R&D Activities of Core Wireless Technologies toward 6G Radio Access

Jun Mashino, Yosuke Fujino, and Riichi Kudo

Abstract

Technical research for the 6th-generation mobile communication system (6G) expected to be implemented in the 2030s has been advanced to achieve extreme high data rate/capacity, extreme low latency, extreme high reliability, and extreme coverage extension for non-terrestrial areas. In this article, we introduce the following core wireless technologies developed by NTT Network Innovation Laboratories toward 6G, i.e., orbital angular momentum multiple-input multiple-output (OAM-MIMO) multiplexing transmission, underwater acoustic communication, and wireless-link-quality prediction.

Keywords: OAM multiplexing, underwater acoustic communication, wireless-link-quality prediction

1. Introduction

Mobile communication systems, which are now essential for our daily lives, have evolved once every ten years. The 5th-generation mobile communication system (5G) service has been provided since 2020 in Japan, and much research for 6G, expected to be implemented in the 2030s, has been conducted around the world. The vision with mobile communication systems has been providing mobile multimedia functions including displaying websites, movie content, and reinforcement of application software in the 3G/4G era. The vision in the 5G/6G era will be expected to take on a role as a society infrastructure that can address various social issues and support diverse industries.

Use cases, target performance, and technology candidates expected for 5G evolution and 6G are described in NTT DOCOMO's 6G White Paper [1], including the concept of 6G combined with innovative networking and information technologies for the Innovative Optical and Wireless Network (IOWN) led by the NTT Group. Technical development in 6G addresses not only basic performance enhancement (e.g., extreme high data rate/capacity, extreme low latency, extreme high reliability, and extreme massive connectivity) but also new challenges including extreme coverage extension to the sky, sea, and space (**Fig. 1**). In this article, we introduce the following three core wireless technologies developed by NTT Network Innovation Laboratories toward 6G, i.e., orbital angular momentum multiple-input multiple-output (OAM-MIMO) multiplexing transmission, underwater acoustic communication, and wireless-link-quality prediction.

2. OAM-MIMO multiplexing transmission for terabit-class wireless communication

The benefit of 5G is high-speed transmission by introducing wide bandwidth in the high-frequency band called millimeter waves, which is being used in mobile communication systems for the first time. The final target in 5G radio access is 20-Gbit/s transmission in future evolution, and 6G radio access is expected to reach 100-Gbit/s transmission by exploring a higher-frequency band known as the sub-THz band to obtain more radio resources. However, a high density of base-station antennas has to be deployed compared with current systems due to the problems of straightness of radio waves and coverage holes due to blocking in such a higher-frequency band. Therefore, a flexible network and easy installability are required for xHaul* connecting between base-station equipment. If wireless high-capacity xHaul is achieved, it will be possible to provide a highly dense

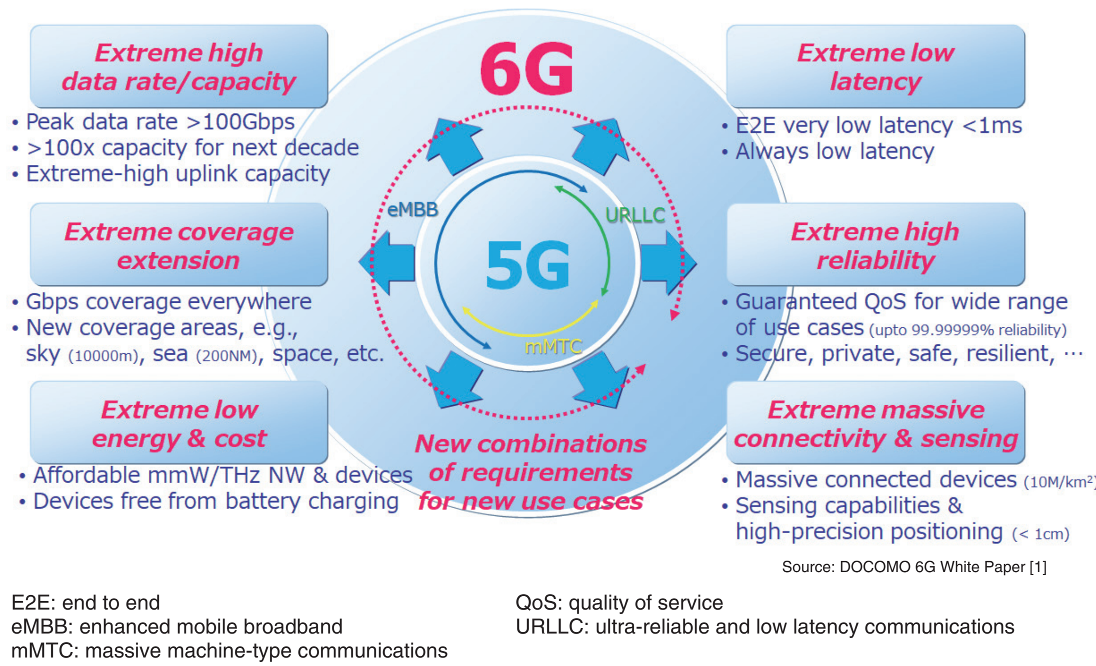

Fig. 1. Requirements for 6G wireless technology.

deployment solution of base-station equipment in areas where there is difficulty in optical wiring or temporary expansion of base-station equipment. However, wireless xHaul for 6G requires an extremely high capacity of over 1 Tbit/s (terabit-class) transmission in consideration of radio access evolution described above, function split between base-station equipment, and accommodation of multiple types of base-station equipment (**Fig. 2**).

NTT Network Innovation Laboratories has conducted advanced research on OAM multiplexing technology. OAM is a physical property of electromagnetic waves characterized by a helical phase front in the propagation direction. Since these characteristics can be used to create multiple orthogonal channels, wireless communication using OAM can increase radio-spectrum efficiency. Given an electromagnetic wave having this OAM property, the trace of the same phase takes on a helical shape in the propagation direction. Different data signals can be transmitted simultaneously by transmitting different signals using radio waves having different OAM modes. Since radio waves having this OAM property cannot be received without a receiver having the same number of phase rotations at the time of transmission, multiple radio waves having different OAM modes can eventually be separated without mutual interference.

OAM-MIMO multiplexing transmission, originally proposed by NTT, uses coaxial uniform circular array (UCA) antennas for OAM transmission and reception in consideration of practical implementation. We combined OAM and existing MIMO technology by treating UCAs with different radii as sub-array antennas for MIMO transmission so that an extreme amount of spatial multiplexing can be achieved while preventing the use of higher-order OAM modes, which is inappropriate for long-distance transmission (**Fig. 3**). Load reduction for baseband digital signal processing is one of the advantages of OAM-MIMO since signal processing can be separated into analog passive circuits for OAM and digital signal processing for MIMO. This contributes to low-energy consumption and achieving transmission with much wider bandwidth.

An indoor experimental trial was conducted in the 28-GHz band to challenge the limit of spatial multiplexing. The results indicate that OAM-MIMO can multiplex 21 spatial streams in combination with vertical/horizontal polarization and achieve high-capacity transmission of 201.5 Gbit/s [2] (**Fig. 4**). An outdoor experimental trial was also conducted in the 40-GHz band to prove the feasibility of long-distance

* xHaul: Unified transport network infrastructure connecting between base-station equipment, e.g., fronthaul, midhaul, and backhaul.

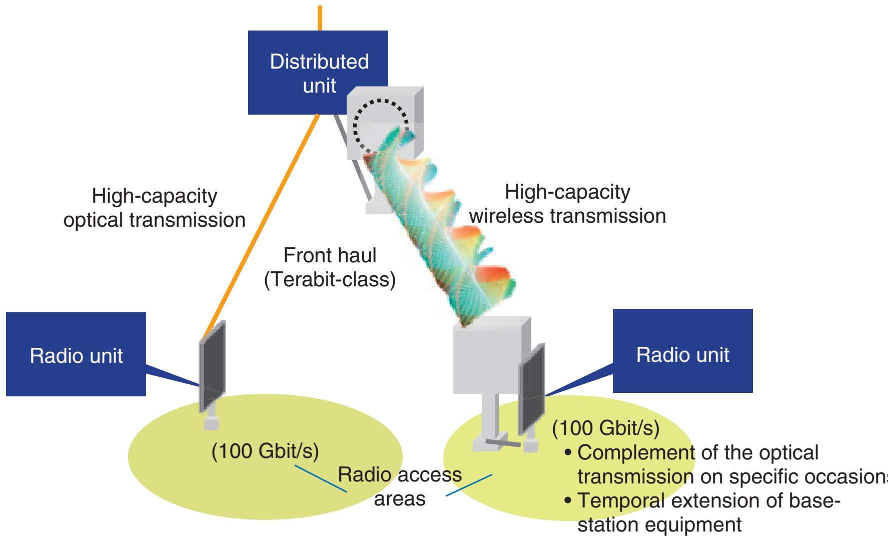

Fig. 2. An example of xHaul for base-station equipment.

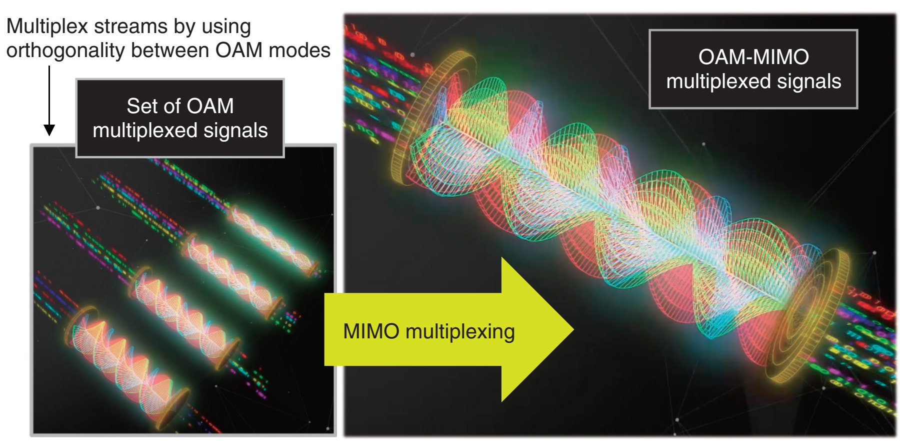

Fig. 3. Concept of OAM-MIMO multiplexing transmission.

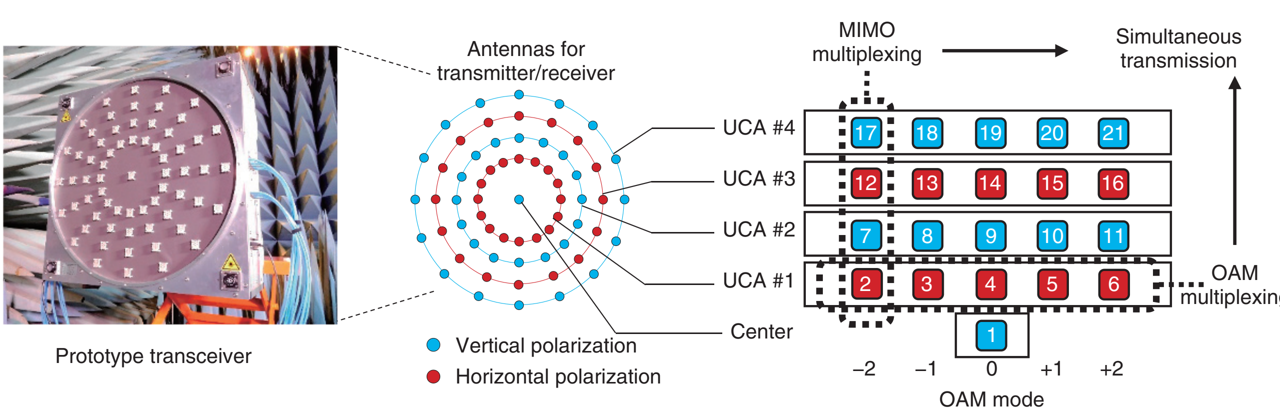

Fig. 4. Transceiver antennas and assignment of 21 spatial streams.

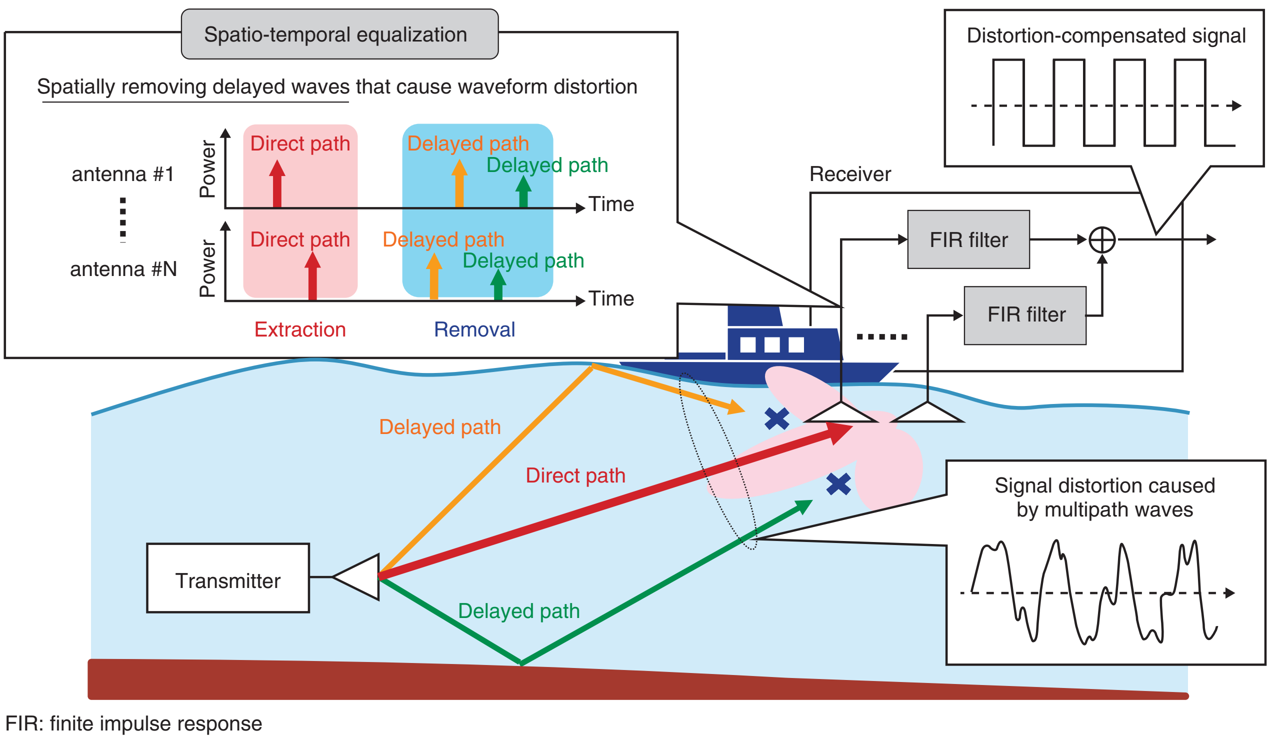

Fig. 5. Concept of spatio-temporal equalization.

transmission. It was successful in 117-Gbit/s transmission for 200 m [3]. We are now pushing forward with our research to achieve terabit-class wireless communication required for xHaul in 6G by expanding the bandwidth up to 10 GHz and combining it with 20–40 spatial streams in advanced OAM-MIMO technologies.

3. Underwater acoustic communication to extend coverage into the ocean

The development of offshore resources, such as oil and gas fields, has been growing, and remotely operated vehicles (ROVs) are used for offshore development. Unmanned remote construction using ROVs is also being researched to improve worker safety and operational efficiency in port and harbor construction. Since the Mbit/s-class underwater communication capable of transmitting high-definition video has not yet been commercialized, these ROVs are connected to support vessels on the sea by long wired cables. The main drawback of wire-controlled ROVs is their high operational cost due to large support vessels and dedicated operators to hoist the long and heavy cables. Therefore, Mbit/s-class high-speed underwater communication that enables wireless remotely controlled ROVs is highly desired. Underwater communication using various media such as radio waves, sound waves, and light have been studied. We have focused on sound waves, which are suitable for stable long-distance communication, and are working to improve the speed of underwater acoustic communication.

Not only in underwater acoustic communication but in any wireless communication, waveform distortion occurs as a result of combining many waves from different paths. Therefore, wireless communication requires equalization to compensate for this waveform distortion. Due to the extremely slow propagation speed of sound waves compared with radio waves, waveform distortion drastically changes in underwater acoustic communication, which makes equalization more complicated. The conventional equalization technique, which compensates for the inverse response of waveform distortion, cannot track fast fluctuations in waveform distortion of underwater acoustic communication because the inverse response cannot be estimated in time. As a result, the communication speed of conventional underwater acoustic communication has been limited to several tens of kbit/s [4].

To overcome the fast fluctuations in waveform distortion, we proposed an equalization technique called spatio-temporal equalization [5] (**Fig. 5**). This technique

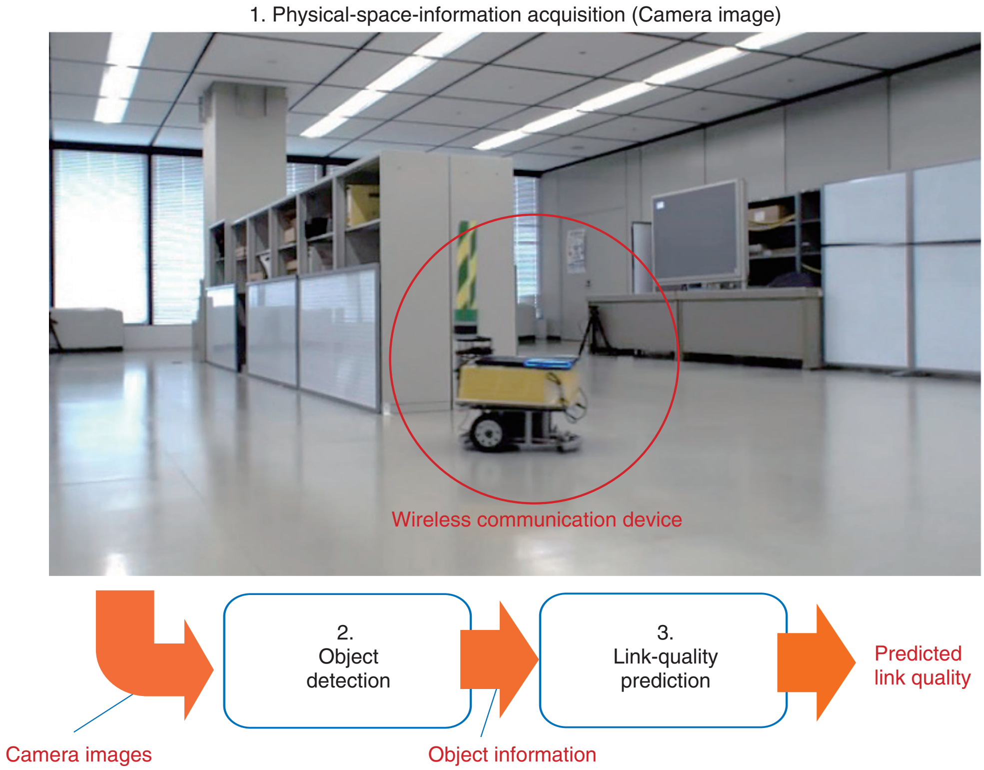

Fig. 6. Link-quality prediction using camera images.

achieves equalization by spatially removing the delayed waves that cause waveform distortion using adaptive beamforming. Spatio-temporal equalization does not require the estimation of the inverse response of waveform distortion, enabling Mbit/s-class high-speed acoustic communication.

We conducted transmission experiments in the ocean to verify the effectiveness of this technology and succeeded in transmitting 5.12 Mbit/s at a distance of 18 m and 1.2 Mbit/s at a distance of 60 m [6]. We are currently working on achieving more than 1 Mbit/s at a distance of 300 m by combining bandwidth-division transmission technology, which uses multiple transmitters, with different resonance frequencies to transmit broadband signals.

4. Wireless-link-quality-prediction technologies using physical space information

In the 6G era, the use of physical space information will be more familiar because of various activities for Society 5.0 [7], which was proposed as a future society that Japan should aspire to. The huge amount of physical space information will be stored in cyber space and become more accessible from everywhere. NTT Network Innovation Laboratories started to research the physical space information use to promote the evolution to wireless communication systems [8, 9]. The throughput and capacity in wireless communication systems have been basically enhanced using wireless system information and settings. The requirements for wireless communication systems are diversified and advanced because of emerging services. This raises the expectation of highly reliable wireless accesses. Physical space information use is one of the keys to evolve wireless communication systems since the long-term movement of communication devices and surrounding objects can be extracted from the physical space information. Long-term prediction enables proactive actions with sufficient time to prepare the advanced controls and develop the roles of wireless communication systems.

Throughput prediction using camera images is shown in **Fig. 6** as an example of our work. Cameras first obtain images including communication device. A device is then detected from the obtained images by using object-detection algorithms with a pre-learned model. Finally, the wireless-link-quality-prediction model predicts link quality by using the detected object information. The exteriors of communication devices are learned using object-detection algorithms that are based on deep learning, and the detected position and movements of communication devices on the image are used to predict future link quality. Since a large number of cameras and sensors are expected to be connected to the IOWN All-Photonics Network, sustainable system design is also being researched to enable the addition and deletion of cameras and sensors for prediction systems. The artificial-intelligence-driven experimental rooms in which multimodal features including physical space information and wireless system parameters are automatically measured are being developed to evaluate the performances of various machine learning technologies using big data measured in an experimental environment. The accurate prediction in the short and long term enables proactive controls, such as switching to better wireless connections, to change the application data rate or control the movement of communication devices and surrounding objects by detecting the link disconnection beforehand. We believe that physical-space-information-based wireless-link-quality prediction will extend the use cases of reliable wireless communication.

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