Near-Field Measurement System for 5G Massive MIMO Base Stations

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[Summary] Development of next-generation 5G communications methods is progressing worldwide with anticipated adoption of Massive MIMO technology using the micro and millimeter-wave bands. Since Massive MIMO uses antenna directivity, it requires new measurement methods. Previous directivity measurement methods use far-field measurements that require a large measurement environment, large equipment, and long measurement times. Additionally, measurement of the millimeter-wave band expected to be used by 5G to offer larger transmission capacity over longer distances causes problems with reduced measurement sensitivity due to propagation losses. Solving these issues requires new low-cost methods such as near-field measurements (NFM). This article presents test results clarifying NFM operating principles as a first step.

1 Introduction

The 5G mobile communications method is expected to use Massive MIMO[1), 2)] technology for base stations. Massive MIMO technology uses a large number of antenna elements for multi-user MIMO transmissions. It aims to greatly increase throughput at communications with each user by freely setting antenna directivity to divide the communications space. The technology for setting antenna directivity at Massive MIMO base stations is key, making directivity measurement an important evaluation item.

Previously, base station antenna directivity was measured at the antenna itself by isolating the RF circuits. However, the increased number of elements used by Massive MIMO antennas makes it difficult physically to provide a measurement connector at each antenna element. In addition, to reduce costs, the antennas and RF circuits are being increasingly integrated, which is expected to result in removal of measurement connectors. As a result, instead of using the antenna itself, the directivity of the entire base station must be measured.

The basic directivity measurement method uses Far-Field Measurement (FFM)[3)] in an anechoic chamber but this causes issues with needing large equipment, such as the anechoic chamber and the turntable positioner. Moreover, at FFM, a carrier wave at high frequency, such as the millimeter-wave band, suffers large loss, causing problems with small dynamic range. One antenna measurement method for solving these problems is Near-Field Measurement (NFM)[4), 5)] that calculates the far-field directivity from the antenna near-field electromagnetic field distribution using electromagnetic field theory. The NFM method has small electromagnetic wave loss because measurement is performed close to the antenna and also has the merit of supporting antenna diagnostics using the antenna near-field distribution in addition to antenna directivity measurement. Moreover, it is also possible to calibrate the antenna elements using back-projection[6)]. However, the NFM method requires measurement of the antenna near-field amplitude and phase distribution. Consequently, since evaluation is impossible by isolating antenna elements, a base station reference signal is required to calculate phase. As described above, the previously used NFM method cannot be used as is because Massive MIMO base stations have no measurement connectors, and capture of the reference signal is likely to be difficult because just the antenna itself cannot be evaluated. As a result, a new NFM method is required.

This article proposes a fixed reference antenna method along with an adjacent phase difference measurement method[7)] as a new type of NFM method for Massive MIMO base stations with integrated antenna elements and no measurement connectors. It presents some test results verifying effectiveness in the 28-GHz band.

2 Near-Field Measurement Method (NFM)

2.1 Measurement Principle

The electromagnetic wave regions[8)] in front of an antenna aperture are shown in Figure 1.

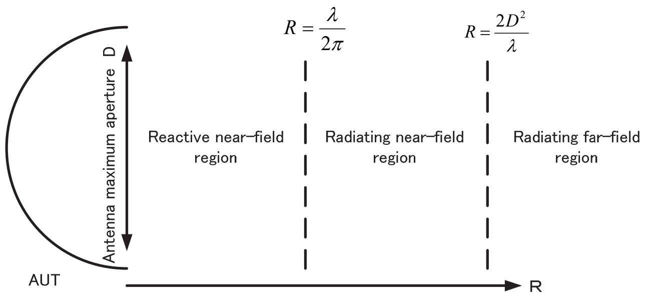

Figure 1 Antenna Measurement Regions

The region closest to the antenna aperture is called the reactive near-field region where the electromagnetic components have no impact on the antenna radiation. The region where directivity does not change with distance from the antenna aperture is called the radiating far-field region (far field). Generally, antenna directivity is expressed as the directivity in this radiating far-field region. The Far-field is defined as a remote position more than R by an antenna aperture when antenna aperture length is D and R satisfies the next equation.

$$R > \frac{2D^2}{\lambda} \qquad (1)$$

where, λ is the free-space wavelength. The maximum power W_a that can be received over free space by an Rx antenna is expressed by the equation

$$W_a = \left(\frac{\lambda}{4\pi R}\right)^2 G_t G_r W_t \qquad (2)$$

where, G_t, is the Tx antenna gain, G_r, is the Rx antenna gain and W_t is the Tx power. From Eq. (1), for a high-gain antenna with a large aperture (D), the attenuation in free space (Eq. 2) become larger as R becomes larger. Moreover, since the millimeter-wave band has a smaller wavelength λ, the free space attenuation becomes larger and the measurement dynamic range becomes smaller. As a result, there is a problem with achieving very accurate measurement of low-level side lobes at far-field directivity measurement.

The radiating near-field region between the reactive near-field region and the far field is a region where the directivity changes with distance. The NFM method measures the field distribution in this radiating near-field region to calculate the far-field directivity. In concrete terms, the antenna vicinity is scanned with a probe antenna connected to a Vector Network Analyzer (VNA) and the far-field directivity is obtained by data processing from the transmission coefficient (S_{21}) amplitude and phase distribution. The measurement accuracy in the antenna vicinity is higher than FFM due to the small free-space attenuation.

There are several NFM methods depending on the Antenna Under Test (AUT) scanning range[9]. This article describes a planar NFM with simple data processing for high-gain antennas. Figure 2 shows the relationship between the AUT and scanning range. For planar NFM (NFM hereafter), the plane about 3λ from the AUT is scanned as a rectangular plane by the antenna probe to measure field amplitude and phase. The sampling interval at this time must be λ/2 or less. The amplitude and phase distribution of this measured plane is a Fourier-transformed function defined by the AUT and probe antenna directivities[4]. After finding this function by reverse Fourier transformation, the AUT directivity is determined by filtering-out the probe antenna directivity. This processing is called probe correction. The actual Fast Fourier Transform (FFT) data processing is executed by a PC to calculate the directivity at high speed.

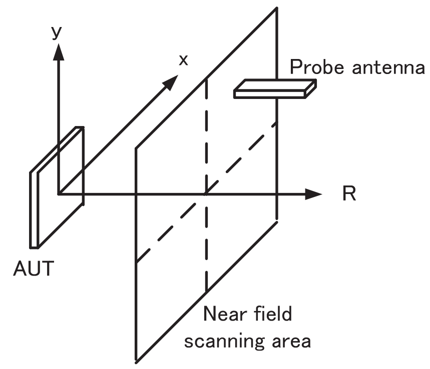

Figure 2 Planar NFM Scanning Plane

2.2 Advantages of NFM

The NFM method has many advantages over FFM (Table 1). Since NFM measures at close range, measurement is possible without an anechoic chamber, so there is no need for large-scale infrastructure. Moreover, since millimeter-wave band equipment is compact, measurement is also possible in a regular laboratory space using a simple anechoic box, helping cut costs and shorten measurement times compared to configuring a measurement system and equipment in a large anechoic chamber. Moreover, since a region with small free-space losses is measured, results with good measurement accuracy are obtained. In addition, NFM also captures the AUT 3D directivity, whereas FFM mostly only measures 2D directivity in the horizontal plane (H) and vertical plane (E) using one rotating turntable.

Capturing 3D directivity like NFM using FFM requires more complex equipment and longer measurement time. As another advantage of NFM, if the antenna design directivity is not achieved, the cause can be diagnosed because the amplitude and phase near the AUT can be captured, helping improve performance. Additionally, back-projection processing can capture an even more detailed field distribution near the antenna element, which is useful data at massive MIMO base station calibration.

Table 1 Comparison of NFM and FFM

	NFM	FFM
Measurement Location	Simple Anechoic Chamber	Anechoic Chamber
Measurement Distance	Near Field Approx 3λ (ex. 32 mm to 54 mm@28 GHz)	Far Field (ex. 3 m or 10 m)
Directivity Measurement	3D Directivity	2D Directivity (3D Directivity measurement requires equipment and time)
Antenna Diagnostics and Analysis	Supported	Difficult

2.3 Massive MIMO Base Station Measurement Issues

As described above, NFM is more effective than FFM at Massive MIMO base station measurement. However, since Massive MIMO base stations will probably not have connectors for measurement, neither the VNA S_{21} nor the electromagnetic field amplitude and phase distribution can be measured. Although a spectrum analyzer can measure amplitude, it cannot measure the phase distribution directly. As a result, one issue with applying NFM to measurement of Massive MIMO base stations is how to obtain the phase distribution. The following section proposes two methods, using either a fixed reference antenna method, or an adjacent phase difference method, and presents some actual tests.

3 Proposed Fixed Reference Antenna Method

3.1 Measurement Principle

The fixed antenna method calculates the phase distribution of the near-field scanning plane using a separate fixed reference antenna and a probe antenna. Figure 3 shows the measurement system for the proposed fixed reference antenna method. The XY positioner is used to scan the front plane of the base station device under test (DUT) with the probe antenna, and the received signal is input to the measuring instrument. Separately, the signal received from a reference antenna fixed at a position where it has no impact on the probe antenna is input to the measuring instrument. Obtaining the difference in the signals from both antennas makes it possible to determine the relative phase at the probe antenna sampling position even for a DUT with no measurement connectors. The amplitude distribution uses the amplitude received by the probe antenna as is. Obtaining the amplitude and phase distribution like this supports calculation of directivity using NFM far-field conversion processing for a DUT without measurement connectors.

Moreover, the measuring instruments receiving the signals from both antennas can be a dual-signal input spectrum analyzer, VNA, oscilloscope, etc. Additionally, a high-gain (high-directivity) reference antenna can be used to improve the accuracy when calculating the phase of powerful received signals. Furthermore, the position where the DUT directivity null point is avoided must be fixed.

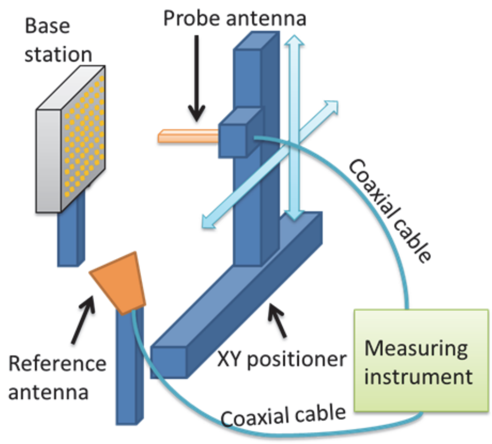

Figure 3 Fixed Reference Antenna Method Measurement System

3.2 Operating Principle Verification (Demonstration) Test

We verified the operating principle using a 1×4 bow tie antenna array as the DUT connected to a signal generator (SG) as shown in Figure 4[9]. Table 2 lists the measurement system specifications and Figure 5 shows an image of the measurement system. The signals received by the probe antenna and reference antenna are loaded to a PC after capture using a digital storage oscilloscope. The phase at the probe scanning plane is calculated after Fourier transformation of these signals to obtain the signal difference. Figures 6 and 7 show the directivity after conversion from the calculated amplitude and phase distribution. The solid black line in both figures is the directivity found by the previous NFM method using a VNA instead of a signal generator; the red line is the directivity found using the fixed reference antenna method. Both figures show good agreement between the results for both methods in both the horizontal and vertical planes, verifying the effectiveness of the fixed reference antenna method.

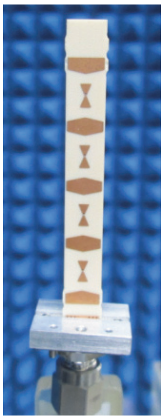

Figure 4 DUT (1×4 Bow Tie Antenna)

Table 2 Measurement System Main Specifications

Measurement Frequency	28.0 GHz
DUT	1×4 Bow Tie Antenna Array + SG
Probe Antenna	WR-34 Open End Waveguide
Reference Antenna	WR-34 Horn Antenna Gain: 20.5 dBi @ 28 GHz

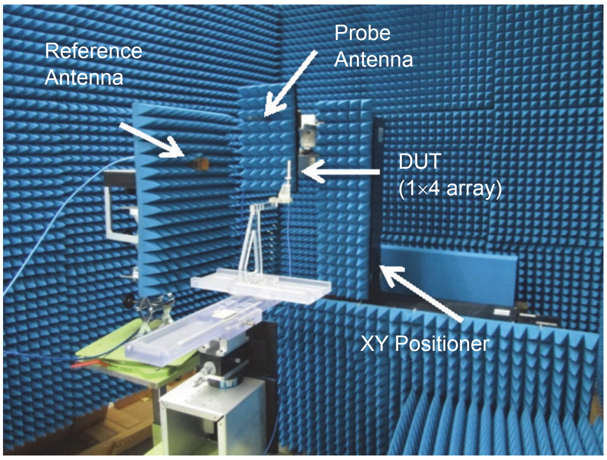

Figure 5 Measurement System

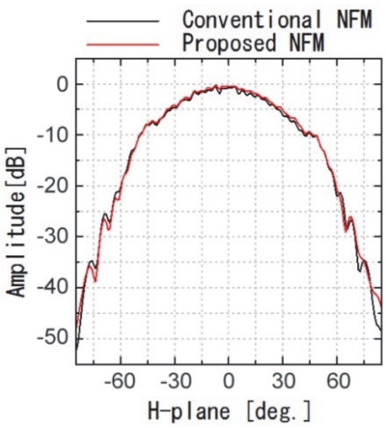

Figure 6 Horizontal Plane Directivity Comparison

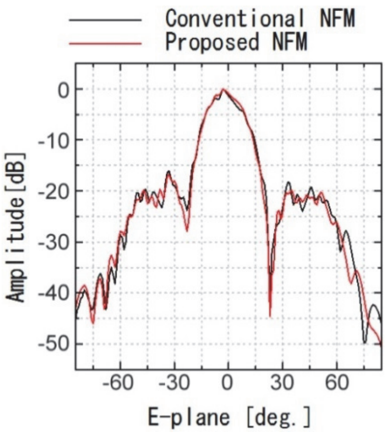

Figure 7 Vertical Plane Directivity Comparison

3.3 Advantages and Issues

Since the fixed reference antenna method finds the phase at each measurement position independently, theoretically, it has small uncertainty compared to the adjacent phase difference measurement method described below. However, this method suffers from the following issues. Since the reference antenna must be positioned at a location where it has no impact on the near-field scanning plane, it is located at –90° viewed from the DUT in this measurement. Because the measured DUT has a sufficiently wide directivity in the horizontal plane, it is possible to receive sufficiently powerful signal even at a position of –90° in the horizontal direction. However, with a strongly directive DUT, the reference antenna may be unable to receive a sufficiently strong signal. As a result, although comparatively good measurement accuracy can be expected for a DUT with directivity in both the horizontal and vertical planes, for a DUT with strong directivity in both vertical planes, there are concerns about the impact on the directivity measurement results as the uncertainty of the phase distribution becomes larger.

4 Proposed Adjacent Phase Difference Method

4.1 Measurement Principle

The adjacent phase difference measurement method is a NFM method for antennas with strong directivity (large aperture plane). This method determines the phase by capturing the difference between signals received simultaneously at multiple probe antennas aligned to satisfy the sampling interval at the near-field scanning plane. This principle is explained in Figure 8.

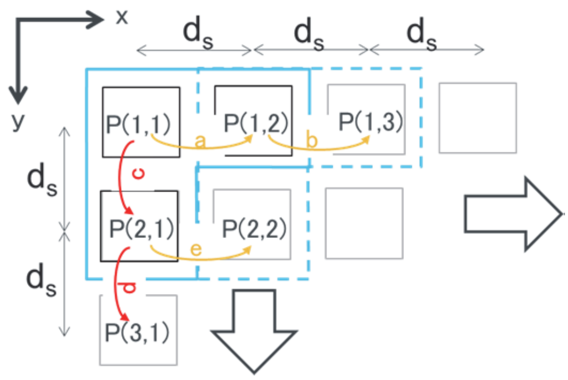

Figure 8 Adjacent Phase difference measurement method Block Diagram

In Figure 8 showing the near-field scanning plane, the rectangles (P(1,1)...) indicate the probe antenna position. Here, the sampling interval (d_s) must be λ/2 or less. In this case, the top and bottom left and right have a form like Γ and assume a probe with three parallel-aligned antennas (area bounded by blue line). At this time, when the phase ($P_\theta(1,1)$) of the signal received at P(1,1) is specified as

$$P_\theta(1,1) = \theta_0 \tag{3}$$

$P_\theta(1,2)$ is found from the phase difference a between $P_\theta(1,1)$ and $P_\theta(1,2)$ as

$$P_\theta(1,2) = P_\theta(1,1) + a = \theta_0 + a \tag{4}$$

Similarly, $P_\theta(1,3)$ is found as

$$P_\theta(1,3) = P_\theta(1,2) + b = \theta_0 + a + b \tag{5}$$

After that phases are found sequentially until $P_\theta(1,n_x)$, where n_x is the sampling number on the x-axis. Likewise, on the y-axis, the phase is found as

$$P_\theta(2,1) = P_\theta(1,1) + c = \theta_0 + c \tag{6}$$

$$P_\theta(3,1) = P_\theta(2,1) + d = \theta_0 + c + d \tag{7}$$

up to $P(n_y,1)$, where n_y is the sampling count on the y-axis. At other sampling points, the phase is found as

$$P_\theta(2,2) = P_\theta(2,1) + e = \theta_0 + c + e \tag{8}$$

by sequential calculation up to $P_\theta(n_y,n_x)$. Accordingly, it is possible to determine the relative phase distribution for the entire near-field scanning plane. In addition to finding amplitude distribution directly using the amplitude of the probe selected from the multiple probes, it can also be found by averaging the signals received from multiple probes at the same sampling point. Using this type of data processing supports capture of the amplitude and phase distributions of the NFM scanning plane for a DUT with no measurement connectors to find the directivity using far- field conversion.

Unlike the fixed reference antenna method, this method solves the issue of not obtaining sufficient Rx signal strength because measurement uses only the signal directly in front of the antenna. It is believed to be especially effective for measurement of large aperture Massive MIMO antennas.

4.2 Adjacent Probe Antenna

The adjacent phase difference measurement method requires the multiple probe antennas to be parallel with a near-field scanning plane sampling interval of λ/2 or more. However, the isolating waveguide used previously as an NFM probe antenna has a dimension exceeding this value in the H-plane direction (long side of waveguide aperture) so it cannot be used as is. As a result, a new probe antenna examination is required. In concrete terms, for a measurement frequency of 27.5 GHz to 30 GHz, at the upper frequency limit (30 GHz), since λ = 10 mm, the probe antennas must be aligned parallel at an interval of 5 mm or less. Here, assuming the probe antenna wall thickness is 1 mm, the aperture length (a) for each antenna probe is 4 mm or less. Since the internal dimensions of the standard waveguide (WR-28) used at this frequency are 7.11 mm × 3.56 mm, the waveguide cannot be used without modification to an internal dimension of 4 mm × 4 mm or less.

In this development, we used a double-ridge waveguide[11) to implement this adjacent probe antenna. This double-ridge waveguide has a vertical-ridge construction and has the effect of shifting the cutoff frequency to the lower range compared to a normal waveguide. Using this effect fixes the waveguide usage frequency band and the waveguide internal dimensions can be reduced. Figure 9 shows a double-ridge waveguide designed for actual use by the simulator. Figure 10 shows the permissivity characteristics of waveguides of the same dimensions without a ridge and with the designed ridge. Based on Figure 10, without a ridge, the cutoff frequency remains at or above 35 GHz but with a ridge design the cutoff frequency can be shifted to 25 GHz or less, supporting operation at the measurement frequency. The CST MICROWAVE STUDIO was used in this simulation.

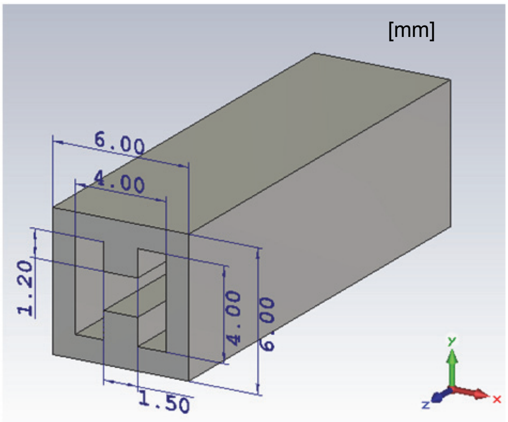

Figure 9 Double-Ridge Waveguide Dimensions

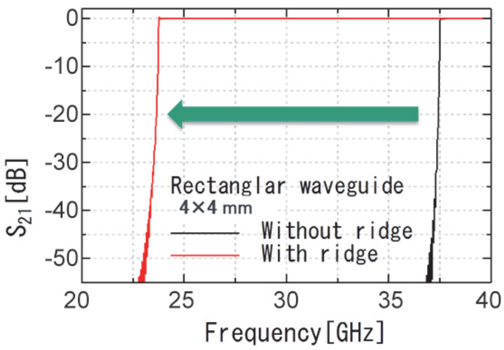

Figure 10 Change in Cutoff Frequency With/Without Ridge

Figures 11 and 12 show the developed waveguide probe antenna with three of these double-ridge waveguides. The tip of the probe is an open-type double-ridge waveguide and the back end connects to a WR-28 waveguide using a taper conenector design. In addition, there is a slit design between the probe antennas to reduce the adjacent probe antenna coupling. Since the developed adjacent probe antenna is difficult to manufacture due to the complex machining, it was manufactured from SUS316 using a 3D printer.

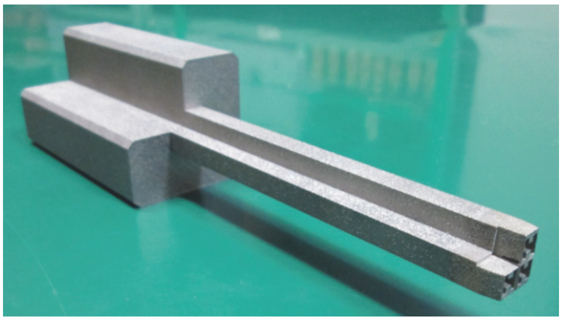

Figure 11 Adjacent Probe Antenna Appearance

Figure 12 Adjacent Probe Antenna Opening

4.3 Operating Principle Verification Test

The operating principle of the adjacent phase difference measurement method was verified using the developed adjacent probe antenna. The test setup is shown in Figure 13 and Table 3 lists the system specifications. To simulate a DUT with a stronger directivity than the 1×4 bow tie antenna used at the fixed reference antenna method demonstration verification test, a 2×4 bow tie antenna array was (Figure 14[12]) was connected to a signal generator. The connected probe antenna was mounted on an XY positioner and the front plane of the DUT was scanned. The signals received at the adjacent probe were input to each port of a 4-port VNA (Anritsu MS46524B) using coaxial cable via coaxial to waveguide converter. The MS46524B measures the phase difference between signals received at two ports. This phase difference and the received field level are loaded to a PC that computes the near-field scanning plane amplitude and phase distribution according to the principles described in section 4.1.

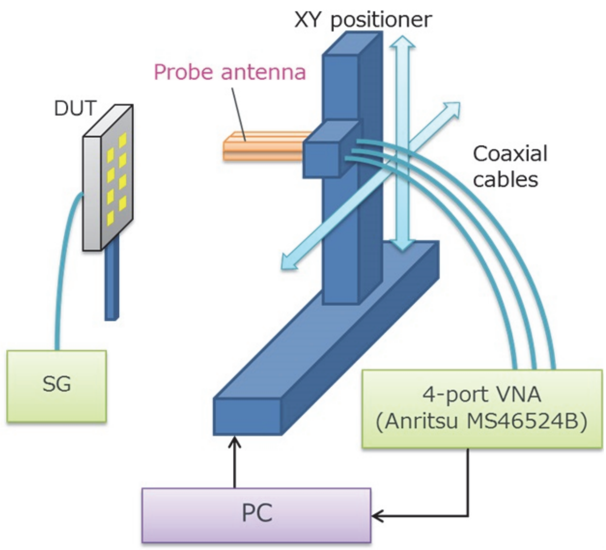

Figure 13 Adjacent Phase difference measurement method Test System

Table 3 Test System Specifications

Measurement Frequency	28.0 GHz
DUT	2×4 Bow Tie Antenna Array + SG
Probe Antenna	Adjacent Probe Antenna (Figures 11 and 12)
Measuring Instrument	4-port VNA (Anritsu MS46524B)

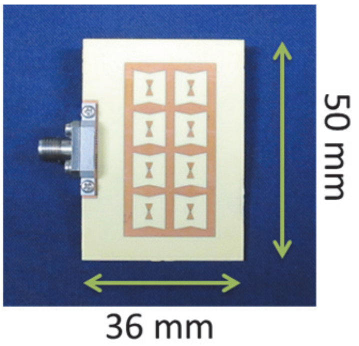

Figure 14 DUT (2×4 Bow Tie Antenna Array)

Figures 15 and 16 show the converted far-field directivity converted from the calculated near-field scanning plane field distribution. The solid black lines in these figures are the directivity of the same 2×4 bow tie array measured using the previous NFM method; the red lines show the directivity measured using the adjacent phase error method. From Figure 16, the vertical plane directivity is well matched, but Figure 15 shows a side-lobe-level drift effect in the horizontal plane. With the high-angle side-lobe drift, the main-lobe coincide with conventional NFM measurement results. As a results, the operating principle of the adjacent phase difference method is confirmed.

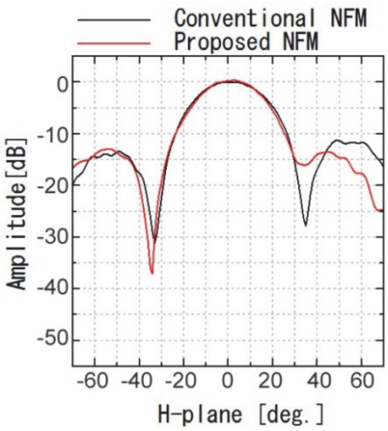

Figure 15 Horizontal Plane Directivity Comparison

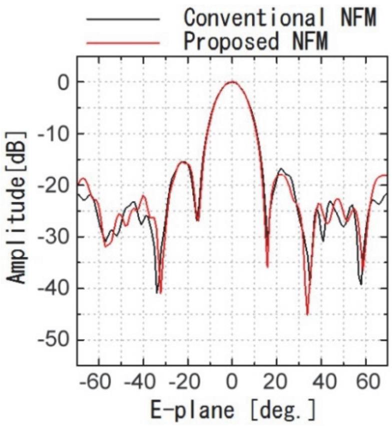

Figure 16 Vertical Plane Directivity Comparison

4.4 Advantages and Issues

Since the adjacent phase difference measurement method can calculate the phase just for the probe antenna positioned directly in front of the antenna, it solves the problem of increased measurement uncertainty caused by the installation position of a reference antenna such as the fixed reference antenna method. As a result, it is a better method than the fixed reference antenna method for measuring a DUT with many antenna elements and strong directivity.

However, since the calculated phase drift at each measurement point affects the adjacent measurement point, there is an issue with larger uncertainty compared to the fixed reference antenna method. Additionally, the observed horizontal-plane side-lobe drift at the demonstration verification test is a problem. The results of analysis of this drift using another simulator clarified that this is due to the probe antenna having phase angle characteristics. Correction for amplitude characteristics is performed by probe correction, but phase-related correction is difficult. To solve this issue, we are examining increasing the number of probe antennas to five and using a symmetrical overall probe antenna form, as well as using data processing to cancel the phase characteristics.

5 Conclusions

This article proposes two NFM methods currently in development as systems for measuring the directivity of Massive MIMO base stations with no measurement connectors and presents demonstration test results verifying the operation principles. The results of the fixed reference antenna method show good agreement with previous methods but there is an issue with the reference antenna setting position.

The adjacent phase difference method has the possibility of larger uncertainty than the fixed reference antenna method, but is more applicable in principle to measuring a DUT with strong directivity. In addition, although the operating principle verification test indicated an issue with some side-lobe drift in the H-plane directivity, it showed that directivity measurement is possible. We intend to improve this H-plane drift issue by developing a new probe antenna.

For future developments, in addition to measuring directivity using NFM methods, we will also propose solutions for calibrating Massive MIMO base station using methods such as back-projection to help development and deployment of 5G and millimeter-wave technologies.

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