Underwater Communication System to Expand Possibilities of Ocean Development

Hiroyuki Takeda   Kiyoshi Fukui

The use of underwater unmanned vehicles (AUVs, ROVs, etc.) is currently attracting attention in the areas of ocean resources and renewable energy development. Unmanned vehicles greatly improve the efficiency of ocean development over traditional manned vehicles, thus has the potential to significantly advance ocean development. However, to efficiently explore the vast oceans, coordinated operation of multiple unmanned vehicles is required, and in order to make the coordinated operation possible, communication between the unmanned vehicles is necessary.

Based on the above needs for ocean development, OKI is working on the development of an underwater communication technology that contributes to the coordinated operation of unmanned vehicles. The target specifications for this technological development are communication speed of 32 kbps and communication distance of 2 km (BER: Bit Error Rate of 10^{-2}). Additionally, communication must be possible in an environment where several unmanned vehicles coexist. This article introduces this initiative.

Development Background and Goals

Underwater acoustic communication is a key technology that will expand the operation possibilities of underwater unmanned vehicles. **Figure 1** is a concept image of the underwater acoustic communication, which shows the possibilities of this communication technology. In the operation shown in **Figure 1**, one unmanned vehicle must cover a range of at least several kilometers in order to efficiently search and investigate the ocean. Details will be skipped, but there are problems that in water, electromagnetic waves are strongly attenuated and light is largely scattered by floating debris. Therefore, it is expected that underwater radio wave communication will be used only for extremely short distances (within 10m) and optical communication for around 100m. Thus, “acoustic” communication becomes the realistic choice for long-distance communication on the order of several kilometers.

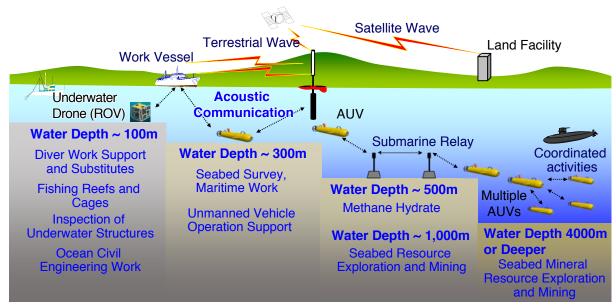

Figure 1. Concept Image of Underwater Acoustic Communication

However, acoustic communication also has limits. First, there is a limit to realizing a wideband transmitter. Second, although not as much as radio waves, the attenuation becomes greater as the sound frequency increases. This limits wideband (high-speed) communication to short distances. Therefore, there is a trade-off relationship between communication distance and speed, and as the communication distance/speed product, 40kbps x km is considered the performance standard[1)]. This performance standard was stated in Reference 1) published in 2000, and even now, the specifications published by underwater acoustic communication manufacturers are mostly below this standard.

In developing an underwater acoustic communicator, OKI set a design goal of 32kbps x 2km (64kbs x km), which exceeds the specification of existing products. Underwater unmanned vehicles require communication on the order of several kilometers, and at least this level of communication speed was considered essential for the vehicles to periodically transmit information (images, etc.) analyzed from sensor data. Taking into account that the transmitted contents are not command signals but analysis results of sensor data such as images, the target BER was set to 10-2, which is the minimum necessary for high-speed (32 kbps) communication at a distance of 2km.

Conceptual Underwater Acoustic Communication System

In the previous section, the communication performance of a single modem (modulator-demodulator) for use in the underwater acoustic communicator was specified. However, in aim to develop an underwater mobile communication system, performance consideration of a single modem is inadequate. A network system consisting of several nodes similar to surface wireless must be constructed.

Figure 2 shows the OKI's conceptual network for product commercialization.

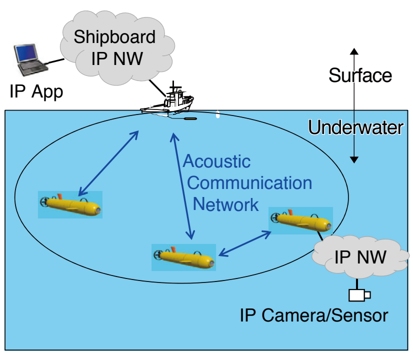

Figure 2. Conceptual Network for Product Commercialization

For communication between underwater unmanned vehicles, an acoustic communication network that supports multi-hop communication (communication performed using modems installed in the vehicles as relay points) is constructed. In this network, collected data from the vehicles are transmitted immediately via acoustic communication to the mothership making it possible to efficiently search a wide ocean area. Moreover, multi-hop communication can extend the communication distance further beyond the 2km limit of a single modem. While acoustic communication is used underwater, the network system seamlessly connects to the IP NW (general-purpose NW) used with networked shipboard equipment and external facilities.

Figure 3 shows the modem data structure (concept). The physical and datalink layers that depend on the communication transmission path were newly designed for acoustic communication. The network layer uses the Mesh-Under protocol[2)] for multi-hop communication. Information beyond the Ethernet level is encapsulated to allow secure connectivity of underwater acoustic communication (multi-hop communication) with the mothership without concern for IP NW protocol.

Application Layer	Encapsulation	IP App
Network Layer	Mesh Under	
Datalink Layer	Acoustic MAC	802.3MAC
Physical Layer	Acoustic PHY	Ethernet
	Acoustic Communication NW	IP NW

Figure 3. Data Structure for Underwater Acoustic Modem

Underwater Acoustic Communication Issues

The previous section touched on the entire system, but this section will deal with the physical layer (modulation/demodulation). Modulation/demodulation is performed to propagate bit strings (information) over a communication path (water, air) and convey information to the other party, and it is part of the system that is greatly affected by the type of communication path.

Major issues facing underwater acoustic communication are (1) multipath interference due to the water surface and seafloor reflections, and (2) large Doppler effect associated with mobile communication. Each of these issues and their countermeasures will be explained.

Figure 4 is an example of multipath and multipath interference. Multipath is caused by the delayed arrival of multiple waves reflected from boundary surfaces such as the water surface or seafloor, as shown in the upper part of **Figure 4**. The effect of multipath is shown in the lower part of **Figure 4** (for simplicity only the direct wave and one reflected wave are depicted). The unit for modulation of the bit string is called a symbol. If the kth symbol is demodulated to match the section of the direct wave represented by the dashed line as shown in **Figure 4**, the reflected wave of the k-1th symbol will be intermixed and demodulation cannot be performed correctly. Therefore, a countermeasure is necessary against this multipath interference.

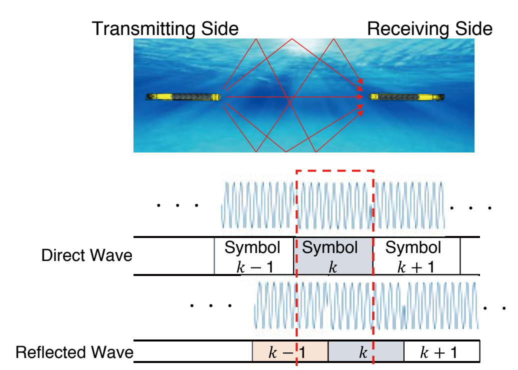

Figure 4. Multipath Interference

OFDM (Orthogonal Frequency Division Multiplexing), which is also used in Wi-Fi, was chosen as the modulation method for the underwater acoustic communication to be developed. OFDM has excellent resistance to multipath interference described above, and it is a type of frequency division multiplexing that divides the band used for communication into smaller bands (subcarriers) as shown in **Figure 5**.

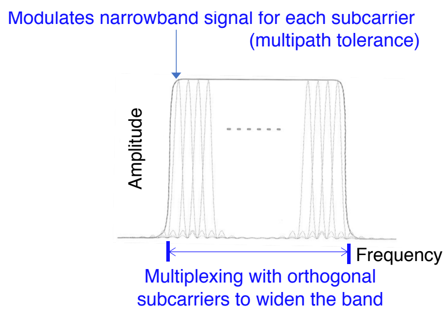

Figure 5. Image of OFDM

In order to send large volumes of data, it is necessary to widen the communication band, but wideband modulation is susceptible to multipath delay. Therefore, similar to OFDM, narrowband signals are modulated for each subcarrier, multiplexed, and transmitted over a wide band (there is an orthogonal relationship (internal product is 0) between OFDM subcarriers, and the subcarriers are guaranteed not to interfere with each other). This enables high-speed transmissions that are resistant to multipath delay.

OFDM has another mechanism called guard interval (**Figure 6**) that is strong against multipath. Guard interval is capable of handling large delays by copying the last part of the symbol to the beginning of the symbol. As shown in the example of **Figure 6**, at the time of kth symbol demodulation, only the direct wave and the reflected wave of the kth symbol (the guard interval is also a copy of the kth reflected wave) are present, and intermixing of the reflected wave from the k-1st symbol is eliminated, thus interference between symbols can be prevented.

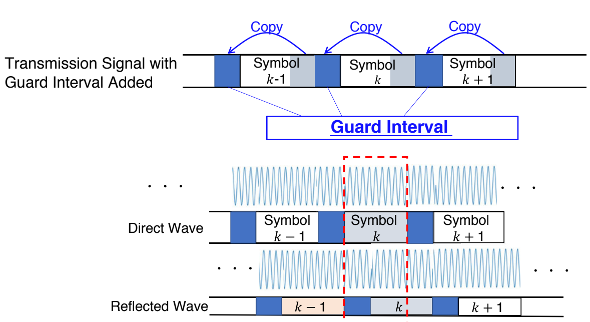

Figure 6. Guard Interval to Prevent Inter-Symbol Interference

The length of the guard interval is set longer than the delay expected in the usage environment. Likewise, in the development of underwater acoustic communication modems, the length of guard interval is determined by estimated propagation delay (how long the reflected waves are delayed) and propagation loss (how many reflections should be considered) based on assumed usage conditions (water depth, transmitter/receiver depth, etc.). Sound wave propagation model used in sonar development was used to estimate the propagation loss/delay.

Next, (2) “large Doppler effect associated with mobile communication” will be explained. Doppler effect or shift is a phenomenon in which frequency of sound changes as the sound (wave) moves (it is easy to understand if the siren of a moving ambulance or fire engine is imagined). The frequency change due to this Doppler effect negates the orthogonal relationship between the subcarriers in **Figure 5** and causes interference between the subcarriers. Therefore, in principle, OFDM has low resistance to the Doppler effect. Moreover, the Doppler effect on OFDM is a particularly difficult problem in acoustic communication, as it is more pronounced in slow-transmitting sounds.

The acoustic communication under development is for use in underwater unmanned vehicles, so it is necessary to address the Doppler effect. The aim is to enable communication at a relative speed of 10kt (the relative speed when the unmanned vehicles move in opposite directions at 5kt each, 1kt is 0.5m/s).

The Doppler effect causes the received waveforms to expand and contract according to speed (speed is average since the degree of expansion and contraction differs slightly for each multipath). A signal known on the receiving side is inserted before and after the OFDM symbol, and the expansion/contraction ratio of this known signal is measured. Based on the ratio, the OFDM symbol (in which the orthogonality between subcarriers is lost) is restored. A Doppler compensation method based on this idea is currently under study.

Current State of Development

In 2020, a desk study was conducted to achieve a communication speed of 32kbps/2km, and OFDM design parameters were derived (including the guard interval explained in the previous section). The aforementioned compensation for the Doppler effect was also examined, and a physical layer simulator was developed to perform future verification of the compensation method as well as other aspects of underwater acoustic communication.

Furthermore, testing/evaluation were performed using an anechoic tank. The tank did pose some limitations, but verification of communication performance in the horizontal direction provided promising results in obtaining the 32kbps/2km target.

In 2021, while continuing to study a specific method for implementing the Doppler compensation, work was started on designing the underwater multi-hop to be adopted in the concept network of **Figure 2**.

Basic performance was confirmed in the anechoic tank tests of 2020, but starting in 2021 and running through March 2022, performance verification will be carried several times out on the open sea. In the open sea test, the Doppler compensation method under consideration will be verified while the transceiver is actually in motion. The validity of the guard interval determined in 2020 will also be verified. **Photo 1** shows the actual open sea test conducted in September 2021. The Doppler compensation method was verified in this test by collecting data while a transceiver was suspended under a moving ship. The test was also successful in acquiring data from a maximum of 800m in the horizontal direction.

OKI believes that the realization of this technology will greatly improve the operation efficiency of underwater unmanned vehicles in ocean development. Specifically, the technology will contribute to the coordinated operation of multiple unmanned vehicles and interlinks with onshore facilities without restricting the movement of the vehicles. OKI will work to commercialize this technology in 2022, but technology development will continue beyond 2022 to further contribute to ocean development. ◆◆

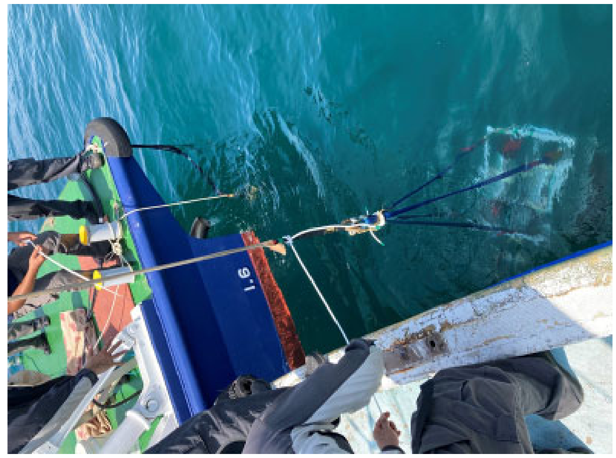

Photo 1. Actual Open Sea Testing (September 2021)

■ 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
2) Masanori Nozaki, Hiroshi Nishimura, Yuki Kubo, Kentaro Yanagihara: Wireless multi-hop routing method for smart networks, OKI Technical Review, Issue 218, Vol.78 No.1, p78, October 2011 (in Japanese)

● Authors

Hiroyuki Takeda, Research & Development Department, TOKKI Systems Division, Solution Systems Business Group

Kiyoshi Fukui, Network Technologies R&D Department, Innovation Promotion Center

TIPS【Glossary】

ROV (Remotely Operated Vehicle)
An unmanned underwater robot that is remotely controlled and is often operated via an umbilical cable (cable for power supply and communication, but some without a cable). Sometimes called an underwater drone.

AUV (Autonomous Underwater Vehicle)
An underwater robot that has a built-in CPU and power source enabling it to act autonomously (such as avoiding obstacles) without control from the mothership.