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Implementation of Bidirectional High-Rate Underwater Acoustic Communication Systems for Fully Wireless-Controlled Remotely Operated Vehicles

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Abstract

The use of underwater equipment, including remotely operated vehicles (ROVs), is being considered in marine industries. As radio communication is difficult underwater, wired control is used in most cases. The achievement of wireless-controlled ROVs could increase the safety and efficiency of underwater work in many aspects. This paper describes the implementation of our developed high-speed acoustic communication modem, which is capable of bi-directional communication and can transmit video. We demonstrate video transmission and remote control via acoustic communication in actual sea areas using a ROV equipped with the modem.

1 Introduction

In recent years, the use of remotely operated vehicles (ROVs) has been considered in various marine industrial fields, such as equipment inspection, port construction, and aquaculture farm monitoring. When operating ROVs, the operator has to confirm status information such as through underwater video in real time, so ROVs and off-shore monitoring-controlling systems are usually connected with communication cables (i.e., tether cable), which limits the range of movement and maneuverability underwater. If an underwater wireless communication system capable of transmitting video could be realized, ROVs could be made wireless, dramatically increasing the flexibility of ROV operations.

When transmitting video from underwater, it is necessary to transmit 100-kbps class signals for low image quality and 1-Mbps ones for HD quality [1]. Acoustic signals are promising candidates for wireless transmission medium underwater because they are less susceptible to water turbidity and have a wide reach. However, considering the available bandwidth and channel distortion in acoustic links, transmission over 100-kbps class signals is challenging and still in the research stage (see [2], for example).

FAU's HS-HFAM is a pioneering study on high-speed acoustic communication modems [3]. Using high-precision DFE and a parallel algorithm for correcting and tracking Doppler shift, the system successfully transmits real-time images over a distance of 88 m at a rate of 87.7 kbps. HERMES [4], developed by FAU, is capable of bi-directional communication by frequency division duplexing (FDD) and transmits 400-kbit sonar data in 4.6 seconds at a distance of 120 m with diversity-based DFE. Other studies on 100-kbps-class modems are detailed in [5]. Currently, there are very few reports on Mbps-class research (e.g., [6][7]).

We are now working on Mbps-class acoustic communication technology to increase the transmission rate for wireless remote control for ROVs. We previously proposed a method to compensate for double-selective fading by removing some multipath waves in the spatial domain. Using this technology in combination with MIMO (multiple-input multiple-output), acoustic transmission up to 5.1 Mbps was demonstrated in offline signal processing with a bandwidth of 320 kHz, 8 by 16 MIMO, and QPSK modulation [7]. With real-time signal processing, high-quality video transmission using acoustic communication becomes possible, enabling remote control for ROVs.

Thus, we have implemented a first prototype of a bi-directional acoustic modem using our signal processing on FPGA, GPU, and CPU devices. In Dec. 2022, we conducted a field experiment with the developed acoustic modem on a commercial ROV specially customized for wireless control. We achieved real-time video transmission from the ROV to a support vessel and command transmission from the vessel, demonstrating wireless ROV operation underwater. This paper describes the configuration of the wireless communication system for remote controlling ROVs. We then describe the signal processing of the physical layer and MAC protocols as well as the results of the field experiment.

2 Implementation of Underwater Acoustic Communication Systems

2.1 Overview of Communication System

Figure 1 shows a block diagram of the acoustic communication system between the ROV and support vessel. The uplink (from ROV to vessel) transmits video and status information. The downlink (from vessel to ROV) transmits control commands to move, dive, change the camera direction of the ROV, etc. The uplink requires high-speed communications in excess of 100 kbps to transmit video data; the downlink requires about 10 kbps to send commands.

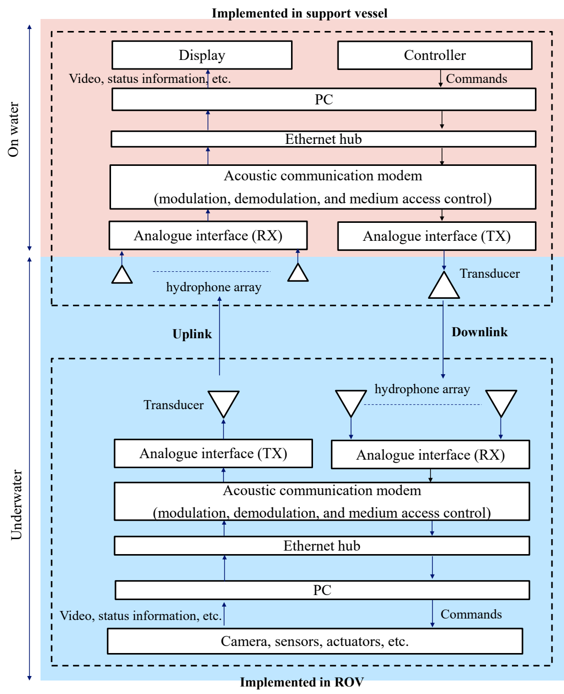

Figure 1 Block diagram of communication system

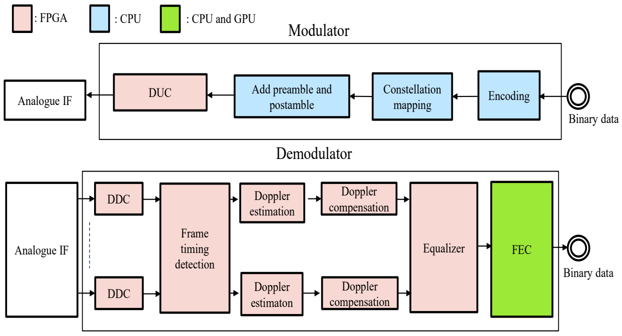

Figure 2 Block diagram of signal processing

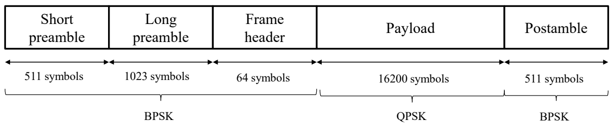

Figure 3 Structure of physical data frame

We used FDD as the duplex transmission method. We assume the maximum transmission distance between the support vessel and ROV to be 300 meters. In the case of TDD, a guard time for propagation delay of up to about 200 msec in one direction is required, as well as a transmission delay for waiting for switching links. When FDD is used, bi-directional asynchronous continuous transmission is possible, so FDD was used as the duplex method for real-time performance. Depending on the requirements, high-frequency and broadband transmission is performed for the uplink, and low-speed communication using lower frequencies is performed for the downlink.

To utilize commercial sensors, cameras, and the ROV itself as much as possible, data is exchanged via Ethernet. Thus, the host interface is Ethernet. Acoustic communication modems perform modulation and demodulation processing and handle Ethernet packets using a dedicated MAC protocol. The following sections detail the physical layer modulation and demodulation process and MAC protocol.

2.2 Physical Layer Signal Processing

Figure 2 is a block diagram of the modulation and demodulation process. The modulator encodes binary data by LDPC and BCH codes and transmits it in the frame format shown in Figure 3. For effective use of the limited bandwidth, we use DVB-S2 [8] compliant codes (code length: 16,200) with excellent correction efficiency and cliff performance. To estimate the Doppler shift from the received frame length, we use a fixed frame length. The output signal is obtained by converting baseband signals into band-pass ones through DUC (digital up conversion) processing.

The receiver performs multi-channel reception and processing. DDC (digital down conversion) converts the received band-pass signal into a 2x oversampled baseband signal. A data frame is accepted by the receiver when the cross-correlation value between a short preamble and one of any receiving channel's signals exceeds a certain threshold. Due to the symbol rate and arrangement of the receiving array, the beginning of the frame may vary by several tens of samples from one receiving channel to another, so the cross-correlation between the short preamble and received signal is calculated around a rough detection position in all channels, and the exact position of each channel is determined by the peak value.

For the same reason above, Doppler shift is also estimated for each received channel. The Doppler shift is estimated based on the ratio of received frame length to transmitted frame length [9]. It is corrected by applying resample and phase rotation processes to the received frame.

The equalizer performs spatio-temporal equalization [7] using short and long preambles as a training series. To consider processing load, signal processing is performed with 1x oversampling. The spatio-temporal equalization is identical in configuration to [10], with the number of filter taps intentionally shorter than the delay profile. Thus, delayed waves exceeding the number of taps can be removed in the spatial domain and residual waves are equalized in the time domain. Based on the frame header value, the modulation scheme of the payload section is recognized for the equalizer to make a tentative decision.

Finally, the bit string is decoded by LDPC decoding and BCH decoding based on soft decision.

DDC and DUC, which require high sample rate processing, are implemented in dedicated circuits on FPGA as well as synchronization and equalization, which require a large number of operations. Error correction is implemented on the CPU and GPU. While this system supports MIMO transmission, it is not used in the demonstrations below, so the description is omitted.

2.3 MAC Protocols for Wireless-Controlled ROVs

The MAC layer is designed to use general Ethernet frames and characteristic PHY frames to achieve bidirectional communication through FDD-based underwater acoustic communication. As mentioned in the previous section, PHY frames are fixed-length for Doppler compensation, and the data length is normally larger than that of variable-length Ethernet frames to reduce overhead. For effective use of PHY frames, the MAC layer encapsulates multiple Ethernet frames from multiple host terminals in a single PHY frame. Frame conversion and transmission/reception operations in the MAC layer are performed independently for uplink and downlink. To prioritize real-time performance in the MAC layer, retransmission control is not used.

In the MAC layer, the control protocol is designed to be used to achieve operation with link control over underwater-characteristic lossy links. An enhanced MAC header structure based on the Ethernet MAC header is used to measure link quality, and a communication-quality feedback function over bidirectional acoustic communication links is integrated. We assume that host terminals work with Internet protocol and user datagram protocol based protocol stacks. Retransmission controls may be performed at the application level in the host terminal to ensure communication quality.

3 Field Experiment

A field experiment was conducted on December 15, 2022 in Shimizu Port, Shimizu-ku, Shizuoka City (in shallow water of approximately 20-m depth) to confirm video streaming from the ROV and remote control operation from the support vessel. An iron pipe was suspended from a support vessel at sea and fixed in the sea. The ROV was operated wirelessly via acoustic communication to take pictures of the pipe. After dropping the ROV to a depth of 5 m, acoustic signal transmission was started. The distance between the ROV and vessel ranged from 5 to 10 meters. Table 1 shows the specifications of the communication system

Figure 4 shows an ROV equipped with an acoustic communication device. This ROV is a prototype customized for wireless video transmission and remote control based on FullDepth's commercial product [11]. Also, the acoustic communication device is a prototype. The transmitter on the ROV side is a D140 from Neptune Sonar Ltd. [12], and the receiver is a Teledyne Marine TC4033 [13]. Figure 5 shows the acoustic communication equipment, transmitter, and receiver on the support vessel side. The transmitter is NeptuneSonar's D11BB, and the receiver is NeptuneSonar's D140H [12].

The support vessel side has 8 channels of equalizers, a feedforward filter with 30 taps, and a feedback filter with 20 taps, for a total of 260 taps. The ROV side has 4 channels, a feedback filter with 40 taps, and a feedback filter with 20 taps, for a total of 180 taps.

Table 1 Experimental specifications

	Downlink	Uplink
Number of transducers (TX)	1 (Support vessel)	1 (ROV)
Number of hydrophones (RX)	4 (ROV)	8 (Support vessel)
Center frequency	12.5 kHz	110 kHz
Frequency bands	7.5 kHz – 17.5 kHz	50 kHz – 170 kHz
Baud rate	10 kBd	120 kBd
Modulation format	QPSK	QPSK
Net coding rate	81.2%	81.2%
Frame efficiency	86.1%	86.1%
Transmission rate (PHY)	14.0 kbps	167.8 kbps
Length of frame	1831 msec	152.6 msec

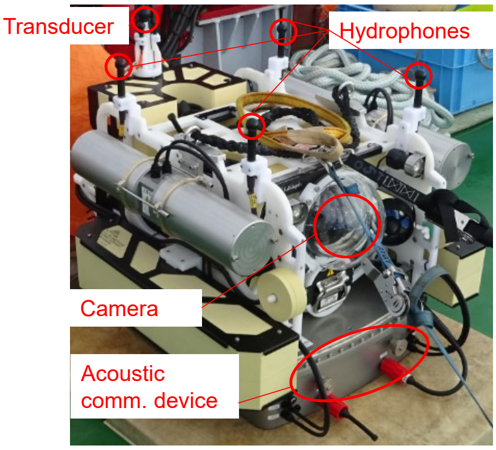

Figure 4 Picture of ROV

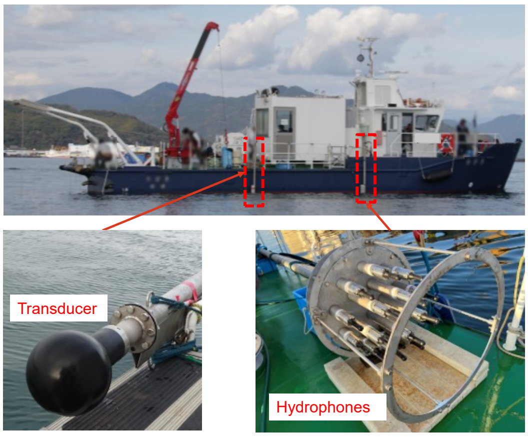

Figure 5 Picture of support vessel

For the transmission of physical frames, the frame transmission interval in the MAC section was set to 160 ms for uplink and 2000 ms for downlink so that physical frames did not overlap due to signal processing delays. The theoretical throughput in the MAC section is therefore 164 kbps and 13.2 kbps, respectively.

Figure 6 shows the characteristics of the experimental system observed from uplink packets received at the support vessel. The upper panel shows the SNR characteristics and CRC check results of the uplink packets accepted by the receiver on the support vessel side. In the

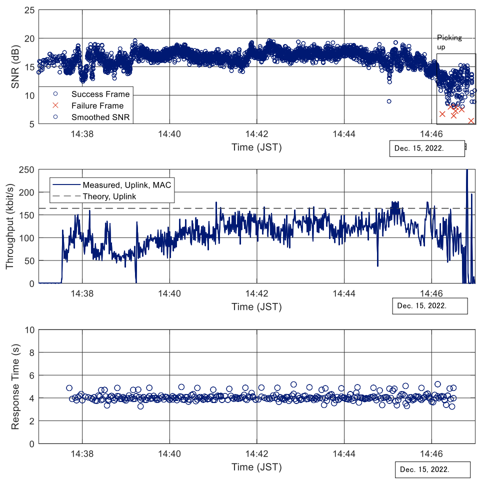

Figure 6 Performance characteristics

Figure 7 Example of transmitted video capture (480 p, 10 fps)

last section, packet loss occurred due to ROV salvage operations, but in other sections, all packets accepted by the receiver can be demodulated. The middle row shows the throughput characteristics in the MAC section. The throughput achieved the theoretical value. In sections with large video fluctuations, the throughput exceeded theoretical ones, and some packets were lost in the MAC layer but were generally received. The bottom row shows the ping response characteristics. Due to the nature of the signal processing in the physical layer, a theoretical delay of 4 seconds was generated in the up/down round trip. The observed response time was about 4 seconds, which means that there was almost no delay due to computational time for digital signal processing.

Figure 7 is an example of a transmitted video capture, showing that the iron pipe was observed. Despite a 4-second delay, it was still possible to control the ROV while checking the video image.

4 Conclusion

We developed bi-directional and high-speed acoustic communication systems for wireless remote control of ROVs. In a field experiment, video transmission and command control from the ROV were demonstrated using an acoustic communication system set to 167.5-kbps uplink and 14.0-kbps downlink.

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