW-Aloha, and a dummy MAC protocol as influenced by packet length and packet generation rate

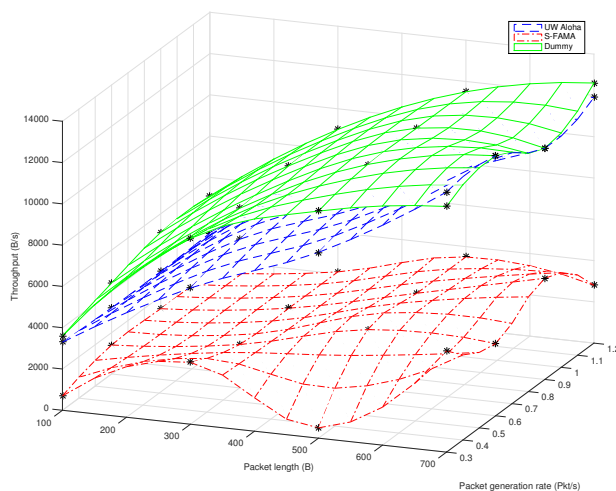


Fig. 7. The overall throughput of Slotted FAMA, UW-Aloha, and a dummy MAC protocol as influenced by packet length and packet generation rate

packets sent, both in the MAC layer. For example, packets dropped in the MAC layer before being sent out does not count. The overall throughput is the total amount of data received at the receiver over the 5-minute experiment period. As seen in Figure 6, it is clear that packet delivery ratio is negatively correlated with packet generation rate for UW-Aloha and the dummy mac, while Slotted FAMA looks quite sporadic. On the other hand, the packet lengths have a minimal effect on UW-Aloha, while negatively affecting the dummy protocol. This shows UW-Aloha's advantage in maintaining packet delivery ratio while increasing the throughput. In general, we observe that in terms of packet delivery ratio, UW-Aloha performs much more superior to Slotted FAMA, though Slotted FAMA is still better than the dummy protocol, which has no regulations at all.

Figure 7 shows how the throughput of each protocol is

affected by packet length and packet generation rate. Unsurprisingly, all three protocols see a slight upward trend as the two parameters increase. In terms of comparison, the clear winner is the dummy protocol, since it does not wait for channel clearance or ACK signals, nor does it retransmit any packets but simply sends packets out as soon as it receives them. Interestingly, the high throughput of the dummy protocol actually attests to the performance of UW-Aloha, as it can reach throughput levels almost as high to the dummy protocol. Slotted FAMA has lowest throughput, making a huge trade-off in throughput for a slight gain in packet delivery ratio.

VI. CONCLUSION

In this paper we presented an underwater networking system for AUVs that leverages the SDN paradigm through use of a centralized network controller. Our design decouples the control and data planes by utilizing a dedicated channel for the controller to disseminate control packets to the AUVs. Using this design we were able to greatly simplify the task of AUV routing, even satisfying the stringent alignment requirements necessitated by the optical channel. We also implemented a small-scale replica of this underwater SDN system in our remotely-accessible testbed, which allows us and anybody in the world to develop new protocols and run experiments with ease. Using the testbed, we compared two existing underwater MAC protocols in a multi-hop network scenario. These experiments indicate that UW-Aloha gives high throughput whilst simultaneously guaranteeing relatively high packet delivery ratios.

For our future work, we intend to deploy our system into a larger body of water, such as the nearby marina or open ocean so that we can more realistically evaluate network properties and protocols. Additionally, we will incorporate optical modems into our testbed to test the performance of a acoustic-optical hybrid implementation in our underwater SDN system.

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