The SEANet Project: Toward a Programmable Internet of Underwater Things

Emrecan Demiros, Jiacheng Shi, Anh Duong, Neil Dave, Raffaele Guida,
Bernard Herrera, Flavius Pop, Guofeng Chen, Cristian Cassella, Sayedamirhossein Tadayon,
Matteo Rinaldi, Stefano Basagni, Milica Stojanovic, Tommaso Melodia
Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115

***Abstract*—Wirelessly networked systems of underwater devices are becoming the basis of many commercial, scientific, and military applications. In spite of increased attention in the last few years, underwater wireless networking technology still suffers from major limitations, including severe hardware dependence. In this paper, we introduce the SEANet Project, an NSF-funded effort that aims at developing a new generation of programmable platforms and a networking testbed to enable the vision of a programmable Internet of Underwater Things (IoUT). SEANet will be based on new software-defined platforms based on an open architecture to enable the flexibility to define, add, update, and swap new components in both hardware and software. SEANet is designed to support data rates at least one order of magnitude higher than existing commercial platforms over short and moderate range links. Moreover, the SEANet project will explore the design of new custom-designed ultra-wide band Microelectromechanical systems (MEMS) transducers that allow operating over much wider acoustic bandwidth (i.e., $0.01-2\mathrm{MHz}$) than possible with bulk piezoelectric transducers. We present a set of preliminary experiments showing that SEANet can outperform existing software-defined radio SDR-based acoustic modems based on a commercial off-the-shelf (COTS) SDR platforms. We also demonstrate the real-time reconfiguration capability of SEANet and preliminary performance of the MEMS transducers.**

I. Introduction

Wirelessly networked systems of underwater devices are becoming the basis of many commercial, scientific, and military activities at sea, including (i) climate change monitoring, pollution control and tracking; (ii) providing sophisticated control systems for the oil and gas industry; (iii) reducing the seafood trade deficit through data-driven aquaculture; (iv) disaster prevention through underwater equipment monitoring or Tsunami warning systems; (v) tactical surveillance; (vi) ocean exploration [1], [2].

In spite of increased attention in the last few years, underwater networking technology still suffers from major limitations. Today, most existing commercial modems are designed primarily to establish low data rate connectivity over long ranges (i.e., on the order of at least $1\ \mathrm{km}$ with lower than $35\ \mathrm{kbit/s}$) by leveraging low frequencies (less than $30\ \mathrm{kHz}$) [3]–[6]. However, when transmitting over short or moderate range links, it would be desirable to use wider bandwidths in the ultrasonic regime (e.g., $0.1-2\ \mathrm{MHz}$) and communicate at higher data rates. While there has been work aimed at providing high data rates [7]–[9], regrettably, no existing modems provide the flexibility to trade link distance for data rate.

Proprietary Architectures. In existing commercial modems, the physical layer, including all signal processing and waveform generation and decoding functionalities, is implemented in hardware and is proprietary. Higher layers are often not even defined. This limits the ability to experiment with new transmission schemes, waveforms, networking protocols, and distributed data processing applications.

Narrowband and Bulky Transducers. Most existing modems are dependent on bulk piezoelectric transducer that can typically operate over fixed, narrow frequency bands (i.e., at most a few tens of kHz). As a consequence, the modems cannot implement dynamic spectrum access allocation schemes to adaptively transmit on different frequency channels.

Limited Support for Networked Operations. Most commercial modems offer support for rudimentary networking functionalities. As a consequence, they lack (i) an architectural framework encompassing control at all layers, (ii) integration with the waveform generation functionalities, and (iii) integration with standard Internet.

The SEANet project has been funded by the US National Science foundation to develop an open platform for flexible experimentation with underwater networked systems. SEANet will provide a testbed (i.e., a network composed of multiple platforms) to enable development, prototyping, and testing of next-generation networking schemes, as well as networked monitoring applications with fixed and mobile underwater devices. SEANet aims at developing a 50-node networking testbed with the vision of a programmable IoUT in which IoUT platforms are deployed in the underwater environment (e.g., ocean, sea, lake) equipped with different sets of sensors; integrated into submerged mobile nodes (e.g., Unmanned Underwater Vehicles (UUV), divers, submarines); and consolidated with surface nodes (e.g., buoys, ships, Autonomous Surface Vehicles (ASVs). SEANet platforms are connected through acoustic links underwater, while surface nodes can act as gateways between underwater and terrestrial networks. SEANet will be based on a new software-defined IoUT platform called SEANet IoUT, which adopts some of the design and architectural concepts of the SEANet G2 networking platform [10]. The proposed networking testbed and networking platform will separate themselves from the existing solutions [11]–[17] as follows.

Open Architecture. SEANet IoUT is based on an open architecture enabling flexibility to define, add, update, and swap components in terms of both hardware and software.

Programmable Software Architecture. SEANet IoUT has a fully programmable software architecture, which enables the capability to (i) add/update functionalities at all layers of the protocol stack; (ii) operate at every layer of the protocol stack with an option to hide the implementation details of each layer; (iii) implement cross-layer control strategies through a structured architecture; (iv) reprogram physical layer functionalities (i.e., modulation, coding, power, as well as switching between different physical layer schemes altogether) running on a programmable logic in real time; and (v) natively

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support Internet-based applications and network monitoring tools through a Linux operating system.

Hardware Reconfiguration - Swappable Front-ends. The SEANet IoUT modular hardware design is based on standard interfaces that enable hardware reconfiguration through swappable/upgradeable hardware modules. Specifically, SEANet IoUT supports seamless integration with different transducers and operationally over different spectrum bands through swappable front-ends.

Megabit/s Data Rates. SEANet IoUT is designed to support high data rates over short and moderate range links using acoustic waves. While there are few promising approaches using alternative technologies such as radio-frequency or optical signals to achieve high data rates [18]–[23], they can either only achieve a few meters of range, or they require specific channel conditions (dark and clear waters) limiting their operationally [24]. Data rates of $522\,\mathrm{kbit/s}$ over short links (e.g. $10\,\mathrm{m}$) and data rates in the order of $1\,\mathrm{Megabit/s}$ on a controlled lab environment have already been demonstrated with previous generation platforms using bulk piezoelectric transducers [10]. In light of these developments, Megabit/s data rates are foreseen over short-range links (e.g., $50-100\,\mathrm{m}$ in the $0.01-2$ MHz acoustic spectrum) with pMUT based ultra-wide band acoustic front ends.

Ultra-Wide Band Acoustic Front Ends. The project will seek to endow the SEANet IoUT platform with acoustic front ends based on newly designed, ultra-wide band (i.e., $0.01-2$ MHz), *piezoelectric micromachined transducers* (pMUT) based on Aluminum Nitride (AlN) Microelectromechanical systems (MEMS) technology. The pMUT technology allows the development of compact arrays of multiple miniaturized transmit/receive transducer elements, supporting at affordable costs notions such as spatial directivity, beamforming, and massive MIMO in an underwater networked communication system, all integrated in a board compatible with standard CMOS technology.

The rest of the paper is organized as follows. In Section 2, we briefly introduce the general architecture of the SEANet IoUT, while in Section 3 we concentrate on the implementation of the proposed SEANet IoUT. In Section 4, we present the experimental evaluation of the SEANet IoUT prototype. Finally, in Section 5 we draw conclusions.

II. SEANet IoUT Architecture

SEANet IoUT is based on a modular hardware and software architecture enabling (i) hardware and software upgrading/reconfiguration; (ii) cross-layer controllable protocol stack; (iii) rapid prototyping of novel protocol designs and enhancements. In this section, we discuss the hardware and software architecture of the SEANet IoUT platform.

A. Hardware Architecture

SEANet IoUT is based on six basic modules, i.e., main, converter, communication, power, sensor, and RF. Each module has distinct and non-overlapping functionalities, as illustrated in Fig. 1(a). Each module can be interfaced with others through standard interfaces to enable a swappable/upgradable design.

The main module includes programmable hardware logic (PL) and a processing system (PS) taking on different functionalities to achieve hardware and software reprogrammability. Specifically, the programmable logic is responsible for executing processing-intensive physical layer and time-critical MAC functionalities, while the processing system implements software-defined high-level networking protocol functionalities. The converter module incorporates an analog-to-digital converter (ADC) and a digital-to-analog converter (DAC) to provide an interface between the analog and digital domains. The communication module includes a power amplifier (PA) and a low-noise amplifier to amplify analog signals on the transmit and receive side. The communication module incorporates matching circuits for both transmitter and receiver chains to minimize signal reflections caused by impedance mismatches and a switch to enable the use of a single acoustic transducer for both transmitting and receiving acoustic signals in a time-division duplexing fashion. The power module houses a wireless energy transfer unit interfaced with energy harvesting transducers enabling acoustic wireless charging of the central battery unit. The sensor module provides standard interfaces to support multiple sensors simultaneously. The RF module is an optional module designed to support different RF communication technologies (e.g., LTE, Wi-Fi, ZigBEE, Iridium) through standard interfaces.

B. Software Architecture

The software architecture, as illustrated in Fig. 1(b), is built on a Linux operating system running on a System-on-Chip (SoC). The software architecture splits the layers of the protocol stack between the processing system and the programmable logic. Processing-intensive physical layer and time-critical MAC functionalities are assigned to the programmable logic while the rest of the MAC, network, transport, and application layer functionalities are allocated to the processing system.

III. SEANet IoUT Prototype

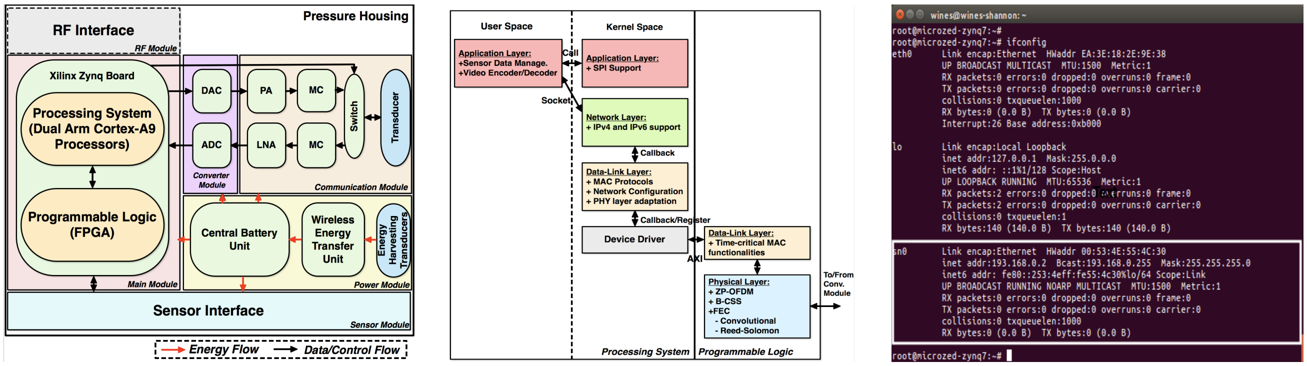
In this section, we report on the latest developments on the SEANet IoUT prototype in terms of hardware and software implementations.

A. Hardware Implementation

The current hardware implementation of the SEANet IoUT prototype is built around a main module incorporating a Microzed development board. Specifically, the Microzed includes a Zynq Z-7020 SoC integrating a dual-core ARM Cortex-A9 based PS and a $28\,\mathrm{nm}$ Xilinx PL on a single chip. The converter module includes an LTC 1740CG ADC, operating on $14-$ bit parallel outputs with $6\,\mathrm{Msample/s}$, and a LTC 1668 DAC, operating on $12-$bit parallel inputs with $50\,\mathrm{Msample/s}$. The current communication module houses a Mini-Circuits ZHL-6A-S+ PA, offering a gain up to $25\mathrm{dB}$, and a AD8338 LNA can operate from $10\mathrm{kHz}$ to $18\mathrm{MHz}$ with a voltage controlled gain up to $80\mathrm{dB}$. Additionally, communication module incorporates a Mini-Circuits $\mathrm{ZX80-DR230+}$ electronic switch. All three modules are connected to each other with standard micro-header connections incorporating GPIO pins to enable swappable and upgradable design.

The current prototype includes two types of transducers. The first is a COTS transducer, Teledyne RESON $\mathrm{TC4013}$, offering an operational frequency range from $1\,\mathrm{Hz}$ to $170\,\mathrm{kHz}$, while the second one is a MEMS transducer.

MEMS Transducers. The current prototype relies on custom MUTs based on AlN ultra-thin piezoelectric film piezoelectric membranes (pMUTs) to overcome the limitations of piezoelectric transducers in terms of size and bandwidth. In addition to that, the post-CMOS compatibility of the microfabrication process used for the fabrication of AlN MEMS devices enables their monolithic integration with low power CMOS electronics, which is an attractive feature for the implementation of high performance, low power and low cost platforms. Currently, the prototype includes a 20×20 pMUT array that



(a) SEANet IoUT hardware architecture.

(b) SEANet IoUT software architecture.

(c) The SEANet IoUT can be used as a standard network interface ("sn0").

Fig. 1. SEANet IoUT architecture.

is initially characterized to have a resonance frequency at 700kHz with a relatively flat bandwidth of 500kHz.

The power module also houses a wireless energy transfer unit that uses acoustic waves to harvest energy and accordingly recharge its battery unit. The details and preliminary experiments are reported in [10].

B. Software Implementation

The current prototypes' software implementation is based on the software architecture depicted in Fig. 1(b). It can be described in terms of PL and PS developments.

Programmable Logic Design. The current prototype implements two different PL designs. The first design includes a zero-padded (ZP)-OFDM transceiver, registers, and AXI interfaces. The details of the ZP-OFDM implementation can be found in [10]. The prototype also implements a "base" design that incorporates a FIFO and a mixer for both transmitter and receiver chains. This design allows device driver to transmit/receive baseband samples to/from the PL directly and accordingly enables to test completely custom waveforms (physical layer) designs from the user space. In both designs, registers that can be accessed from the PS through the AXI4-Lite interface, are used for storing and reconfiguring physical layer parameters in real time. Table I reports the FPGA resource utilization for the two PL designs. Specifically, the "base" PL design uses approximately 4% of the resources, while the ZP-OFDM transceiver design uses up to 82%.

TABLE I
RESOURCE OCCUPATION OF THE PL FOR DIFFERENT DESIGNS.

PL Design	LUTs	LUT %	FFs	FF %	BRAMs	BRAM %	DSPs	DSP %
Base	2194	4.124	3102	2.916	1	1.428	2	1.818
ZP-OFDM	43842	82.410	46078	43.306	87	62.143	152	69.091

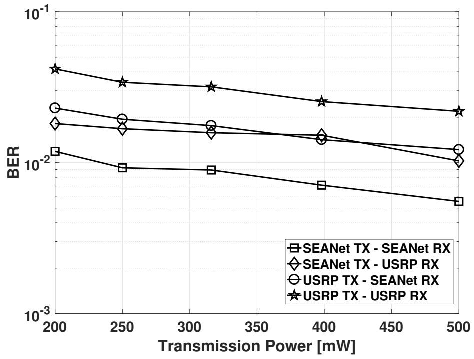
Processing System Design. The processing system of the current SEANet IoUT prototype is running on a "zynq-microzed7 kernel v4.9" Linux distribution which natively supports all Linux compatible applications (e.g., Internet-based applications, network monitoring tools, video encoder/decoder) and leverages transport layer tools (i.e., UDP and TCP sockets). It also offers seamless support to all standard interfaces (i.e., Ethernet, USB, UART, CAN, EBI/EMI, IC, MMC/SD/SDIO, SPI, and GPIO), thus easing the process of integrating external sensor modules. The current prototype implements the device driver enabling (i) data transfer between user space applications and the FPGA PHY layer; (ii) real-time physical layer reconfigurations through FPGA registers; (iii) the realization of a cross-layer controllable protocol-stack.

Device Driver. The device driver is developed to support operations at every layer of the protocols stack with an option to hide the implementation details of each layer. Specifically, it provides three different operation modes, namely *user*, *network* and *debug* mode.

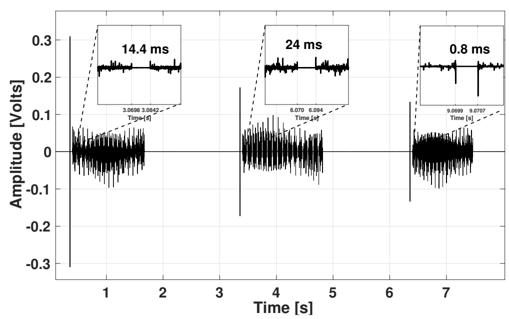
In the *user* mode, the device driver makes the SEANet IoUT's protocol stack appears as a standard network interface which is illustrated in Fig. 1(c) as"sn0". In this way, the SEANet IoUT protocol stack can be leveraged by the standard user space applications through TCP/UDP sockets, while hiding all the protocol implementation details, similar to a standard network interface card. Since the SEANet IoUT protocol stack is based on a the standard IP layer architecture, the SEANet IoUT platform can easily adopt next-generation software-defined networking (SDN) tools [25]. While the user mode of the device driver is primarily designed for SEANet IoUT to run applications and implement routing protocols from the user space, it still allows real-time reconfiguration to be performed at the underlying protocol stack. Specifically, a protocol reconfiguration program running in the user space can dictate reconfigurations at the MAC layer running in the kernel space and physical layer running on the PL through the AXI4-Lite interface and registers. This reconfiguration mechanism allows implementing fully cross-layer controllable protocol stacks.

In the *network* mode, the device driver enables direct access to the physical layer running on the PL from the user space through the AXI-Stream interface. This means that the driver can feed/receive data directly to/from the physical layer from the user space by-passing the underlying data-link layer protocol of SEANet IoUT. In this way, the driver enables the capability of testing solely physical layer performance and developing/adopting custom data-link and network layer protocols implemented in the user space. Similar to the user mode, the network mode also supports reconfiguration at the physical layer through the AXI4-Lite interfaces.

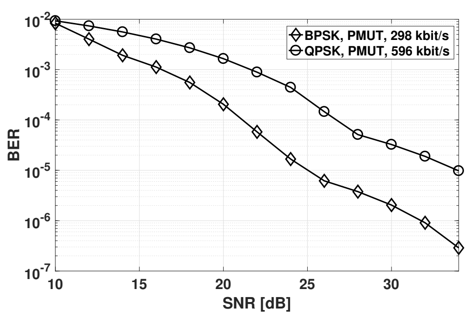
In the *debug* mode, the device driver also enables direct access to the PL via the AXI-Stream interface. However, this time in accordance with the underlying "base" PL design, the device driver allows baseband samples to be fed/received into/from the PL directly to test custom waveform (physical layer) designs from the user space. Specifically, the current version of the device driver provides interfacing support for GNU Radio [26], an open-source software that offers a plethora of C++ digital signal processing blocks, through a custom driver block and Matlab through a FIFO [27]. In summary, the SEANet IoUT can operate as a typical



(a) BER versus transmission power for different pairs of platform.



(b) Recorded output signal (in electrical domain) of the SEANet IoUT.



(c) BER versus SNR for different modulation schemes (BPSK and QPSK)

Fig. 2. Experimental results.

SDR platform that enables rapid prototyping, fully agile and adaptive design for underwater communications and networks [28].

IV. Performance Evaluation

In this section, we report on the results obtained from three sets of experiments focusing on assessing the different characteristics and aspects of the SEANet IoUT prototype.

BER vs Transmission Power. We compared the bit-error-rate (BER) performance of the SEANet IoUT prototype against a software-defined underwater acoustic platform designed based on a COTS SDR platform, USRP N210 [27]–[30]. Both platforms are tested using the exact same setup leveraging a ZP-OFDM communication scheme, as defined in [10], [17], occupying a bandwidth of 125 kHz at the center frequency of $125\,\mathrm{kHz}$. Specifically, both platforms are interfaced with the same Teledyne RESON $\mathrm{TC}4013$, which are deployed in a water test tank, approximately a meter apart from each other. Moreover, both platforms are leveraging the PAs and LNAs, as defined in Section. III-A, with same gain configurations. In order to assess the transmitting and receiving performance of each platform separately, we used different pairs of transmitter and receivers in the experiments. Figure 2(a) shows that SEANet IoUT outperforms the USRP-based platform both in terms of transmitter and receiver performance. Particularly, when SEANet IoUTs are used both for transmitting and receiving operations, at least 4 times improvement in BER performance at all transmission power levels is recorded. The main factor behind the observed performance improvement is that the SEANet IoUT incorporates bandwidth and frequency optimized converters and converter interfaces, unlike the USRP-based platform. Because of this, the SEANet IoUT prototype minimizes the out-of-band noise and interference and accordingly outperforms the USRP-based platform in terms of BER performance.

Real-time Reconfiguration. We showcased the real-time reconfiguration capability of the SEANet IoUT by reconfiguring the guard interval time between the ZP-OFDM symbols on a per-packet basis, as illustrated in Fig. 2(b). The varying guard interval times for each packet can clearly be observed from the windows zooming between the symbols. The configuration is controlled from the PS through high-level software in real time, thanks to the device driver. This feature is specifically important, because in this way SEANet IoUT is able to define processing-intensive and time-critical functionalities (i.e., physical layer and time-critical MAC layer functionalities) in software while executing them in hardware. Consequently, unlike solely software-defined implementations that have high processing latency [17], [28] with limited data rate support; or solely hardware-defined implementations that have inadequate reconfiguration capabilities, SEANet IoUT offers low-latency processing and accordingly high-data-rate support as well as the real-time reconfiguration capabilities.

MEMS Transducer Evaluation. We evaluated the performance of the pMUTs with a set of preliminary experiments. In the experiments, due to the lack of waterproof covering for the pMUTs, we used a $10\,\mathrm{cm}$ tissue phantom to mimic an underwater channel, which is known to have similar characteristic [31], [32]. Specifically, we used a ZP-OFDM scheme with a bandwidth of $B = 500\,\mathrm{kHz}$ at a center frequency of $600\,\mathrm{kHz}$. Figure 2(c) shows the BER performance of pMUTs and PZTs versus signal-to-noise-ratio (SNR) for different modulation schemes (i.e. BPSK and QPSK). We were able to reach a data rate of $596\,\mathrm{kbit/s}$ with a BER of 10^{-5}. These results demonstrate that pMUTs can offer large bandwidth and accordingly high rates owing to their flat frequency response even in the non-resonating region.

V. Conclusions

In this paper, we introduced the Project SEANet. The objective of the project is to to develop a new generation of programmable platforms called SEANet IoUT and a networking testbed to enable the vision of a programmable IoUT.

To that end, we first described the architecture and implementation details of a SEANet IoUT platform prototype. Later, we presented a set of experiments where we demonstrated (i) SEANet IoUT can outperform an existing SDR-based acoustic modem in terms of BER performance operating in the same setup and configurations; (ii) real-time reconfiguration capability of the SEANet IoUT; (iii) preliminary performance of the MEMS transducers.

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