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A HIGH-SPEED HIGH-FREQUENCY ACOUSTIC MODEM (HS-HFAM) FOR PORTS AND SHALLOW WATER OPERATION

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Abstract

Homeland defense, anti-terrorism and force protection organizations need to efficiently inspect ship hulls and piers for foreign objects. Existing diver teams are time and manpower intensive, and ordnance searches are particularly hazardous to divers. The use of Unmanned Underwater Vehicles (UUV) in the field of hull survey and port security greatly reduces the risk to divers. Some UUVs are now capable of hovering around a target or the hull of a ship and record high-definition sonar images, while keeping key personnel at a safe distance from a potentially dangerous device, typically a hundred meters away from the point of deployment. Having human-in-the-loop capability is essential to efficiently execute this type of operation, and requires the transmission of images to a remote user. Today, this high-bandwidth information is transmitted by cable, which severely limits the UUV maneuverability and prevents the UUV from operating in confined areas. A one-way high-speed high-frequency acoustic modem (HS-HFAM) operating between 262 kHz and 378 kHz has been developed to replace such cable. High data rates are made possible using a high-resolution decision feedback equalizer (DFE) with a parallel algorithm tracking and compensating large Doppler, developed at Florida Atlantic University (FAU).

INTRODUCTION

UUV technology has found new applications in the field of hull survey and port security, and remains a key feature of mine counter-measure operations. Some UUVs are now capable of hovering around a target or the hull of a ship and record high-definition sonar images. The image quality is sufficient to visually identify potential threats. The UUV can operate while keeping key personnel at a safe distance from a potentially dangerous device, typically up to 200 m away from the point of deployment. Having human-in-the-loop capability is essential during this type of operation, and requires the transmission of images to a remote user. Today, this high-bandwidth information is transmitted by cable, which limits the UUV maneuverability, causes drag, increases the chances of entanglement and prevents the vehicle from operating in confined areas, near propellers and around pilings. Acoustic channels, though noisy, are the only reliable means for wireless communication. When combined with the latest technology of data compression, a broadband acoustic modem may transmit the same high-resolution images in compressed format while the hovering UUV performs its mission without risk of entanglement. This article describes the operation and performance a high-speed high-frequency acoustic modem (HS-HFAM) used for that purpose. The system is capable of transmitting data at coded rates of up to 150000 bits per second (bps), at a maximum range of 100 m, operating between 262 kHz and 378 kHz. At the present time, the range is limited to 100 m due to power amplifier limitations.

The three major concerns associated with broadband acoustic communication at high frequencies in harbors are reverberation, Doppler shift and, to a lesser extent, noise. Acoustic reverberation, originating from the scattering of acoustic waves off the surface, bottom, walls and obstacles, causes inter-symbol interference (ISI). In the frequency domain, reverberation is equivalent to frequency-selective fading. Frequency-selective fading also includes the effect of sound refraction due to sound velocity gradient. Doppler shift is due to the relative motion of the communication platforms and boundaries, especially the water surface ship hulls and some biological life. The combined effect of various Doppler shift is known as Doppler spread, equivalent to time-selective fading in the frequency domain. Background noise due to boat traffic is relatively benign around 300 kHz (approximately 35 dB re 1µPa/√Hz), however thermal noise causes an increase of 6 dB per octave above 100 kHz [12]. The use of high-frequencies for high-speed underwater acoustic communications has significant advantages. First of all, the transducers are small, efficient and can be fitted in small UUVs. Also, the high bandwidth means high data rate and also excellent dual space-time resolution. With this high spatial resolution, DFE (Decision Feedback Equalizing) processes can better compensate the multipath, which is the main cause of limitation of this type of communication devices.

Kojima et al. managed to transmit video images acoustically at rates of up to 128000 bps at a horizontal range of 500 m and at depths of up to 3000 m [7]. However, the acoustic communication system operated only in deep waters using directional transducers kept at a minimum of 300 m from the sea surface and sea bottom to minimize the impact of multipath on the communications. Pelekanakis, Stojanovic and Freitag developed a vertical acoustic communication system employing variable rate M-QAM modulated data transmitted over a short vertical channel [9]. This system achieves excellent results with bit rates up to 150 kbps which is sufficient to support real-time transmission of compressed video. Unfortunately, this acoustic communication system operates only vertically, that is with very short multipaths and using directional transducers. Also, the M-QAM modulation is very sensitive to noise and interference if M is larger than or equal to 16, as the modulation requires a very accurate estimate of the relative power between symbols. Kebkal and Bannasch proposed to modulate the information using a carrier swept across a broad range of frequencies to achieve high data rates in reverberant environments [4], which efficiently separates multipath arrivals by converting their time delays into their frequency reallocation. The multipath resolution is proportional to the sweep rate. Interesting results have also been published using various acoustic array processing techniques based on DFE [1][2][10], maximum-likelihood [12] and multiple-inputs multiple-outputs techniques [5][6]. However, these techniques do not directly compare to small, high-speed acoustic modems as they require complex receiver structures, most of them of large size due to lower frequencies of operations.

SYSTEM DESCRIPTION

The signal processing technique used in the HS-HFAM prototype is derived from the work on high-speed acoustic communications in shallow waters performed by Beaujean et al. [1-3][8]. The receiver signal processing is summarized in Figure 1, and a system diagram of the HS-HFAM is described in Figure 2. The source transmits each message in three distinct parts used to detect, synchronize, identify and transfer encoded data, while ensuring efficient, error-free reception of the data. The first portion of a message is a 2.7 ms chirp transmitted between 262 and 338 kHz, with a dead-time of 4 ms, and used for detection and synchronization. A second portion contains the message header information which contains basic information about the data being sent. A header is composed of three distinct preambles, which contain such essential information as the symbol duration (40 μs, 20 μs, 13 μs), the type of modulation used (BPSK, QPSK) and the message size. The preambles last 5.1 ms and, separated with a 3 ms dead-time and are modulated using direct sequence spread spectrum modulation.

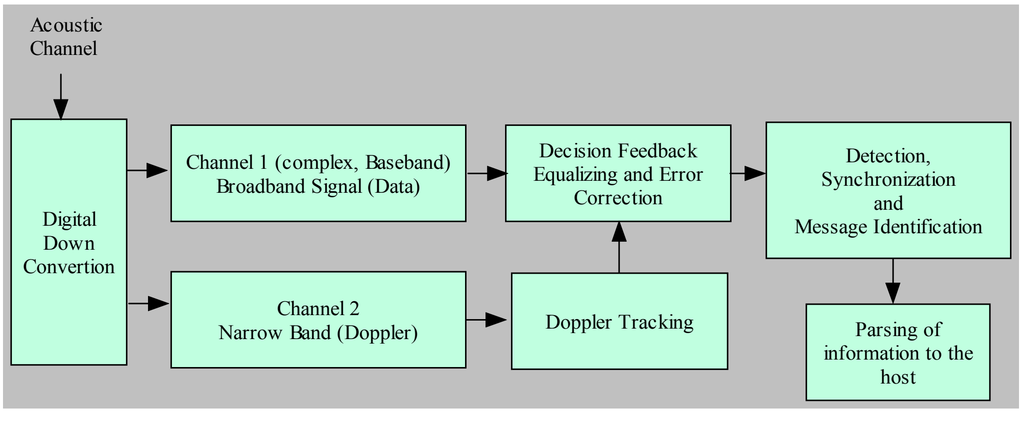

Figure 1. HS-HFAM Receiver, Signal Processing.

The last portion contains the actual data being sent. This sequence is partitioned into frames, which last 28.1 ms in the fastest mode and up to 51 ms in the slowest mode. 256 training symbols are sent for each packet, no matter what the modulation is. Following the training sequence, the message is encoded using a CRC-16 and

BCH(15,11,1) code. The source is composed of an FAU-designed low-power DSP board coupled with a broad-band power amplifier, while the receiver unit uses technology developed in collaboration with EdgeTech. Both source and receiver units are equipped with a broadband ITC-1089D transducer. The real-time receiver decoding software is derived from previous work in underwater acoustic communications by Dr. Beaujean [1-2], and consists in an efficient lattice-structured DFE combined with a Doppler tracking process and error coding.

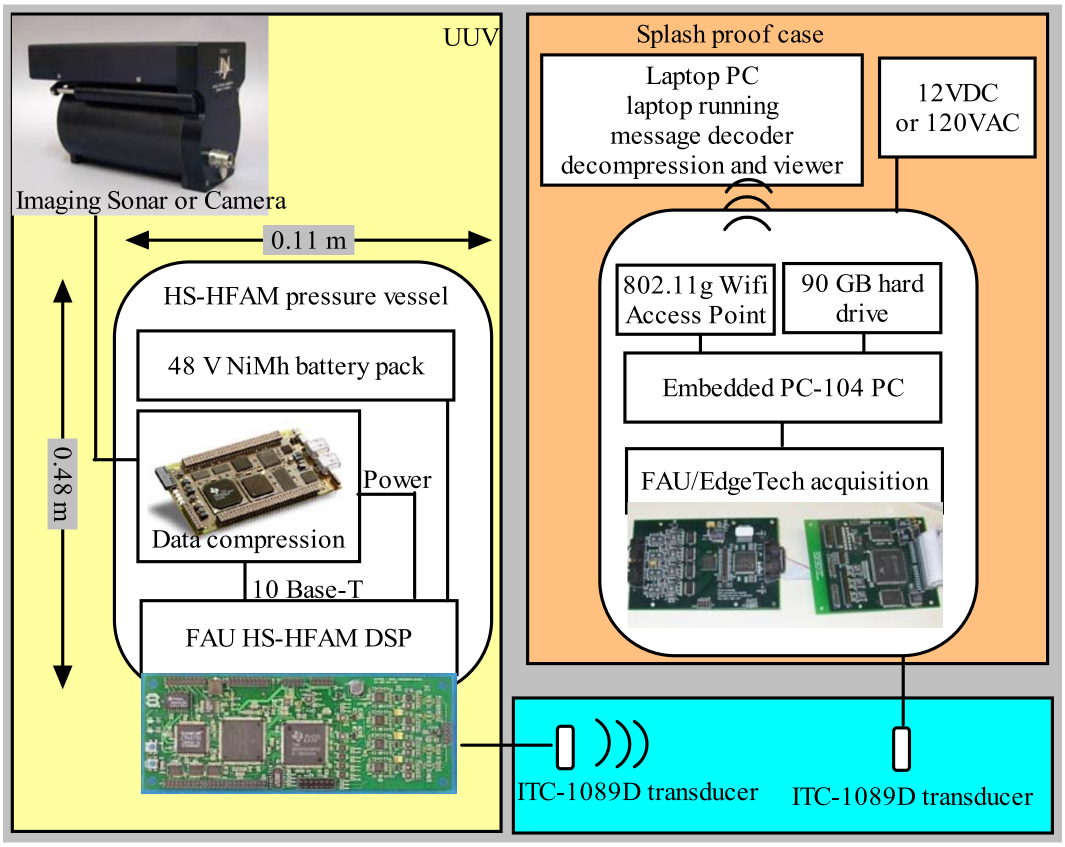

Figure 2. FAU High-Speed, High-Frequency Acoustic Modem.

EXPERIMENTAL RESULTS

Two sets of experiments were conducted in January 2006: (1) a very shallow water measurements (1 to 2 m of water depth) in the noisy environment of the FAU SeaTech marina, with relatively slow motion of the target, and (2) a shallow water measurements (13 to 15 m of water depth) in the south turning basin of Port Everglades, allowing for longer range and higher relative speed. The experimental setup in the SeaTech marina is presented in Figure 3. The receiver is placed on the dock, at 1.5 m from a concrete wall, between wood pilings. The source is placed on the back of a kayak, moving at speeds up to 1 m/s. Due to the limited space however, relative motion is typically of the order of 0.25 to 0.5 m/s. Both source and receiver are placed 0.5 m below the surface. The range between source and receiver varied from 25 m to 50 m. An omni-directional source of 173 dB (0.63 W of acoustic power) is used during these tests. In the future, a more powerful source amplifier will be used, combined with a better suited transducer. Doppler, on the other hand, can only be compensated for by the combination of the built-in Doppler tracking algorithm and DFE, which also handles ISI.

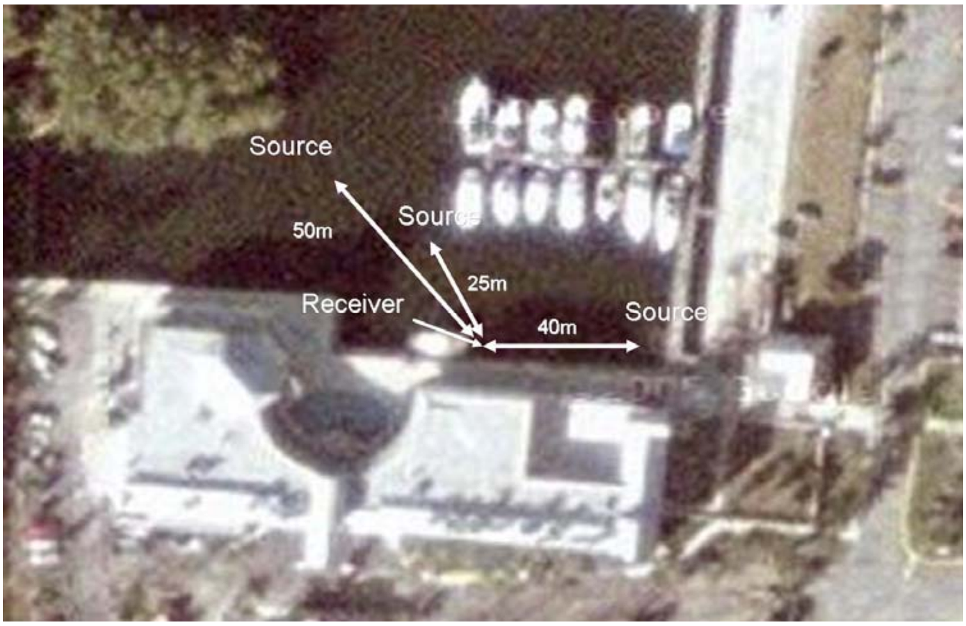

Figure 3 - Sky and side view of the SeaTech marina, indicating the source and receiver locations (25 and 50 m ranges) during the experiments of Jan 2006.

Data were collected over the course of several hours, a message being transmitted every two seconds. The shear number of messages and data collected does not allow for a detailed study of each message. Instead, relevant information of the acoustic environment is shown in the form of the impulse response of the acoustic channel when the source is located at 50 m from the receiver (Figure 4). Real-time measurement of the Doppler spread (Figure 5) using the 375 kHz tone is also provided. The background noise PSD is approximately 32 dB re 1μPa/√Hz between 262 kHz and 338 kHz. Figure 4 indicates that the reverberation is only benign in this type of environment and at these frequencies. Measurements in the marina and the turning basin confirmed this statement. Overall, the reverberation time tends to remain within 1 ms, and very occasionally reaches 2 ms. This observation can be directly tied to the loss of coherence of the scattered sound. Again, these tests took place in the proximity of boat hulls, concrete wall and shallow water, which constitute a highly reverberant environment. Therefore, the use of broadband, high-frequency signals not only limit the background noise level (typically associated with thermal noise), but also the amount of coherent ISI due to sound reverberation.

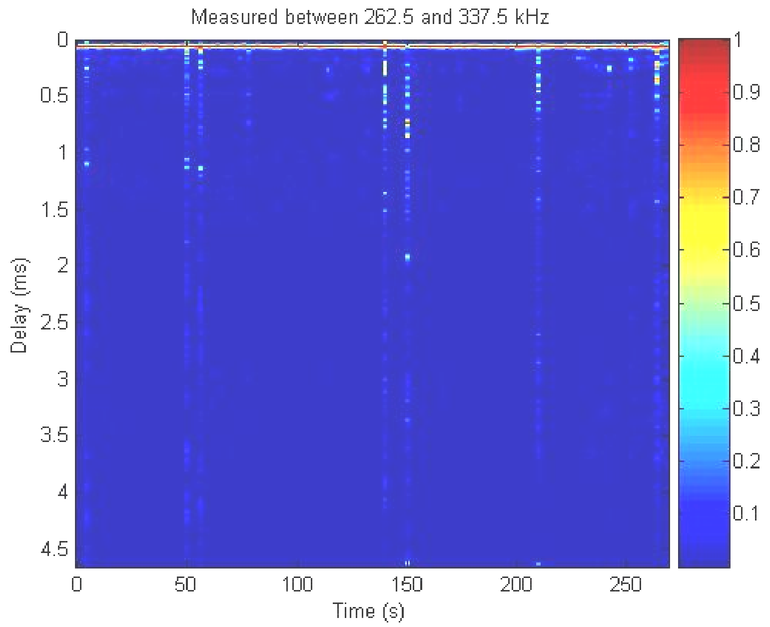

Figure 4 - Impulse response of the acoustic channel when the source is located at 50 m from the receiver, SeaTech Marina, Jan 24th 2006.

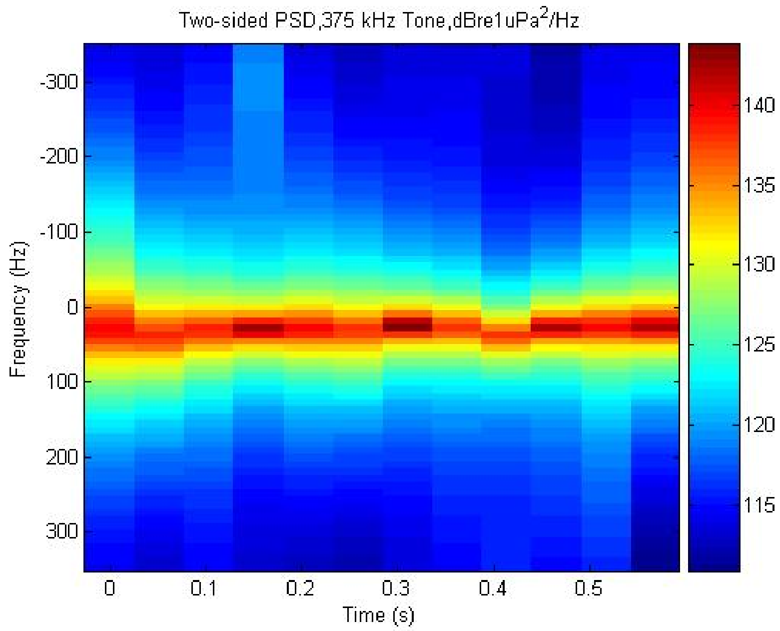

Figure 5 - Real-time measurement of the Doppler spread during the transmission of a message; the source is located at 50 m from the receiver, SeaTech Marina, Jan 24th 2006.

Unfortunately, these advantages come at a price: Doppler shift and spread. As shown in Figure 5, even when the source is in slow motion, 50 Hz of Doppler shift and as much Doppler spread are observed at 375 kHz. These observations are even more apparent in the second set of experiments in the turning basin. Doppler and SNR are the two limiting factors in the overall performance of the communications system. A snapshot of the communication system performance measured during the experiments is shown in Figure 6, during the transmission of 25 messages: the bit error rate (BER) for each message, defined as the ratio of erroneous information bits received (after error coding) to the total number of information bits, is plotted against time. SNR and peak Doppler shift measurement are over-imposed on the BER plots. Although the Doppler is fairly limited during the marina test, small drops in performance appear as the SNR becomes too low and/or the Doppler becomes larger. Information is transmitted at a coded rate of 100000 bps, where each symbol was QPSK-modulated and lasted 20 µs symbols. The decoder handles the fluctuations of SNR and Doppler very well indeed: the BER does not exceed 0.5% except for one message with a BER of 52%. A more careful study indicates that this error is due to a sudden increase in Doppler shift to 110 Hz, associated with the motion of the source, which was not estimated properly by the decoder. Overall results indicate that the link remains extremely reliable despite the fluctuations in Doppler and in SNR.

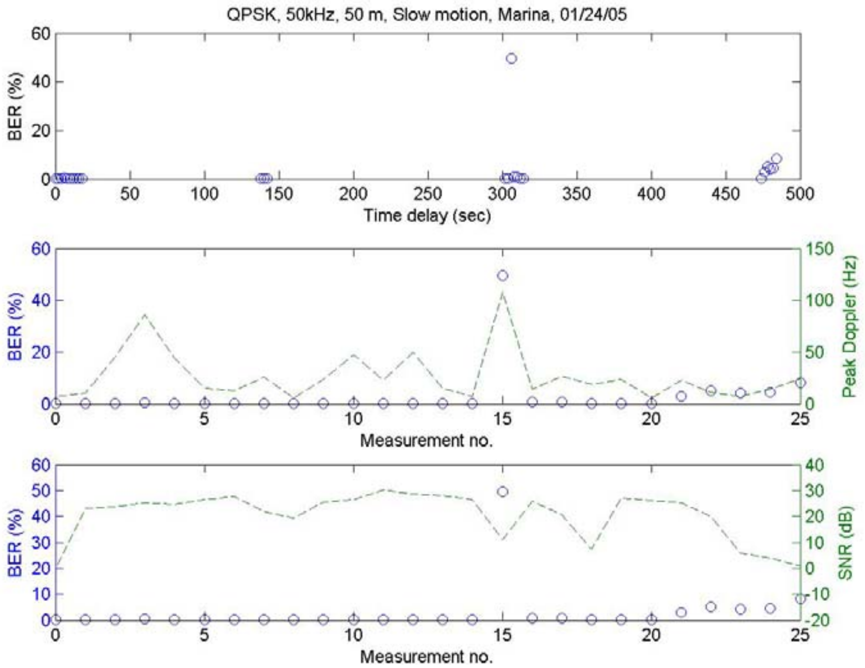

Figure 6 -Performance review for messages using 20 µs symbols (QPSK), when the source is located at 50 m from the receiver, SeaTech Marina, Jan 24th 2006.

Overall, acoustic communications were made possible at rates up to 150000 bps (coded) at a range of 50 m. At 75 m, acoustic communications was still possible up to 50000 bps (coded), due to limitations of the source power amplifier. Accurate Doppler correction was required to perform broadband underwater acoustic communications at high-frequencies, along with a sufficient SNR. In the near future, a more powerful source amplifier will be used, combined with a better suited transducer to achieve a range of 300 m.

CONCLUSIONS

Acoustic communications were made possible at a coded rate up to 150000 bps at a range of 50 m. At 75 m, acoustic communications was still possible up to 50000 bps, due to limitations of the source power amplifier. Accurate Doppler correction was required to perform broadband underwater acoustic communications at high-frequencies, along with a sufficient SNR. However, results observed at 75 m under adverse conditions in terms of Doppler and SNR (4 dB) indicated that the BPSK modulation still provides acceptable results using 20 μs and 40 μs symbols. The results were obtained using an output acoustic power of only 0.63 W, which set a limit on the range of the HS-HFAM in this configuration. This also showed that the HS-HFAM was remarkably power efficient and very well suited for small UUVs and divers: 93121 bits/J at 100000 coded bps and 130692 bits/J at 150000 coded bps.

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