Expected Application Spaces and Supporting Technologies in 5G

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Fifth generation (5G) mobile network services have finally started and many applications as well as new services are expected to be introduced into our life and work. As a next-generation infrastructure, 5G networks have been aimed at significantly increasing speed and capacity from 3G/4G wireless communications. Also 5G will provide drastically evolved communication networks connecting a massive number of devices to the internet and providing high reliability and low latency. This paper overviews requirements that 5G will meet and also discusses its underlying technologies, especially from the perspective of development of millimeter-wave technology.

1. Introduction

The mobile network has evolved year by year, and now services based on 5G mobile communication systems are finally available. Since mobile communication networks were introduced in the 1980s, telephones have evolved from car phones including the shoulder phone, into mobile phones, into smartphones which started with the iPhone. The form of mobile communication has also shifted from simple voice communication to data communication, and nowadays a voice call function has become merely one among many applications of current smartphones. The communications systems have developed from analog (1G) to digital (2G) represented by GSM (global system for mobile communication), a communication system which was standardized in Europe and finally became a de facto standard in the world. Following LTE systems (3G), commonly used worldwide and based on CDMA (code division multiple access) technology, the systems progressed to LTE-Advanced (4G). LTE-Advanced systems use OFDMA (orthogonal frequency division multiple access) technology and MIMO (multi-input multi-output) technology to speed up communications using multiple antennas for both transmission and reception. Until 5G, high speeds and large capacity were achieved by these technological innovations, so it can be said that communication speed has increased considerably; which has become about 100,000 times over the past 30 years [1)].

Communication traffic continues to increase mainly due to access to large data loads such as high-definition photos and videos (Fig. 1) and thus further increasing speed and capacity is the first requirement for 5G. On the other hand, 5G differs from previous generations in that its goals are not only speeding up communication but also securing high reliability, ultra-low latency and multiple, simultaneous connections. Accomplishing these goals will allow greater convenience of life, connecting all things to the network, a concept called Internet of Things (IoT), and using its low-latency characteristics to provide new infrastructures that improve industrial and societal efficiency and create new added value. The role of mobile networks has changed from providing simple calling functions to serving as a platform supporting remote information processing and social media services. The advancement of mobile networks will not only remarkably enhance people's convenience, but also raise productivity and add more value. This will be done by utilizing cloud services, big data, IoT, artificial intelligence (AI), virtual reality (VR)/augmented reality (AR) and other technologies, in all industries as well as the IT industry.

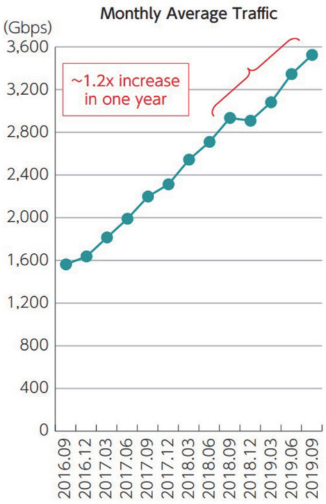

Fig. 1 Changes in mobile communication traffic in Japan. (Source: "Information and Communications in Japan 2020", Japan Ministry of Internal Affairs and Communications)

First, this paper describes the requirements for 5G and three main technologies to support them. It then goes on to describe the features of millimeter-wave (mmWave) technologies newly introduced in 5G and the gist for the development.

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Abbreviations, Acronyms, and Terms.

IoT—Internet of Things. Catching the status and operating things via internal by installing sensor and communication equipment on.

BF-IC—Beamforming integrated circuit that can move the beam to the target by function of beam scanning.

FC-IC—Frequency conversion IC that makes frequency conversion.

Acoustic device—A device that uses the piezoelectric effect to convert high-frequency signals into acoustic waves. Utilizing feature that the wavelength of the acoustic waves is much shorter than that of electromagnetic waves, compact devices have been realized. But it cannot be applied to millimeter wave due to the limit of process miniaturization and the increase in transmission loss.

Patch antenna—An antenna composed of planar element on ground. One-side size is typically a half of wavelength.

Array antenna—An array of antennas with the same shape by which a large gain can be obtained and the radiation direction can be controlled by adjusting the phase and amplitude of each element.

Array factor—Radiation characteristics that are determined only by the configuration of the array such as dimension, location, feeding amplitude and phase. If the individual antenna elements have the same characteristics, the radiation characteristics of the array antenna are given by the product of the characteristics of the element and the array factor.

Sub-array—When the element of an array antenna is composed of multiple antenna elements, it is called a sub-array.

Side lobe—An antenna that shows the strongest radiation in one direction may also radiate in the other directions, which are called side lobe.

Grating lobe—Side lobe generated by array with large pitch.

SiGe—Germanium adopted silicon. It has higher electron mobility and better high-frequency characteristics than pure silicon.

CMOS—Silicon semi-conductor that uses complementary of p- and n-types metal–oxide–semiconductor field-effect transistor (MOSFET). It is widely used for logical function but has been applied for high-frequency applications thanks to process miniaturization and circuit evolution recently.

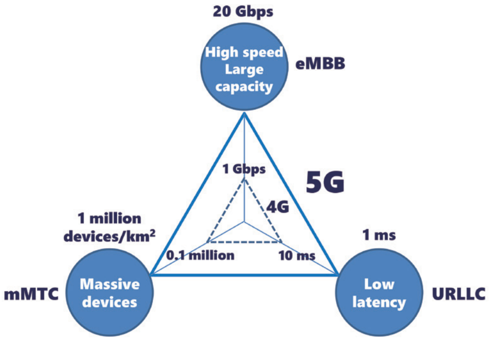

Fig. 2 Three application spaces in 5G.

Table 1 Major specifications of 5G mobile network.

Item	4G	5G
Peak data rate	DL: 1 Gbps UL: 0.5 Gbps	DL: 20 Gbps UL: 10 Gbps
User experienced data rate	10 Mbps	1,000 Mbps
Connection density	100,000 devices/ km^2	1,000,000 devices/ km^2
Latencya	10 ms	eMBB: 4 ms URLLC: 1 ms
Reliability	-	99.9999%

2. Three Requirements for 5G

International standard specification of 5G has been discussed by the Third Generation Partnership Project (3GPP) since 2015, and various service requirements and fundamental technologies of the networks have been specified. The latest release, Release 16 Stage 3, completed in July 2020, specifies a protocol for 5G networks to realize an architecture that meets the defined requirements 2). The standardization of the following three requirements was completed with Release 16. The 3GPP Release lists the main requirements for 5G as follows (Fig. 2):

① Enhanced mobile broadband (eMBB)
② Massive machine type communication (mMTC) for multiple simultaneous connections
③ Ultra-reliable and low-latency communications (URLLC)

New Radio (NR) is a new radio access technology for 5G to replace 4G LTE. New frequency bands are newly added to the 3GPP 5G specification to satisfy the following requirements: one is a sub-6 band (450 MHz to 6 GHz, FR1), the other is a mmWave band (24.25 GHz to 52.6 GHz, FR2). In the sub-6 GHz band, the frequencies including 3.5 GHz and 4.9 GHz are added, where the channel bandwidth is expanded to 100 MHz at the maximum (LTE is 20 MHz). In the mmWave band, the use of 28 GHz and 39 GHz bands is specified, where the channel bandwidth is expanded to 400 MHz at the maximum (Fig. 3). Technological innovation based on the expansion of bandwidth, especially for the mmWave bands, has become the most important and direct factor to fulfill the 5G requirements.

The first requirement of further speed increases and

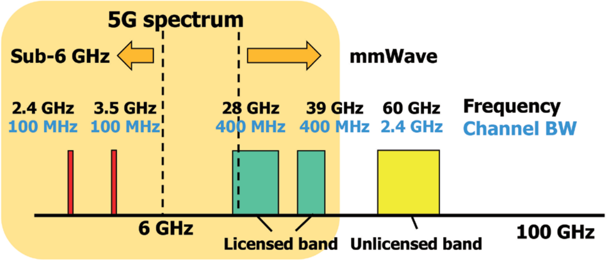

Fig. 3 Frequency spectrum in 5G.

capacity enlargement can be said to be an extension of the evolution of conventional mobile network generations. The target 5G access speed is 20 Gbps maximum for a downlink, 20 times faster than 4G, and 10 Gbps maximum for an uplink.

Maximum communication capacity is explained by Shannon's law and given by the following equation:

$$C = W\log_2\left(1+\frac{S}{N}\right) \qquad (1)$$

where C represents the communication capacity, W the channel bandwidth and S/N (signal-to-noise) power ratio. In 5G, the use of mmWave bands contributes directly to the increase in communication capacity. In addition, 5G, like 4G, adopts a C/U plane separation, which separates the user plane (U-plane) from the control plane (C-plane) to establish communication in a network. Use of mmWave in the U-plane enables considerable increases in communication capacity. This requirement can be applied to using large-capacity images and control signals at smart factories as well as downloading large-capacity data rapidly in smart phones. The first requirement for further speed increases and capacity enlargement can be met prior to the other ones.

The second requirement is multiple simultaneous connections, which can be realized by increasing connection density and coverage, and extending battery life. The target is simultaneously connecting 1 million devices/km^2 using macrocell base stations that employ low carrier frequencies of sub-6 GHz on the assumption of installation of terminals with low traffic density such as smart meters and sensors. This requirement is essential to the realization of the IoT society. Efficient data transmission with reduced control signals, low power consumption of devices, and the spread of base stations are the keys to satisfying the requirement, which is expected to happen in two to three years after eMBB.

The third is high reliability and ultra-low latency communication. High reliability can be achieved by shortening signal transmission time, reducing time to re-transmit signals when a reception error occurs, and securing multi-connections. In this ultra-low latency scenario, a delay of 1 ms or less is the goal, which is also benefited from the use of wide frequency bands because the wider a transmission frequency band is, the shorter the transmission time is. For example, when OFDM is used as it is in 4 G, the subcarrier interval of 5G NR is 240 kHz while that of LTE is 15 kHz. This results in a delay of 1/16 for 5G. High reliability and ultra-low latency communication are utilized in wide fields such as in remote smart healthcare treatment support and autonomous driving. In addition, edge terminals can be miniaturized to a simple structure with a single function because their main data processing can be quickly carried out by cloud computing over the network through the combination of their high-speed and large-capacity communication abilities. The practical use of this requirement is also expected to come about following 5G capacity enlargement.

3. mmWave Technologies for 5G

3.1 Advantages and Disadvantages in Using mmWave

5G NR differs greatly from the conventional generations such as 4G in that it uses mmWave. Below are the advantages and disadvantages of mmWave compared to Sub-6:

- ●Advantages
  - Its wide bandwidth enables high speed, high capacity and low latency simultaneously.
  - Since its wavelength is short, the antenna size is small. This makes it easy for an antenna array to allow beamforming and produce many narrow beams.
- ●Disadvantages
  - It suffers high spatial attenuation, which limits transmission distances.
  - Its transmission shows strong straightness and thus requires line-of-sight (LOS) paths.
  - Its high penetration loss through glass and walls makes the penetration difficult.
  - The length of the circuits to distribute and feed signals must be minimized because signals are severely degraded when they pass through the substrate material. This makes it difficult to separate active devices from antenna elements.
  - Since its frequency exceeds the permissible range for surface acoustic wave (SAW) devices, it is necessary to replace the SAW filters with ones that directly process electromagnetic waves.

Since mmWave travels only a short distance and the mmWave communication is impossible in a non-line-of-sight environment, it is necessary to install many small cells with narrow coverage. Figure 4 shows the difference between small cells employed in Sub-6 or LTE systems and macrocells in mmWave systems. In a wireless communication system shown in Fig. 5, the power of electromagnetic waves transmitted from a transmitter to a

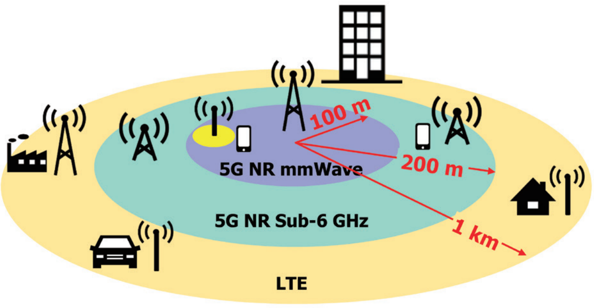

Fig. 4 Comparison of small-cell size between 5G and 4G.

receiver is given by the Friis transmission equation [3]:

$$P_r = G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2 P_t \qquad (2)$$

where P_t and P_r represent the transmit and receive powers, G_t and G_r the transmitter and receiver antenna gains, r the distance, and λ the wavelength, respectively.

Figure 6 compares the received power at 3.5 GHz and 28 GHz when both antenna gains are the same. The results show that the received power at 28 GHz is about 18 dB less than that at 3.5 GHz when the two transmitters are placed at the same distance from the receivers. In other words, the power received at 1 km away at 3.5 GHz can only be received at 130 m away at 28 GHz. In addition to the above-mentioned dissipation loss, absorption loss caused by oxygen and moisture in the air as shown in Fig. 7, needs to be added as well [4].

3.2 mmWave Antenna Configuration

The size of antennas used for wireless communication is generally proportional to the wavelength used. For example, the length of one side of a patch antenna is a half wavelength, that is, only 5.4 mm at 28 GHz. Therefore, antennas can be easily arrayed by using multiple elements in mmWave. For example, in the above case, the received power can be increased if the antennas with a gain of 10 dBi are used at mmWave frequencies.

Figure 8 shows the gain of the array factor of a linear array. This figure also indicates that a gain of about 11 dBi can be sufficiently achieved by an antenna with 8 elements, taking into account that the gain of a patch antenna is usually higher than 2 dBi.

Arraying antenna elements means that the antenna can narrow the beam. Because communication targets in 5G are generally mobile objects, it is necessary for mmWave devices to automatically search and follow the moving communication targets. The beamforming function of array antennas or sub-arrays composed of multiple elements can be realized by independently controlling the phase of their individual elements. It is generally necessary to keep the distance between antenna elements at a half wavelength or less to enable beamforming. If the distance is longer than that, grating lobes appear and the power of side lobes increase considerably [5]. Figure 9 shows an example, in which the beam direction is changed by a linear array of which antenna elements are placed at half-wavelength intervals.

3.3 mmWave Integrated Circuits

Beamforming requires semiconductor devices such as beamforming integrated circuit (BF-IC), which has multiple mmWave signal inputs and outputs connected to individual antenna elements and can control phase and amplitude independently of each other. In addition, devices of frequency conversion IC (FC-IC) are also required for modulating signals into mmWaves. These devices are collectively called radio frequency IC (RF-IC). Beamforming can be controlled by analog, digital or hybrid systems, but the present mainstream system is the analog system.

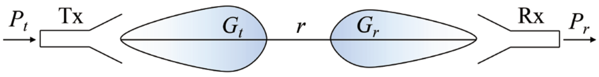

Fig. 5 Wireless signal transmission system.

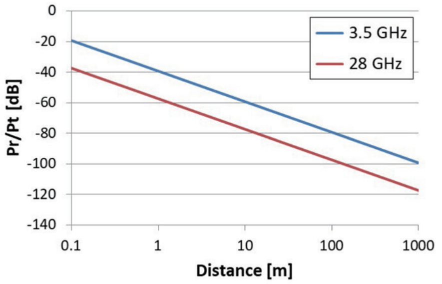

Fig. 6 Transmitted power comparison for Gr=Gt=2 dBi.

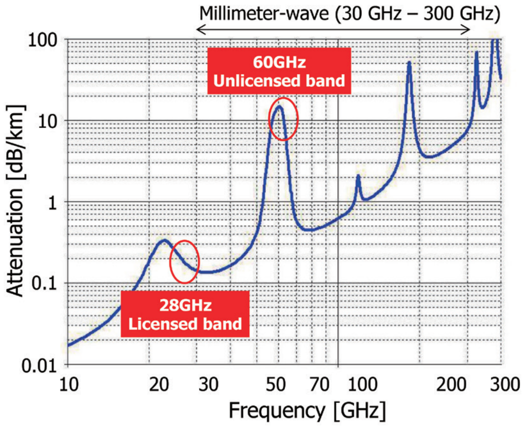

Fig. 7 Electromagnetic-wave attenuation in air.

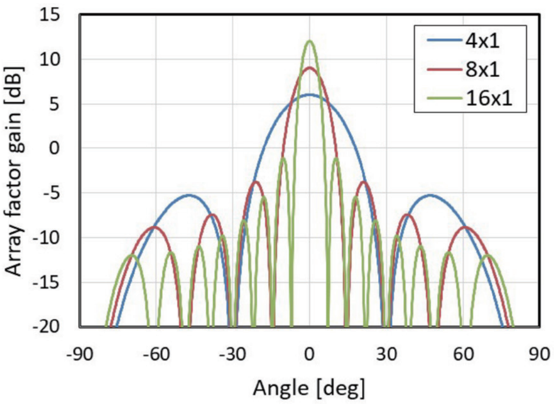

Fig. 8 Array factor gain of linear array.

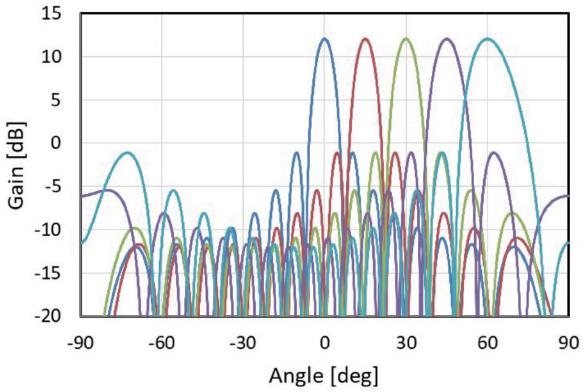

Fig. 9 Beamforming with 16-element array.

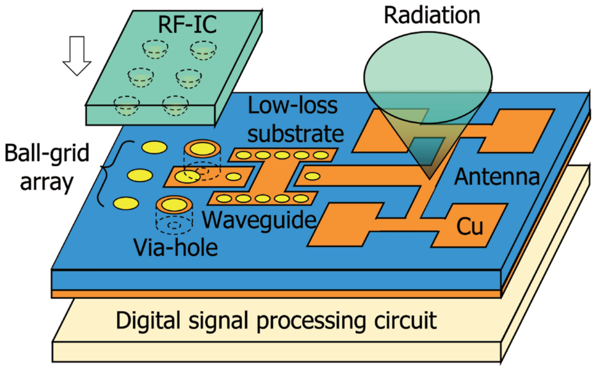

Fig. 10 Millimeter-wave antenna-in-package.

By the refinement of the process as well as the advance of the architecture and circuit in high-frequency technology [6], low-cost silicon-based SiGe and CMOS have been used instead of compound semiconductors as semiconductor materials for mmWave devices. This greatly contributes to the practical applications of mmWave technology [7].

3.4 mmWave Antenna Module

Because mmWaves suffer high loss when passing through common materials, it is necessary to connect signals from RF-ICs to array antennas with the shortest wiring length. To that end, a packaging method called Antenna-in-Package (AiP) [8] has been adopted. This method combines antenna elements and RF-ICs by configuring transmission lines in a low-loss substrate (Fig. 10).

3.5 Suitable Substrate Materials for mmWave

Loss in an electromagnetic waveguide is calculated as the sum of conductor loss and dielectric loss. The conductor loss depends on the finite conductivity. Current concentrates on the surface of the metal to increase the resistance as the frequency increases. The loss is proportional to the square root of the frequency. On the other hand, the dielectric loss is proportional to the dielectric loss tangent (also called tanδ or Df). The dielectric loss is proportional to the frequency given that the dielectric loss tangent is a constant. Consequently, since the dielectric loss becomes substantial as the frequency increases, the mmWave loss becomes very high for common materials. The dielectric loss is also related to the relative permittivity (also called ε_r or Dk), the lower Dk is, the lower the loss becomes.

Waveguides are hollow metal pipes known as a low-loss transmission line thanks to the lack of dielectric loss, but they are so voluminous and heavy that above-mentioned AiP method cannot be applied. mmWave AiP requires a low-loss dielectric substrate with low Dk and Df. For example, FR4 (Dk = 4.1, Df = 0.03, typical, hereinafter the same), which is well known as a general substrate material for microwave applications, cannot be used in mmWave frequencies because of high loss. Fluororesin (PTFE) (Dk = 3.4, Df = 0.007), liquid crystal polymer (LCP) (Dk = 3.1, Df = 0.004) [9], low-temperature fired ceramic (LTCC) (Dk = 7.0, Df = 0.005) [10], and quartz glass (Silica) (Dk = 3.8, Df = 0.0005) [11] are mentioned as the materials showing low loss even in the mmWave frequencies. Figure 11 compares the loss of a microstrip-line having a thickness of 100 µm. The characteristics of these materials are as follows: LCP is flexible, LTCC is suitable for multi-layer applications, and Silica has ultra-low loss.

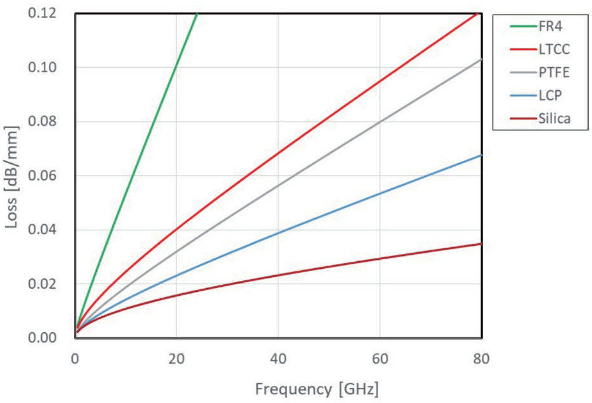

Fig. 11 Loss in microstrip-line (100 µm-thickness, 50 Ohm).

3.6 mmWave Filter

Although so many SAW devices are used in the microwave band, using them in the mmWave band is impossible due to the difficulty of meeting the requirement for more refined electrodes and increased transmission loss. On the other hand, in the mmWave band, the wavelength is shortened to about millimeters, so filters that can directly process electromagnetic-waves using transmission lines can be used [12]. Such filters are indispensable components in wireless communication.

Waveguide-based filters have good characteristics, but they are too large in size and difficult to be used in small modules. Incorporating filters in a dielectric material is a practical option, but low-loss materials with sharp resonance must be used [13]. In particular, compact filters with a low profile can be fabricated by using a

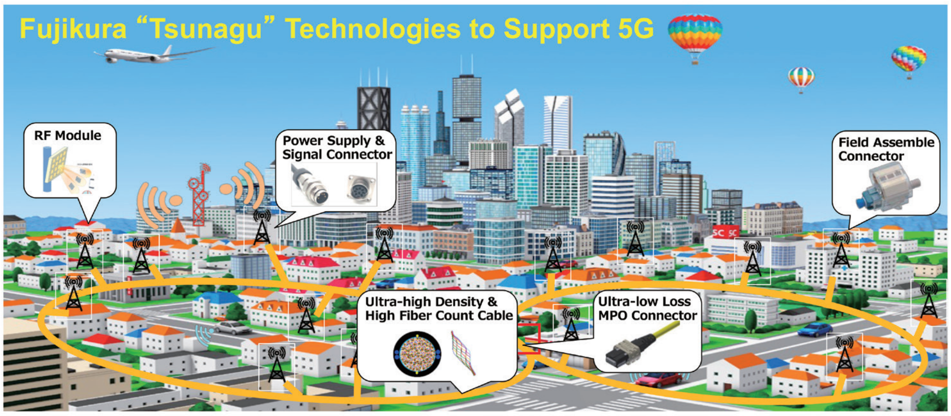

Fig.12 Fujikura "Tsunagu" Technologies to support 5G.

microstrip-line or strip-line as a base, because the transmission line is narrow and flexible to allow for routing. These filters can be used in mmWave antenna modules.

4. Conclusion

5G mobile networks are going to provide basic infrastructures to support the revolution in daily life and the creation of new services with the three requirements. In 5G NR, these requirements are fulfilled only after new frequency bands such as mmWave bands are allocated and appropriate technologies are successfully introduced. In this paper, challenges and solutions of the technology implementation have been described, especially from the mmWave point of view. Based on the technical outline described here, Fujikura is developing mmWave devices and will support 5G with optical components shown in Fig. 12.

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