A Very High Bit Rate Broadband Acoustic Modem for Short-to-Medium Range Data Transmission in Ports and Shallow Water using Spread Spectrum Modulation and Decision Feedback Equalizing

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LONG-TERM GOALS

The long term goal of this program is to develop underwater acoustic modem technology for real-time wireless transfer of high-definition images and sonar data over short-to-medium range operations in shallow water. A specific deployment goal is an acoustic tether that provides human-in-the-loop capability for an AUV performing a ship hull inspection.

OBJECTIVES

The objective of this project is to develop a prototype Very High Bit Rate Broadband Acoustic Modem, capable of achieving true data rates of up to 100 kbps at a maximum range of 300 meters, for a maximum rate-range of 30 kbps-km. The frequency band of operation is 240 kHz to 360 kHz approximately. High data rates are made possible using the high-resolution decision feedback equalizer with parallel algorithm for tracking and compensating large Doppler developed by Dr. P-P. Beaujean.

This prototype modem consists of two components: a topside acoustic modem and an underwater acoustic modem. The notebook personal computer is to run the receive modem software as well as a limited user interface. The receive modem software demodulates, decodes and reconstructs the data in real-time, and send it to the user interface and display software. The communications link between the portable topside unit and the notebook computer is TCP/IP over Ethernet. The benefit of physically separating the portable topside unit from the computer hosting the receive modem software is that the computer could be deployed remotely from the portable topside unit. The Ethernet communications link between the computer and portable topside unit allows many physical connectivity options, wired or wireless. The underwater acoustic modem is a small, low power, self-contained unit suitable for mounting on a hovering Autonomous or Unmanned Underwater Vehicle. It encodes and modulates...
input data from devices such as cameras, sonars and sensors, and uplinks the data to the topside acoustic modem in very high bit rate, broadband one-way acoustic transmissions.

**APPROACH**

Each message contains three distinct parts used to detect, synchronize, identify and transfer encoded data, while ensuring efficient, error-free reception of the data (Figure 1). The first portion of a message is a 2.7 ms chirp transmitted between 247 and 273 kHz, with a dead-time of 3 ms, and used for detection and synchronization. The second portion is a 5.1 ms message header, which contains the symbol duration (40 μs, 20 μs, 13 μs) and the type of modulation used (BPSK, QPSK). The data packet is received 3 ms after the message header. The number of information bits is set to 9120 plus 32 CRC bits, coded with BCH (15,11,1). The message starts with a 512-bit training sequence. The actual packet duration varies from 91.5 ms to 549.1 ms depending on the modulation. The true information bit rate varies from 16243 bps to 87768 bps. A tone is transmitted simultaneously at 375 kHz for efficient Doppler tracking. Table 1 summarizes the system characteristics for a variety of data packets used.

![Figure 1. Very High Bitrate Acoustic Modem message format.](image)
<table>
<thead>
<tr>
<th>Modulation Type</th>
<th>BPSK</th>
<th>BPSK</th>
<th>BPSK</th>
<th>QPSK</th>
<th>QPSK</th>
<th>QPSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol Duration</td>
<td>40 μs</td>
<td>20 μs</td>
<td>13 μs</td>
<td>40 μs</td>
<td>20 μs</td>
<td>13 μs</td>
</tr>
<tr>
<td>Symbol Bandwidth</td>
<td>25 kHz</td>
<td>50 kHz</td>
<td>75 kHz</td>
<td>25 kHz</td>
<td>50 kHz</td>
<td>75 kHz</td>
</tr>
<tr>
<td>Information bits/ frame</td>
<td>9120</td>
<td>9120</td>
<td>9120</td>
<td>9120</td>
<td>9120</td>
<td>9120</td>
</tr>
<tr>
<td>Packet duration (ms)</td>
<td>0.5491</td>
<td>0.2745</td>
<td>0.1830</td>
<td>0.2745</td>
<td>0.1373</td>
<td>0.0915</td>
</tr>
<tr>
<td>Message duration (s)</td>
<td>0.5615</td>
<td>0.2869</td>
<td>0.1954</td>
<td>0.2869</td>
<td>0.1497</td>
<td>0.1039</td>
</tr>
<tr>
<td>Information rate (bps)</td>
<td>16243</td>
<td>31784</td>
<td>46668</td>
<td>31784</td>
<td>60935</td>
<td>87768</td>
</tr>
<tr>
<td>Packet coded rate (bps)</td>
<td>25000</td>
<td>50000</td>
<td>75000</td>
<td>50000</td>
<td>100000</td>
<td>150000</td>
</tr>
<tr>
<td>Bits-per-Joule (bit/J)</td>
<td>2461.1</td>
<td>4815.8</td>
<td>7070.9</td>
<td>4815.8</td>
<td>9232.6</td>
<td>13298.2</td>
</tr>
</tbody>
</table>
Figure 2. Very High Bitrate Acoustic Modem receiver signal processing.
The data is collected using the high-resolution, low-noise acquisition system developed by EdgeTech in collaboration with FAU. The acquisition system produces complex base-band signals with a 24-bit resolution. This data is processed with a commercial off-the-shelf notebook PC, connected to the acquisition unit via Ethernet, using the Very High Bitrate Acoustic Modem decoder presented in Figure 2. Each incoming message is detected, authenticated, equalized and decoded, and the output is relayed to a de-multiplexer which routes relevant information to each application. At present, the applications are the DIDSON topside display and the vehicle control display.

The core of the decoder is a set of parallel Doppler-compensated lattice-ladder decision feedback equalizers combined with soft-decision BCH decoding. Each equalizer within the set is started at a different location of the training sequence, with a number of feed-forward taps sufficient to cover most of the multipath and a small number of feedback taps. By doing so, each equalizer identifies a path in the least-square sense and creates a time-varying filter that best matches this portion of the multipath. Only the equalizers producing the lowest mean-squared error estimation of the training sequence are retained. This technique requires a very good time resolution of the acoustic channel, which can be obtained with the broadband acoustic signals transmitted by the Very High Bitrate Acoustic Modem source. Each equalizer binary output is combined with the corresponding binary output from the other equalizers and is decoded with a soft-decision BCH routine. The integrity of the received message is tested using a CRC-32, and the information is relayed to the de-multiplexer, along with a quality level for each bit and an error flag.

**WORK COMPLETED**

The following STTR Phase II tasks have been completed:

Task 1: System Specifications,

Task 2: Portable Topside Unit (see Figure 3),

Task 7: Data Acquisition Server/Client Software,

Task 8: User Interface and Display Software.
RESULTS

The first series of experiments took place from early February 2007 until mid-March 2007. The source was placed on a kayak and moved to various locations, up to a maximum range of 118 meters. The source transducer was kept as far as possible from the water surface to minimize the pressure release impact. When the water depth was very low, the transducer would sit in mid water. Blue circles mark the various source locations in Figure 4. Whenever the source was close to the dock, live DIDSON sonar images were transmitted, otherwise canned DIDSON sonar images were transmitted. Within a message, 8000 bits were allocated for the image and 928 bits were allocated for other sensor information (temperature, depth, …).

The source speed varied between 0 and 0.5 m/s, the water depth varied from 0.5 to 3 meters depending on tide and location. Figure 4 also shows the bathymetry measured at low tide of the experimental area. The receiver was located between 1 and 1.5 meters below the water surface. The receiver location is shown as a red circle in Figure 3. Messages were transmitted at a rate of two per second, using full power and the 6 modulations listed in Table 2. A typical mission would last 5 to 6 hours.
Each battery pack would allow for approximately 18 hours of continuous operations. The bottom type was mud and sand, and the brackish water characteristics were very similar to those of South Florida coastal waters, due to the proximity of Port Everglades inlet. There was no control on boat traffic or depth sounders, and numerous schools of fish were present. Table 2 shows a performance summary of the communication system at the same location using six different transmission modes. The data was collected on 21 March 2007, from 1 pm until 5 pm. Overall, the bit error rate remains well within 4% at 88 meters range, estimated over a total of 15,578,752 information bits transmitted.

Table 2. Overview of the Very High Bitrate Acoustic Modem performance at 88 meters range for experiments conducted in SeaTech Marina, Port Everglades, Florida.

<table>
<thead>
<tr>
<th>Modulation Type</th>
<th>BPSK</th>
<th>BPSK</th>
<th>BPSK</th>
<th>QPSK</th>
<th>QPSK</th>
<th>QPSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol bandwidth (kHz)</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>25</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>No. of messages</td>
<td>324</td>
<td>217</td>
<td>379</td>
<td>217</td>
<td>425</td>
<td>303</td>
</tr>
<tr>
<td>No. of data bits received</td>
<td>2954880</td>
<td>1777664</td>
<td>3104768</td>
<td>1777664</td>
<td>3481600</td>
<td>2482176</td>
</tr>
<tr>
<td>Mean BER (%)</td>
<td>3.85%</td>
<td>3.93%</td>
<td>0.84%</td>
<td>3.93%</td>
<td>3.36%</td>
<td>3.01%</td>
</tr>
</tbody>
</table>

The Very High Bitrate Acoustic Modem recently completed multiple ship hull inspection missions at AUV Fest 2007, summarized in Table 3. The SPAWAR CETUS-II and BlueFin HAUV-1 platforms were used to perform these hull inspections, and both were equipped with the Very High Bitrate Acoustic Modem as well as a complete suite of sensors. No significant interference was observed between these sensors and the acoustic modem.
Table 3. Summary of ship hull inspection missions completed by the Very High Bitrate Acoustic Modem during AUV Fest 2007.

<table>
<thead>
<tr>
<th>Date</th>
<th>Vehicle</th>
<th>Duration</th>
<th>No. information bits received</th>
<th>Average BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/8/2007</td>
<td>BlueFin HAUV-1</td>
<td>30 min</td>
<td>16,443,360</td>
<td>1.77%</td>
</tr>
<tr>
<td>6/9/2007</td>
<td>BlueFin HAUV-1</td>
<td>30 min</td>
<td>16,989,920</td>
<td>2.50%</td>
</tr>
<tr>
<td>6/9/2007</td>
<td>BlueFin HAUV-1</td>
<td>10 min</td>
<td>6,602,880</td>
<td>1.80%</td>
</tr>
<tr>
<td>6/10/2007</td>
<td>SPAWAR Cetus-II</td>
<td>80 min</td>
<td>50,223,840</td>
<td>2.13%</td>
</tr>
<tr>
<td>6/10/2007</td>
<td>BlueFin HAUV-1</td>
<td>45 min</td>
<td>15,276,000</td>
<td>3.08%</td>
</tr>
<tr>
<td>6/10/2007</td>
<td>SPAWAR Cetus-II</td>
<td>20 min</td>
<td>10,114,080</td>
<td>3.13%</td>
</tr>
</tbody>
</table>

Figure 5. Very High Bitrate Acoustic Modem connected to a DIDSON sonar in a CETUS-II shell during AUV Fest 2007.
IMPACT/APPLICATIONS

Having human-in-the-loop capability is essential during hull surveillance and port security missions, and requires the transmission of images to a remote user. At the present time, cables are used, which prevents the usage of hovering AUVs in operating in confined areas, near propellers and around pilings. An alternate solution is to combine the latest technology of data compression with a broadband acoustic modem operating at short range. The proposed work will demonstrate, during realistic missions, that a high-speed acoustic modem can be deployed to transfer high-quality sonar images in real-time and provide human-in-the-loop capability to a hovering AUV.

RELATED PROJECTS

“Installation and Experimentation of a High-Speed, High-Frequency Acoustic Modem (HS-HFAM) coupled with a Wavelet-Based Embedded Compression Unit on the CETUS II for Real-Time Transmission of Compressed DIDSON Data to a Topside Unit”, Dr. P-P. Beaujean (PI), Sponsored by the Office of Naval Research (Dr. Swean). ONR award number N00014-05-1-0604.

“High-Speed, High-Frequency Acoustic Modem (HS-HFAM) Unit for Real-Time Transmission of Multi-User Multiplexed Data and Diver-Carried DHINS Image and Navigation Data to a Topside Unit for Operations in Ports and Very Shallow Waters”, Dr. P-P. Beaujean (PI), Sponsored by the Office of Naval Research (Dr. Swean). ONR award number N00014-05-1-0604.

REFERENCES


PUBLICATIONS


P.P.J. Beaujean, P.M. Blue and D. Kriel, “A High-Speed High-Frequency Acoustic Modem (HS-HFAM) for Ports and Shallow Water Operation”, 13th International Congress on Sound and Vibrations, Vienna, Austria, July 2006. [published].

