High-frequency, highly directional short-range underwater acoustic communications

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***Abstract*— The underwater acoustic channel is a challenging environment for achieving high data rate communications due to multipath, attenuation, noise and propagation delay. Performing and maintaining adaptive channel equalization requires significant computational overhead, leading to costly and power-hungry devices. Here we describe a high-frequency acoustic modem design intended to mitigate the equalization requirement through highly directional, high frequency transmissions centered at 750 kHz. The high frequency additionally confers a data rate of up to 125 kbps between modems spaced on the order of meters apart. The modems are designed to record ambient noise before re-transmitting the recorded data in an encoded manner using high frequency transmissions through a separate, directional transducer. Such modems could be used to facilitate a cable-less benthic hydrophone array made from on-the-fly replaceable nodes. In order to determine inter-element spacing and to perform beamforming on the recorded data between modems, a synchronized yet independent Symmetricom® chip-scale atomic clock (CSAC, model SA.45s) was incorporated into a custom signal conditioning and timing board inside each modem. Lab-based experimental results show the feasibility of high-frequency acoustic communication (ACOMMS) between these modems.**

Keywords*— Underwater communication, directional communication, transducer design, beamforming, de-minimus acoustic communication

I. Introduction

The wireless transfer of data underwater poses a difficult challenge. Radio transmissions attenuate rapidly unless extremely low frequencies are used. Optical transmissions – while capable of extremely high data rates – rely upon a transparent or semitransparent medium and thus cannot be used over long ranges and/or in murky water. In addition to attenuation and noise, ACOMMS methods are complicated by highly reverberant environments that cause multiple arrivals from a single transmission, necessitating continuous equalization [1][2]. When a number of underwater acoustic sensors are required to simultaneously record in a time-synchronized manner (i.e., a hydrophone array), the individual hydrophones are usually connected via a physical cable that provides both power and a conduit for data transfer to a central data acquisition device. Typically, the hydrophones are separated by a distance equal to half the wavelength of the desired listening frequency, so rarely beyond the attenuation limits of high-frequency acoustic transmissions. As there are logistical advantages to deploying a wireless array, there is interest in the exploitation of high-frequency, close-range acoustic communications for this purpose [3] and more general close-range scenarios in which ACOMMS is preferable [4][5][6][7].

This article presents a modem design that acts as one element of a wireless hydrophone arrray system, that uses a high-frequency directional transducer to transmit low-frequency recording data between elements [8]. This work demonstrates the feasibility of the directional communications system with experimental results obtained from laboratory tank testing. A description of the device is provided in Section II. Section III introduces the experimental layout. Section IV displays experimental results showing the efficacy of the high-frequency communications aspect of the system. A discussion follows the results in Section V, and Section VI details the plans for an at-sea networking and array processing experiment scheduled to occur before the IEEE OCEANS'15 conference at which this paper will be presented.

II. Reconfigurable Acoustic Modem Platform (RAMP)

The RAMP system is built of nodes designed to form a distributed network. Each node consists of a lithium-ion battery pack, voltage regulator and battery control module, a National Instruments compactRIO™ 9025 controller with a field programmable gate array (FPGA) backboard (NI 9113), a custom-built circuit board and an amplifier contained in an Aluminum PREVCO® housing. The Symmetricom® CSAC was mounted on the custom board and served to both produce a timing signal and also the high-frequency multiplier. A 10 MHz square wave from the CSAC was divided until a 750 kHz square wave was obtained. A 750 kHz sine wave, used as the center frequency multiplier for a binary phase-shift-key signal, was created by passing the square wave through a high-Q filter (Q factor of 10, ± 39 kHz). A broad-band hydrophone and a directional high-frequency transducer were connected to the internal circuitry through watertight connectors. A schematic diagram of the internal arrangement of these components is shown in Fig. 1.

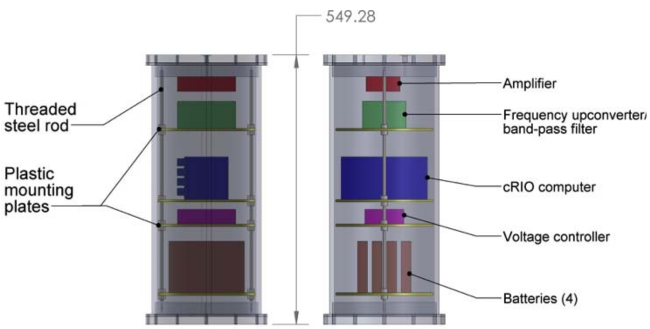

Figure 1. A schematic of the node showing the internal structure and layout of electrical hardware. Dimensions are in mm.

III. Experimental Setup

A. *Physical arrangement*

Three RAMP nodes were positioned in an equilateral triangle arrangement of side length 2 m in an indoor fresh-water tank of 6 by 6 m width and 4 m depth, largely isolated from external sound sources (Fig. 2). Transducer and hydrophone pairs were positioned at the same depth, in plane with the transducers and hydrophones connected to the other nodes. Care was taken to position the pairs as far from the tank walls as possible, so as to maximize the time window between the beginning of the direct arrival and the beginning of the first wall reflection. All recordings discussed in this paper consist only of short-duration, direct arrivals. In order to update software and quickly download recorded data, the nodes were connected to a network switch through waterproof network cables. A personal computer running LABVIEW® 2013 controlled LABVIEW® real-time software running on each compactRIO™.

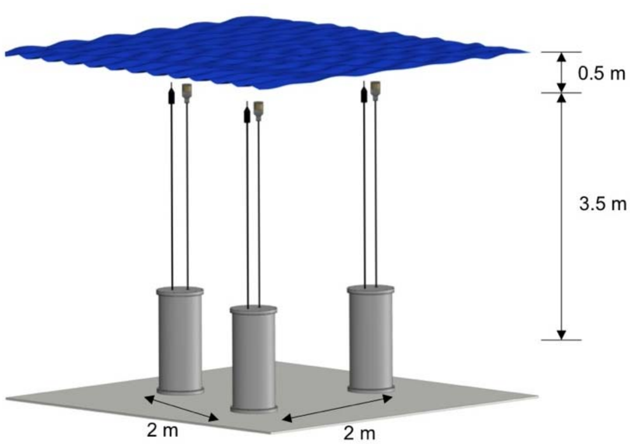

Figure 2. Experimental setup showing node and hydrophone/transducer positions inside the test tank.

B. *Data Flow and communications architecture*

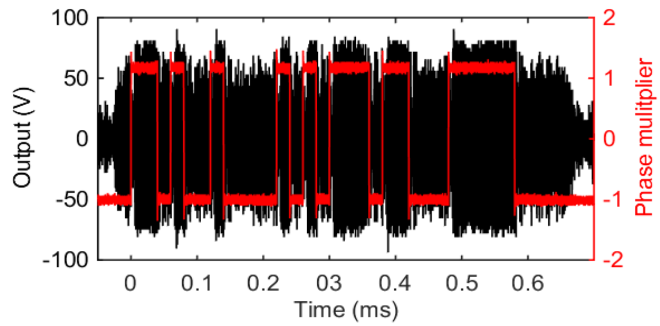

Figure 3. Example output of a 31-point m-sequence from the compactRIO™ (red) and after multiplication with the 750 kHz carrier wave and amplification (black). A slight amplitude shift key effect is evident as the phase multiplier was not exactly ±1.

Binary transmission packets were converted to a binary phase multiplier and sent from the compactRIO™ controller via a digital output module (NI 9402). The packets were multiplied by the 750 kHz sine wave and passed through a 46 dB amplifier before transmission via an axisymmetric directional hydrophone designed for peak resonance at 750 kHz [8]. Fig. 3 shows a representative phase multiplier and resultant binary phase-shift-key (BPSK) signal transmitted from a node. A low-Q band-pass filter cascaded the output of the mixer for which the filter bandwidth was 100 kHz, with a roll-off of approximately 20 dB per decade. Transmissions were made at 50, 62.5, and 100 kbps and were within this practical limitation. Transmissions were also made at 125 kbps in order to investigate the efficacy of the RAMP system at reduced signal amplitude. Recording was performed with an EAI® 870 wide-band preamplified hydrophone with a sensitivity of 190 dB re 1 V/μPa @ 700 kHz. The hydrophone output was split into two channels. One channel was used to record ambient noise at a lower sample rate and is not discussed here.

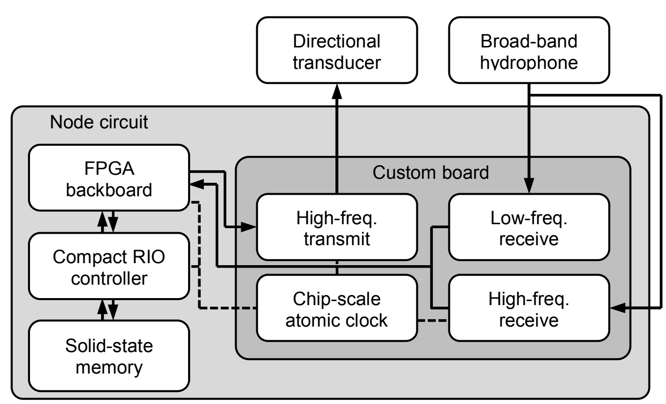

Figure 4. Data flow in transmission and reception modes (solid lines), and incorporation of the CSAC in timing and signal generation (dashed lines).

The other was passed through a de-multiplier that removed the 750 kHz center frequency, leaving only the phase multiplier. The phase multiplier was received by an analog receiver module (NI 9223) and analyzed by the FPGA backplane (NI 9113) on the compactRIO™. A matched filter running on the FPGA triggered recording and decoding of the signal when an appropriate preamble m-sequence was detected. A schematic of data flow in transmission and reception is shown in Fig. 4. Due to the short spacing between the nodes and the walls of the enclosure, the time window between the beginning of the direct arrival and the beginning of the first wall reflection was approximately 2.7 ms. To avoid contamination of the direct arrival with any wall reflections, the maximum packet length used in this experiment was 1 ms. No multipath from surface reflection or from other sources was detected during the time window encompassing the direct arrival.

IV. ACOMMS RESULTS

Table 1 shows the signal lengths and sample sizes for bit rates from 50 to 125 kbps as tested in the tank. All transmissions demonstrated an in-tank bit error rate (BER) of zero. Fig. 5 displays the phase plots associated with the decoded BPSK signals at each bit rate. The observed scatter is most likely a result of signal-to-noise ratio, with decreasing signal power due to shorter symbol duration and, to a lesser extent, a reduction in transduction efficiency away from the maximum at 750 kHz. The 125 kbps transmission was beyond the designed physical limitations of our communications system. Nevertheless, error-free decoding was demonstrated in the controlled tank environment.

V. DISCUSSION

This paper demonstrates the performance of an FPGA-based high-frequency ACOMMS system that uses highly directional transducers to mitigate multipath over short distances. While the results shown here were obtained in an enclosed tank environment, it is feasible that similar performance will be exhibited by the system in the ocean if the transducers and hydrophones are subject to little movement. Data rates of 125 kbps are comparable to cutting-edge ACOMMS transmissions over short ranges [4][5]. The hardware system employed to create and decode the BPSK signal discussed here is unconventional and exhibits some limitations that prevent higher data rates and more robust communications protocols. Due to the square-wave nature of the compactRIO™ digital output, only two phase states are possible. Furthermore, due to the design of the frequency multiplier and the relatively narrow operating band of the transducer, conventional temporal synchronization preambles

TABLE I. TRANSMISSIONS

Bit Rate (kbps)	M-Sequence Length	Sample Size (N)
50	32	1248
62.5	64	4288
100	64	2624
125	128	5120

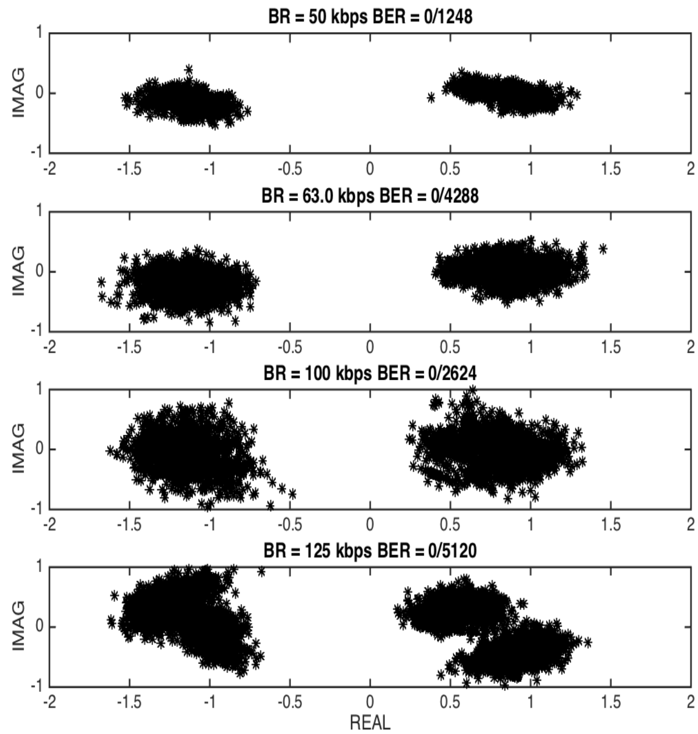

Figure 5. Phase plots from decoded BPSK signals at bit rates from 50 to 125 kbps. 'BR' indicates bit rate, 'BER' indicates the bit error ratio.

such as frequency modulated sweeps are not possible. To obtain definitive BER values, further testing with larger sample size is required to obtain statistically robust measures. At-sea experiments where horizontal reflection is not an issue and significant ambient noise exists will provide more operationally relevant measurements and will permit comparisons with other ACOMMS protocols in real-world conditions.

VI. FUTURE WORK

An at-sea test of the RAMP system equipped with the directional transducer and the omnidirectional high-frequency hydrophone is planned to occur in October 2015 in shallow water off Panama City, FL, at a site indicated in Fig. 6A. Here, the nodes will be deployed on a level sea floor that is comprised of a soft sand/silt bottom at a depth of 12 m (Fig. 6B). A horizontal inter-node spacing of 5 m will permit beamforming of low-frequency targets such as passing surface vessels while remaining small enough to enable testing of multi-node reception (i.e., more than one neighbor will be within acoustic range). Subsurface buoys will enable the precise alignment of transducers and hydrophones so that narrow-beam transmissions between nodes may be reliably intercepted. In this configuration, low-frequency acoustic recordings of ambient noise acquired by each node will be encoded and re-transmitted via the high-frequency, multipath-free communication channel described here to a master node.

Timestamp information pertaining to each transmission will be obtained from the independent yet synchronized CSAC devices in each node.

VII. Acknowledgements

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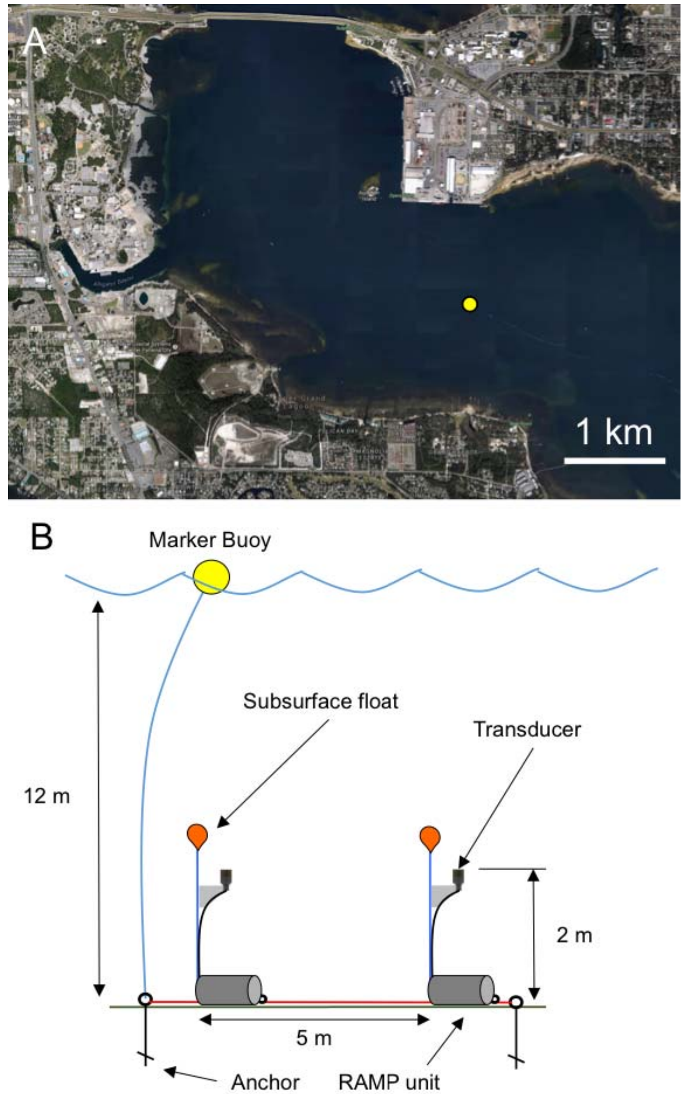

Figure 6. (A): A satellite image showing the location of the planned network deployment in the harbor at Panama City, FL. (B): A schematic showing the arrangement of the RAMP nodes on the sea floor.