R&D Activities of Core Wireless Technologies to Implement the Social Infrastructure for IOWN/6G

Hirofumi Sasaki and Seiji Ohmori

Abstract

NTT and NTT DOCOMO are working together to implement “5G Evolution & 6G powered by IOWN,” a combination of 6th-generation mobile communication system (6G) networks and the Innovative Optical and Wireless Network (IOWN). In this article, we introduce NTT Network Innovation Laboratories’ initiatives for the IOWN/6G era, including orbital angular momentum multiplexing transmission technology in the sub-terahertz band for ultra-high-speed, large-capacity communications and underwater acoustic communication technology for extreme coverage extension.

Keywords: 5G Evolution & 6G powered by IOWN, orbital angular momentum multiplexing, underwater acoustic communication technology

1. Introduction

Nearly four years have passed since the commercial launch of 5th-generation mobile communication system (5G) services in 2020, and its adoption is gradually increasing. In 2023, the national 5G population-coverage ratio reached 96% in Japan [1], and the proportion of 5G smartphones in total smartphone shipments increased to 95% [2]. The mobile communication system, which is essential to the information and communication infrastructure, undergoes a generational change approximately every ten years. Various initiatives and research and development (R&D) efforts are currently underway in many countries and organizations for 6G, which is expected to be implemented in the 2030s. The Innovative Optical and Wireless Network (IOWN), which is promoted by the NTT Group, is an initiative for the next-generation communication infrastructure, to be practically implemented around 2030, similar to 6G, and will be an important communication-infrastructure foundation in the 6G era. The fusion of the 6G network, IOWN, and information-processing technologies is expected to evolve into a social infrastructure that can address various social issues and provide diverse value. This convergence of 6G and IOWN technologies is called “5G Evolution & 6G powered by IOWN,” on which NTT and NTT DOCOMO are working closely [3]. The following technical requirements for 6G are described in detail in the DOCOMO 6G White Paper [4]: extreme high data rate, high-capacity communications, extreme low latency, extreme coverage, extreme high reliability, extreme low energy and cost, and extreme massive connectivity and sensing.

In this article, we introduce NTT Network Innovation Laboratories’ initiatives for the IOWN/6G era, including orbital angular momentum (OAM)*1 multiplexing transmission technology in the sub-THz band*2 for ultra-high-speed, large-capacity communications, and underwater acoustic communication technology for extreme coverage extension.

*1 OAM: OAM is one of the physical properties of radio waves and is expressed as the product of the positional coordinate and its conjugate momentum. Radio waves with different OAM are uncorrelated and can be superimposed and separated independently.

*2 Sub-THz band: The sub-terahertz band refers to the frequency range between 100 GHz and 1 THz. It is characterized by extremely short wavelengths (ranging from several hundred micrometers to several millimeters) and strong linearity.

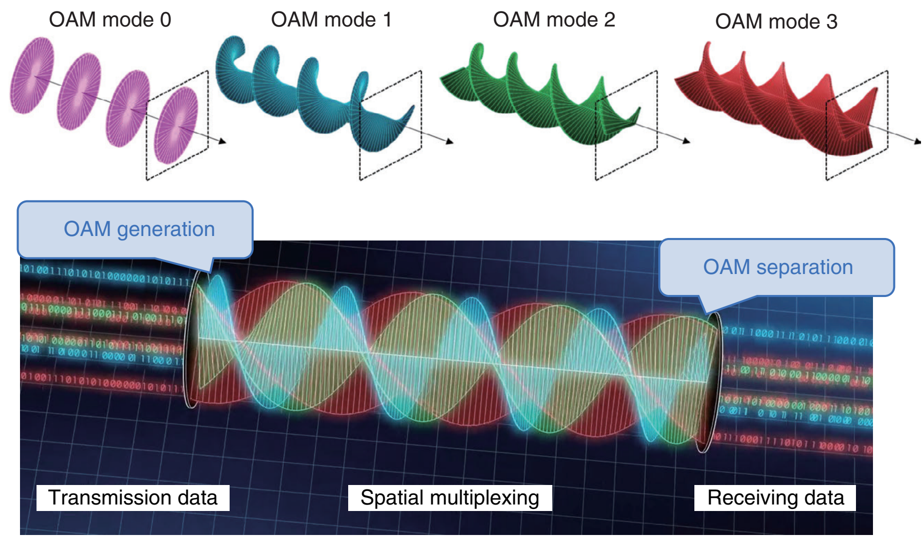


Fig. 1. Schematic of OAM multiplexing transmission technology.

2. OAM multiplexing transmission technology in the sub-THz band

The demand for wireless communications is increasing exponentially and will continue to grow even after 5G. 5G has introduced high-frequency bands called millimeter-wave bands for the first time, providing high-speed wireless communication services by broadening the transmission bandwidth.

In these high-frequency bands, however, radio waves show high straightness and are strongly affected by shielding and propagation losses, requiring base-station facilities and antennas to be placed at higher density. Thus, a more flexible network configuration and higher installability will be required for xHaul*3 connecting base stations and core networks. Wireless transmission technology is a good option to meet these demands and can be used in various scenarios, such as high-density deployment of fixed or temporary base stations in environments where fixed optical wiring is difficult, to take advantage of the flexibility and installability of wireless connection. Considering the functional sharing among base-station facilities and the subordinate connection of multiple facilities, xHaul requires extremely high transmission capacity exceeding 1 Tbit/s. NTT is engaged in R&D of terabit-class wireless transmission technology to support the high-capacity network and information-processing infrastructure of IOWN/6G and prepare for the increasing future demand for wireless communications.

There are three directions that can be taken to increase capacity in wireless communications: increase the spatial multiplexing*4 order, broaden the transmission bandwidth, and increase the modulation level. NTT is taking the approach of increasing the spatial multiplexing order through the use of a new principle based on electromagnetic waves having OAM and broadening the transmission bandwidth using the sub-THz band.

OAM is a physical property of radio waves, and radio waves with OAM (so-called OAM waves) have identical phase trajectories with a helical structure that spirals in the propagation direction (**Fig. 1**). The phase of an OAM wave propagates in a rotation symmetrical to the propagation axis, and OAM waves with integer multiple of the phase rotations are orthogonal to each other. Accordingly, multiple OAM waves with different spiral structures can be superimposed and separated without them interfering with each other if we use a receiver that can receive each OAM wave with its corresponding phase rotation.

NTT takes an approach using an analog circuit called a Butler matrix to increase the spatial multiplexing order by multiplexing multiple OAM waves.

*3 xHaul: General term for transmission networks, such as fronthaul, mid-haul, and back-haul, that connect base-station facilities and core networks.

*4 Spatial multiplexing: A transmission method with which multiple data series are transmitted in parallel by using multiple spatially independent radio waves simultaneously and in the same frequency band.

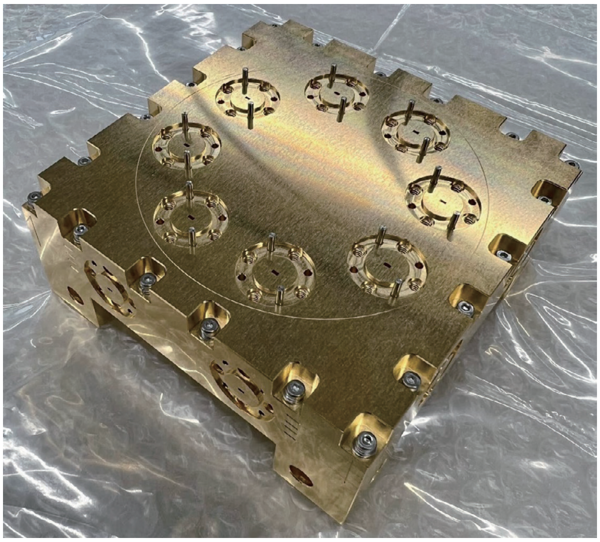
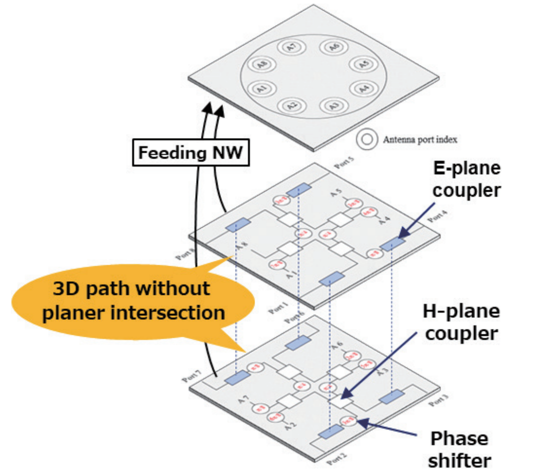


Fig. 2. An antenna-integrated Butler matrix developed for the sub-THz band.



NW: network

Fig. 3. Schematic of multilayer 3D path of the Butler matrix.

This approach reduces the enormous amount of digital signal processing required to eliminate interference between multiplexed data streams in high-capacity communications exceeding 1 Tbit/s. NTT has promoted R&D of sub-THz-band waveguide technology and developed an antenna-integrated Butler matrix that operates with a wide bandwidth and low loss (**Fig. 2**). The antenna-integrated Butler matrix is designed to simultaneously generate and separate eight different OAM waves over a very wide bandwidth, i.e., 135 to 170 GHz, which can be used to multiplex and transmit eight data signals. By executing OAM multiplexing transmission with two different polarizations, it is possible to multiplex and transmit twice as many data signals simultaneously without them interfering with each other.

To transmit eight OAM waves simultaneously by using the Butler matrix, the phase of the radio waves must be controlled with extremely high precision. Since the phase of radio waves varies with frequency, it is extremely difficult to control the phase uniformly over a wide bandwidth by using an analog circuit. We first analyzed the unique radio-wave propagation in a waveguide, which is different from free space, and developed a phase shifter that can theoretically align the advance of phases uniformly over a wide bandwidth.

By designing a multilayer three-dimensional (3D) path (**Fig. 3**) that includes the aforementioned phase shifter so that all paths are electrically equal in length and planar intersections in the circuit (which degrade performance) are eliminated, we developed a prototype Butler matrix that can provide the necessary phase for each OAM mode over 35-GHz width. One characteristic of this Butler matrix is that it is designed as a hollow waveguide, and compared with general dielectric-substrate circuits, it can prevent dielectric loss and radio-wave leakage, achieving low loss despite being a high-frequency circuit.

We conducted transmission experiments using the antenna-integrated Butler matrix and achieved the world's first high-capacity wireless transmission totaling 1.44 Tbit/s in the sub-THz bands of 135.5 to 151.5 GHz and 152.5 to 168.5 GHz in March 2023 [5] (**Fig. 4**), and 1.58 Tbit/s was achieved by further reducing waveguide losses [6]. The next step in this research is to establish and demonstrate terabit-class wireless transmission technology over longer distances exceeding 100 m while envisioning various application scenarios of this technology as xHaul.

3. Underwater acoustic communication technology

3.1 Background

6G, which is being researched and developed for implementation in the 2030s, is expected to not only upgrade mobile communication systems on land but also extreme coverage extension by developing communication areas including air, sea, and space, which have been unexplored areas concerning mobile

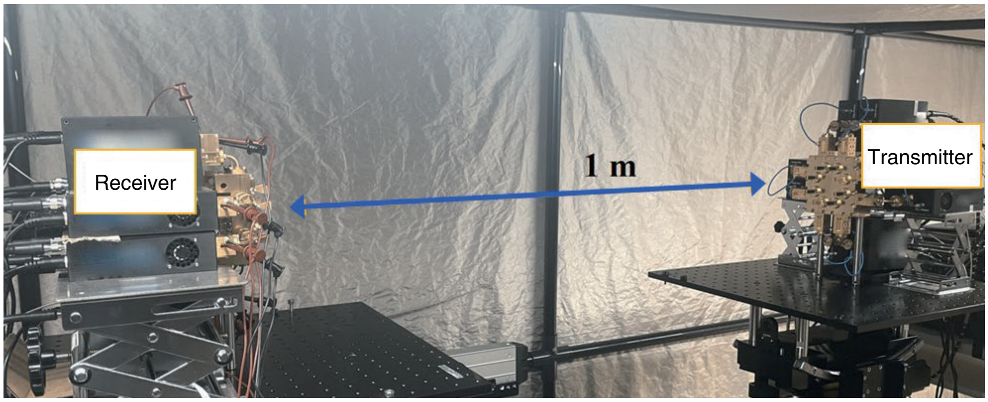


Fig. 4. OAM multiplexing transmission experiments using the Butler matrix.

communication systems [4]. Regarding the sea, it is necessary to improve efficiency by using information and communication technology in sea-based industrial fields such as underwater-resource exploration and port-facility construction, but the use of wireless communications has been difficult.

NTT has been engaged in R&D of underwater acoustic communication technology to enable underwater wireless communications. In November 2022, NTT succeeded in transmitting 1 Mbit/s at 300 m using this technology for the first time and developed a fully wirelessly controlled remotely operated vehicle (ROV) [7, 8].

3.2 Proof of concept for submarine-communication-cable maintenance service

Submarine communication cables are the cornerstone of communications between continents, and most modern international Internet communications are conducted through these cables. The maintenance and inspection of these cables is important, and in the NTT Group, NTT World Engineering Marine (NTT-WE Marine) conducts such maintenance and inspection. Preventive maintenance is important to prevent large-scale communication failures such as disconnection of submarine communication cables. The risk of failure is particularly high in shallow sea areas within a water depth of 30 m, and there is a risk of damage to the exterior and protective pipes as well as the cutting of cables, so inspection is essential. However, inspection divers manually conduct all inspections, which involve risks and is not practical. Therefore, NTT-WE Marine and many other companies are making efforts to improve the inspection efficiency of submarine communication cables by using underwater robots such as ROVs.

However, ROVs are currently controlled through wired connections because wireless communications are difficult under water. In the inspection of submarine communication cables, the inspection range is often from a few meters to a few hundred meters. In shallow waters within a depth of 30 m, where most preventive maintenance is carried out, not only marine structures such as ships and buoys but also rocks and corals on the seafloor become obstacles. Therefore, the operation of the control cables of wire-controlled ROVs is a major challenge.

In September 2023, NTT and NTT-WE Marine conducted a proof of concept (PoC) to investigate an actual submarine communication cable using a fully wirelessly controlled ROV equipped with NTT’s underwater acoustic communication technology. **Figure 5** shows an overview of this PoC. A controller for controlling a wireless ROV and underwater-acoustic-communication device are installed in a cable-laying ship, and the wireless ROV is controlled using underwater acoustic communications from the ship. The underwater video captured with the wireless ROV is wirelessly transmitted through underwater acoustic communications, and the condition of the underwater communication cable on board is confirmed. **Figure 6** shows the communication quality and a video frame showing video quality. The submarine-communication-cable inspection with the wireless ROV was carried out for about 1 h, and the success rate of video-frame transmission during that time was about 96%, confirming that submarine-communication-cable inspection with a wireless ROV is possible.

To further improve the performance of the underwater

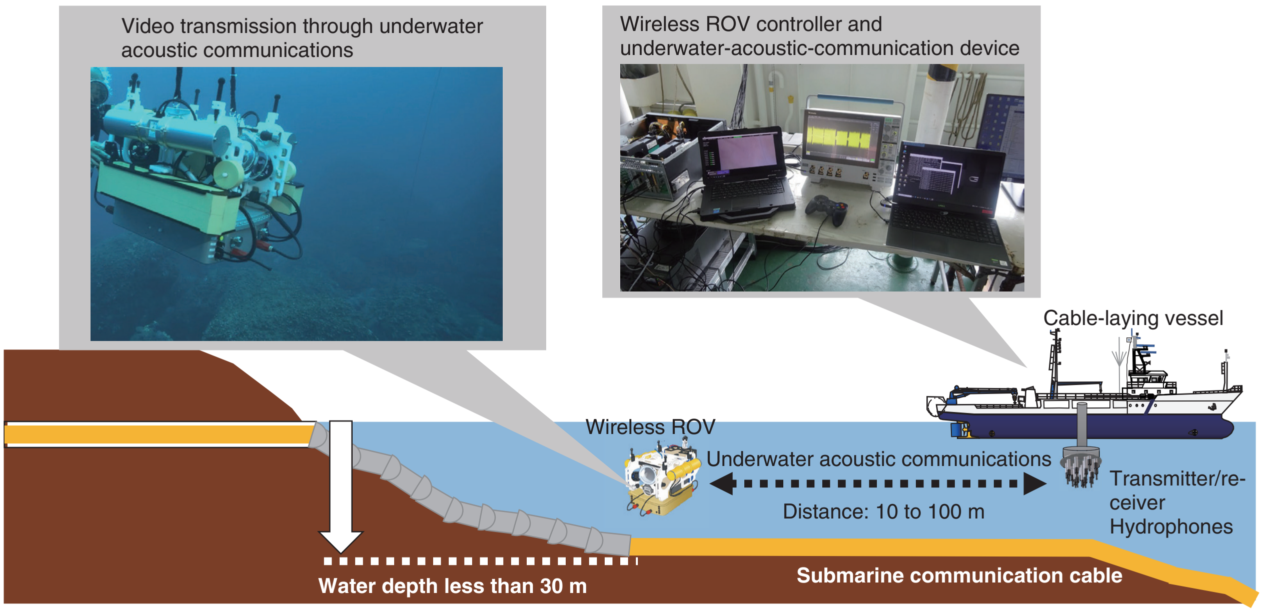


Fig. 5. Overview of PoC of submarine-communication-cable inspection using a fully wirelessly controlled ROV.

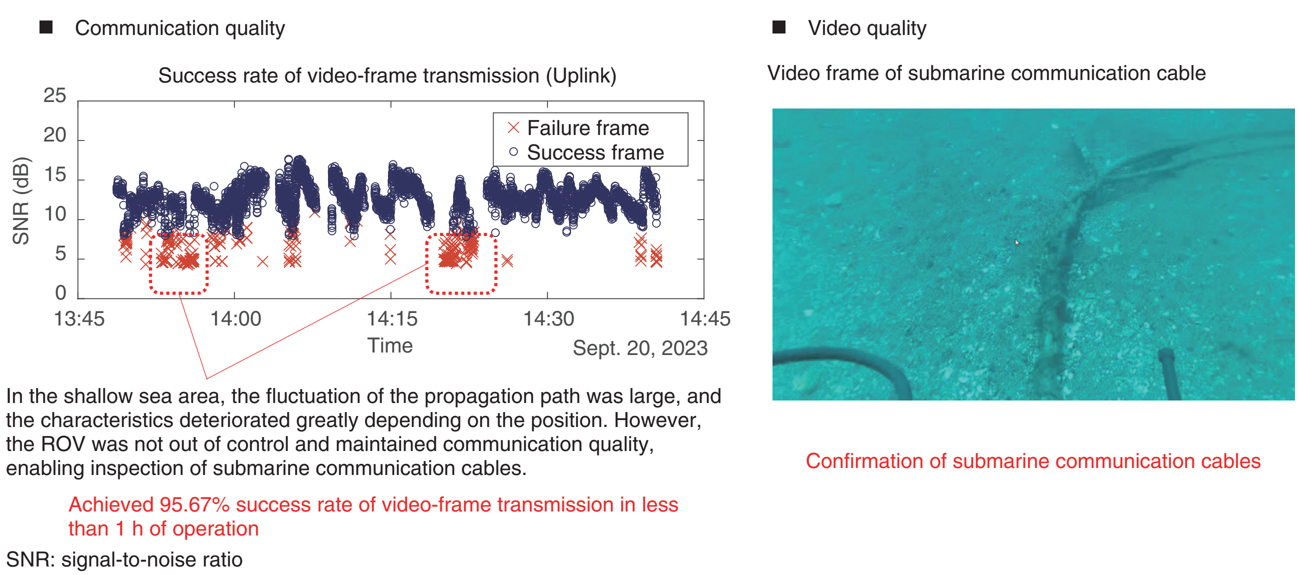


Fig. 6. PoC results.

acoustic communication technology, we will investigate underwater positioning technology to identify where inspection points are located on the seafloor where the Global Positioning System cannot reach and improve the efficiency of inspection work for submarine communication cables.

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