Investigation of Underwater Acoustic Modems: Architecture, Test Environment & Performance

Presented by:

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Introduction

• Underwater (UW) acoustic communication have several design challenges which need to be carefully address including modem size, power consumption, interference, data-rate and communication distance.

• In this presentation, recent developments in UW acoustic modems in last five years are investigated.

• From last five years (2 samples per year) are presented here.

• The architecture, specifications, testing environments (indoor/outdoor) and results are discussed.

• Qualitative analysis of UW acoustic modems is also presented.

• This investigation is useful for researchers and designers of the domain.
SeaModem

- Developed by the University of Calabria, Italy, (2015). (http://www.applicon.it/)
- Open hardware/software platform for UW communication.
- Consists of Power and DSP boards as shown in fig. 1.
- Class D amplifier can transmit up to 40W in different levels.
- Operates in the 25-35 kHz frequency band.
- Piezo-ceramic transducer is used for communication.
- Power board has switch to use single transducer as transmitter/ receiver.
- It uses MFSK modulation with selectable (2-4-8) tones with data-rate 750, 1500, 2250 bps.
- DSP board consists of TMS320C5000™, 16 bits audio CODEC and NOR flash memory.
- To provide user interface UART serial port is used.
SeaModem (cont…)

- Error detection and correction is performed by cyclic redundancy check and Viterbi algorithms respectively.
- The modem uses TCP-like (two-way with ACK) and UDP-like (one-way without ACK) communication protocols.
- SeaModem network architecture allows one to address up to 15 modems within the same area.
- The modem allows one to calculate range by two different (one-way) and (two-way) range estimation methods.
- It allows to add a guard period between symbols to reduce inter-symbol interference.
- It also provide capability to host BeagleBone for additional functionalities as shown in fig. 2.
- Sound speed estimation and time-stamp are also possible on each TCP and UDP packets.

Fig. 2. SeaModem Power & DSP boards.
SeaModem (cont...)  

• The modem was tested in 100m long, 3m deep pier (noisy due to the presence of boats) as shown in fig.3.
• The modem transducers were kept at about 1m depth.
• The modem was tested by taking the average of five range measurements for each of 20 range points.
• The absolute and relative ranging errors are shown in fig. 4 and 5 that is always kept under one meter.
Seatrac

- Developed by Newcastle University, UK (2015) as part of EU FP7 project CADDY (http://www.caddy-fp7.eu/).
- The objective of CADDY project was to make a network of diver, small AUV and small ASV to improve safety.
- The modem is based on 150MHz ARM Cortex M4 processor.
- It operates in the frequency band of 24-32 kHz.
- The combined modem/USBL unit is shown in fig. 6.
- The size of modem is 55mm x 160mm.
- Class D amplifier is used to transmit signals.
- It includes various sensors including:
  - pressure sensor
  - temperature sensor
  - 3-axix gyro
  - accelerometer
  - compass

Fig. 6. Seatrac modem
Seatrac (cont…)

• The modem has been tested using SS with low data rate 100bps in the range of 1.5 km.

• Short messages were exchanged between a pair of devices, the packet delivery rates were between 95-100%.

• The estimated positions in X-Y plane is shown in fig. 7.

• Fig. 8 shows (a) X-Z plane positions & (b) standard deviation (SD) of position vs range.
Seatrac (cont...)

- Medium data-rate (1.4kbps) SS transmission was carried out in shallow water channels.

- Signals were recorded and processed offline using system parameters shown in fig. 9.

- Fig 10-11 shows the results from the transmission of 200 packets over a distance of 1.6 km in 10m deep channel.

- Fig. 10 shows the output signal to interference (SIR) + noise ratio (SINR) is plotted over the 200 packets.

- Fig. 11 shows the number of errors measured in each packet which deteriorates with the ship noise.
Micro-Modem

• Developed by Gangneung-Wonju National University, Korea, (2014).

• The size of modem is small 70mm x 40mm, consumes low-power and works at moderate distance and data-rate.

• The prototype and block diagram is shown in fig. 12-13.

• Following are the specifications.
  – MCU - STM32F103 (Cortex M3).
  – Resonant frequency 70kHz.
  – Power consumption is 8W.
  – Transducer size 34mm.
  – Battery 29.6V, 8.8AH (Li-ion)
  – Power consumption 8W
Micro-Modem *(cont...)*

- The first test was performed in a pond 80m x 40m and 6m deep as shown in fig. 14.
- Two modems were deployed in the LOS path and transducers were submerged in 1m deep.
- Error performance of the modem was investigated at the distance of (D) 30m & 60m with different data rates.
- 200 frames were transmitted for each tests.
- The error rate increases gradually as the data-rate increase as shown in fig. 15.
- Due to shortened symbol duration, communication was not possible after 500 bps.

![Experimental setup for pond tests.](image)

<table>
<thead>
<tr>
<th>Data rate</th>
<th>D=30 m FER</th>
<th>D=30 m BER</th>
<th>D=60 m FER</th>
<th>D=60 m BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 bps</td>
<td>1.0 \cdot 10^{-2}</td>
<td>7.8 \cdot 10^{-3}</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>300 bps</td>
<td>1.3 \cdot 10^{-1}</td>
<td>1.3 \cdot 10^{-3}</td>
<td>4.5 \cdot 10^{-2}</td>
<td>4.3 \cdot 10^{-4}</td>
</tr>
<tr>
<td>400 bps</td>
<td>8.0 \cdot 10^{-1}</td>
<td>5.7 \cdot 10^{-2}</td>
<td>8.0 \cdot 10^{-2}</td>
<td>2.4 \cdot 10^{-3}</td>
</tr>
<tr>
<td>500 bps</td>
<td>8.0 \cdot 10^{-1}</td>
<td>6.9 \cdot 10^{-2}</td>
<td>7.0 \cdot 10^{-1}</td>
<td>1.3 \cdot 10^{-2}</td>
</tr>
</tbody>
</table>

![Error rates w.r.t. distance and data-rate.](image)
Micro-Modem (cont...)

- The second test was performed in Gyeongpo lake in Korea (1.6 x 0.7) km and 3m deep with salinity.
- FER and BER measured at distances 100 to 500 m with fixed data-rate 5kbps are shown in fig. 17.
- Two hundred frames with 16-byte data were transmitted to obtain results.
- Results show that the error free communication was possible at 100m and performance was degraded gradually as distance increases up to 500m.
- The error-rates could be lowered by reducing data-rate or applying channel compensation.

<table>
<thead>
<tr>
<th>D</th>
<th>FER</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m</td>
<td>5.0 \cdot 10^{-3}</td>
<td>3.9 \cdot 10^{-5}</td>
</tr>
<tr>
<td>200 m</td>
<td>6.0 \cdot 10^{-2}</td>
<td>1.1 \cdot 10^{-3}</td>
</tr>
<tr>
<td>300 m</td>
<td>8.5 \cdot 10^{-2}</td>
<td>3.2 \cdot 10^{-3}</td>
</tr>
<tr>
<td>500 m</td>
<td>2.8 \cdot 10^{-1}</td>
<td>4.0 \cdot 10^{-2}</td>
</tr>
</tbody>
</table>

Fig. 16. Experimental setup for lake tests.

Fig. 17. Error rates w.r.t. distance.
UW Acoustic Modem

- Developed by Northwestern Polytechnical University, China, (2014).

- The block diagram and basic framework of UWA modem is shown in fig. 18-19.

- It is based on dual-core OMAP-L138 floating and fixed-point DSP processor.

- The work mode of the communications platform is classified as transmitting, receiving and sleeping mode.

- The parameters including work status, system status, port selection and baud rate are set via PC and assigned to the DSP through serial port.
UW Acoustic Modem (cont...)

- The modem has been tested in lake experiments at the distance of 10 km as shown in the fig. 20.

- After launching the hydrophones the boat engines were turned off to keep a quite environment.

- The communication rate reached up to 4kpbs with BER performance $10^{-3}$ to $10^{-4}$.

- Channel estimation results are shown in fig. 21, which has obvious sparse features, containing 3 main path and the max. delay spread reaches 35ms.

- The error rate statistics presented in fig 22, shows that major portion of the error blocks occurred at frame 3 and 8 when other ship was passing by the receiver.
Full duplex multi-user modem

• Developed by Harbin Engineering University, China, (2013).

• Block diagram of the modem is shown in the fig. 23.

• The modem consists of two digital boards, a pre-amp board, a power amplifier board and MSP430 main controller board as shown in fig. 24.

• It uses OFDM and CDMA with SS for realizing full-duplex and multi-user communication.

• A TMS320C6455 DSP board process digital signals in real time for OFDM and S3C2440 ARM board is used for SS processing.
Full duplex multi-user modem (cont...)

- The experiments were conducted in Yellow sea in China.
- Modem 1 and 2 were operating under full-duplex mode, while modem 3 was operating in multi-user mode as shown in fig. 25.
- The average depth was 20m and the modem depth was 5m.
- The full-duplex function was verified by two modems at a distance of 3km with data-rate OFDM (710bps) and SS (10bps).
- Multi-user operation was verified by three modems with data-rate OFDM (710bps) and SS (19bps).
- Fig. 26 shows sound speed profile (with blue line) and sea water temperature (with red line).
- Channel impulse response (CIR) is shown in fig. 27.
UW bio-mimetic fish robots

• Developed by Gangneung-Wonju National University, Korea, (2013).

• The research was focused on real-time water quality monitoring system using bio-mimetic fish robots.

• The working range of each fish robot is set to 500m from the docking station.

• The max. data-rate for acoustic communication was determined to 4.8kbps.

• The circular shape modem 70 mm x 40 mm consists of two analog transmission and reception boards and one digital board as shown in fig. 29.

• Fig. 30 shows a commercial USBL system adopted for this application.
UW bio-mimetic fish robot (cont...) 

- The experiments were conducted in Gyeongpo lake, Korea and results are summarized in fig. 31.

- For each experiment to acquire a BER, 400 frames consisting of 16 bytes were transmitted at data-rate of 5kbps.

- The error at a distance of 350 m could be due to underwater creature and topography.

- The system-level experiment was conducted in Han river (930m wide and 10 m deep) near Seol as shown in fig. 32.

- An UW communication link was formed between the docking station and the bio-mimetic fish robot to control and report UW sensing data in real-time.
Bidirectional Acoustic Modem

- Developed by Gangneung-Wonju National University, Korea, (2012).
- The size of modem is 70mm x 35mm with cylindrical shape.
- It consists of analog transmission and reception boards and digital MCU board as shown in the fig. 34.
- Binary modulation scheme with non-coherent detection is used in the modem.
- To provide omni-directivity, a commercial transducer is used with the modem.
- The modem can communicate bi-directional using the same transducer.
Bidirectional Acoustic Modem (cont…)

• For in-door lab tests, small water tank of size (2.9x 0.75x 0.6) m was used and transducers were in LOS at center of water tank.

• Field tests were performed in 500m wide & 15 meter deep river.

• The results shows BER around $10^{-3}$ can be achieved up to 100 meters. As distance increased by 150 meters, the BER deteriorates as shown in fig 38.

• It was observed that up to the distance of 500 m reliable communication was possible when 26 kHz resonant frequency transducer was used.

<table>
<thead>
<tr>
<th>$T$</th>
<th>$p = 10^{-1}$ analysis</th>
<th>$p = 10^{-1}$ experiment</th>
<th>$p = 10^{-2}$ analysis</th>
<th>$p = 10^{-2}$ experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>0.9618</td>
<td>0.9240</td>
<td>0.2677</td>
<td>0.3420</td>
</tr>
<tr>
<td>29</td>
<td>0.8304</td>
<td>0.5420</td>
<td>0.0383</td>
<td>0.0160</td>
</tr>
<tr>
<td>27</td>
<td>0.6114</td>
<td>0.1700</td>
<td>0.0036</td>
<td>0.0040</td>
</tr>
<tr>
<td>25</td>
<td>0.3761</td>
<td>0.0369</td>
<td>0.0003</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Fig. 36. Packet loss probability w.r.t. $T$; $L=31$.

Fig. 37. Packet loss probability in water tank experiment.

Fig. 38. BER w.r.t. distance.
High Reliable chirp UW Modem

- Developed by Key Lab. of UW Acoustic Comm. & Marine Information Technology, China.

- Hardware design is based on software defined radio (SDR) as shown in fig. 39. To exchange data in real-time, between PC and modem UART is used.

- The size of modem is 10 cm x 7.5 cm x 5 cm which includes two digital and analog boards and a transducer as shown in the fig. 40.

- It is based on M-ary different chirp spread signals (MCSS) with onboard TMS320DM642.

- At the transmitter, one information symbol carries $k$ bits messages. The receiver consists of a bank of correlators, and each correlator matches to one of the four possibilities if transmitted orthogonal sequences.
High Reliable chirp UW Modem (cont...)

- Pool and sea tests were performed to validate results of the modem.
- The transmitting frequency range was in between 20 kHz – 30 kHz with (200 to 300) bps data rates. The experiments were repeated at a distance of 20 m for error-free transmission with 100 kHz sampling frequency in 25 m x 6m pool.
- Sea tests were carried out in Wuyuan Bay, China. The data rate was 300 bps with zero bit error rate at a distance of 212 m and transmission power was less than 0.97W.
- Fig 41-42 shows the noise and signal received from the modem.

Fig. 41. Transmitter.  
Fig. 42. Receiver.
A Low-cost and High-efficient Modem

• Developed by Universitat Politecnica de Valencia, Spain, (2011).

• The modem consists of 8-bit microcontroller with additional components and the circuit as shown in the fig. 43.

• Due to the efficiency in term of bandwidth, binary coherent frequency shift keying modulation scheme is used.

• Commercial piezoelectric transducer, Hummingbird XP 9 20, is used in the modem with 85kHz frequency to reduce the cost of the system.

• During the experiments, 1kpbs data-rate with 1kHz BW. was achieved.

• The modem prototype is shown in fig. 44.
A Low-cost and High-efficient Modem (cont...)  

- The modem was tested in the port of Gandia, Valencia (Spain).
- In horizontal test successful communication was possible up to 100 m distance between the modems inside the port area as shown in fig 45(a).
- The vertical testing was performed inside and outside of the port with the distances of 10 m and 17 m respectively with successful reception as shown in the fig. 45(b) and (c).
- Received signal levels could not be measured accurately due to unavailability of environmentally protected instruments.
- The experimental results of in-door test performed in 20m x 8 m water tank are shown in fig. 46.

<table>
<thead>
<tr>
<th>Power amplifier Voltage</th>
<th>5V</th>
<th>10V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power dissipated by AB-class custom amplifier</td>
<td>43 mW</td>
<td>191 mW</td>
</tr>
<tr>
<td>Power dissipated by D-PP-B-class amplifier</td>
<td>16 mW</td>
<td>68 mW</td>
</tr>
<tr>
<td>Power transferred to the transducer</td>
<td>12 mW (10dBm)</td>
<td>48 mW (17dBm)</td>
</tr>
<tr>
<td>Received input voltage</td>
<td>34 µV</td>
<td>66 µV</td>
</tr>
</tbody>
</table>
Omni-directional UW Acoustic Modem

- Developed by Gangneung-Wonju National University, Korea, (2011).
- The modem consists of transducer, analog and digital blocks as shown in the fig. 48.
- The ARM Cortex-M3 processor is used in the modem with 14.8 lithium battery.
- The modem is controlled by a PC using RS-232 interface.
- The analog board is equipped with a transformer, which can supply voltage up to $200V_{pp}$ to the transducer.
- The transducer used in the design has resonant frequency of 70 kHz and can supply up to power of 190W.

Fig. 47. Block diagram.

Fig. 48. Modem prototype
Omni-directional UW Acoustic Modem (cont...)

- Indoor performance evaluation of the modem was conducted in a water tank as shown in the fig. 49.
- The transducers were placed in the water medium at a distance of 200 cm and modems in front of the water tank.
- The modems were connected to the laptops using RS-232 cable to control and monitor data transmission.
- The error-free transmission was possible at a data-rate of 0.2 kbps at a distance of 200 cm in water tank, as shown in fig. 50.
- An outdoor experiment was conducted in a 40m x 60m x 1m pond at a distance of 40 m, with data rate of 0.2 kbps and BER $3.3 \times 10^{-4}$. 
## UW acoustic modems designed in last 5 years

<table>
<thead>
<tr>
<th>Modems</th>
<th>Year</th>
<th>Platform</th>
<th>Range (m)</th>
<th>Data Rate (bps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SeaModem</td>
<td>2015</td>
<td>TMS320C5000</td>
<td>100</td>
<td>750, 1500, 2250</td>
</tr>
<tr>
<td>Seatrac</td>
<td>2015</td>
<td>Cortex-M4</td>
<td>1500</td>
<td>100</td>
</tr>
<tr>
<td>Short range micro-modem</td>
<td>2014</td>
<td>Cortex-M3</td>
<td>60</td>
<td>500</td>
</tr>
<tr>
<td>UW Acoustic modem</td>
<td>2014</td>
<td>OMAP-L138</td>
<td>10,000</td>
<td>4000</td>
</tr>
<tr>
<td>Full-duplex multiuser modem</td>
<td>2013</td>
<td>TMS320C6455 and Cortex-A8</td>
<td>3000</td>
<td>OFDM 710 SS 19</td>
</tr>
<tr>
<td>UW bio-mimetic fish robots</td>
<td>2013</td>
<td>-</td>
<td>500</td>
<td>5000</td>
</tr>
<tr>
<td>Bidirectional acoustic micro-modem</td>
<td>2012</td>
<td>-</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>High reliable chirp UW acoustic modem</td>
<td>2012</td>
<td>TMS320DM642</td>
<td>212</td>
<td>300</td>
</tr>
<tr>
<td>Low cost - high efficient modem</td>
<td>2011</td>
<td>8-bit Microcontroller</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Omni-directional UW acoustic modem</td>
<td>2011</td>
<td>Cortex-M3</td>
<td>40</td>
<td>200</td>
</tr>
</tbody>
</table>
Conclusion

• Ten modems have been investigated from the last five years (two samples per year).
• It is found that TMS320 DSP and Cortex are leading platforms used in modem development.
• Each modem has a different architecture and designed for different applications, hence it is difficult to draw qualitative conclusion.
• The outcomes of the investigation would be valuable for researchers, designers, and developers of the domain.
Thank you

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