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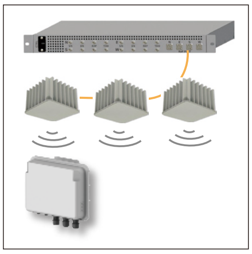

mmWave Communication System for 5G and Beyond: Advancements toward 6G

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Our company is developing Analog Radio-over-Fiber (A-RoF) technology for wireless signal transmission, enabling the transmission of radio waves through optical fiber while maintaining their waveform for 5G and 6G wireless communication. This paper introduces our efforts in developing A-RoF technology, focusing on enabling the economically viable deployment of millimeter-wave (mmWave) radio communication systems , which are essential for broadband wireless communication in the eras of 5G and 6G. Additionally, we showcase the application of A-RoF technology in the 5G millimeter-wave distributed antenna system (DAS) and industrial 5G terminals supporting millimeter-wave communications.

Keywords: 5G, 6G, millimeter-wave, A-RoF, DAS

1. Introduction

Due to the advancement of AI and the spread of Augmented Reality and the Metaverse, the mobile communication traffic is expected to increase 14-fold by 2030 and 190-fold by 2040 compared to that of 2020, when 5G was introduced.(1) Radio waves in the Sub-6 GHz band, which are mainly used in mobile communication at present, and those in the millimeter-wave band (several dozen GHz), whose bandwidth is several to 10 times greater than that of radio waves in the Sub-6 GHz band, are expected to be utilized to handle the increasing traffic.

However, the millimeter wave is characterized by (1) line-of-sight propagation and low diffraction, (2) high transmission attenuation by obstacles, and (3) high susceptibility to absorption and scattering due to rain and fog, resulting in a short propagation distance. Thus, in millimeter-wave communication, many Radio Unit must be installed at appropriate locations to form small cells. However, installation spaces for conventional millimeter-wave Radio Unit are limited due to their large size and high-power consumption. This brings a challenge to the 5G millimeter-wave deployment.

When Analog Radio-over-Fiber (A-RoF) technology is applied to a base station, Radio Unit, which is located in remote site from the base station, does not require a digital processing. The architecture is simple, comprising only an amplifier, an antenna and analog components, enabling low power consumption and small size. This significantly enhances the flexibility of installation locations for Radio Unit. Thus, A-RoF technology is considered one of the promising technologies that will contribute to 6G ultra-high-speed communication using distributed MIMO system, which multiple antennas are placed separately and cooperate within a communication area.

We have studied the applicability of A-RoF technology to 5G millimeter-wave communication systems and distributed antenna systems (DAS). We have also developed industrial 5G millimeter-wave terminal, and demonstrated effective utilization of millimeter-wave communication. This paper introduces our initiatives in millimeter-wave communication systems.

2. Architecture and Requirements of A-RoF-Based Wireless System

A 5G millimeter-wave system is discussed as an example of a millimeter-wave wireless system. Figure 1 shows the architectures of 5G millimeter-wave base stations supporting analog beamforming as an example: Open Radio Access Network (O-RAN) Fronthaul architecture(2) using the Common Public Radio Interface (CPRI), which is an existing Mobile Fronthaul interface, and A-RoF-based architecture.

Though A-RoF offers advantages in reducing the power consumption and the size of Radio Unit, it is

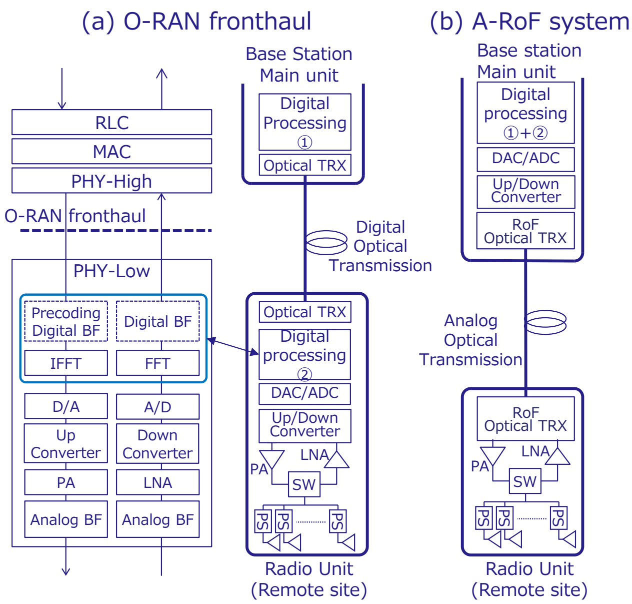

Fig. 1. Examples of the function allocation of base station

affected by nonlinear distortion caused by electro-optical conversion devices and optical fiber transmission, since analog signals are transmitted via optical fiber.[3] These distortions depend on the type of optical devices in use and the optical fiber transmission distance. Thus, in an A-RoF based wireless system architecture, the influence on signal quality needs to be studied.

We focused on two signal integrity characteristics for A-RoF based millimeter-wave base stations: (1) for downlink transmission, Error Vector Magnitude (EVM) after transmission, and (2) for uplink reception signals, reception dynamic range after transmission. We verified the performance by simulation and actual measurement (Fig. 2).

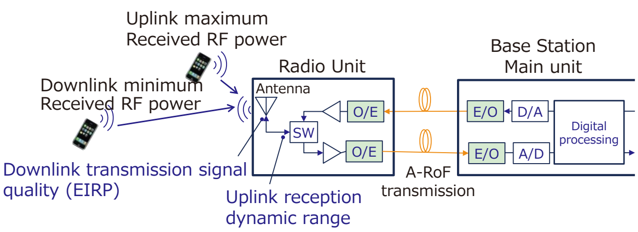

Fig. 2. Downlink transmission signal quality and uplink reception dynamic range

3. A-RoF Transmission Characteristics of 5G Wireless Signals

There are two A-RoF architectures for millimeter-wave base station. One is an architecture of optical fiber transmission by millimeter-wave frequency directly, and the other one is an architecture called "Intermediate Frequency over Fiber" (IFoF),[4] in which a frequency converter is implemented in a Radio Unit and analog signals are transmitted via optical fibers by intermediate frequency for ease of Electro-Optical conversion and optical fiber transmission.

The former offers an advantage in further simplifying the hardware of the Radio Unit. The latter delivers an advantage in making an economical system by using optical devices, whose operating frequency is several GHz and which are commonly used in 10-gigabit Ethernet and FTTH. These two systems can be adopted depending on the wireless system requirements.

This chapter reports the results of our study on the influence of chromatic dispersion of optical fiber transmission[5] and the uplink reception dynamic range[6],[7] when applying IFoF to a 5G millimeter-wave wireless base station.

3-1 Simulation of downlink A-RoF transmission characteristics

The bandwidth of the millimeter-wave band is wider than that of conventional 4G and 5G Sub-6 GHz, and is susceptible to the influence of chromatic dispersion of optical fibers. Meanwhile, the chromatic dispersion tolerance is known to be highly dependent on the type of optical modulation device.[3] We conducted optical transmission simulations on a Mach–Zehnder interferometer Modulator (MZM), an Electro-absorption Modulator integrated with a DFB Laser (EML), and a Directly Modulated Laser (DML) as optical modulation devices, and compared the chromatic dispersion tolerance. Though the wavelength band of optical fiber transmission can use both the 1.3 µm band and the 1.5 µm band, we conducted a study using the 1.5 µm band, which is significantly influenced by chromatic dispersion but enables easy expansion of transmission capacity by Wavelength Division Multiplexing (WDM).

The frequency chirp characteristics Δf (t) in the Electrical-to-Optical conversion and modulation device (E/O) is expressed by the following formula.[8]

$$\Delta f(t) = \frac{\alpha}{4\pi}\left\{\frac{dP_{norm}/dt}{P_{norm}} + \omega_C(P_{norm} - 1)\right\} \quad \cdots\cdots\cdots\cdots (1)$$

Here, α is the transient chirp parameter, ω_C is the adiabatic chirp parameter, and P_{norm} is the optical intensity standardized by the average optical intensity. For the characteristics of the frequency chirp of each E/O, we used the chirp parameters shown in Fig. 3 as typical examples.

Figure 4 shows the simulated results of the impact of chromatic dispersion [ps/nm] on the EVM. Assuming wavelength dispersion of 17 [ps/(nm·km)] at wavelength of 1.55 µm for standard single-mode fiber and transmission distance of 20 km, it is observed that both the EML and MZM exhibit sufficient tolerance to chromatic dispersion.

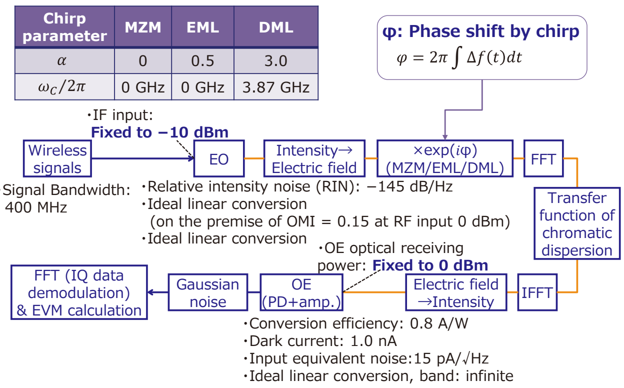

Fig. 3. Downlink transmission signal quality and uplink reception dynamic range

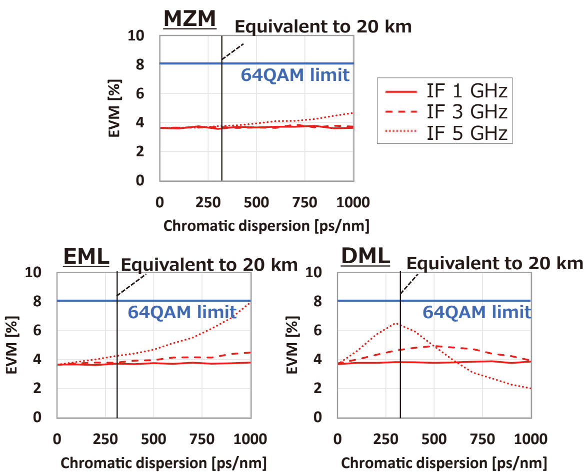

Fig. 4. Influence of chromatic dispersion caused by standard single mode fiber transmission

On the other hand, the DML shows degradation in EVM at high frequency and large chromatic dispersion condition. Due to the chirp characteristics of the DML, an improvement in EVM is also observed when chromatic dispersion is relatively small such as an IF of 5 GHz and a chromatic dispersion is below 650 [ps/nm]. This implies that there are some applications where the DML can be effectively utilized.

3-2 Simulation of uplink A-RoF transmission characteristics

In the uplink reception, it is necessary to handle wide range of input power from terminals located both at the far end and near end.

We conducted transmission simulation to study the dynamic range of uplink reception in the case of EML as shown in Fig. 5. First, we calculated the input power at the Front End (FE) using the propagation loss and antenna gain at each point by changing the distance between the antenna and the terminal (Fig. 6). We estimated that dynamic range of 40 dB (-50 dBm to -90 dBm) was required for the input power at a propagation distance of 10 m to 180 m.

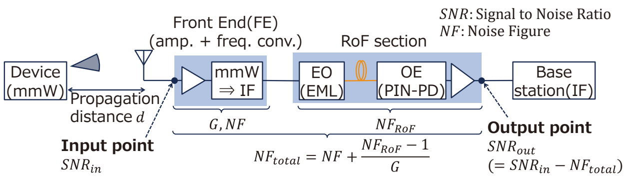

Fig. 5. Block diagram of uplink A-RoF reception

Specifications for wireless unit	
Center frequency	28 GHz
Transmission EIRP	26 dBm
Propagation model	(1) Urban Micro Street Canyon LOS* + margin (2) Free space model
Antenna height	10 m
Gain of a single antenna element	5 dBi
Number of antenna elements	16

*3GPP TR38.901 V16.0.0, Oct.2019.

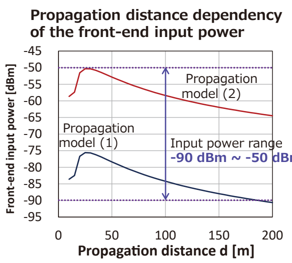

Fig. 6. Uplink input power range at Front End

For small input signal (-90 dBm) reception, we conducted an optical transmission simulation based on the block diagram shown in Fig. 5. We calculated the minimum reception sensitivity at the FE input point. Figure 7 shows the results of minimum reception sensitivity of FE versus FE gain. Here, the minimum reception sensitivity was defined as the input power of the FE where the block error rate was 10% (equivalent to SNR -7.8 dB)[9] with the channel quality indicator (CQI) 1 of the terminal. For the EML extinction curve, the actual measurement data were used. We confirmed that a minimum input power of -97 dBm was feasible when the FE gain was set to 40 dB or more.

For large input signal (-50 dBm), we confirmed that the intermodulation distortion after IFoF transmission was less than -40 dB when FE gain was set to 40 dB (Fig. 8).

Specs for IFoF transmission	
Signal bandwidth	50 MHz
Center frequency	3.275 GHz
NF of the front end	7 dB
EML extinction curve	Fitting of measurement values
RIN of laser	-143 dB/Hz
PD optical receiving power	0 dBm
PD conversion efficiency	0.8 A/W
PD dark current	1.0 nA
Input equivalent noise	25 pA/√Hz
Optical wavelength	1550 nm
Dispersion parameter	17 ps/(km · nm)
linewidth enhancement factor α	0.5

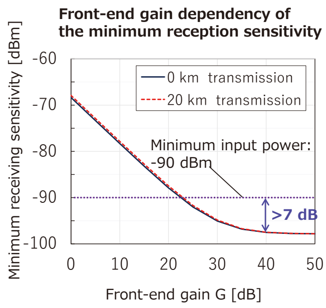

Fig. 7. Frontend gain dependency of unlink A-RoF uplink reception

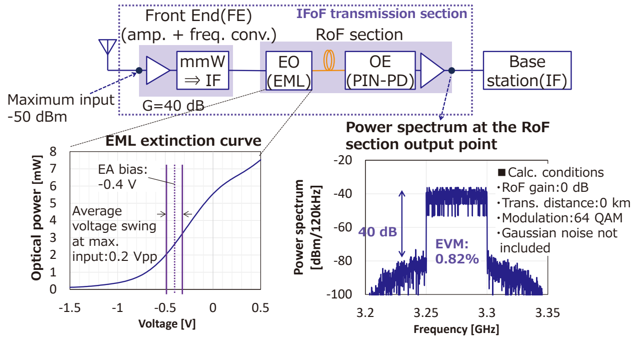

Fig. 8. Signal spectrum after A-RoF transmission when Front End input signal power is maximum

3-3 Evaluation results and consideration using the IFoF prototype optical module

The Radio Unit, which is deployed in various locations, is expected to be small in size and low in power consumption. So, miniaturization of optical modules used in Radio Unit is one of the important issues. We developed a Small Form-factor Pluggable (SFP)*1-type A-RoF transceiver module, which is compact and easy to install and maintain.[10] An overview of the prototype A-RoF module is shown in Fig. 9.

Item	Configuration
Form factor	SFP (integrated transmitter and receiver)
Optical connector	LC type
Transmission method	Intensity modulation-direct detection
Optical wavelength	1550 nm band
EO	Electro-absorption Modulator integrated semiconductor Laser (EML)
OE	PIN-PD

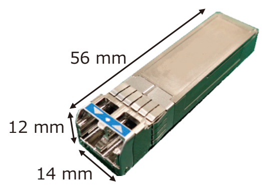

Fig. 9. Overview of the SFP-type A-RoF optical module

Figure 10 (a) shows the transmission characteristics evaluation setup for the A-RoF module. OFDM signals with center frequency of 3.5 GHz, signal bandwidth of 50 MHz, and subcarrier spacing of 60 kHz were generated from the Signal Generator (SG). The signals were input into the A-RoF module (SFP_1) via the SFP evaluation board. The optical signals output from SFP_1 were received by the A-RoF module (SFP_2) on the other side via a standard single-mode fiber and an optical attenuator (ATT). The optical reception power was set to 0 dBm. The electric output signals from SFP_2 were connected to the Signal Analyzer (SA) via the SFP evaluation board to measure EVM.

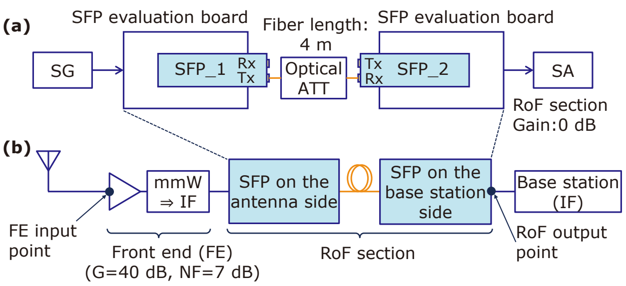

Fig. 10. (a) Evaluation setup of transmission characteristics for the SFP-type A-RoF optical module, (b) corresponded base station uplink architecture

The input power dependency of EVM on SFP_1 is shown in Fig. 11 (a). The range of EVM being 8% or less was approximately 38 dB. Next, we studied the applicability of this A-RoF module to the uplink of A-RoF based base station by calculation. Here, assumed uplink block diagram is shown in Fig. 10 (b). The 50 MHz-bandwidth OFDM signals received by the antenna were input into the Front End (FE) and down converted into IF (3.5 GHz), and connected to the Base Station via the RoF section. In this setup, the FE input power dependency of SNR at the RoF output point was calculated in Fig. 11 (b). For the FE unit, the gain and NF were assumed to be 40 dB and 7 dB, respectively.[6] For the NF in the RoF section, the value were calculated based on the input SNR and output SNR. The input SNR assumed the thermal noise, and the output SNR was converted from the EVM measurement result (Fig. 11 (a)). Within the input power range of -90 dBm to -50 dBm[6] to the FE, which was estimated in Chapter 3-2, a margin of 1 dB or more was secured for the required SNR[9] of the channel quality index (CQI) 4 (QPSK, code rate: 0.3) at the minimum input level. Meanwhile, At the maximum input level, the required SNR[9] of CQI 15 (64 QAM, code rate: 0.93) was satisfied. It also shows that the influence of signal distortion caused by saturation of Electrical-to-Optical conversion and Optical-to-Electrical conversion in the RoF section was minimal.

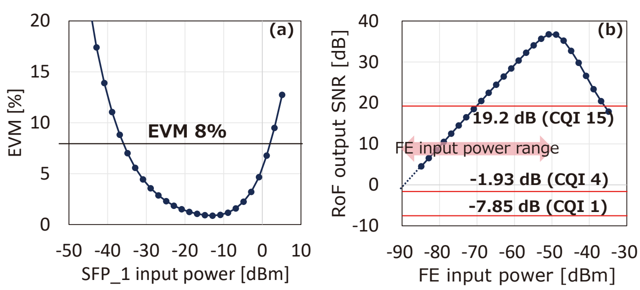

Fig. 11. (a) EVM measurement result, (b) estimated SNR of RoF output signal

4. mmWave Distributed Antenna System

The study in Chapters 2 and 3 showed that A-RoF can be used for the transmission of 5G wireless signals. Here, a millimeter-wave distributed antenna system is discussed as an example of A-RoF use case.

The loss of millimeter-wave signals when they transmit into buildings from outdoor base station is higher than that of the Sub-6 GHz band signals, often requiring indoor antennas. Also, there are many obstacles in the indoor environment, it is necessary to install multiple antennas to cover blind spots. A DAS, which is configured to distribute wireless signals to multiple extended antennas, is considered effective way for indoor deployment of such millimeter-wave communication.

In the Sub-6 GHz wireless frequencies for which conventional DASs have been used, it was possible to distribute wireless signals to antenna by using a coaxial cable. Given the high transmission loss of millimeter-wave signals via coaxial cables, an RoF based DAS which uses optical fibers to distribute millimeter-wave signals, whose transmission loss is small (0.3 dB/km to 0.4 dB/km), is suitable.

In the system shown in Fig. 12, a DAS Remote Node consists of an Electro-Optical converter, a frequency converter (for conversion into intermediate frequency and millimeter-wave signals), an amplifier, and an antenna. In contrast to a base station extension, which is conventionally called a "Remote Radio Head" or a "Remote Unit," a DAS Remote Node consists only of analog circuits. Thus, a simple, low power consumption system can be realized. Also, an A-RoF based DAS enables simultaneous transmission of multiple wireless signals by frequency division multiplexing. This capability makes it well-suited for infrastructure sharing, allowing multiple communication carriers to offer services concurrently using same system.

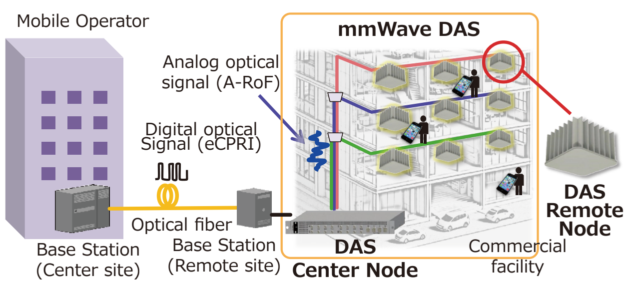

Fig. 12. Millimeter-wave distributed antenna system

5. An Industrial 5G Terminal supporting 5G mmWave

5G terminals supporting 5G millimeter-wave are the key to spreading 5G millimeter-wave communication systems using the millimeter-wave frequency band. We have developed an industrial 5G terminal that can be used for both public 5G services, which are deployed by mobile carriers, and local 5G services, which are used by companies and local governments to build dedicated 5G networks in limited specific areas. This 5G terminal support New Radio-Dual Connectivity (NR-DC*2), which enables high-speed and stable wireless communication by incorporating both millimeter-wave and Sub-6 antennas into the housing. This feature allows concurrent communication in the frequency bands of both mmWave, which realizes high-speed communication, and Sub-6, which achieves stable communication.

The appearance and system architecture example are shown in Fig. 13, and the equipment specifications are shown in Table 1.

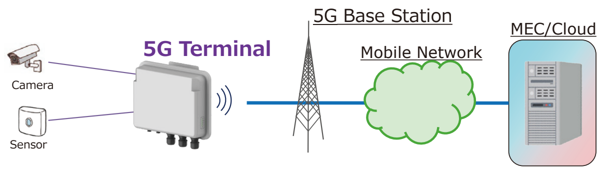

Fig. 13. Appearance of 5G millimeter-wave terminal and example system configuration

Table 1. Specification of the 5G terminal

Item	Specifications
5G	3GPP*3 Rel-16 SA mode*4 Frequency: Sub6 & mmWave
Wireless LAN	IEEE802.11 a/b/g/n/ac/ax
Wired LAN	100/1000BASE-T × 3
Other Interfaces	RS-485 × 1, Digital input output (DI × 1, DO × 1)
Size	315 × 247 × 82 mm
Weight	3.0 kg
Power supply	PoE or AC100V (AC adapter)
Power Consumption	Max. 25W
Operating environment	Operating temperature: -20 to 50°C Operating humidity: 5 to 95%
Cooling method	Natural cooling (fanless)
Ingress Protection	IP66
Other functions	Router, VPN passthrough/client, NAPT, DHCP, Edge computing function

Table 2 shows an example of the NR-DC communication performance.

Table 2. Throughput performance

Direction	Throughput (example)
Downlink (base station to terminal)	About 2.5 Gbps
Uplink (terminal to base station)	About 0.6 Gbps

Our 5G terminal operates in a wide temperature range (-20°C to 50°C) and has dustproof and waterproof functions. Thus, it can be used in factories with severe environmental conditions and in outdoor environments. For a product inspection at factories by AI processing, high-resolution image data is required. The use of millimeter-wave high-speed communication makes it possible to quickly collect large-sized image data and improve productivity at factories. In terms of outdoor applications, a high-speed communication can be built quickly by installing this 5G terminal at a building that is not connected to a high-speed communication line. This 5G terminal also has an edge-processing function,*5 making it easy to implement additional applications required by users. Optimal solutions that meet user requirements can be realized in combination with the edge-processing function and high-speed millimeter-wave communication.

6. Conclusion

Toward economical social implementation of wireless communication systems using millimeter-wave, which will be essential for broadband wireless communication in the 5G and 6G eras, we studied the applicability of A-RoF to millimeter-wave communication systems and demonstrated its usability. As an example of application of A-RoF, we showed its applicability to a 5G millimeter-wave distributed antenna system. We also introduced an industrial 5G terminal capable of handling 5G millimeter-wave signals. By leveraging these key technologies, we will contribute to the economical commercial deployment of 5G and 6G communication systems by taking advantage of the broadband characteristics of millimeter-wave signals.

7. Acknowledgement

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Technical Terms

*1 Small Form-factor Pluggable (SFP): One of industrial standards of optical transceivers, which are used for network equipment and are hot pluggable to equipment ports.

*2 NR-DC: An abbreviation for New Radio-Dual Connectivity. A technology for operation by combining Sub-6 and millimeter-wave signals in 5G communication.

*3 3GPP: An abbreviation for 3rd Generation Partnership Project. A standardization organization that develops specifications for mobile communication systems.

*4 SA mode: An abbreviation for stand alone. SA mode is a mode for a service provided through 5G alone. NSA is a service provided through a combination of 4G and 5G.

*5 Edge processing function: A function for processing and analyzing data near end users.

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