Development of Underwater Acoustic Communication for Underwater Networks

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Currently, in the field of marine resource and marine renewable energy development, the use of underwater drones, such as Autonomous Underwater Vehicles and Remotely Operated Vehicles, is attracting attention. The use of drones has the potential to greatly advance marine development by significantly improving the efficiency of work that until now was performed using conventional manned vehicles. However, to explore the vast sea in an efficient manner, a coordinated operation of multiple drones is necessary, and to coordinate the operation, underwater communication between the drones is expected to be required.

Possible underwater communication methods include acoustic waves, optical waves, and electromagnetic waves. Although optical waves and electromagnetic waves are fast, they attenuate significantly underwater and limit communication to short distances of less than 100m (optical waves are also affected by the turbidity of the water). For long-distance communication of over 1km, acoustic waves are the method of choice due to their low attenuation and low environmental dependency.

Since 2020, OKI has been expanding its acoustic communication technology (vertical communication link) for use in drones, and it has reached a stage where it can demonstrate one-to-N communications from a surface vessel on the actual sea surface to underwater drones (intended usage environment). The initiative is presented in this article.

OKI's Underwater Acoustic Communication Modem

OKI began working on the development of acoustic communication technology and modems for use in underwater drones in 2020. In developing the modem, elemental technologies to deal with 1) problems specific to underwater and acoustic communication, such as multipath and Doppler effect (STEP 1: horizontal communication); 2) establishing communication in an environment with multiple drones (STEP 2: data communication with multiple vehicles); and 3) communication over longer distances or avoidance of shadow zones (areas where sound cannot reach) by using drones as relay points (STEP 3: multi-hop communication), were set as development goals.

The progress of STEP 1 through 3 is shown in **Figure 1**. Although underwater information can be obtained using various sensors on board the drones, forming a network with drones as nodes will enable thorough gathering of information from the sea. Note that **Figure 1** is a future concept, and the experiments conducted in STEP 1 and STEP 2 were performed using transducers hung from vessels and not with actual drones.

STEP 1, horizontal communication, was verified in an experiment on the actual sea surface in March 2023, and STEP 2, data communication with multiple vehicles, was tested using three vessels and verified in March 2024. An overview of the developments for STEP 1 and 2 is provided below.

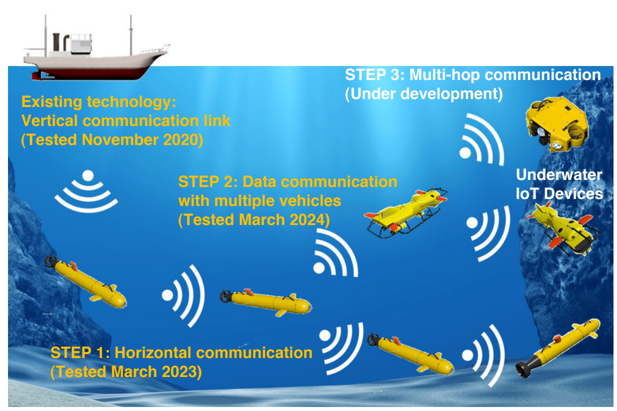

Figure1. Progress of OKI's Underwater Acoustic Communication Technology

STEP1: Horizontal Communication

In developing the horizontal communication technology, OKI set a target of achieving a data rate of 32kbps at a range of 2km, which exceeds the standard of other devices on the market. The typical rate of 20kbps at a range of 2km is to be increased 1.6 times to 32 kbps. There is a trade-off between data rate and range, and rate-range product of 40kbps-km is considered the performance standard[1].

Considering the usages such as STEP 2 and STEP 3 shown in **Figure 1**, it is assumed that the drones will be operated at intervals on the order of kilometers, and the high target is based on that assumption. It was thought that this data rate will enable adequate transmission of information collected by the computer inside the drone such as type of sound source determined from acoustic sensor data, still images, etc. However, to achieve the target, it is necessary to deal with the issues of multipath and Doppler effect mentioned previously. Dealing with these issues is the main focus of this STEP's development.

(1) Multipath Countermeasures

Multipath is a phenomenon where multiple sound waves from a source are reflected from surface boundaries such as the sea surface or seabed and arrive at the receiving end with delay. OFDM was adopted as the basic communication method. The method is also used for terrestrial radio communication, and it has multipath resistance. However, due to the difference between radio and sound as communication media, the delay time of multipath waves in acoustic communication is extremely longer compared to radio (about 200,000 times that of radio). Hence, normal OFDM mechanism alone is insufficient to counter the multipath issue.

Therefore, spatial diversity processing that improves communication stability by using multiple acoustic receivers was adopted to suppress multipath. Considering the frequency used for communication (about 10kHz to 30kHz) and the size of the drone that will use the acoustic communication modem, the size (length) of the receiving array was set to 1m or less (**Figure 2**). As for the specific processing, several methods were compared, but based on the results of sea trials, the maximum ratio combining method, which is a method that maximizes the SNR (Signal Noise Ratio) when receivers are combined to obtain an output, was selected. The method has a relatively small computational load and does not require environmental information such as the speed of sound.

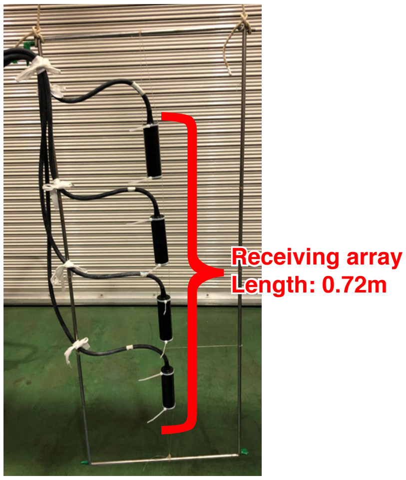

Figure 2. Receiving Array used in Actual Sea Trial

(2) Doppler Effect Countermeasures

Another major issue that needed to be addressed underwater was the Doppler effect. The Doppler effect is the expansion and contraction of waveforms (frequency changes) that occur due to the movement of an object, and in communications, these shifts in frequency between the transmitter and receiver affects communication performance. The effect is particularly noticeable in acoustic communications. OKI's aim was to enable communication even at a speed of 10kt. 1kt is approximately 0.5 m/s. This is the relative speed assumed when drones approach each other at a standard underwater operation speed of 5kt. To counter the Doppler effect, it is necessary for both the transmitter and receiver to transmit a known reference signal and waveform, measure the degree of change in the waveform caused by the Doppler effect, and then compensate for the change to regain the original waveform (Doppler compensation process).

From the results of desk studies and actual sea trial, OKI has developed a new method to improve operational stability at low SNR based on the autocorrelation method that enables relatively stable communication performance even in conditions with large multipath effect. The method prepares two or more identical known waveforms, measures the time difference between the waveforms, and calculates the deviation from the case without Doppler.

(3) Demonstration Experiment

The countermeasures developed and described in (1) and (2) are not only desk studies, and tests near Uchiura, Numazu City were also conducted to demonstrate the design results on the actual sea surface. In particular, the set target of "data rate of 32kbps at a range of 2km" was achieved during the test in March 2023.

The test was conducted using two vessels in an area with a depth of 1000m. One vessel was equipped with a transmitter and the other with a receiver. The communication performance was evaluated in a stationary state at distances of 250m, 500m, 1000m, 2000m, and 3000m between the vessels. The results are shown in **Figure 3**. At a distance of 2km, a BER (Bit Error Rate) of 0.01 or less was obtained without error correction code. The BER was 0.0001 or less with error correction code, and therefore stable communication can be expected.

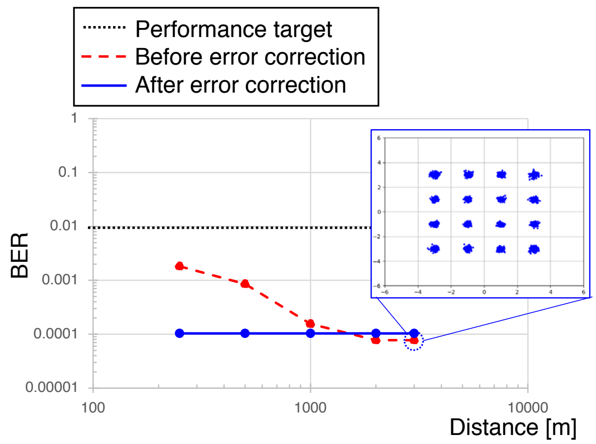

Figure 3. Stationary Communication Performance during Sea Trial

Resistance to the Doppler effect was also verified during the test. **Figure 4** shows the test setup (left) and the results (right). The test was again conducted using a transmitting vessel and a receiving vessel in an area with a depth of 100m. The transmitting vessel cruised at 8kt due to the limitations of the test jig while the receiving vessel remained stationary. Although the speed changed significantly near the closest point between the vessels, a stable speed estimate was possible and recovery of the waveform was also possible without any problems.

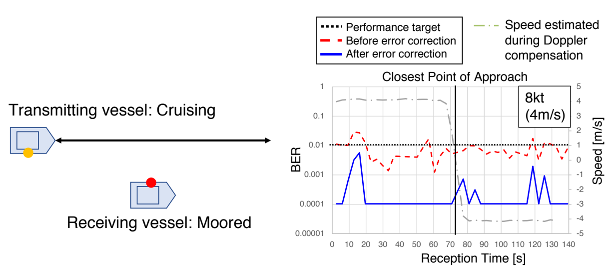

Figure 4. Verification of Doppler Compensation Process (Left: Test Setup , Right: Test Results)

STEP 2: Data Communication with Multiple Vehicles

This section explains the technological developments for data communication with multiple vehicles (1-to-N communication). In 1-to-N communication, acoustic signals transmitted from multiple devices can interfere with each other and cause errors (frame collisions). A study was conducted on a transmission control method that can reliably transmit data to the destination even under such a condition, and performance was evaluated through simulations and sea trial. In previous sea trials, performance evaluations were conducted using unidirectional communication. However, for the first time, the performance was evaluated using bidirectional communication with multiple simultaneous transmissions. Therefore, as part of the operational verification, the aim was to achieve similar performance in both simulations and sea trials.

(1) Issues with 1-to-N Communication

Acoustic signals have a lower attenuation rate than radio signals and enables long-distance communication underwater. However, signal speed is slow at about 1500m/s resulting in large propagation delays. This large delay causes issues in controlling transmission.

In terrestrial wireless communication, a method called CSMA/CA is used to avoid frame collisions. The method checks for transmissions from other devices before transmitting and sends frames only when other transmissions are not detected. However, if the delay is large, detecting the transmissions of other devices in real-time becomes difficult, and therefore the use of CSMA/CA can actually decrease performance. For this reason, the ALOHA method, which does not avoid collisions, was adopted, and a retransmission control was used to ensure frames lost due to collisions or other causes are transmitted correctly.

ACK-based retransmission control was used in the system, but this is also affected by large propagation delays. In ACK-based retransmission control, after a frame is sent, the transmitting side waits for a certain period, and the success or failure of the transmission is determined based on whether an ACK is received from the destination within that period. This waiting period is set taking into account the round-trip propagation time from when the frame is sent until the ACK is received. Therefore, as the expected propagation delay becomes longer, the required waiting period becomes longer, and this reduces transmission efficiency. To counter the decrease in efficiency due to ACK, Block ACK method, described below, was considered.

(2) Block ACK Method

Confirming the transmission of each frame using ACK becomes inefficient when frames are transmitted consecutively since it is necessary to wait until the ACK is received before transmitting the next frame. Therefore, Block ACK method, which is often used in the wireless communication, was applied to underwater acoustic communication. Block ACK method improves throughput by transmitting frames consecutively and returning a single

ACK for multiple frames instead of one ACK after each frame.

Block ACK method was evaluated through simulation taking into account the propagation delay and frame loss due to interference that are inherent in underwater acoustic communication. The evaluation was performed on a network consisting of two transmitters and one receiver at a communication distance of 2,000m. The ALOHA access control was used, and with the frame size of 1,500 bytes, the maximum number of frames that can be transmitted in a block was four.

Figure 5 shows the simulation results. In the figure, the normalized throughput on the vertical axis is the proportion of time used to receive successfully transmitted frames during the total time while the normalized traffic on the horizontal axis is the proportion of frame lengths generated during the total time. The results without block ACK are the results when waiting for an ACK after each frame transmission.

Without Block ACK, the normalized throughput's upper limit of about 0.05 was reached around the normalized traffic of 0.06, whereas there was about a 1.3 times improvement in the upper limit using Block ACK.

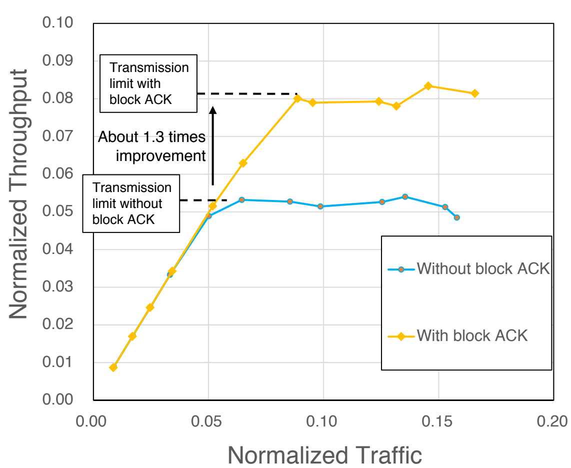

Figure 5. Simulation Results of Block ACK Method

(3) Verification of Basic Operation in Real Environment

During the sea trial, priority was given to the verification of basic operations and due to the limited time available, evaluation of block ACK was not possible. Therefore, evaluation without block ACK was compared with the simulation results.

The sea trial was conducted in an area 100m deep using three vessels: one vessel for receiving data and returning ACK, and two vessels for transmitting data and receiving ACK. The arrangement of the vessels is shown in **Figure 6**. The vessels were arranged so that the distance between each vessel was 100m. Transmissions and receptions were performed while the vessels were stationary, and operation without block ACK (wait for ACK after each frame transmission) was verified. Additionally, data was transmitted frequently to create a situation where interference is likely to occur and throughput was measured.

The results of the sea trial are shown in **Figure 7**. The point marked with ◆ in the figure is the actual throughput measured in the sea trial, and the points marked with ● are the results of a simulation performed under the same conditions as the sea trial. The throughput in the sea trial during high load was 0.071 while the upper throughput limits calculated in the simulation were 0.075 to 0.081, verifying that the sea trial and simulation produce similar results.

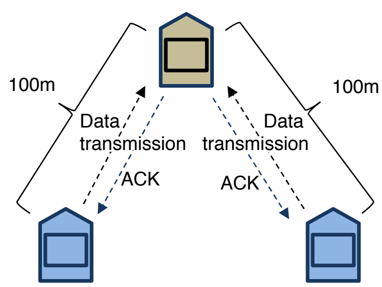

Figure 6. Verification of 1-toN Communication

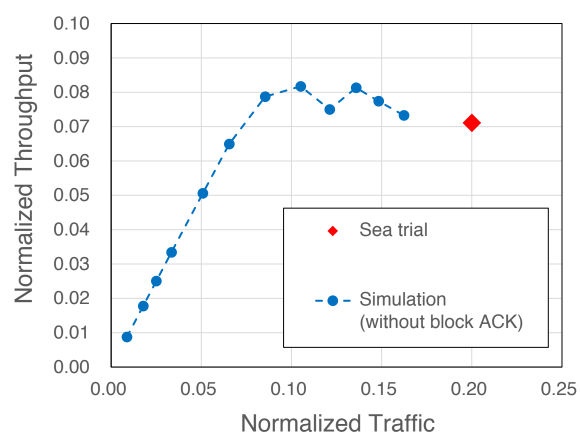

Figure 7. Sea Trial Results of 1-to-2 Communication

Future Developments

This article explained the outline of developments for STEP 1: horizontal communication and STEP 2: data communication with multiple vehicles as depicted in **Figure 1** of technological development steps. OKI is currently carrying out development to implement STEP 3: multi-hop communication and at the same time developing a communication modem implemented with the new communication methods developed so far (scheduled for release in FY2026). ◆◆

References

1) Daniel B. Kilfoyle, Arthur B. Baggeroer: The State of the Art in Underwater Acoustic Telemetry, IEEE JOURNAL OF OCEANIC ENGINEERING, VOL.25, NO.1, p4-p27, 2000

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TIPS 【Glossary】

OFDM: Orthogonal Frequency Division Multiplexing
Technology used in digital communications. It is a communications method that divides the communication band into smaller bands called subcarriers for transmission, and has excellent resistance against multipath interference. It is widely used in wireless LANs.

Receiving array
Arrangement of multiple receivers used to improve the signal-to-noise ratio.

CSMA/CA: Carrier Sense Multiple Access / Collision Avoidance
Control method for accessing a medium and used in wireless communication. Before transmitting, carrier sense (detection of transmission signals from other devices) is performed, and usage status of the wireless channel is confirmed before transmission. If a transmission from another device is detected, the device waits for a random period of time before performing carrier sense again.

ALOHA
Control method for accessing a medium. When the transmitter has data to send, it starts transmitting immediately, regardless of the usage status of the wireless channel.