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Mooring Load Monitoring of a Wave Energy Converter using A Self-Synchronizing Underwater Acoustic Network

Pierre-Philippe Beaujean
Dept. of Ocean and Mechanical Engineering
Florida Atlantic University
Boca Raton, Florida, USA
pbeaujea@fau.edu

Nigel Kojimoto
CalWave Power Technologies
San Francisco, California, USA
nigel@calwave.energy

Budi Gunawan
Sandia National Laboratories
Albuquerque, New Mexico, USA
bgunawa@sandia.gov

Frederick Driscoll
National Renewable Energy Laboratory
Boulder, Colorado, USA
frederick.driscoll@nrel.gov

***Abstract*— A self-synchronizing underwater acoustic network, designed for remote monitoring of mooring loads in Wave Energy Converters (WEC), has been developed and tested. This network uses Time Division Multiple Access and operates self-contained with the ability for users to remotely transmit commands to the network as needed. Each node is a self-contained unit, consisting of a protocol adaptor board, an underwater acoustic modem and a battery pack. A node can be connected to a load cell, to a topside user or to the WEC. Every node is swapable. The protocol adaptor board, named Protocol Adaptor for Digital LOad Cell (PADLOC) supports a variety of digital load cell message formats (CAN, MODBUS, custom ASCII) and underwater acoustic modem serial formats. PADLOC enables topside users to connect to separate load cells through a user-specific command.**

Keywords— Self-synchronizing, Underwater, Acoustic, Network

I. Introduction

Underwater acoustic communications technology has become a ubiquitous part of undersea operations. Oil and gas industry, military, fishing industry, as well as scientific and recreational communities use underwater acoustic modems produced by a well-established industry. Underwater acoustic modems are routinely used to communicate with submarines, Unmanned Underwater Vehicles (UUV), sensor nodes [1] and divers, to name a few examples. The scientific community has also looked into acoustic methods to communicate with marine mammals. There have been numerous publications and conferences reviewing the state-of-the-art in underwater acoustic communications in the past 30 years, showing the evolution of this technology [2-6].

This paper reports on the development and testing of a self-synchronizing underwater acoustic network developed for the remote monitoring of mooring load in Wave Energy Converters (WEC) [7][8]. This network uses Time Division Multiple Access and operates self-contained with the ability for users to remotely transmit commands to the network as needed. Each node is a self-contained unit, with a protocol adaptor board, an FAU-DPAM underwater acoustic modem and a battery pack. A node can be connected to a load cell, a topside user or the WEC. Every node is swapable. Put in the context of such state-of-the-art underwater acoustic communication technology, the system presented here provides two innovative aspects: a self-synchronizing Time Division Multiple Access network, where each node is equiped with a protocol adaptor board that handles the timekeeping and power saving features, and the compatibility with a variety of digital load cell message formats (CAN, MODBUS, custom ASCII). The result is a network capable of operating without any human intervention over periods of several months to relay undersea load cell measurements.

II. Technical Description

A. Protocol Adaptor for Digital LOad Cell (PADLOC)

The Protocol Adaptor for Digital LOad Cell (PADLOC), shown in Figure 1, is a novel board that supports a variety of digital load cell message formats (CAN, MODBUS, custom ASCII) and underwater acoustic modem serial formats.

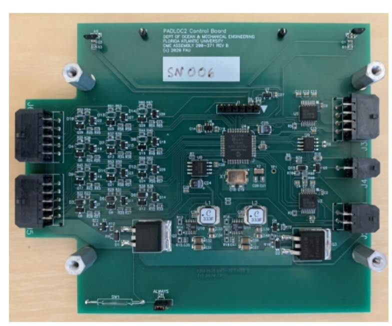

Fig. 1. Protocol Adaptor for Digital LOad Cell (PADLOC) electronics board.

PADLOC enables the topside user to connect to separate load cells through a user-specific command. This is especially

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important if the user is monitoring multiple load cells during deployment or maintenance, when the primary data system may be offline. Each PADLOC board handles formatting, buffering and has a one-on-one serial connection with each digital load cell and acoustic modem contained in a node. In addition, each PADLOC board handles the timekeeping and power saving features for each node. The only limitation is the data bit rate and delay limitations associated with the underwater acoustic modem.

B. PADLOC node and Underwater Acoustic Network

Each unit is called a node and is self-contained, with the PADLOC electronics and software, an FAU-DPAM underwater acoustic modem and a battery pack (Figure 2). Each node is rated for 100 m depth operations. It can be connected to a load cell, a topside user or the WEC. Every unit is swapable.

A four node self-synchronizing network has been developed to demonstrate the load cell monitoring capability using the PADLOC technology for the CalWave WEC. This WEC comprises a central submerged device taut moored using multiple anchors. The concept of operation is shown in Figure 3. The four nodes are shown in Figure 4.

The CalWave WEC comprises a central submerged device equipped with an umbilical connection to shore for electrical communication and power transmission. In its complete configuration, the WEC device is deployed in approximately 23 m of water depth and 700 m from a pier. The distance between the WEC device and each mooring cell is less than 10 m.

Two load cells are installed on 2 anchors. Each load cell are tied to a battery-powered wireless acoustic communication PADLOC unit (referred to as CELL unit from here on), also installed on the mooring line. These units relay load measurements and statistics to a MASTER PADLOC unit (referred to as MASTER unit from here on) installed on the WEC device.

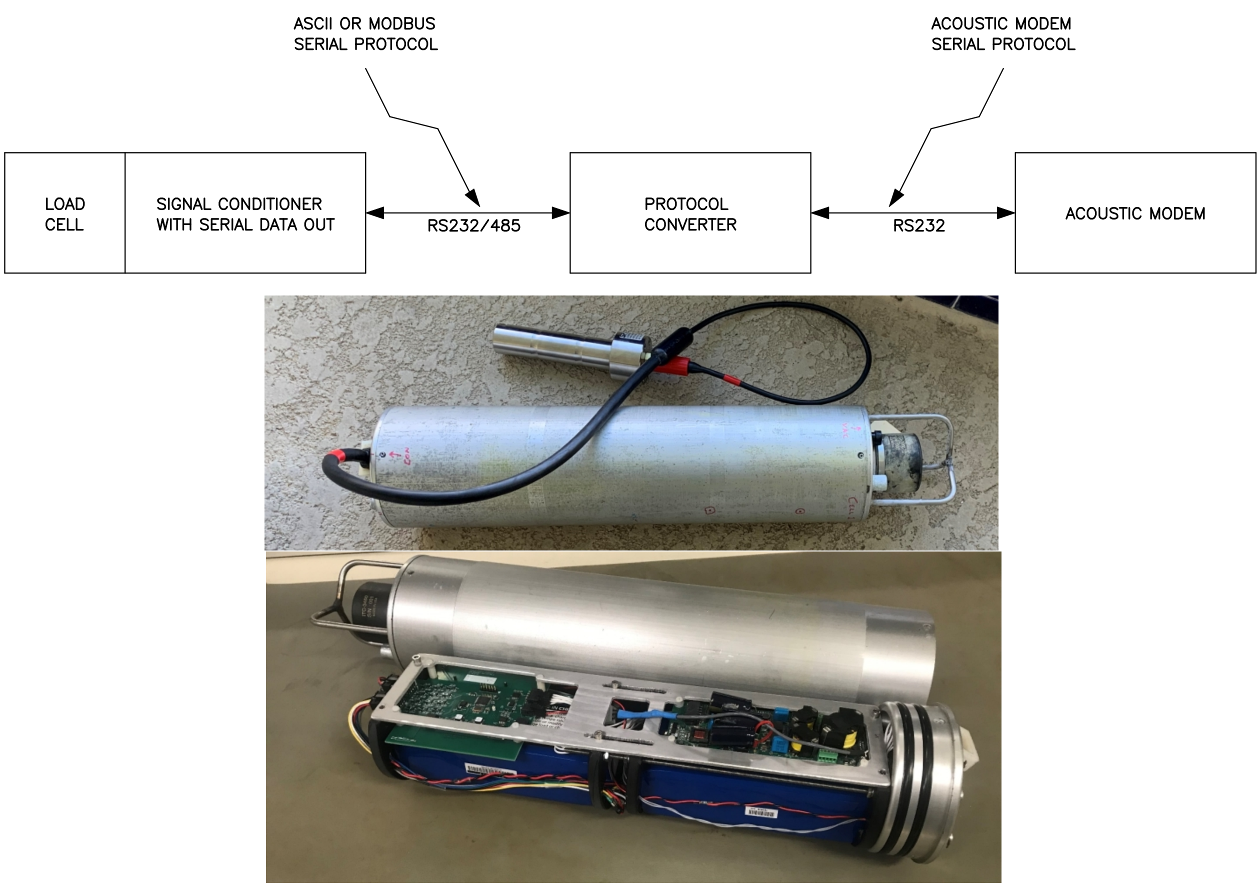

Fig. 2. Top: Underwater Digital Load Cell and Underwater Acoustic Modem connected using a Protocol Converter (PADLOC). Middle picture: PADLOC units in its packaged configuration connected to a load cell unit. Bottom picture: Open PADLOC unit, with the PADLOC electronic board (left), the FAU-DPAM underwater acoustic modem (right) and 560 W-Hr Li-Po battery (bottom).

The batteries are rated for a continous 180 day operation in slow mode (1 hour communication cycle) or 45 days operation in fast mode (15 min communication cycle). In addition, a topside user node is available to communicate with the WEC from the pier. Each load cell is monitored for a one-minute duration every five minutes. Statistical data (minimum, maximum, average, and standard deviation) are locally stored and time-stamped, then relayed once every fifteen minutes to the WEC. Twice every 15-minute cycle, the system relays status information from the WEC and commands from the operator on shore.

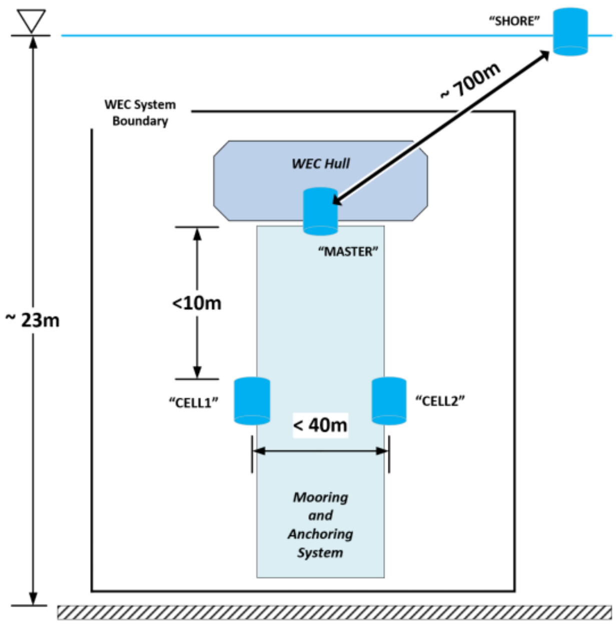

Fig. 3. CONcept of OPerationS (CONOPS) for the mooring monitoring of the WEC unit.

C. *Signal Processing and Network Algorithm*

In each node, the FAU DPAM is configured in its most reliable (and slowest) communication mode. The FAU DPAM is a well-documented device [9-13], so that only a brief description of the underwater acoustic transmission is provided. The acoustic signals are modulated using Frequency Hopping Multi-Frequency Shift Keying (FH-MFSK), between 16 kHz to 29 kHz (16 kHz to 32 kHz nominal). In this case, 3 bits of coded information is contained in every symbol (a frequency-modulated impulse). Each symbol uses one out of 8 possible 296 Hz frequency bands. To prevent inter-symbol interference due to acoustic reverberation, each symbol uses a specific set of frequency bands over a period of four symbols.

Concatenated error coding is used to correct any residual error, combining a Reed-Solomon (RS 234,255) code and a convolutional code (k=7,1/2). A CRC 16 error checking code is present in every message. Only messages with a successful CRC test are retained, so that there is virtually no chance that an erroneous message is sent to the user. The actual data rate is 73 bps, and each message contains 256 bits of information (32 bytes). A brief mathematical description of the modulation and demodulation algorithms is provided in the Appendix section.

In order to keep this document concise, a top-level desciption of the network algorithm is given in Figure 5.

III. Simulation and Experimental Results

A. *Point-to-Point Acoustic Communication Simulation*

This section covers some performance simulation results for the proposed CONOPS, over a period of 6 months for point-to-point communication between one load cell and the topside user. The simulation assumes the following sequence: (i) during the first two hours, the load cell is monitored during deployment and messages are sent continuously at a rate of 3 messages per 2 seconds (using the FAU DPAM communication mode 4 [13], which is the most reliable mode); (ii) the load cell is then monitored for 6 months at a rate of one message per hour using the same communication mode. The corresponding point-to-point data rate in the simulation and in every experimental test is 73 bits-per-second.

This simulation does not duplicate exactly the network algorithm described in Figure 5 but provides the appropriate

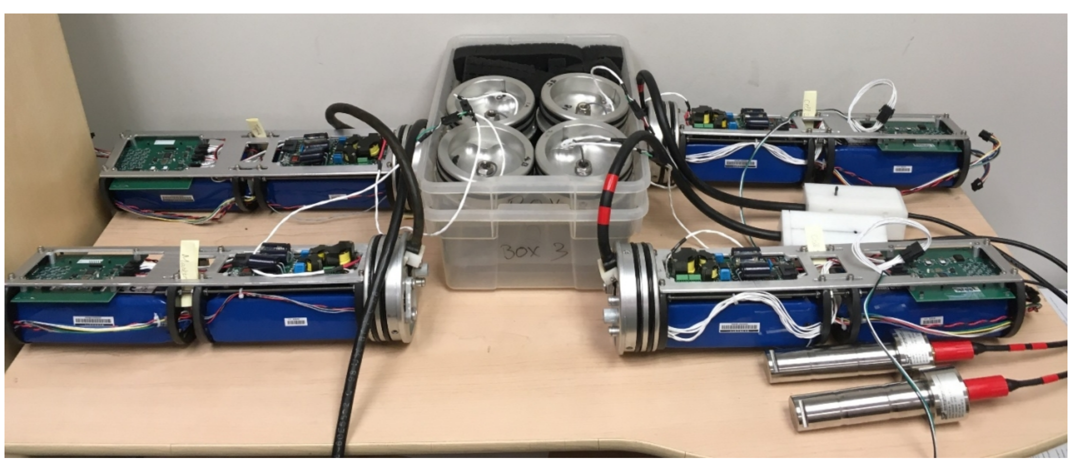

Fig. 4. Bench test setup, with four packaged PADLOC units (the cylinders are removed) and transducers in a small water tank. The two load cells are connected (at the bottom right of the picture).

POWER UP
Turn on the unit by placing a magnet near the reed switch.

START MISSION
Start the mission by placing the magnet near the mission hall sensor.

FLASH MEMORY DUMP
If a topside user is connected using a serial cable to either CELL1 or CELL2 unit, it is prompted to access and dump the flash memory containing the load cell data collected.

↓

WEC TIME SYNC

- MASTER requests time from the WEC and wait until it receives the time information in the proper message format.
- Once the proper time message is received, MASTER updates its clock and acknowledges the new sync and confirms no additional timing message is needed.
- Following this, MASTER verifies how much time is left until the next communication cycle, which starts at the beginning of each hour. If there is not enough time to complete a synchronization cycle (14 min), MASTER waits until the beginning of the following hour. If there is enough time, MASTER starts the synchronization cycle.

↓

SYNC CYCLE

A complete SYNC cycle has two parts: CELL1/CELL2 sync and SHORE sync.

- During SYNC CYCLE, MASTER syncs every other unit to the WEC time.
- A complete SYNC CYCLE lasts 450 s and is performed only once.

↓

MAIN CYCLE

- A complete MAIN cycle starts when all the units are synchronized.
- In fast mode, there are 4 cycles per hour, starting at the beginning of the hour. In slow mode, there is only one cycle per hour.

During each cycle:
- MASTER resynchronizes itself with the WEC and propagate the time information to both CELL units and SHORE. In addition, MASTER collects the load statistics collected by each CELL. Finally, MASTER exchanges status and commands with SHORE.
- Each CELL completes 3 load cell data acquisition. By default, 120 observations are stored, one observation every 0.5 s In addition, each CELL calculates the statistics (min, max, mean, std dev) of the last load cell observations (by default the last 120 observations). This statistical information is transmitted acoustically to the MASTER.
- SHORE exchanges status and command messages with MASTER and with the topside user laptop.

Fig. 5. PADLOC Network Algorithm.

statistical information to verify that the nodes will communicate properly over a period of 6 months. This underwater acoustic communication simulation tool has been used extensively in prior research and is well documented [14-17]. The simulation calculates the Frame Error Rate (percentage of corrupt messages), the total number of messages sent, the total number of corrupt messages and the total energy used by the FAU DPAM connected to the load cell. The values are calculated as a function of range (from 10 to 500 m), assuming a water depth of 10 m. The simulation assumes that the Source Level is 168 dB to conserve energy (the maximum Source Level is 186 dB for the FAU DPAM. The simulation assumes a Nakagami factor of 1, which would correspond to a rough sea surface. The Nakagami factor is a common indicator of the non-stationarity of a wireless communication channel, and is a function of the sea state in the case of an underwater acoustic channel used for wireless acoustic communications [14].

Figure 6 shows the frame error rate (percentage of corrupted messages) as a function of range. The estimated energy

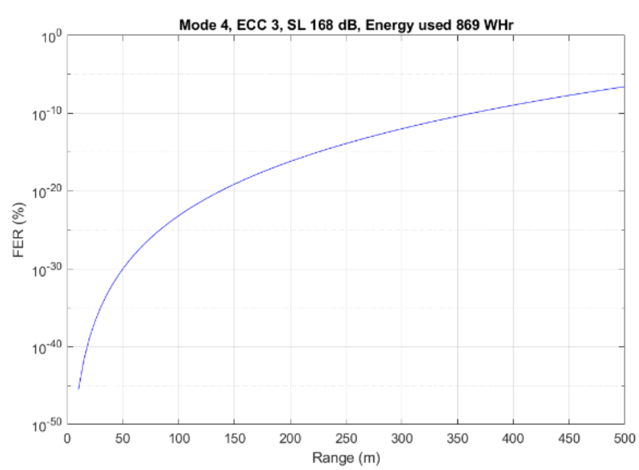

Fig. 6. Performance simulation result for the proposed CONOPS.

consumption over 6 months is 869 W-Hr. Using 11520 transmitted messages, the simulation indicated that the topside operator would receive every message without error, at any range if the FAU DPAM is operated in slow mode.

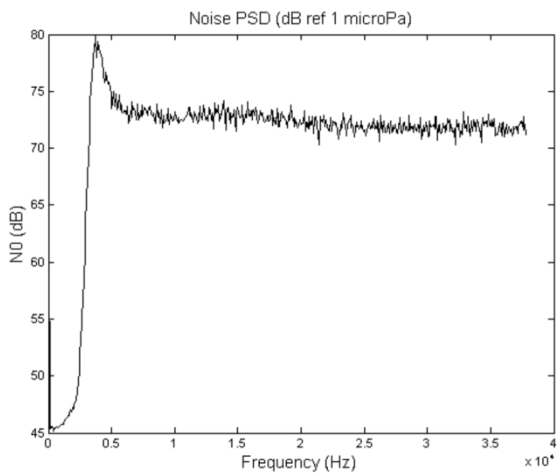

Fig. 8. Measured Noise Power Spectral Density.

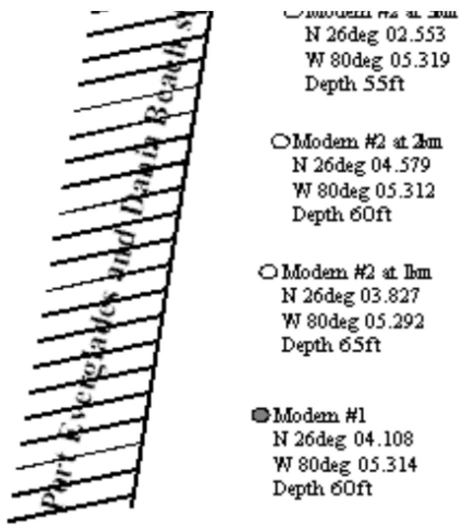

Fig. 7. Dual-Purpose Acoustic Modems Locations.

B. *Point-to-Point Acoustic Communication Field Testing*

1) System Characteristics and Experiments

The purpose of this at-sea test was the performance evaluation of the Dual-Purpose Acoustic Modem (DPAM) used in every PADLOC unit.

Two DPAMs were tested along the coast of Port Everglades, Florida, in a water column of 20 m. The modems, deployed off the side of small vessels, were successively positioned 1, 2 and 3 km apart (Figure 7). Each DPAM transmitted signals from 15.2 kHz to 31.9 kHz with an average source level of 187 dB ref. 1μPa.

2) Channel Characteristics

The noise Power Spectral Density (PSD), averaged over time and receiver location, is shown in Figure 8.

At each location, the noise PSD was averaged over the duration of 100 symbols, or 1.354 seconds. Little variation of the noise PSD was observed as a function of range during the experiments. Figure 8 shows that the measured noise was only slightly colored, with a slope of 0.1 dB (re.1μPa^2/Hz)/kHz. The average value of N_o was estimated at 72 dB (re.1μPa^2/Hz) between 15.2 kHz to 31.9 kHz (Figure 8).

Figure 9 shows the spectrogram of the received signal at a distance of 1 km. Time and frequency selective fading can be clearly observed. Figure 10 shows the sound speed profile as a function of depth. The plot shows a variation of the order of 1 ms^{-1} of the sound velocity as a function of the depth. This indicates that the channel was iso-speed, and no significant sound refraction was expected. The reverberation times are presented in Table I for each location. Table II shows the measured SNR at the same locations.

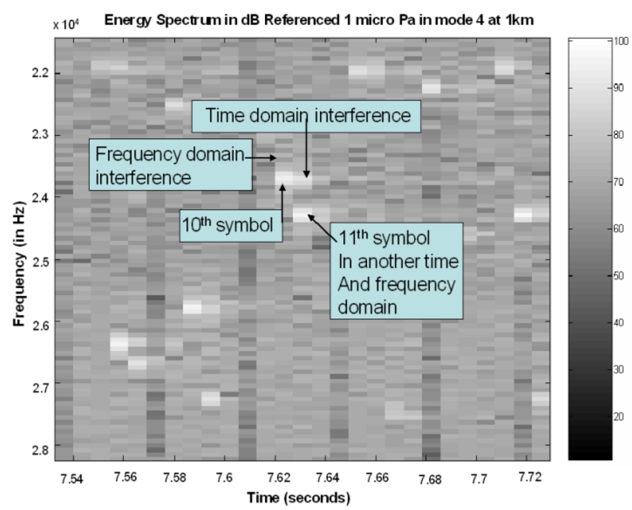

Fig. 9. Measured Sound Speed Profile.

Fig. 10. Measured Sound Speed Profile.

3) Measured performance

Table III summarizes the performance obtained for the modem at 500 m, 1, 2 and 3 km, in terms of the FER (percentage of lost messages), and indicated an excellent performance of the acoustic communication system up to 3 km range.

TABLE I. MEASURED REVERBERATION TIME VS. RANGE

Distance (m)	*Reverberation time (s)*	*Reverberation time (number of symbols)*
500	40.62	4
1000	40.62	4
2000	27.08	2
3000	27.08	2

TABLE II. MEASURED PERCENTAGE OF LOST MESSAGES VS. RANGE

Distance (m)	*Percentage of lost messages (%)*
500	0
1000	0
2000	20
3000	0

TABLE III. MEASURED BIT ENERGY-TO-NOISE PSD RATIO AND AVERAGED SNR

Distance (m)	*Averaged E_b/N_o (dB)*	*Averaged SNR (dB)*
500	30.1	35.1
1000	25.4	30.2
2000	16.2	21.1
3000	7.1	12.5

C. Network Pool Test

The second series of tests was performed with the four fully packaged PADLOC units using the time division feature (shown in Figure 11). The units were first tested over a period of several weeks, by placing the transducers in a small tank and operated at 1% and 6% of the maximum power. Although this appears to be a benign environment, such a small tank causes a major amount of reverberation. Thus this is considered a fairly challenging configuration.

Following this, a series of tests were completed in a large shallow pool outside of the FAU SeaTech building (Figure 7). The units were aligned along the curved edge of the pool. CELL1 (front) was 2.8 m apart from MASTER. MASTER was 3 m apart from CELL2. CELL 2 was 1.5 m apart from SHORE. For the communication between MASTER and CELL nodes, the FAU DPAMs were operated at 6% of the maximum power. For the communication between MASTER and SHORE, the FAU DPAMs were operated at 1% of the maximum power. This significantly lower power setting was selected to simulate the greater distance between MASTER and SHORE during actual field operations. These tests were repeated over several days and underwater acoustic communication proved 100% reliable.

Fig. 11. Deployed units from front to back: CELL 1, MASTER, CELL 2, SHORE.

D. PADLOC and Load Cells Field Testing

The subscale X-Wave device was successfully deployed and continuously operated off the coast of San Diego for 10 months, from September 2021 – July 2022 (Figure 12).

Fig. 12. Deployed CalWave X-Wave WEC.

The device served as a test platform to validate CalWave's numerical models and support up-scaling towards higher-power devices. Mooring tension measurements from PADLOC units will be used in future iterations to optimize anchor designs, PTO dynamics, and hull structures. Two PADLOC units were deployed over a period of 45 days off the coast of California in October and November 2021, and successfully completed their assigned task. Figure 13 shows a picture of two PADLOC units connected to load cells and deployed near the mooring location of the CalWave WEC. However, for

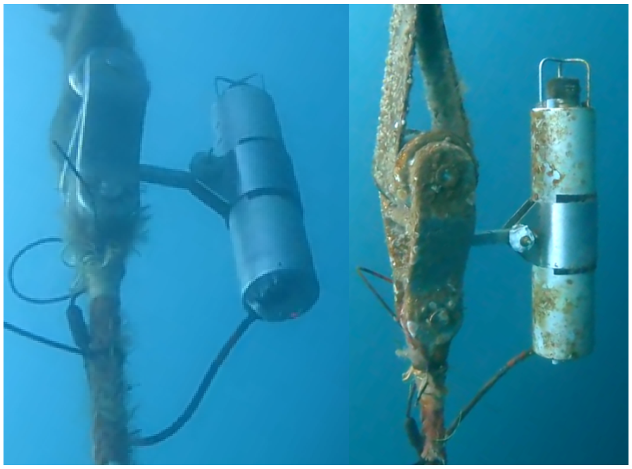

Fig. 13. Underwater picture of one of the PADLOC units before (left) and after (right) two months spent underwater. October-December 2021, San Diego, CA.

technical and logistical reasons, the complete four-node network has not been deployed at this time. Note that additional experimental results are also available in [18].

IV. Summary and Conclusions

A self-synchronizing underwater acoustic network, designed for remote monitoring of mooring loads in Wave Energy Converters (WEC), has been presented along with a series of experimental results. Additional experimentation is underwork off the coast of Florida and in the mid-Pacific in late 2022 and 2023, at longer ranges and in deeper waters.

Acknowledgment

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Appendix

This appendix section contains a brief mathematical formulation of the DPAM signal modulation and demodulation. Additional information can be found in [9-11].

A. Acoustic Modem Signal Modulation

The DPAM acoustic modem first sends a known detection sequence of 8 symbols $s_j(t)$, $j=1,\ldots,8$ at the beginning of each message. Each of the 8 symbols occupies a specific frequency band.

Following these detection symbols, two symbols $s_9(t)$ and $s_{10}(t)$ are transmitted to identify the FEC and hopping mode of the message. The first symbol carries one frequency among 3 possible frequency bands, corresponding to each one of three FEC techniques (Reed-Solomon, convolutional or concatenated).

The second symbol carries one of the four different frequency bands, representing each one of the four possible frequency hopping modes. The acoustic modem is designed to transmit messages in frames, each containing N_{data} = 256 bits of information. A 16-bit Cyclic Redundancy Check (CRC) code is added to the sequence for a total of N_{frm} = 272 bits before FEC. In the case of Reed Solomon coding, the N_{frm} = 272 bits are converted to a sequence of N_{msg} = 384 bits. The convolutional coding converts the 272 bits sequence to a N_{msg} = 588 bits sequence. The concatenated technique converts the original 272 bits to a N_{msg} = 780 bits sequence.

In all cases, the coded sequence is convolutionally interleaved, and modulated using Frequency-Hopped M-ary Frequency Shift Keying (FH-MFSK).

Each symbol $s_j(t)$ is a combination of frequency-modulated chirp signals. Each chirp envelope is a Blackman-Harris time window, which reduces frequency leakage between chirps. Each symbol $s_j(t)$ is represented by a frequency modulated signal within a specific band.

$$s_j(t) = b(t)\sum_{p=1}^{P_{\mathrm{mode}}} cos\left(2\pi\left(f_{h,j,p,q} + f_{j,p,q} + \frac{W_s t}{2T_s}\right)t\right)\mu Pa \quad (1)$$

$$b(t) = \frac{10^{SL/20}}{P_{\mathrm{mode}}}\left(0.42 - 0.5\, cos\left(2\pi\frac{t}{T_s}\right) + 0.08\, cos\left(4\pi\frac{t}{T_s}\right)\right) \quad (2)$$

Where $f_{h,j,p,q}$ is the hopping frequency for symbol j, mode q and band p; $f_{h,j,p,q}$ is the carrier frequency for symbol j, mode q and band p; W_s =*295Hz* is the symbol bandwidth when P_{mode} = 1 and T_s =*13.56 ms* is the symbol duration.

When a symbol uses multiple bands (P_{mode}), the total symbol bandwidth is P_{mode} W_s. Each symbol is a sum of P_{mode} chirps. Every chirp is sampled at F_s= 75600 Hz, lasts T_{chirp}=T_s=13.54 ms, and occupies a bandwidth W_{chirp}=295.31 Hz. Up to Q_{max}=56 frequency bands can be used, of which Q_{data}= 32 are reserved for data. There are four different transmission modes, corresponding to four different modulation techniques based on frequency hopping. Each mode is characterized by a number of bits-per-symbol k_s, a number of hops M_H, a number P_{mode} of frequency bands used per hop.

B. Acoustic Modem Signal Demodulation

The first step is to detect the incoming message and to find, within reasonable accuracy, the first sample of this same message. The known series of Q = 8 symbols $s_j(t)$, $j=1,\ldots,8$, located at the beginning of each message serves these two purposes: message detection and time synchronization.

Each detection symbol of the detection sequence occupies one frequency band, centered on frequency f_j , $j = 1,\ldots,Q$. The demodulation of each detection symbol is performed using the cross-correlation between the incoming faded symbol and a set of complex reference symbols:

$$R_{\tilde{r}_j,\tilde{s}_p}(\tau) = \frac{1}{2T_s}\int_{-T_s}^{T_s}\tilde{r}_j(t)\tilde{s}_p^*(t+\tau)dt \quad p = 1,\ldots,32 \quad (3)$$

$Z_{j,p}$ is defined as the peak of correlation of symbol number j across all $p=1,\ldots,32$ and occurs at sample number c_j. A given number Q', $0 < Q' \leq Q$, of symbols must be detected in the correct order from the synchronization sequence of Q symbols for the process to identify the signal as a message. Synchronization is achieved by averaging the value of c_j obtained for each detection symbol $j=1, \ldots, 8$.

The second step is to identify the message format, using the received symbols for j=9 and j=10. $s_{FEC,p}(t) = s_9(t)$ occupies one out of 3 possible frequency bands, corresponding to each one of three FEC techniques (Reed-Solomon, convolutional or concatenated). The demodulation of symbol 9 is performed using the cross-correlation with all 3 possibly transmitted symbols:

$$R_{\tilde{r}_9,\tilde{s}_p}(\tau) = \frac{1}{2T_s}\int_{-T_s}^{T_s} \tilde{r}_9(t)\tilde{s}^*_{FEC,p}(t+\tau)dt \quad p = 1,\ldots,3 \qquad (4)$$

$Z_{9,p}$ is defined as the peak of correlation of symbol number j for each $p=1,\ldots,3$. The value of p for which $Z_{9,p}$ is maximum corresponds to the type of FEC used.

The symbol $s_{10}(t)$ carries one of the four different frequency bands, representing each one of the four possible frequency hopping modes. The operation used to identify the hopping mode is very similar to the one used to identify the FEC mode: received symbol 10 is cross-correlated with all 4 possibly transmitted symbols, and the outcome with the highest peak of correlation is retained.

The message demodulation process begins with cross-correlating each incoming symbol $r_j(t)$ with P_{mode} groups of P_{max} frequency bands:

$$R_{\tilde{r}_j,\tilde{s}_p}(\tau,q) = \frac{1}{2T_s}\int_{-T_s}^{T_s} \tilde{r}_j(t)\tilde{s}^*_{p,q}(t+\tau)dt \qquad (5)$$

Given $q = 1,\ldots,P_{mode}$, $Z_{j,p}(q)$ is defined as the peak of correlation of symbol number j for each $p=1,\ldots,P_{max}$. The value of p for which $Z_{j,p}(q)$ is maximum corresponds to a three-bit value in modes 2,3 and 4, and to a two-bit value in mode 1. The operation is repeated for each frequency group, and the coded binary information contained in symbol $r_j(t)$ is recovered.

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