An SDN Architecture for Under Water Search and Surveillance

Ruolin Fan, Ciarán Mc Goldrick[†], and Mario Gerla
Department of Computer Science,
University of California, Los Angeles, CA, USA
Email: {ruolinfan, gerla}@cs.ucla.edu
[†] School of Computer Science and Statistics,
Trinity College Dublin, Dublin, Ireland,
Email: ciaran.mcgoldrick@scss.tcd.ie

***Abstract*—Underwater Wireless Networking (UWN) schemes and applications have been attracting considerable interest in recent wireless communication studies. The nature of water, as a carrier medium, imposes very significant constraints on the both the characteristics and information carrying capacity of underwater communication channels. Currently, acoustics and optics are the two main physical platform choices. Acoustics offers relative simplicity. Optics has a big bandwidth advantage but is much more complex to implement and manage. Combining the two technologies together allows them to synergize with each other, maximizing the advantages of each carrier. An SDN architecture, which separates the control and data planes, allows for the full advantages of using an acousto-optic combination. In this setup, the longer-ranged acoustic channel serves as the control plane, allowing the controller to issue mobility and network related commands to AUVs far away, and the shorter ranged but much faster optical channel serves as the data plane, allowing for fast transfer of data. This paper presents such a system using JANUS, the NATO defined standard now considered for adoption among NATO members, for the control channel.**

I. Introduction

As a result of increasing demands from off shore industry, Underwater Wireless Networking (UWN) has attracted special focus in recent wireless communication studies. Due to the physical characteristics of the underwater channel, various Electro-Magnetic (EM), optical, and acoustic communication technologies have been applied to UWN for different communication ranges [11]. 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 has advantages in bandwidth and propagating speed, yet its communication range is limited by the absorption and backscatter in water, though not as severely as EM waves. Acoustic waves have the longest transmitting range in underwater environments, but present challenges in communicating in the temporally and spatially varying underwater acoustic channel, being affected by long propagation delays, limited available bandwidths, and high error rates. Currently, acoustics and optics are the two modes of communication seriously considered by most researchers, with the bulk of attention paid to acoustics because of its relative simplicity - it acts the same as EM in the air, except for long propagation delays. Optics, on the other hand, is much more complicated. Aside from its short communication range, optical PHY link is typically line of sight and is usually unidirectional, requiring relative localization among nodes. At the same time, these very same properties give optics the potential for covertness, since a finely aligned optical beam eludes interceptions. All of these properties of different propagation media give very interesting trade off scenarios, and some even offer the opportunity to combine multiple methods to create a hybrid approach [8].

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 metadata related to network functionality is transmitted. This is done by utilizing a centralized network controller (the Open Flow Controller) that has an up-to-date view of the network and defines network behavior among all the nodes based on user demands. The work by [10] gives a comprehensive survey of ongoing research in the SDN area.

The use of the SDN centralized control for UW networking is motivated by the complex nature of the tradeoffs between different options that makes a distributed optimization (integrating the controls in the data plane) very difficult to design. We thus define an under water SDN architecture, complete with a central network controller that mainly handles routing and movement decisions for each AUV. The control plane is separated from the data plane by using a separate control channel. In this paper we propose to use JANUS, the NATO defined standard now considered for adoption among NATO members.

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. 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 [17]. The concept of Software Defined

Networking (SDN) has been recently introduced for next generation underwater communication networks [1]. Hardware prototypes for software-defined underwater acoustic modems, i.e. SEANet [2], has also been implemented.

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 search and surveillance mission. The basic architecture is depicted in Fig 1. Close to the Ocean floor are the AUVs, that are networked together to form a mesh network feeding to an Unmanned underwater Support Vehicle (USV) basically a small unmanned submarine. The USV serves as gateway between the AUVs and the surface vessel, which drives the search. The USV may or may not be tethered to the Surface Vessel. The tether, if present, will provide power to the USV and will relay video and images captured by the AUVs to the vessel. Consider a search for a downed plane in the Ocean. A possible mission may consist of 10 vessels, covering say, a 10 km front. Each vessel drives 10 USVs and each USV control a network of 10 AUVs (spaced 10m one from the other). So, each vessel receives 100 videos/images from the AUVs. One can assume that the AUVs are communicating optically with the USV point to point, or through a multi-hop tree structure. The topology is determined by the Open Flow SDN controller that in this case resides on the Vessel and manages a 1km region (with 10 USVs and 100 AUVs). If water conditions and visibility are good, less than 10 AUVs may be required and the extra AUVs are kept in a bay within the USV. As water conditions worsen, the OF controller is informed by the AUV low quality signal alerts and directs the construction of a multi hop optical tree (note: the tree construction is directed via the acoustic control channel). If the visibility is unfeasible for optics, that communications revert to acoustics. The communications degrade from video to schematic images [8]. Given the periodicity of the images and the multiple sources, FAMA protocols are more appropriate than S-ALOHA, so the OF Controller switches the AUVs to acoustic mode with FAMA protocols. In a tethered system, the video/image processing is done on the vessel. All the OF commands originate from the vessel based OF controller (though load sharing with the USV may be considered). If video quality is good, the search operation can be manually guided from the vessel. Namely, by interacting with the OF Controller some AUVs can be manually directed to the Ocean floor spots of interest.

In some scenarios the entire search operation can be carried out without man in the loop (see Figure 1). In this case each USV is in charge of the AUV search patrol. Image/video processing is done on the USV. The USV hosts the OF controller proxy. The USV proxies communicate with the surface unit which hosts the main OF controller. The surface unit may be a floating energy generator based on wave motion. There is no tether, minimal information about the success of the search is propagated to the surface unit acoustically. In turn, the surface units communicate with a ground station that supervises the entire operation. Periodically the USV surfaces to recharge. A back up USV takes its place.

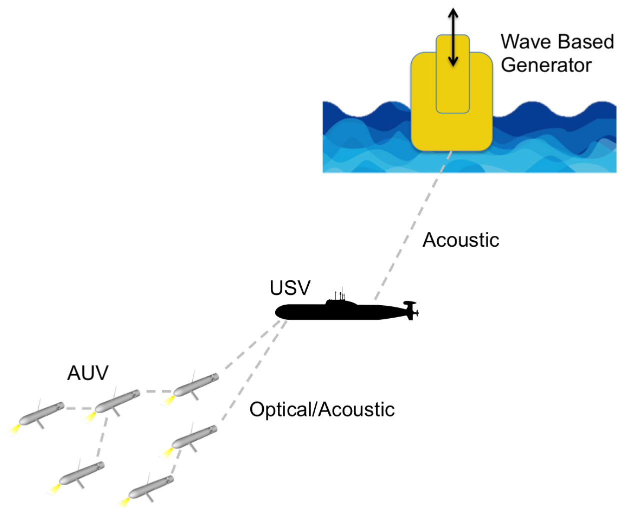

Fig. 1. Untethered, unmanned SDN architecture: the USV communicates with the wave generator acoustically and the AUVs using a combination of acoustics or optics

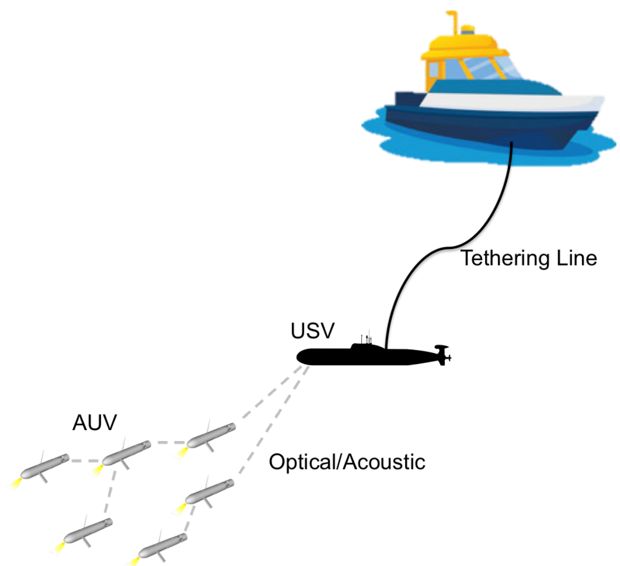

Fig. 2. Tethered SDN architecture: the USV is connected to the ship by a physical line, but directs the AUVs wirelessly using acoustics or optics

In order to manage the AUVs, the OF Controller need to gather information from them. The location is computed by each AUV exploiting beacon from OF Controller, pressure gauge and compass. Together with location also the orientation in polar coordinates is computed. This is necessary to align the AUV directive LED cluster antennas to form the desired topology (say, tree or star). Link turbulence and visibility is monitored, error rate for acoustic and optical transmissions is reported, good put is recorded, remaining battery power is read. In addition, the OF Controller commands the actuators (eg jets, bladder for resurfacing, etc)

In a previous study [4], we addressed another application, oil drilling pit monitoring. (see Figure 2) This is basically a surveillance operation. At the center of the system is the OF 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. The static controller plays the role of the USV in the search example The 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 also acts as a data gateway to the ocean surface through various means (tethered link or other approaches).

A. Support for the OF Control Channel - JANUS

The acoustic control channel must be simple, robust, built according to well accepted standards, energy parsimonious and capable of traveling over large distances (eg from surface to ocean floor). The JUNUS NATO standard fits this bill.

JANUS is an open-source robust signaling method for underwater communications, freely distributed under the GNU General Public License version 3 .

JANUS has been developed at the Centre for Maritime Research and Experimentation (CMRE) with the collaboration of academia, industry and government with the intention of creating an inter-operable communications standard.

JANUS performance has so far been evaluated by many collaborating partners at centre frequencies from 900 Hz - 60 kHz and over distances up to 28 kilometers in waters all over the world.

JANUS packet and bit error rates have been computed as functions of the signal to the noise ratio (SNR) and time spread over periods extending from hours to months. Signal correlation times have been computed and long-term experiments by CMRE in 2008 and 2009 have helped quantify robustness during variable environmental conditions.

A cabled network of oceanographic instrumentation has measured the ambient noise, water temperature, water velocity, internal wave and tidal information during JANUS transmission and reception for correlating message decoding performance with environmental parameters.

JANUS's open and public nature ensures that academia, industry and governments may all benefit from its use. The tools necessary to create a JANUS signal, encode in a desired frequency band and decode a received signal are all freely available on this site. A traditional hardware underwater acoustic modem is not even required.

At the physical layer, JANUS signaling uses a coding scheme known as Frequency- Hopping (FH) Binary Frequency Shift Keying (BFSK) to transmit digital data as a sequence of short duration tones (its packet encoding process is represented in Figure 3).

FHBFSK has been selected for its known robustness in the harsh underwater acoustic propagation environment and simplicity of implementation. FH-BFSK is a common phase-insensitive (incoherent) physical encoding technique, already used in commercially-produced modems, and is known to be robust to a variety of environmental conditions. It is also robust to packet collision, supporting a degree of multiple simultaneous access that is valuable in a simple protocol with a limited medium access control complexity.

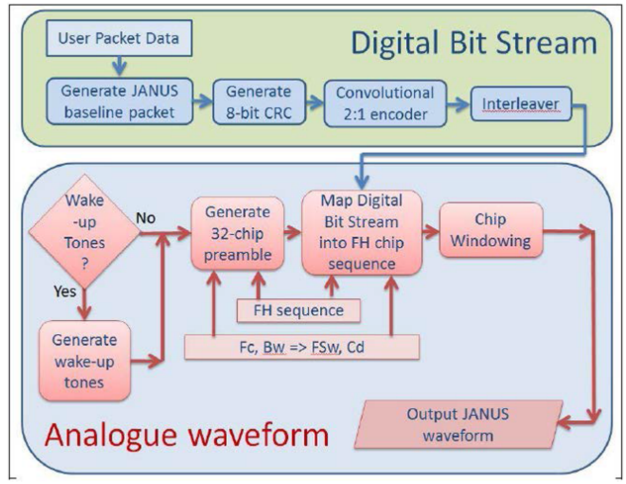

Fig. 3. Block diagram of the JANUS Baseline Packet encoding process

The primary advantages of using JANUS for UW acoustic OF control channel are the following:

- Simplicity of design. Among the least complicated forms of acoustic communications yet devised.
- Robust to noise. This signal should be detected when the signal to noise ratio (SNR) in a given band is at better than -2 dB.
- Robust without tracking for "reasonable" amounts of relative speed (range rate).
- JANUS is the optimal approach to use for asynchronous, multi-access (multi-user) applications.
- Optimal for robustness in the presence of all types of interference, including intentional jamming.
- Depending on SNR, JANUS may be quite difficult for third parties to detect by conventional means; for example, by energy detectors of all forms.
- JANUS is a "constant envelope" waveform. Thus, a transmitter is not concerned with amplitude crest factors, and thus may allocate maximum power to the transmission.

B. Support for the optical PHY

As earlier described, the under-water SDN architecture also supports the optical physical layer in favorable conditions. 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 [5], which is comparable with the power-saving acoustic radios. The uni-directional property of optical radios requires relative localization among radios, which is supported by UAVs. Incidentally, unidirectionality makes duplex communication a possibility (ie. radios can send and receive packets at the same time). This is not possible with acoustic modems. Finally, the directionality, though mainly

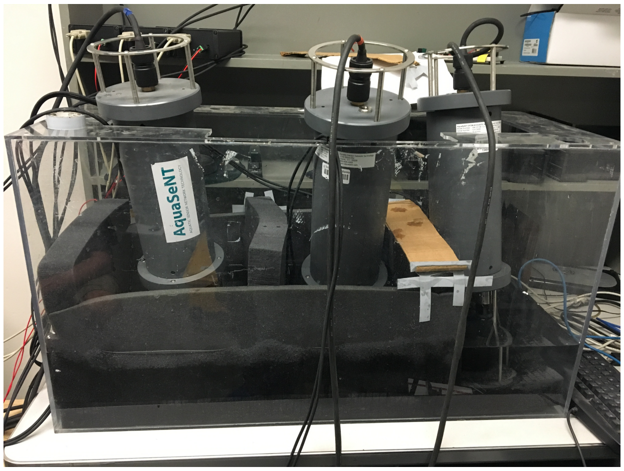

Fig. 4. Our implementation of the under-water SDN scenario in the improved WaterCom [7] testbed

seen as a disadvantage, can be valuable when covertness is a requirement, making optical radios ideal for covert military operations.

The tasks of the OF Controller in the optical PHY case are nearly identical to those in the acoustic PHY case. Here, the control plane continues to use the acoustic channel JANUS, but the data plane has now been moved to the optical one. Due to the need for directivity in optical transmissions, the controller's knowledge about each node's location becomes even more critical. Once AUVs receive both routing information as well as network topology information, they can direct their transmission beams toward the correct direction.

IV. Implementation

We implemented parts of the acoustic version of this system in our WaterCom [7] testbed. WaterCom allows anyone to set up and execute simple experiments remotely through our server reachable via the URL <apus.cs.ucla.edu>.

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 4.

These six modems are connected with the WaterCom server, via which we remotely control the modems. The underwater protocol stack SeaLinx [12] 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.

V. Conclusion

In this paper we presented an underwater networking system for AUVs that taps into the SDN paradigm, using a centralized network controller. Additionally, our design decoupled the control and data planes by utilizing a dedicated channel (JANUS) for the controller to disseminate control packets to the AUVs. With this design we were able to greatly simplify the task of AUV routing, even satisfying the stringent alignment requirements that come with the optical channel. For our future work, we plan to include the M FAMA MAC protocol in our improved [4] WaterCom [7] under water SDN testbed and expand our implementation into a larger body of water, such as the LA Marina so that we can have more realistic propagation characteristics in the experiments.

Acknowledgment

This project was partially supported by NSF award number 1205757, Ocean-TUNE: A Community Ocean Testbed for Underwater Wireless Networks (2012-2016).

References

[1] I. F. Akyildiz, P. Wang, and S.-C. Lin. Softwater: Software-defined networking for next-generation underwater communication systems. *Ad Hoc Networks*, 2016.

[2] E. Demirors, G. Sklivanitis, T. Melodia, S. N. Batalama, and D. A. Pados. Software-defined underwater acoustic networks: toward a high-rate real-time reconfigurable modem. *Communications Magazine, IEEE*, 53(11):64–71, 2015.

[3] M. Doniec and D. Rus. Bidirectional optical communication with aquaoptical ii. In *Communication Systems (ICCS), 2010 IEEE International Conference on*, pages 390–394. IEEE, 2010.

[4] R. Fan, L. Wei, P. Du, C. Mc Goldrick, and M. Gerla. A sdn-controlled underwater mac and routing testbed. In *Proceedings of MILCOM 2016*, page NPP8. AFCEA, 2016.

[5] N. Farr, A. Bowen, J. Ware, C. Pontbriand, and M. Tivey. An integrated, underwater optical/acoustic communications system. In *OCEANS 2010 IEEE-Sydney*, pages 1–6. IEEE, 2010.

[6] C. L. Fullmer and J. Garcia-Luna-Aceves. *Floor acquisition multiple access (FAMA) for packet-radio networks*, volume 25. ACM, 1995.

[7] C. M. Goldrick, M. Matney, E. Segura, Y. Noh, and M. Gerla. Watercom: A multilevel, multipurpose underwater communications test platform. In *Proceedings of the 10th International Conference on Underwater Networks & Systems*, page 14. ACM, 2015.

[8] S. Han, R. Chen, Y. Noh, and M. Gerla. Real-time video streaming from mobile underwater sensors. In *Proceedings of the International Conference on Underwater Networks & Systems*, page 21. ACM, 2014.

[9] S. Han, Y. Noh, U. Lee, and M. Gerla. M-fama: A multi-session mac protocol for reliable underwater acoustic streams. In *INFOCOM 2013. 32nd Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*. IEEE, 2013.

[10] D. Kreutz, F. M. Ramos, P. Esteves Verissimo, C. Esteve Rothenberg, S. Azodolmolky, and S. Uhlig. Software-defined networking: A comprehensive survey. *Proceedings of the IEEE*, 103(1):14–76, 2015.

[11] L. Lanbo, Z. Shengli, and C. Jun-Hong. Prospects and problems of wireless communication for underwater sensor networks. *Wireless Communications and Mobile Computing*, 8(8):977–994, 2008.

[12] S. N. Le, Z. Peng, J.-H. Cui, H. Zhou, and J. Liao. Sealinx: A multi-instance protocol stack architecture for underwater networking. In *Proceedings of the Eighth ACM International Conference on Underwater Networks and Systems*, page 46. ACM, 2013.

[13] M. Molins and M. Stojanovic. Slotted fama: a mac protocol for underwater acoustic networks. In *OCEANS 2006-Asia Pacific*, pages 1–7. IEEE, 2007.

[14] Z. Peng, Z. Zhou, J.-H. Cui, and Z. J. Shi. Aqua-net: An underwater sensor network architecture: Design, implementation, and initial testing. In *OCEANS 2009, MTS/IEEE Biloxi-Marine Technology for Our Future: Global and Local Challenges*, pages 1–8. IEEE, 2009.

[15] C. Petrioli, R. Petroccia, J. R. Potter, and D. Spaccini. The sunset framework for simulation, emulation and at-sea testing of underwater wireless sensor networks. *Ad Hoc Networks*, 34:224–238, 2015.

[16] M. Stojanovic and J. Preisig. Underwater acoustic communication channels: Propagation models and statistical characterization. *Communications Magazine, IEEE*, 47(1):84–89, 2009.

[17] L. Wei, Z. Peng, H. Zhou, J.-H. Cui, S. Zhou, Z. Shi, and J. O'Donnell. Long island sound testbed and experiments. In *Oceans-San Diego, 2013*, pages 1–6. IEEE, 2013.