Software-Defined Underwater Acoustic Networks: Toward a High-Rate Real-Time Reconfigurable Modem

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ABSTRACT

We review and discuss the challenges of adopting software-defined radio principles in underwater acoustic networks, and propose a software-defined acoustic modem prototype based on commercial off-the-shelf components. We first review current SDR-based architectures for underwater acoustic communications. Then we describe the architecture of a new software-defined acoustic modem prototype, and provide performance evaluation results in both indoor (water tank) and outdoor (lake) environments. We present three experimental testbed scenarios that demonstrate the real-time reconfigurable capabilities of the proposed prototype and show that it exhibits favorable characteristics toward spectrally efficient cognitive underwater networks, and high data rate underwater acoustic links. Finally, we discuss open research challenges for the implementation of next-generation software-defined underwater acoustic networks.

INTRODUCTION

Underwater acoustic networks (UANs) are an emerging research topic because of the key role that this technology will play in military and commercial applications including disaster prevention, tactical surveillance, offshore exploration, pollution monitoring, and oceanographic data collection. A key challenge in the design of UANs stems from the characteristics of the underwater acoustic (UW-A) channel, which exhibits high path loss, noise, multipath, high and variable propagation delay, and Doppler spread. Therefore, reliable communication links are practically feasible only at low data rates. Additionally, the propagation challenges in the underwater environment result in *temporally* and *spatially* varying UW-A channel coefficients, which drives research efforts toward the design of specialized protocols at different layers of the network protocol stack — often with a cross-layer approach.

As of today, the majority of existing deployed UANs are based on commercially available acoustic modems. Even though commercial modems enable a wide range of applications, they rely on inherently *fixed hardware* designs and proprietary protocol solutions that are regrettably far from satisfying the emerging reconfigurability needs of next-generation UANs. As a result, practical deployment of new protocols is either not feasible or prohibitive in terms of both implementation cost and time. Evidently, fixed hardware and closed software architectures that characterize commercial underwater modems prevent UAN applications from benefiting from the latest algorithmic developments.

Lack of standardization agreements for UANs impose additional hurdles in the design of reconfigurable networks. For example, different vendors equip underwater modems with proprietary communication protocols with different implementation requirements across different hardware and software platforms, which, in the end, prevents their integration in heterogeneous UANs. A sizable body of research work in UANs focuses on the development of software/protocol standards that resolve *interoperability* issues among different underwater modems (e.g., JANUS [1]). However, existing architectures are still far from being able to achieve the data rate performance and flexibility required by the next generation of UAN applications.

Finally, the spatial and temporal variations of the UW-A channel require reconfiguration of the communication parameters of UAN devices to provide stable performance in terms of bit error rate (BER) and packet error rate (PER). Currently, commercial modems address adaptation to channel variations by employing a set of predefined operational modes (pre-fixed set of communication parameter values). However, such ad hoc solutions lack i) the ability to switch in real time among a finite number of operational modes, ii) decision making mechanisms to decide and apply adaptation, and iii) the ability to dynamically adapt to all the possible environments because of the finite number of operational modes. Consequently, there is a need for UAN devices that can i) ease deployment and testing of new protocol

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designs, ii) bridge the gap between different network devices and protocols to resolve the interoperability problem in heterogeneous UANs, and iii) intelligently decide and adapt their communication parameters or technology based on the environmental needs in real time.

Software-defined radio (SDR) has recently emerged as a technology platform that enables rapid prototyping of fully agile, intelligently adaptive, and reconfigurable networking devices to accommodate and test novel wireless networking protocols for RF communications. Considering the unique capabilities and features of SDR in RF and the need for flexible, easily reconfigurable UAN devices, in this article, we investigate the software/hardware challenges to build a software-defined acoustic modem (SDAM) and discuss its potential benefits for future UANs. To that end, we review existing software-defined efforts in UW-A and we propose an SDAM prototype based on commercial off-the-shelf (COTS) components. We design and implement physical layer schemes and decision algorithms that exploit both time and frequency degrees of freedom, and we demonstrate the real-time reconfigurable capabilities of the proposed modem with field experiments.

The remainder of this article is organized as follows. We first provide a brief overview of the SDR paradigm and current SDR-based architectures for UW-A communications. Then we propose and describe an SDAM architecture and provide experimental performance evaluation results in both indoor (water test tank) and outdoor (lake) environments. Finally, we discuss open research implementation challenges for future next-generation software-defined UANs.

Software-Defined Architectures for UW-A Communications

SDRs are now prevalent communication platforms in both commercial and military RF applications mainly because of the need for flexible and reconfigurable radio solutions and their ability to follow the rapid evolution of enabling technologies such as analog-to-digital converters (ADCs), digital-to-analog converters (DACs), general-purpose processors (GPPs), field-programmable gate arrays (FPGAs), and graphical processing units (GPUs). However, so far, SDR platforms have seen limited use in the context of underwater communications, primarily because of implementation and development cost challenges compared to RF technologies. A typical SDR architecture comprises a front-end that may include amplifiers, filters, and mixers, connected to an ADC/DAC and a softwarereprogrammable digital processing unit such as a digital signal processor (DSP), FPGA, GPP, or GPU. The SDR architecture provides the basis for software reconfigurable processing at the physical (PHY) and medium access control (MAC) layers, often through existing software tools, including GNU Radio, Simulink, and LabView, which are interoperable with higher-layer protocol implementations (e.g., TCP/IP).

SDR platforms have been adopted by several military programs including the U.S. Joint Tactical Radio System (JTRS) and NATO STANAG 5066, as well as by a variety of commercially available products that feature a mixture of hardware configurations at different cost, for example, USRP, RTL-SDR, HackRF, BladeRF, and PicoSDR. Open-source software packages, such as GNU Radio interface well with SDR systems, allow custom development of application-specific signal processing blocks, and have recently demonstrated their support for embedded devices too such as Xilinx Zedboard and Xilinx ZC702. As a result, a software-defined framework appears to be a powerful proposition for underwater communications that will be able to provide a low-cost and programmable/reconfigurable hardware alternative to commercially available underwater modems. However, SDR principles are not directly applicable to the underwater environment due to the particular (and challenging) characteristics of the underwater channel.

Current underwater networking research can be classified as follows:

- Efforts that involve hardware development of new experimental modems and pertinent software across some or all layers of the protocol stack
- Efforts that involve primarily software development for the network and application layers of the protocol stack of UANs that use commercially available modems

The majority of existing proposals offer only data logging capabilities for offline processing and do not report real-time reconfigurability and online performance evaluation through experimental field studies.

The main objective of high-layer software proposals in underwater networks is the development of a framework that facilitates integration of simulation, emulation, and testing policies and can interface with existing commercial or experimental underwater modems. The work in [2] reviews and compares two software frameworks, SUNSET and DESERT, implemented using the open source network simulators ns-2 and ns-2 miracle. SUNSET has been used as the standard plug-in in the SUNRISE [3] project. SUNRISE is a federation of testing infrastructures that is designed to represent different marine environments and support different applications. OceanTUNE [4] presents a similar testbed suite that provides flexibility in system and network configurations. Aqua-Net [5] is a software framework that uses WHOI micro-modems and Teledyne Benthos modems, and offers a layered architecture that enables cross-layer optimization. The work in [6] proposes an agent-based (service-oriented) architecture on a Java Virtual Machine (JVM), therefore allowing portability from simulation to real-time deployment. A more recent work [7] attempts to depart from OSI-layered implementations and follow a modular cross-layer software-defined architecture.

Lower-layer/hardware proposals in underwater networks concentrate on hardware development of underwater modems and explore their interface with hybrid software architectures that offer reconfigurability at the PHY and MAC layers. In particular, the work in [8] studies a modem architecture that is based on the open-source software tools GNU Radio, TinyOS, and TOSSIM, and the USRP hardware. The work in

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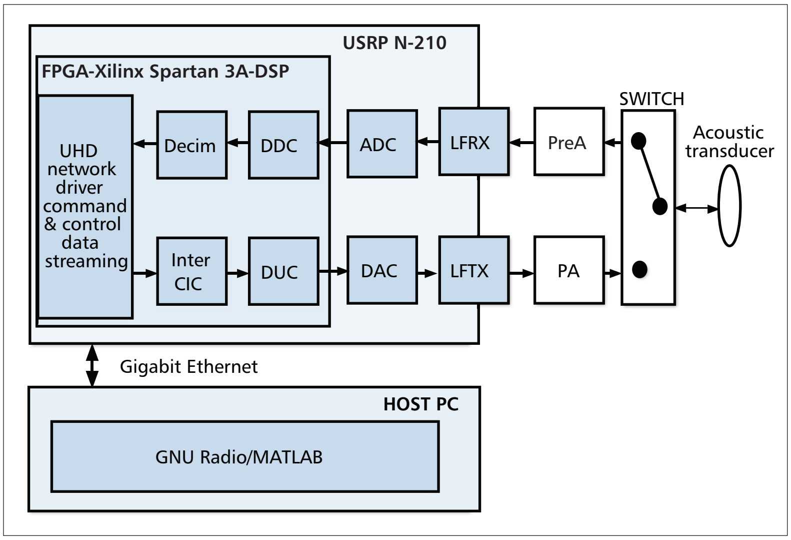

Figure 1. Hardware architecture of the proposed SDAM prototype.

[8] builds an underwater sensor network mote and parallels pertinent developments in the software radio and sensor network literature. Similarly, [9–11] provide early modem prototypes that are based on either FPGA/DSP or FPGA-only technologies and develop in-house software for controlling the PHY and MAC layer parameters.

Proposed SDAM Prototype

In this section, we present our developments toward the design and implementation of a variable-rate fully reconfigurable SDAM that is built from a collection of COTS components. We demonstrate and evaluate, in real-time underwater field experiments, the software-defined capabilities of the proposed modem/design. We provide a complete overview (from hardware to software) of the SDAM implementation, as well as our design considerations for the PHY, MAC, and network layers of the protocol stack.

Hardware Setup

The SDAM is at its core an SDR connected with wideband acoustic transducers through power amplifiers/preamplifiers. The SDAM exploits the unique capabilities and features of an SDR to fulfill the need for flexible, easily reconfigurable UAN devices [12].

The overall hardware architecture of the proposed SDAM prototype is illustrated in Fig. 1, while Fig. 2 depicts the prototype itself. The proposed SDAM is based on a USRP N210, which is a commercially available FPGA-based, SDR platform. We chose to work with LFTX and LFRX daughterboards (DC –30 MHz), which enable the development of a half-duplex transceiver operating in the frequency range of the selected omnidirectional acoustic transducer, Teledyne RESON TC4013, from 1 Hz to 170 kHz. To enhance the communication range of our SDAM, we used a linear wideband power amplifier (PA), Benthowave BII–5002, and a voltage preamplifier (PreA), Teledyne RESON VP2000. We also incorporated an electronic switch, Mini-Circuits ZX80–DR230+ to enable the operation of a single acoustic transducer as transmitter and receiver in a time-division duplex fashion. Baseband signal processing algorithms and protocols are mainly implemented in the host PC, which is connected to the USRP N210 through Gigabit Ethernet (GigE). Each prototype costs approximately $6000 (commercially available alternatives are almost 2× more expensive).

Physical Layer

We consider the design and implementation of two different signaling technologies for different applications based on zero-padded orthogonal frequency-division multiplexing (ZP-OFDM) and direct sequence spread-spectrum (DS-SS). Both technologies aim to maximize channel utilization and spectral efficiency in the challenging underwater environment by providing *online* adaptation at both PHY and MAC layers.

ZP-OFDM: We adopt a ZP-OFDM with a superimposed convolutional error correction coding scheme. In particular, we use a K-subcarrier ZP-OFDM where zero-padding works as a zero-power guard interval alternative to the conventional cyclic prefix. Before subcarrier allocation, data symbols are modulated with either binary phase shift keying (BPSK) or quadrature PSK (QPSK), while $K_P = K/4$ are used as pilot, K_D as data, and K_N as null subcarriers. A guard interval is added between each OFDM symbol to avoid interference among different OFDM symbols, and a pseudorandom noise (PN) sequence is transmitted at the beginning of each OFDM packet for frame detection and coarse synchronization purposes at the receiver. At the receiver side, a low-pass filter (LPF) is first used to reject out-of-band noise and interference. Null subcarriers are used for Doppler scale estimation and compensation, while pilot subcarriers are used for channel estimation and fine symbol synchronization in the frequency domain.

DS-SS: In this scheme, BPSK data symbols are modulated by a random binary code-waveform of length L and duration $1/(B - A)$; thus, transmitted waveforms occupy the whole available bandwidth (A Hz, B Hz) of the device, providing efficient utilization of the underwater acoustic spectrum resources. To avoid inter-symbol interference we ensure that the product between code length L and waveform duration is larger than the multipath spread; hence, we choose large code lengths, which leverage the capability of the selected technique for multiple access. More specifically, we adopt two different transmitter designs, one where a long PN sequence is used for frame detection, synchronization, and channel estimation at the receiver side, and a second where an all-1 sequence of unmodulated bits is used to achieve frame detection and coarse synchronization at the receiver [13]. For the second transmitter setup, we propose a blind receiver design that integrates and executes synchronization, channel estimation, and demodulation in a combined fashion with a low-complexity RAKE-type receiver [13]. The proposed receiver structure offers significant computational efficiency and resistance to multiple access interference, therefore sparking interest in future applications on heavily utilized spectrum resources.

User-Defined Decision Algorithms

Herein, we define the decision algorithms for adaptation in both the ZP-OFDM and DS-SS physical layer schemes. However, we first need to define a reliable feedback communication method to support real-time forward link adaptation, as potential unsuccessful feedback delivery may result in failure of the forward link as well. To that end, we propose and implement a feedback method based on binary chirp spread-spectrum (B-CSS) modulation, which is known to be resilient against the severe multipath and Doppler effects that characterize the UW-A channel. In addition, B-CSS provides a robust low data rate communication scheme with a low-complexity receiver design that very well fits the reliability and robustness requirements of an underwater feedback channel. More specifically, we leverage the quasi-orthogonality of up and down chirps by encoding a "1" bit with an up chirp and a "0" bit with a down chirp. Up and down chirp signals are generated by proper selection of the time-varying instantaneous frequency that ranges from f_0 to f_1, and the period T of a chirp signal. Therefore, if the chirp frequency variation rate defined as $\mu = (f_1 - f_0)/T$ is positive, we generate an up chirp; otherwise, if $\mu < 0$, we generate a down chirp.

Decision algorithms provide the SDAM with the capability to either adapt/change specific communication parameters (of a pre-selected communication technology) or switch between different communication technologies such as ZP-OFDM and DS-SS. Decisions are made by the receiver node based on user-defined algorithms, and are then communicated to the transmitter through the wireless feedback link. We consider three decision algorithms that best illustrate the adaptation capabilities of the proposed SDAM under preset performance constraints.

First, we consider adaptation of the modulation and the error correction coding rate in a ZP-OFDM link to solve a rate maximization problem under preset BER reliability constraints. We assume that the number of data subcarriers, as well as the symbol and guard interval duration in ZP-OFDM remain fixed, and data rate is a function of the modulation order and error correction coding rate. The receiver estimates the signal-to-interference-plus-noise ratio (SINR) per received packet, and jointly decides on the combination of a modulation (BPSK or QPSK) and error correction coding (1/2-rate convolutional code or uncoded) scheme to satisfy a predefined BER threshold constraint.

Second, we provide the SDAM with the capability to switch between ZP-OFDM and DS-SS communication technologies. This is achieved by designing a multiplexer-based adaptation mechanism that is activated upon successful decoding of an incoming packet. The SDAM is preprogrammed with all the primitive modules required for the implementation of both ZP-OFDM and DS-SS physical layer schemes. The enabling signal of the multiplexer is controlled by a Boolean variable that enables DS-SS transmission/reception upon successful reception of a ZP-OFDM packet and vice versa.

Finally, we consider real-time code-waveform adaptation in a DS-SS link to maximize the pre-detection SINR at the destination receiver of interest in the presence of multiple access interference. The receiver first senses the environment and calculates a disturbance (noise plus interference) autocorrelation matrix during the time that the user of interest is silent. Then the receiver estimates the pre-detection SINR for each incoming packet and looks for the best channel waveform of length L that is the solution to an SINR maximization problem. The new channel waveform is communicated to the transmitting source of interest through a chirp-based feedback link. Both the transmitter and receiver need to be synchronized. We implement two parallel processing receiver chains, one working with the updated and another with the preset channel waveform.

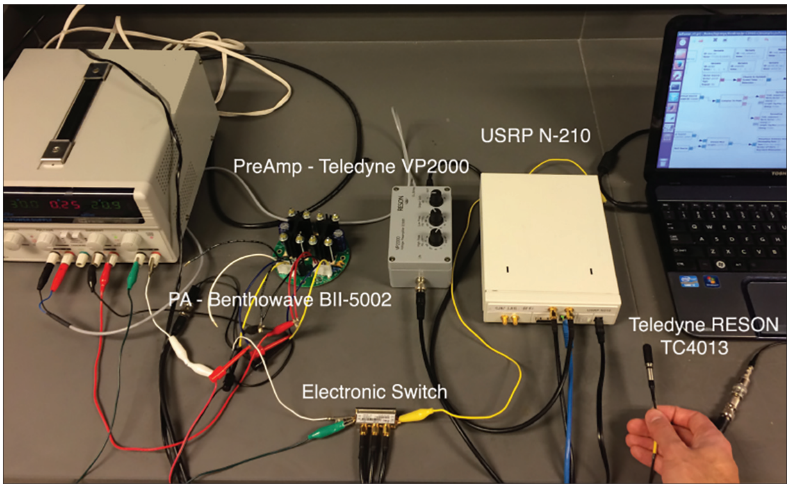

Figure 2. The proposed SDAM prototype.

Medium Access Control

We implement a simple MAC protocol that can support user-defined decision algorithms. Specifically, at the time an SDAM node has data available for transmission, it directly accesses the channel, transmits a data packet, and switches into receive mode, waiting for a feedback message from the destination node. A timeout time is also set for retransmission. In the absence of data, all nodes perform idle listening. Even though the current implementation includes one simple MAC protocol design, several others can be implemented by exploiting primitive built-in functionalities such as timer operations, idle listening, and retransmission.

Network Layer

The proposed SDAM prototype can support IPv4 and IPv6 protocols through an adaptation layer [14]. The adaptation layer offers a set of functionalities, i.e., IP header compression, IP packet fragmentation that enable the interfacing of the traditional IP network layer with the MAC layer of the prototype. Specifically, the traditional IPv4 and IPv6 headers are optimized for underwater acoustic communications to minimize the network delay and energy consumption.

Software Developments

We use an open source software framework called GNU Radio to drive adaptive baseband signal processing. GNU Radio offers a plethora of digi-

GNU Radio offers a plethora of digital signal processing blocks which are implemented in C++, and are usually wrapped into Python classes. Blocks are either instantiated by Python scripts, or used as building primitives of a communication flowgraph.

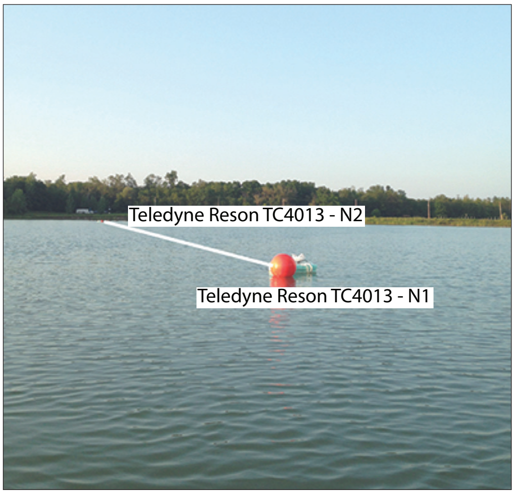

Figure 3. Underwater transducers are held by the red buoys and are deployed 322 ft apart.

tal signal processing blocks that are implemented in C++, and are usually wrapped into Python classes. Blocks are either instantiated by Python scripts or used as building primitives of a communication flowgraph. GNU Radio provides users with the ability to design custom-logic signal processing blocks, simulate them offline, and finally embed them into existing flowgraph designs. In this context, we design and implement custom signal processing blocks and build ZP-OFDM and DS-SS flowgraphs, while at the same time exploit the message passing capabilities of GNU Radio to support adaptive transmitter and receiver physical layer functionalities. Message passing allows the exchange of control messages between different blocks that are located either downstream or upstream in the GNU Radio flowgraph. Therefore, we achieve real-time adaptation by leveraging both GNU Radio's asynchronous messaging features and the properties of a chirp-based feedback link. Decoding of the feedback messages relies on two correlation filters equipped with an up chirp and a down chirp, respectively. We decide on the feedback message bits by comparing the outputs of the respective correlation filters at the receiver, and we update the PHY layer parameters in the forward link flowgraph accordingly. For the needs of communication technology adaptation between ZP-OFDM and DS-SS, we also implement a software multiplexer block.

Experiments

In this section, we present experimental results from three different testbed scenarios and evaluate the proposed SDAM prototype in both indoor and outdoor environments.

Physical Layer Online Adaptation

A series of experiments took place in Lake LaSalle at the State University of New York at Buffalo. Lake LaSalle has a depth of approximately 7 ft. We deployed two SDAM prototypes 322 ft apart from each other as illustrated in Fig. 3. We used ZP-OFDM signals that occupy a bandwidth of $B = 24$ kHz at a carrier frequency $f_c = 100$ kHz. We defined $K = 1024$ subcarriers for each OFDM symbol, where each subcarrier is either mapped with BPSK or QPSK modulation and is either coded (rate 1/2 convolutional error correction codes) or not coded. We also incorporated a guard time of $T_g = 15$ ms between each OFDM symbol.

The objective of this set of experiments is to demonstrate the real-time adaptation capabilities of our SDAM prototype at the physical layer in an outdoor lake environment. Figure 4 depicts experimental data rate and BER evaluation results of both an adaptive modulation/coding rate and a fixed (non-adaptive) scheme for 21 OFDM packet transmissions. The modulation scheme and coding rate of ZP-OFDM change according to a user-defined decision algorithm that aims to maximize data rate under preset BER threshold constraints. In Fig. 4 the BER threshold is empirically set to 10^{-3}, while SINR varies between 10 and 20 dB.

In both adaptive and fixed (non-adaptive) schemes, the SDAM, N_1, starts transmitting at the highest possible data rate, which requires uncoded QPSK modulation. We observe that since the non-adaptive scheme does not provide the SDAM with modulation/coding adaptation capabilities, data rate will remain constant. However, at the time that the SINR profile changes (6th packet), the preset BER threshold is not satisfied. On the other hand, in the adaptive scheme, the SDAM adapts the modulation and coding rate in real time as soon as the SINR decreases. Specifically, when the estimated SINR is lower than 10 dB, the SDAM incorporates 1/2-rate error correction coding and changes the modulation scheme from QPSK to BPSK. As a result, the data rate is adjusted to a lower value to satisfy the predefined BER constraints. Subsequently, as soon as the SINR increases (from packet 11 to 17), the SDAM changes into uncoded BPSK transmission to compensate for the data rate loss. Finally, the SDAM switches back to uncoded QPSK when the SINR reaches the initial level of 20 dB.

Cognitive Channelization

The following set of experiments considers the deployment of three SDAMs in a water test tank. Figure 5 depicts three SDAM nodes, which operate in the same frequency band, 91–99 kHz, and use random binary waveforms of length $L = 63$. N_1, and N_2 act as transmitters, and N_3 as a receiver, while feedback messages regarding the best channel waveform are exchanged between N_1 and N_3. Both transmitters use square-root raised cosine pulses of duration $T_d = 0.16384$ ms, and roll-off factor $\alpha = 0.35$. The number of channel paths is set to $N = 20$ and we measured a multipath spread of 31 waveform bits or 5.1 ms. Both N_1 and N_2 use the same transmission power and are positioned 5.5 ft apart from N_3. The distance between N_1 and N_2 is set at 1.5 ft.

Figure 6 illustrates SINR experimental studies for two different setups. The first setup considers a single transmitter node, N_1, that operates in the absence of N_2. The second setup considers two nodes, N_1 and N_2, that transmit simultaneously at the same frequency band, while a third node, N_3, uses a control channel at a different frequency band to periodically com-

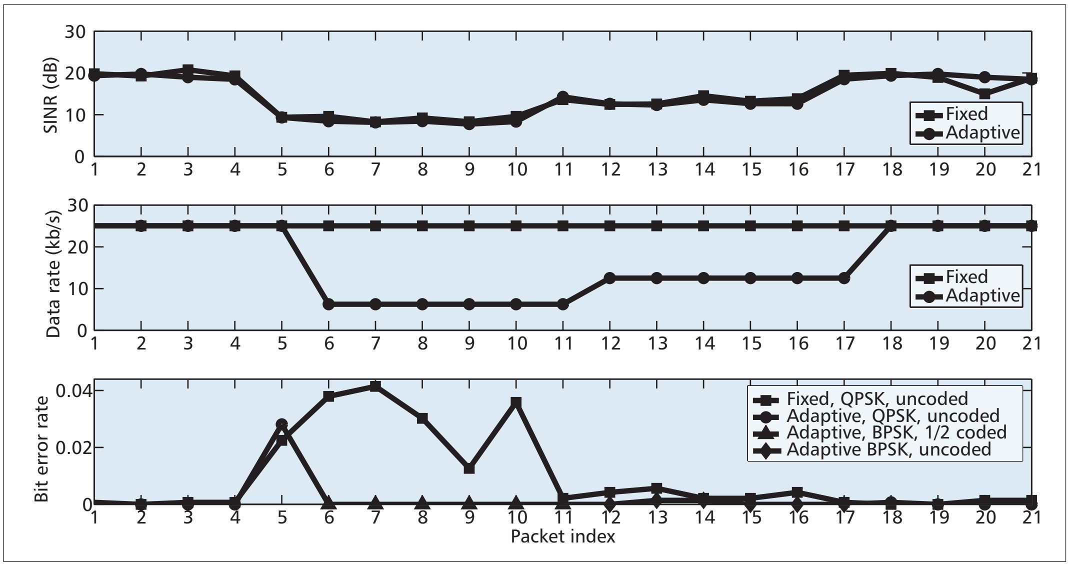

Figure 4. Comparison of adaptive with fixed (non-adaptive) scheme in terms of data rate, and BER for different SINR profiles.

Efforts towards reconfigurable underwater networks can certainly benefit from recent and parallel developments in the SDR literature. The adoption of SDR frameworks in underwater communications must carefully consider the challenges imposed both by the available technology and the underwater environment.

municate to N_1 a new channel waveform. For each setup we consider two different scenarios referred to as cognitive and fixed channelization, respectively. Cognitive channelization assumes that the transmitter node N_1 adapts its channel waveform based on the interference profile of N_2 and the additive noise. In the absence of N_2, waveform adaptation is based only on the noise profile. For the fixed channelization scenario, N_1 does not change the preset waveform. We observe that for both setups, cognitive channelization significantly outperforms fixed channelization in terms of receiver predetection SINR.

The experimental studies in this section show that underwater cognitive channelization is beneficial in both the presence and absence of interference from other signals/users due to the fact that the SDAM efficiently adapts to channel conditions [13].

Communication Technology Adaptation (Future Heterogeneous UW Networks)

Given the primitives of both ZP-OFDM and DS-SS, we also tested the capability of the proposed SDAM prototype to adapt/choose among different communication technologies. We designed an experimental scenario that aims at seamless switching between OFDM packet (BPSK modulation, no error correction coding, $K = 1024$ subcarriers in a bandwidth of 24 kHz) and DS-SS packet (BPSK modulation, no error correction coding, and waveform length $L = 31$ in a bandwidth of 6 kHz) transmissions at carrier frequency $f_c = 100$ kHz, and successfully demonstrated the dual mode capability of the prototype.

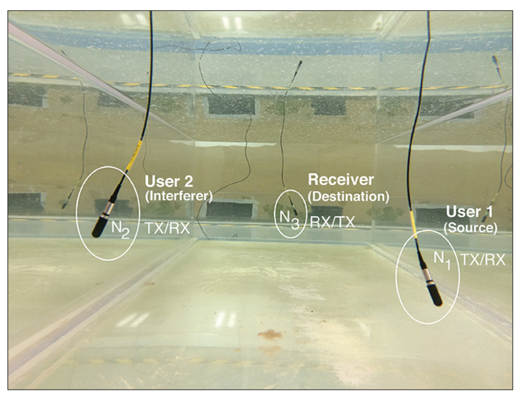

Figure 5. Cognitive channelization water test tank setup.

Software-Defined UANs: Open Research Challenges

Reconfigurability is an essential feature of next-generation underwater networks in early stages of study, especially in the context of real-time joint adaptation across all layers of the protocol stack. Efforts toward reconfigurable underwater networks can certainly benefit from recent and parallel developments in the SDR literature. The adoption of SDR frameworks in underwater communications must carefully consider the challenges imposed by both the available technology and the underwater environment. Below, we present an overview of the core challenges related to software-defined UAN implementations.

Hardware Challenges

Existing commercial or military SDR platforms provide broadband frequency support (DC — 6 GHz) with either fixed or configurable front-ends. However, the majority of the designs are optimized for RF terrestrial communications, and cannot address the challenges of the underwater environment (e.g., acoustic frequencies on the order of kilohertz). In addition, SDR front-ends that can be used directly for underwater communications utilizing the LFTX daughter-card on a USRP platform, which results in operating frequencies in the range of DC to 30 MHz,

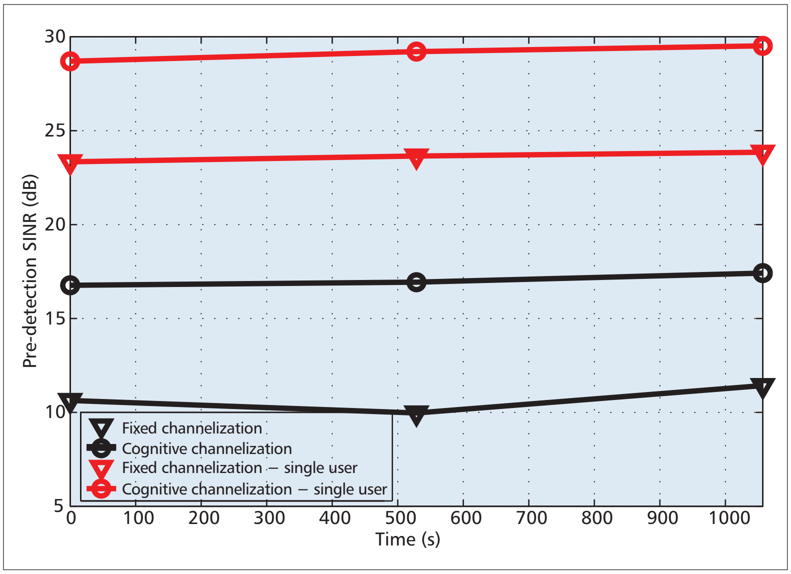

Figure 6. Cognitive channelization is compared to fixed channelization in terms of predetection SINR. The depicted SINR gains consider two different setups: a blind receiver configuration in a multi-user case and in a single-user (N_1–N_3) case.

do not include a power amplifier; thus, underwater communication is limited in terms of range/distance. Furthermore, commercial off-the-shelf (COTS) acoustic transducers are expensive, (their cost is tens of thousands of dollars) due to a proprietary and long process of characterization and analog circuitry optimization. COTS transducers also exhibit application-specific characteristics and low-volume production, and inherently have limited bandwidth capabilities. As a result, experimental prototyping requires careful review of the available COTS hardware components and specifications, and may also require the design of a custom circuit front-end.

Software Portability

One of the major design challenges of SDR or software-defined underwater systems is the development of platform-independent software. Effective proposals need to be able to demonstrate that pertinent software can easily be rebuilt for different SDR platforms with minimum effort/cost. Software interoperability is especially desirable in military systems where standardization is required for both the interconnection between application components, and between application components and system devices. To date, we do not have a complete structured (abstract) methodology/architecture available to implement reconfigurations across all layers of the protocol stack. Such an architecture could benefit future underwater communications by supporting, for example, cognitive functionalities that may lead to high efficiency in spectrum utilization. For instance, software components for static underwater waveform processing could be real-time swapped with cognitive components for adaptive processing to mitigate adverse external conditions (e.g., noise and multiple-access interference).

Computational Capacity

Future wideband high-bit-rate underwater communications require significant computational resources. It is well understood that data rate capabilities are coupled with the front-end design of the software-defined underwater network nodes (e.g., acoustic transducers and power amplifiers) and may vary according to the external environment as well as the role of the underwater software-defined unit in the network (e.g., surface station, AUV, etc.), which poses different weight, cost, and power consumption constraints. Similar to wired computer networks, software-defined underwater acoustic networks may benefit from a separation between data processing and control functionalities. As a result, future software-defined modem architectures could be able, for example, to distribute data processing between hardware and software and exploit parallelism for computation-intensive data processing components (e.g., finite impulse response filters, fast Fourier transform modules).

Energy Efficiency

Energy consumption of submerged units is a significant design challenge for future reconfigurable underwater modems. It is evident that algorithmic implementation on architectures based on application-specific integrated circuits (ASICs) or DSP-on-chip trade reconfigurability for computational and power efficiency. Recently, a new class of technologies such as programmable logic and IP (FPGAs), in-line vector instructions (ARM NEON), and vector execution units (modern GPUs) are breaking the boundaries of device functionalities and aim at creating a multicore blend of functions, as seen, for example, in several new products including TI KeyStone, Xilinx Zynq, and NVIDIA Tegra K1. Multicore architectures require software abstractions to control reconfiguration of tailored functional units or general processing components. For example, the work in [15] implements matching pursuit algorithms for underwater channel estimation in FPGAs (reconfigurable hardware platforms) and provides 210× and 52× reduction in energy consumption over the microcontroller and DSP implementations, respectively.

Real-Time Reconfigurable Processing

While considerable research work for the next-generation processors aim at increasing cycle clocks, mutli-core architecture proposals (i.e., single-instruction multiple-data and multiple-instruction multiple-data) allow a higher average number of instructions to be processed per clock cycle, and offer high performance and reconfiguration by exploiting parallelism. However, even though multi-core DSPs offer optimized features for digital signal processing, we still need to study the trade-off between high performance and low power consumption in software-defined underwater acoustic networks. More specifically, reconfiguration timing constraints can be significantly relaxed due to larger channel coherence times in underwater communication (on the order of seconds) compared to wireless LAN communications (on the order of milliseconds). Relaxed timing constraints imply low power consumption, which is beneficial to battery operated underwater deployments.

CONCLUSIONS

We have discussed SDR technology principles for UANs that need reconfigurable and intelligent network devices. Accordingly, we have proposed an SDAM prototype, based on COTS components, and have experimentally evaluated the proposed prototype in both indoor (water test tank) and outdoor (lake) environments. Then we have demonstrated, under three experimental scenarios, the real-time reconfigurable capabilities of the proposed SDAM prototype and highlighted its favorable characteristics toward spectrally efficient cognitive underwater networks and high data rate underwater acoustic links. Finally, we have reviewed open research implementation challenges for future next-generation software-defined UANs and presented an overview of existing SDR-based architectures for UW-A communications.

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REFERENCES

[1] B. Tomasi, "JANUS: The Genesis, Propagation and Use of an Underwater Standard," *Euro. Conf. Underwater Acoustics*, Istanbul, Turkey, July 2010.

[2] R. Petroccia and D. Spaccini, "Comparing the Sunset and Desert Frameworks for In Field Experiments in Underwater Acoustic Networks," *OCEANS — Bergen, 2013 MTS/IEEE*, June 2013, pp. 1–10.

[3] C. Petrioli *et al.*, "The Sunrise Gate: Accessing the Sunrise Federation of Facilities to Test Solutions for the Internet of Underwater Things," *Underwater Commun. and Networking 2014*, Sept. 2014, pp. 1–4.

[4] J.-H. Cui *et al.*, "Ocean-TUNE: A Community Ocean Testbed for Underwater Wireless Networks," *ACM Int'l. Conf. Underwater Networks and Systems*, Los Angeles, CA, Nov. 2012, pp. 1–2.

[5] Z. Peng *et al.*, "Aqua-net: An Underwater Sensor Network Architecture: Design, Implementation, and Initial Testing," *OCEANS 2009, MTS/IEEE Biloxi — Marine Technology for Our Future: Global and Local Challenges*, Oct. 2009, pp. 1–8.

[6] M. Chitre, R. Bhatnagar, and W.-S. Soh, "Unetstack: An Agent-Based Software Stack and Simulator for Underwater Networks," *Oceans — St. John's 2014*, Sept 2014, pp. 1–10.

[7] J. Potter *et al.*, "Software Defined Open Architecture Modem Development at CMRE," *Underwater Commun. and Networking 2014*, Sept 2014, pp. 1–4.

[8] D. Torres *et al.*, "Software-Defined Underwater Acoustic Networking Platform," *Proc. 4th ACM Int'l. Wksp. UnderWater Networks*, ser. WUWNet '09, Nov 2009, pp. 7:1–7:8.

[9] E. M. Sözer and M. Stojanovic, "Reconfigurable Acoustic Modem for Underwater Sensor Networks," *Proc. 1st ACM Int'l. Wksp. Underwater Networks*, ser. WUWNet '06, Sept 2006, pp. 101–04.

[10] N. Nowsheen, C. Benson, and M. Frater, "A High Data-Rate, Software-Defined Underwater Acoustic Modem," *OCEANS 2010*, Sept 2010, pp. 1–5.

[11] M. Chitre, I. Topor, and T. Koay, "The UNET-2 Modem — An Extensible Tool for Underwater Networking Research," *OCEANS, 2012 — Yeosu*, May 2012, pp. 1–7.

[12] E. Demirors *et al.*, "Design of a Software-Defined Underwater Acoustic Modem with Real-Time Physical Layer Adaptation Capabilities," *Proc. Int'l. Conf. Underwater Networks & Systems*, ser. WUWNET '14, 2014, pp. 25:1–25:8.

[13] G. Sklivanitis *et al.*, "Receiver Configuration and Testbed Development for Underwater Cognitive Channelization," *2014 48th Asilomar Conf. Signals, Systems and Computers*, Nov 2014, pp. 1594–98.

[14] Y. Sun and T. Melodia, "The Internet Underwater: An IP-Compatible Protocol Stack for Commercial Undersea Modems," *Proc. 8th ACM Int'l. Conf. Underwater Networks and Systems*, ser. WUWNet '13, 2013, pp. 37:1–37:8.

[15] B. Benson *et al.*, "Energy Benefits of Reconfigurable Hardware for Use in Underwater Snesor Nets," *IEEE Int'l. Symp. Parallel Distrib. Processing 2009,* May 2009, pp. 1–7.

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Reconfiguration timing constraints can be significantly relaxed due to larger channel coherence times in underwater communication (on the order of seconds) compared to wireless LAN communications (on the order of milliseconds). Relaxed timing constraints imply low power consumption, which is beneficial to battery operated underwater deployments.