SAND2022-12573C

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

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This work was funded by the U.S. Department of Energy's (*DOE*) Water Power Technologies Office (*WPTO*). Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

The National Renewable Energy Laboratory is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC. under contract No. DE-AC36-08GO28308.

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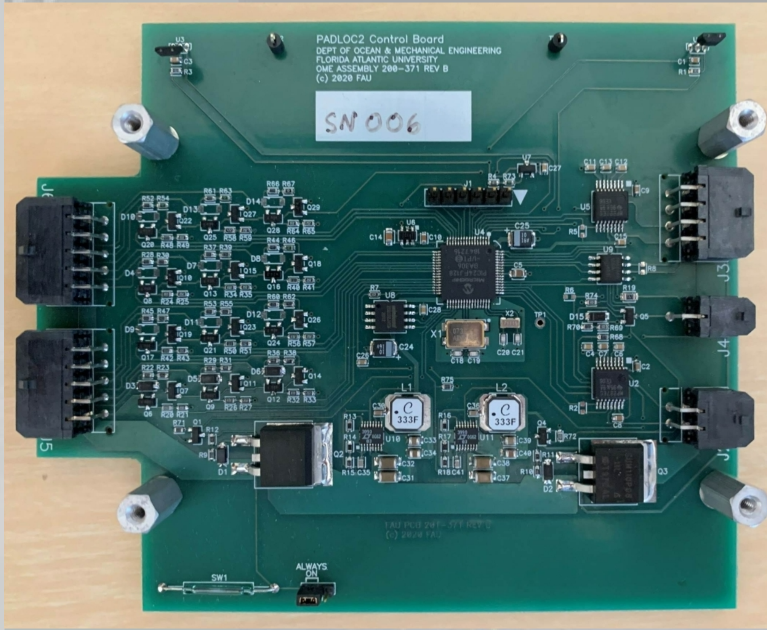
Overview

- 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).
- 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 equipped with a protocol adaptor board that handles the timekeeping and power saving features.
  - 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.

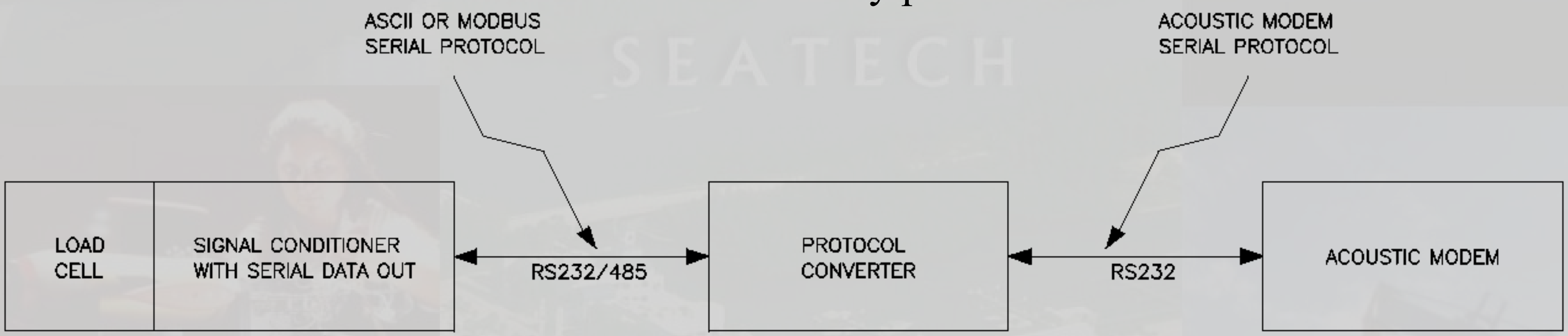
Technical Description

- The Protocol Adaptor for Digital LOad Cell (PADLOC) is a novel board that supports a variety of digital load cell message formats (CAN, MODBUS, custom ASCII) and underwater acoustic modem serial formats.
- PADLOC enables the topside user to connect to separate load cells through a user-specific command. This is especially 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.

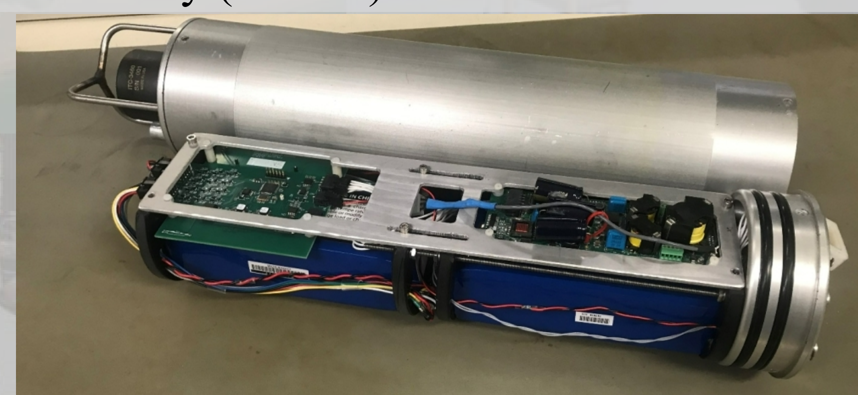


Technical Description

- 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.



- Left: PADLOC unit in its packaged configuration connected to a load cell unit.
- Right: Open PADLOC unit, with the PADLOC electronic board (left), the FAU-DPAM underwater acoustic modem (right) and 560 W-Hr Li-Po battery (bottom).



Concept of Operation

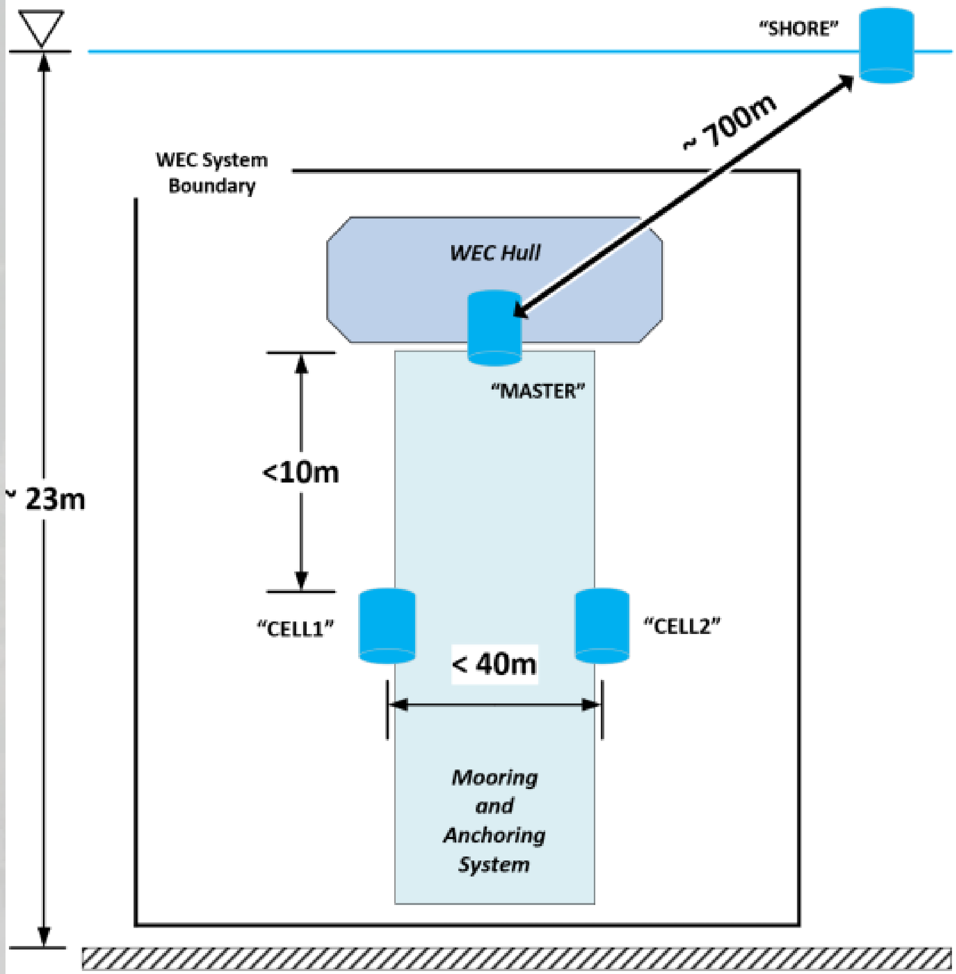
• A four node self-synchronizing network has been developed to demonstrate the load cell monitoring capability using the PADLOC technology for the CalWave WEC.

• In its complete configuration, the WEC device is deployed in 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 CELL PADLOC unit also installed on the mooring line.

• These units relay load measurements and statistics to a MASTER PADLOC unit installed on the WEC device.

• In addition, a topside user node is available to communicate with the WEC from the pier.



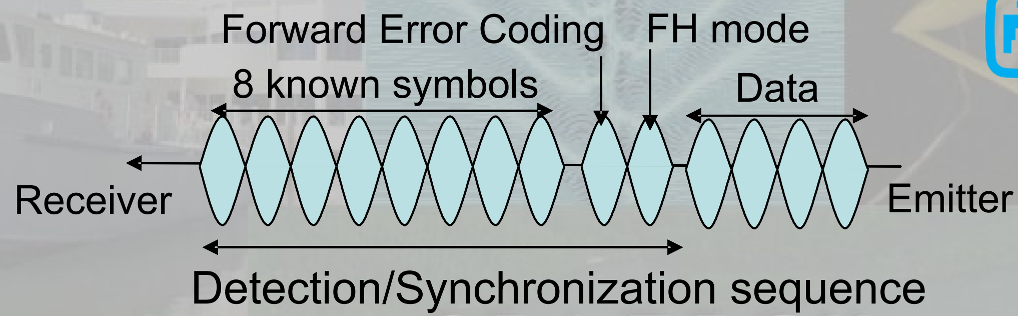
Four Nodes Network Bench Setup

- The batteries are rated for a continuous 180 day operation in slow mode (1 hour communication cycle) or 45 days operation in fast mode (15 min communication cycle).

PADLOC Network Algorithm

Step	Description
POWER UP START MISSION FLASH MEMORY DUMP	- Turn on the unit by placing a magnet near the reed switch. Start the mission by placing the magnet near the mission hall sensor. 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, followed with SHORE sync. During this step, 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.

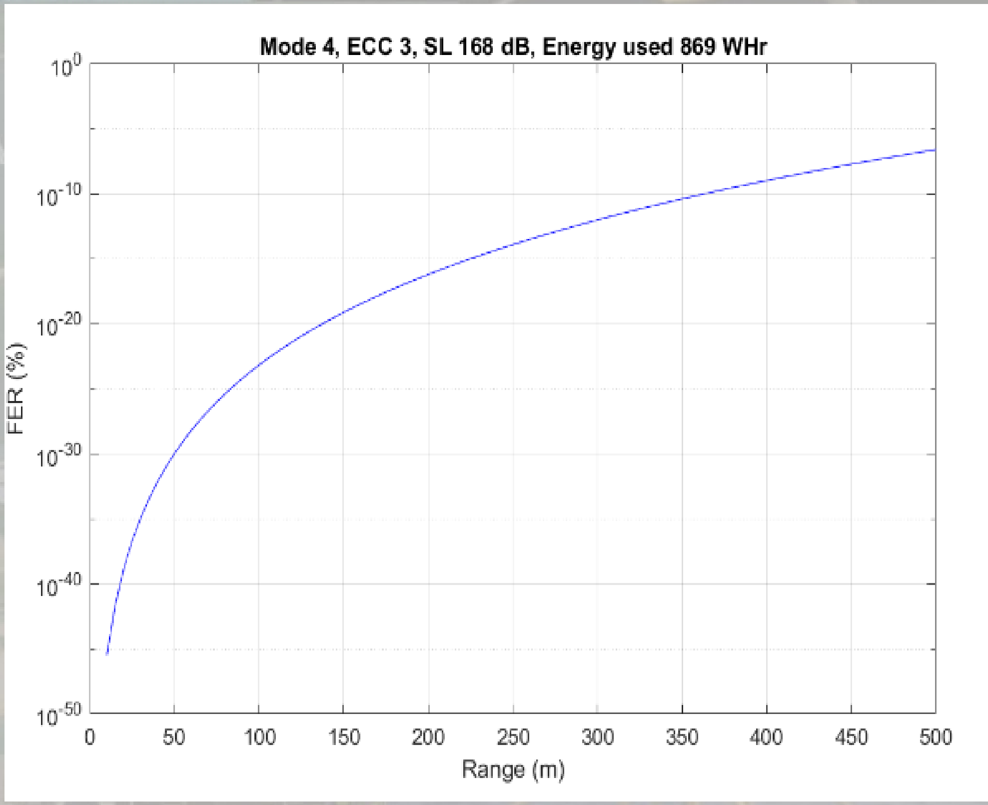
Communication System



- The acoustic modem sends the same known sequence of 8 symbols at the beginning of each message. Each of the 8 symbols occupies a specific frequency band.
- Following these detection symbols, two symbols are transmitted to identify the Forward Error Coding (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. **Concatenated convolutional/Reed Solomon FEC is used here.**
- The acoustic modem is designed to transmit messages in frames, each containing 256 bits of information.
- A 16-bit Cyclic Redundancy Check (CRC) code is added to the sequence for a total of 272 bits before FEC. The concatenated technique converts the original 272 bits to a 780 bit sequence.
- In all cases, the coded sequence is convolutionally interleaved, and modulated using Frequency-Hopped M-ary Frequency Shift Keying (FH-MFSK).
- **In this project:**
  - **3 bits are encoded per symbol**
  - **One frequency out of eight is transmitted for each symbol**
  - **Four groups of frequencies are used for frequency hopping**
  - **The true point-to-point data rate is 73 bits-per-second.**

Simulation Results

- 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:
  - 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.
  - The load cell is then monitored for 6 months at a rate of one message per hour using the same communication mode.
- While this simulation does not duplicate exactly the network algorithm described earlier, it provides the appropriate statistical information to verify that the nodes will communicate properly over a period of 6 months.



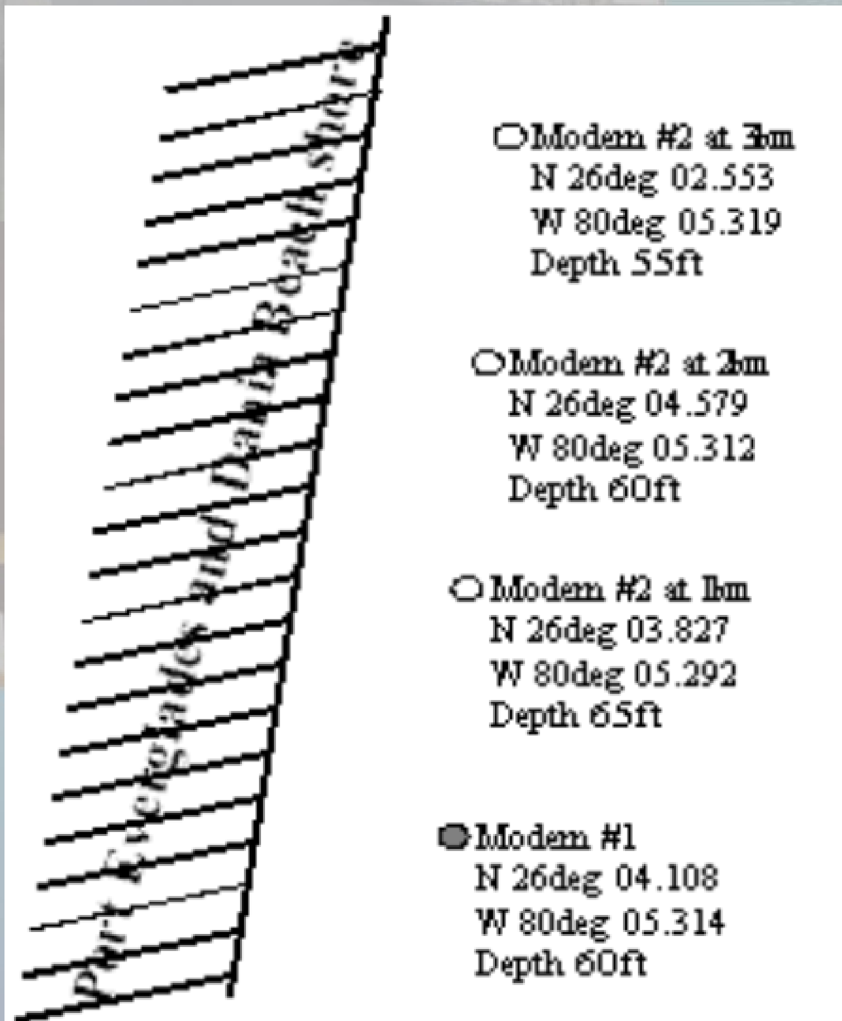
Pool Experimental Results

Deployed units from front to back:
Cell 1, Master, Cell 2, Shore.

• A series of tests was performed with the four fully packaged PADLOC units using the time division feature. 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. This is considered a fairly challenging configuration.

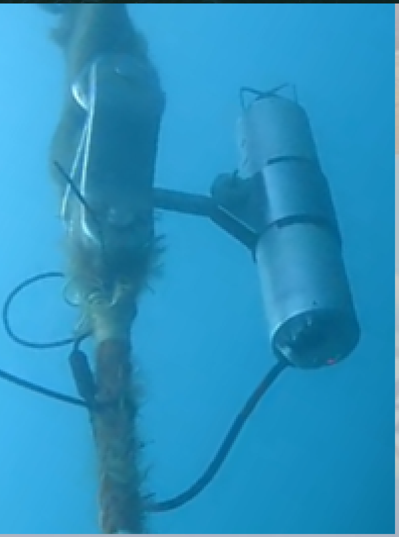
• Following this, a series of tests were completed in a large shallow pool outside of the FAU SeaTech building. The units were aligned along the curved edge of the pool. CELL1 (front) was 2.8 [m] apart from MASTER. MASTER was 3 [m] apart from CELL2. CELL 2 was 1.5 [m] apart from SHORE. For the communication 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.

Recorded Experimental Results in Node-to-Node Configuration



- Node-to-Node had been extensively tested and verified at sea in prior work. The following provides a summary of experimental results collected in previous years (references to additional experimental results are also provided in the reference section of the proceedings).
- In this earlier test, two nodes 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 500 m, 1 km, 2 km and 3 km apart. Each node was operated under the same configuration described in the simulation.
- At a distance of 500 m, 1 km and 3 km, 100% of the messages were received without error. At a distance of 2 km, 80% of the messages were received properly.

Field Testing with the WEC



- 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.

- 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.

Conclusion and Future Work

- A combination of simulation, laboratory testing and field testing have demonstrated that the proposed PADLOC four-node network is operational. The PADLOC units are now in integration phase at CalWave.
- 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.

SEATECH

Questions?