Over-the-Air Testing on Millimeter-Wave Communication Modules

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This paper describes over-the-air (OTA) testing methodology used for the performance evaluation of millimeter-wave (mmWave) communication modules. First, the reason why OTA testing is indispensable for characterizing mmWave communication modules is explained. Next, a basic configuration for OTA testing is illustrated. And two important performance metrics obtained in OTA testing are described. They include equivalent isotropic radiated power (EIRP) and equivalent isotropic sensitivity (EIS). Furthermore, the actual EIRP and EIS results measured in an OTA testing system for 60 GHz band mmWave communication modules are provided. These results are important parameters that are directly related to the quality of wireless communication links in the field application.

1. Introduction

Over-the-air (OTA) testing, as the name implies, measures the characteristics of wireless devices in the air. This method is different from the commonly-used measurement, where the devices are connected via cables. In the conventional measurement, the antenna and the transceiver have separate connectors for the cables connected directly to the measuring instruments to determine the characteristics of the devices individually. On the other hand, OTA testing is to measure the integrated performance of the antenna and the transceiver combined into a radio-frequency (RF) device.

OTA testing is necessary especially for millimeter-wave (mmWave) devices in their developing and manufacturing processes such as design validation, performance evaluation and conformance certification. Fujikura conducts OTA testing to measure the characteristics of mmWave products and is gradually exploring its application to inspection of mass-produced products.

This paper first explains why the measurement of characteristics of mmWave devices requires the use of OTA testing. In the next section, a basic OTA testing system is illustrated. Then, the two main test metrics for OTA testing are described. They include a performance metric, equivalent isotropic radiated power (EIRP), for transmission and the other, equivalent isotropic sensitivity (EIS), for reception. The following section introduces an actual OTA testing system and provides some measurement results. The last section presents conclusions.

2. Why OTA testing is necessary for mmWave devices?

In the mmWave bands, the frequencies range roughly from 30 to 300 GHz, and the corresponding wavelengths are 10 to 1 mm, respectively. Because of the high frequency, mmWave brings the advantage of a broad bandwidth above GHz in communication. However, free-space path loss (FSPL) at mmWave frequencies is extremely high. According to the Friis transmission formula[1)], the FSPL can be expressed by equation (1).

$$\mathrm{FSPL}\ (dB) = 20 log_{10}\ (4\pi d / \lambda) \qquad (1)$$

Equation (1) indicates that the FSPL is proportional to the square of the distance d and inversely proportional to the square of the wavelength λ. Figure 1 shows the calculated FSPL for 2.4 GHz, 5 GHz and 60 GHz radio waves. Compared with the low frequency waves of 2.4 GHz and 5 GHz that are normally used in Wi-Fi networks, a 60 GHz mmWave suffers much higher FSPL. The FSPL at 60 GHz exceeds 100 dB even in a short distance of 100

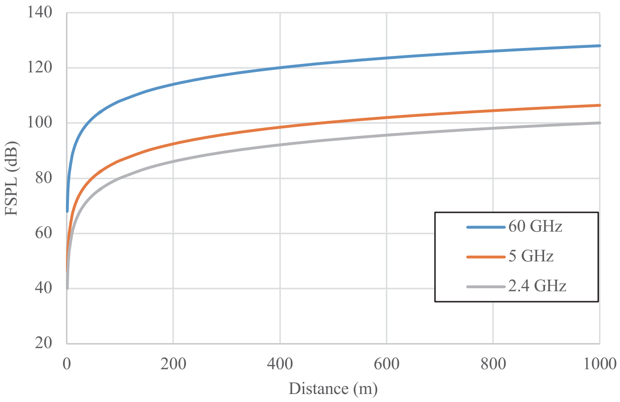

Fig. 1. FSPL vs distance.

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Abbreviations, Acronyms, and Terms.

OTA testing—Over The Air testing
Wireless characteristic test over the air.

EIRP—Equivalent Isotropic Radiated Power
It represents the intensity of the transmission power of radio waves radiated in a specific direction from a directional antenna. In some cases, it indicates the maximum power of radio waves emitted in all directions.

EIS—Equivalent Isotropic Sensitivity
For a directional antenna, among the received power of radio waves arriving from a specific direction, the minimum received power that satisfies the received signal quality criteria.

RF—Radio Frequency
Radio frequency, which refers to the frequency of radio waves radiated over the air

FSPL—Free-Space Path Loss
Attenuation when radio waves propagate in free space.

Wi-Fi—A wireless LAN standard that connects wirelessly to a LAN (Local Area Network).

Antenna-in-Package—A structure in which a high-frequency integrated circuit, antennas, and circuits are integrated.

RFIC—Radio-Frequency Integrated Circuits
High frequency analog integrated circuit.

DUT—Device Under Test
Device under test

SA—Signal Analyzer
Signal analyzers that refers to measuring instruments such as spectrum analyzers and oscilloscopes.

PER—Packet Error Rate
Ratio of the number of erroneously received packets to the total number of packets sent during a specified time interval in a communication.

BER—Bit Error Rate
Coding error rate. ratio of the number of erroneously received codes to the total number of codes (bits) sent during a specified time interval in a communication

SG—Signal Generator
Signal Generator

Arbitrary Waveform Generator—Signal generator capable of generating various modulation signals

m. Therefore, mmWaves are often used for relatively short-distance communication. Likewise, in designing mmWave devices, to minimize transmission line loss, antennas and radio-frequency integrated circuits (RFICs) are generally packaged in a single device using a technology called antenna-in-package (AiP) [2]. Consequently, attaching antenna connectors on the RFIC side is not feasible, and thus performing the conventional measurement is almost impossible either. For radio performance, RFICs and antennas have to be tested as a whole. In this sense, OTA testing becomes essential.

In addition, to increase antenna gain, array antennas have often been used. A great advantage in using array antennas is that they are capable of beamforming[3]. This means that even if the device is fixed, it can electronically control the directivity of electromagnetic waves. For beamforming performance testing, only competent test systems are those that can handle 3D multidirectional measurements and precise positioning of the testing system. OTA testing system can perform direction-oriented measurements.

3. Basic setup for OTA testing

The basic setup for OTA testing consists of a device under test (DUT), a measuring antenna and several instruments for measuring transmission or reception of radio waves. Figure 2 illustrates a basic OTA testing system.

Generally, radiating RF waves is restricted by law, and testing RF devices must be carried out in a prescribed controllable space, which requires an anechoic chamber. In addition, to prevent the influence of reflection interference inside the chamber, it is necessary to cover all the walls inside the chamber with electromagnetic wave absorbers.

As mentioned in Section 2, the FSPL at mmWave is extremely high. At a certain test distance, it is necessary to confirm whether the signal strength to be measured is within the dynamic range of the measuring instrument. If not, signal amplifiers or attenuators are required.

Beamforming evaluation requires a multi-axis positioner since the DUT or the measuring antenna needs to rotate according to different beam directions. This rotation

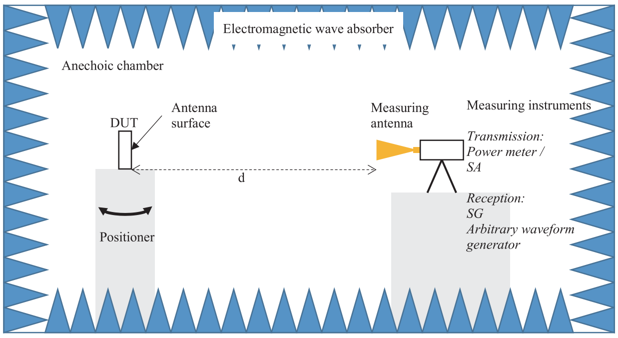

Fig. 2. Basic setup for OTA testing.

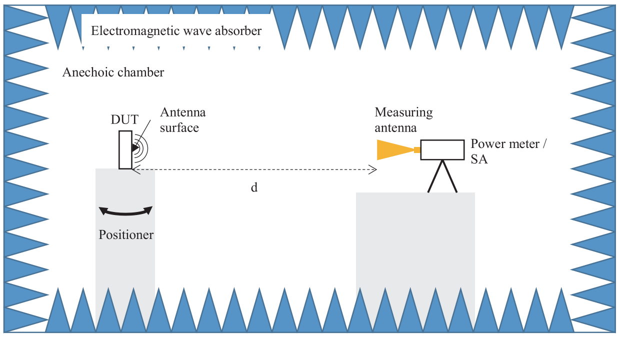

Fig. 3. Basic setup for OTA testing.

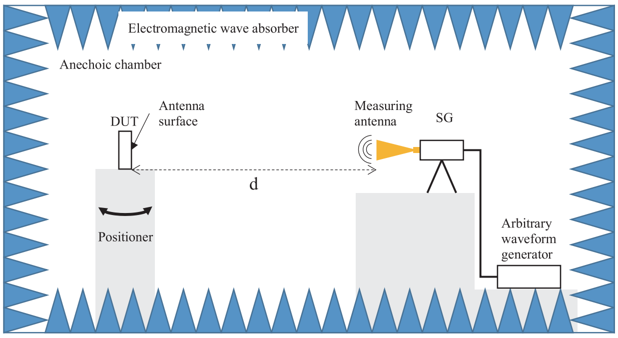

Fig. 4. OTA reception test system.

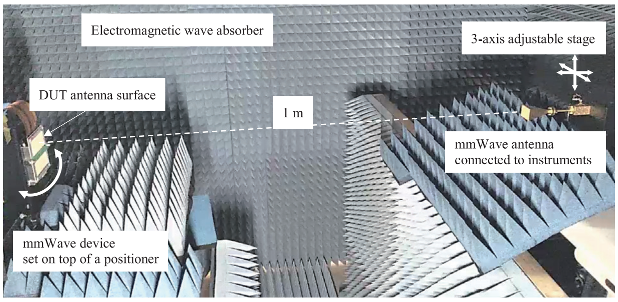

Fig. 5. OTA testing system.

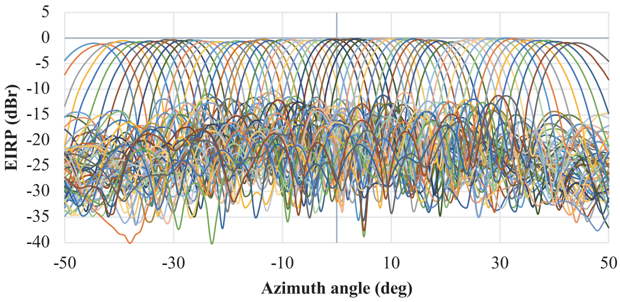

Fig. 6. Radiation pattern 0 dBr = 40 dBm .

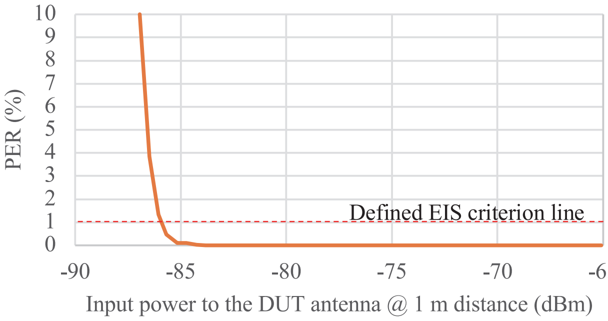

Fig. 7. EIS measurement result.

measurement method helps to obtain measurements of different directional beams.

An accurate OTA test needs a certain distance between the DUT and the measuring antenna. In the near field, the antenna gain depends on the distance, so it is difficult to measure the radiated power accurately. If the distance is far enough, this dependency will disappear. Therefore, OTA testing is usually run at distances longer than the far-field distance[4]. The far-field distance F_D is obtained from equation (2).

$$F_D \geq 2D^2/\lambda \qquad (2)$$

It is a function of the wavelength λ and the antenna length D. For example, a 60 GHz device with an antenna length of 50 mm has a far-field distance of 1 m. The length of the antenna can be considered the total length of mmWave array antennas. The antenna length of Fujikura's 60 GHz mmWave communication module[5] is much smaller than 50 mm, so a test distance of 1 m is far enough to ensure that the OTA testing is run in the far field. Being able to measure at a relatively short distance makes it easier to align the DUT with the measuring antenna. Moreover, for short-distance OTA testing, the effect of atmospheric oxygen absorption can be ignored, which allows a more accurate measurement.

4. Metrics for OTA testing

4.1 EIRP and measurement method

EIRP is defined as power that has to be radiated by an ideal isotropic antenna to give equivalent radiation intensity in a certain direction as a directional antenna. An isotropic antenna is meant to distribute power equally in all directions. In some cases, EIRP is defined as the maximum power emitted by the directional antenna in a given direction with the highest antenna gain. It also points in the direction of the maximum power. EIRP is used as a legal and regulatory indicator for setting upper limits on the radiated power of wireless devices. It is a critical metric for testing the transmission performance of RF devices.

Traditionally, EIRP is calculated using the following equation (3). Whereas P_T is the output power of the transmitter, G_A is the antenna gain, and L_C is the cable loss.

$$\text{EIRP (dBm)} = P_T\ \text{(dBm)} + G_A\ \text{(dBi)} - L_C\ \text{(dB)} \qquad (3)$$

However, as described in Section 2, it is not practical to divide a mmWave device into an antenna and a transmitter for measurements. Therefore, it is necessary to measure the EIRP of the entire mmWave device through OTA testing.

In OTA transmission testing, a detection system consists of a measuring antenna, a power meter with a radio wave sensor, or a signal analyzer (SA). Figure 3 illustrates a system used for OTA transmission testing. In principle, the radiated power of the DUT is measured by the power meter or SA through the measuring antenna. The DUT and the measuring antenna must be direction-oriented to perform measurements of beam directivity. The EIRP of OTA testing can be expressed by equation (4). Whereas P_{read} is the measured power of the power meter or SA, G_M is the gain of the measuring antenna, and FSPL is the free space path loss calculated by equation (1) using the distance d.

$$\text{EIRP (dBm)} = P_{read}\ \text{(dBm)} - G_M\ \text{(dBi)} + \text{FSPL (dB)} \qquad (4)$$

4.2 EIS and measurement method

Sensitivity is defined as the minimum power received by a (high gain) antenna of a device to satisfy the specified received signal quality. Meanwhile, EIS is defined as the equivalent received power obtained by an isotropic antenna when the antenna is at the same position of the aforementioned (high gain) antenna. A typical criterion for the received signal quality is the packet error rate (PER) or the bit error rate (BER). EIS is used to determine the available receiver performance of an RF device. Same as EIRP, EIS is meant to measure directivity.

In general, EIS is calculated using the following equation (5), where P_R is the minimum input power to the receiver to meet the given criterion, G_A is the antenna gain, and L_C is the cable loss. However, as EIRP, OTA testing is required since it is difficult to measure P_R, G_A and L_C separately.

$$\text{EIS (dBm)} = P_R\ \text{(dBm)} - [G_A\ \text{(dBi)} - L_C\ \text{(dB)}] \qquad (5)$$

Figure 4 illustrates a system for OTA reception testing. In OTA reception testing, RF signals are generated by a signal generator (SG). More often, the testing uses modulated signals generated by an arbitrary waveform generator. The RF signals are radiated by a measuring antenna and then received by the DUT. To measure EIS, RF signals from an SG are gradually attenuated until the criterion PER or BER is reached. Then EIS can be obtained from equation (6). Whereas P_{sg} is the SG power corresponding to the criterion PER, G_M is the antenna gain of the measuring antenna, and the FSPL is the free space path loss calculated by equation (1) using the distance d.

$$\text{EIS (dBm)} = P_{sg}\ \text{(dBm)} + G_M\ \text{(dBi)} - \text{FSPL (dB)} \qquad (6)$$

5. OTA testing system and measurements

This section introduces an actual OTA testing system for measuring the performance of mmWave devices and shows a few measurement results. Figure 5 shows an OTA testing system inside an anechoic chamber. A mmWave DUT is set on top of a positioner. The surface of the antenna is aligned to face a horn antenna (measuring antenna) at a distance of 1 m. For accurate alignment, an extra laser marker (not shown in the figure) and a 3-axis adjustable stage are used. The horn antenna is connected to several measuring instruments.

Figure 6 shows a graph of the measured EIRP of 63 directional beams, in other words, a radiation pattern. This data was obtained while the positioner was rotated so that the directional beams were correctly guided to the detection system. This makes it possible to grasp the maximum EIRP with high accuracy.

Figure 7 shows a graph of an EIS measurement. As the input power to the antenna gradually decreases the judgement criterion PER rises. At a PER criterion of 1%, EIS is about -86 dBm.

6. Conclusions

This paper introduces the OTA testing method, setup and metrics for mmWave devices and presents some characteristics of the 60 GHz mmWave communication module developed by Fujikura. The results of the measured EIRP and EIS were presented. EIRP indicates "how far a radio wave can be sent", and EIS indicates "how weak a radio wave can be received and demodulated as effective data".

These are important parameters used for link design of wireless communication. Our 60 GHz mmWave communication module has achieved a throughput of 2 Gbps in communication at a distance of 500 m in field communication tests[5], while a 64.8 GHz transmitted signal with EIRP = +40 dBm is attenuated to -83 dBm at a distance of 500 m. On the other hand, since the Receiver sensitivity performance of this module has EIS = -86 dBm, received power is sufficient.

These results are important feedback on the design[6] of wireless devices and the initial check of the actual performance in real use cases. OTA testing plays an important role in the development of Fujikura's mmWave devices, and we will continue to be committed to creating high-performance, high-quality mmWave products.

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