

An Experimental Study of 28 GHz Analog Beamforming with a Uniform Linear Array

Tetsuya Iye*, Kensuke Tsuda*, Yoshimi Fujii*

*Communication Engineering Department, Kozo Keikaku Engineering, Inc., Tokyo, Japan

tetsuya-iy@kke.co.jp, kensuke.tsuda@kke.co.jp, yfujii@kke.co.jp

Abstract— This paper reports an over-the-air measurement of a uniform linear antenna array for the radio frequency of 28 GHz and discusses the achieved accuracy of beamforming. Two conventional phased array calibration methods, i.e., rotating element electric field vector method and multi-element phase-toggle method, are performed and compared to confirm calibration validity. Both methods realize fine beam steering accuracy of $\delta\theta_{\text{RMS}} = 0.23^\circ$ around the boresight direction. In addition, we confirmed the robustness of the calibration values against frequencies within 200 MHz wide around 28 GHz.

Keywords— 5G NR, OTA measurement, analog beamforming, uniform linear array, calibration

I. INTRODUCTION

As 5G NR begins to be introduced in many countries, research and development of mobile communication technologies in the millimetre-wave (mmWave) band is accelerating. Our research group drives a nationally funded research project called ‘5G Advanced Project’, whose goal is to realize a new wireless network system which satisfies several different traffic requirements simultaneously by evolving 5G technology [1], [2]. Since the mmWave band has the strong attenuation property on the spatial propagation, the beamforming technique using multiple antenna elements is required to compensate for the path loss. Although some reports have already shown experimental trials on the mmWave beamforming [3], [4], more precise control of gain and phase on each antenna element port of antenna array will be required in the beyond 5G or 6G era. Hence, this report discusses the calibration for the antenna array and its accuracy. We aim to realize a hybrid beamforming technique which combines high-accuracy analog beamforming and a new digital beamforming scheme [5] as an advanced 5G technology. To generate the desired beam pattern with high accuracy, a calibration in the excitation amplitude and phase for antenna element ports is necessary for both analog and digital beamforming. Various antenna array calibration methods have been proposed to date [6-12]. While built-in methods in [6],[7] that do not require dedicated measurement setup and can calibrated internal errors automatically are being considered, the far-field measurement method [8-12] has the advantage of being able to measure the elemental electric field, including all effects, in the far-field where the phased array is actually used. Here, we performed the conventional calibration methods in an 8-element uniform linear array (ULA) of 28 GHz consisting of evenly spaced patch antenna elements and report



Figure 1. The uniform linear antenna array with evenly spaced patch antenna elements (P1 – P8) aligned in the horizontal direction.

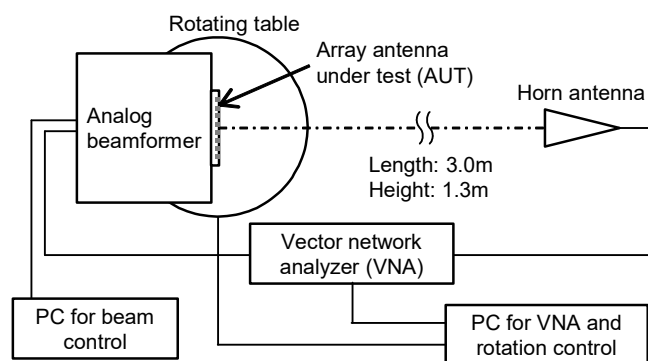


Figure 2. A schematic top view of the measurement system.

the experimental results, which realized high accuracy analog beamforming. In addition, we confirm that the measurement results of beam pattern and directivity accuracy reproduce our previous simulation results [13] and discuss the achieved accuracy from the result.

II. EXPERIMENT

The 8-element vertically polarized ULA for 28 GHz in this work is shown in Figure 1. Patch antenna elements (P1 - P8) are placed at 6 mm intervals. Before performing array pattern measurements of the ULA, VSWR and gain/phase patterns of each antenna element in horizontal and vertical directions are measured, respectively. The electromagnetic simulation for each antenna pattern is also performed for comparison.

Initial phase and gain offset difference between the element ports of the analog beamformer without mounting the ULA are examined prior to the beamforming experiment. It clarified the non-negligible phase and gain difference between the ports up to 20° and 1 dB, respectively, suggesting the need to be calibrated. Then, the calibration in excitation amplitude and

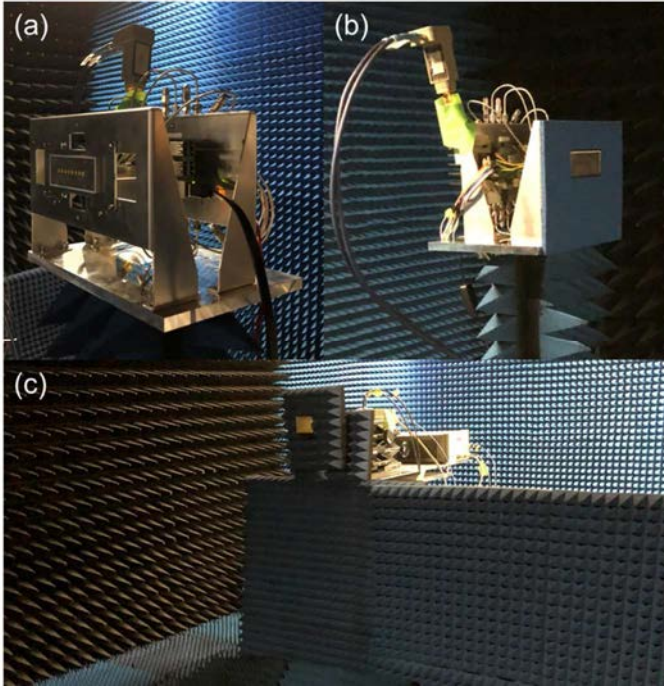


Figure 3. The AUT (a) mounted on the metal plate and (b) surrounded by the absorber sheet, respectively. (c) The horn antenna on the opposite side of the AUT.

phase values for each antenna port is performed in an anechoic chamber. The schematic of the experimental setup is shown in Figure 2. TX and RX measurements are switched by connecting the up down converter to the RX side antenna unit. For both TX and RX measurements, the antenna array under test (AUT) and the horn antenna on the opposite side of it are used as shown in Figure 3. In this work, the rotating element electric field vector (REV) method [8] and the multi-element phase-toggle (MEP) method [9] are adopted as the well-established calibration to realize higher accuracy of the beam control. Thereafter, we measured

the array patterns in the horizontal direction for several excitation methods such as uniform, Chebyshev, and binomial by changing the steering angle θ_s within $-60^\circ \leq \theta_s \leq 60^\circ$. The obtained array patterns are compared with the simulation pattern calculated by integrating each element pattern measured above. For simplicity, only RX measurement results are reported in this paper.

III. RESULTS AND DISCUSSION

The experimental and simulation results of this work are described in the following subsections.

A. Gain and Phase Patterns for Each Antenna Element

Figure 4 summarizes the experimental results of VSWR against frequency, gain and phase patterns of each antenna element in the horizontal and vertical directions, respectively. A small shift to higher frequencies of the order of 300 MHz in VSWR is due to the relative permittivity tolerance of substrate material and minor form errors in the substrate. The fine ripples in Figure 4(b) and 4(c) come from the effects of small surface

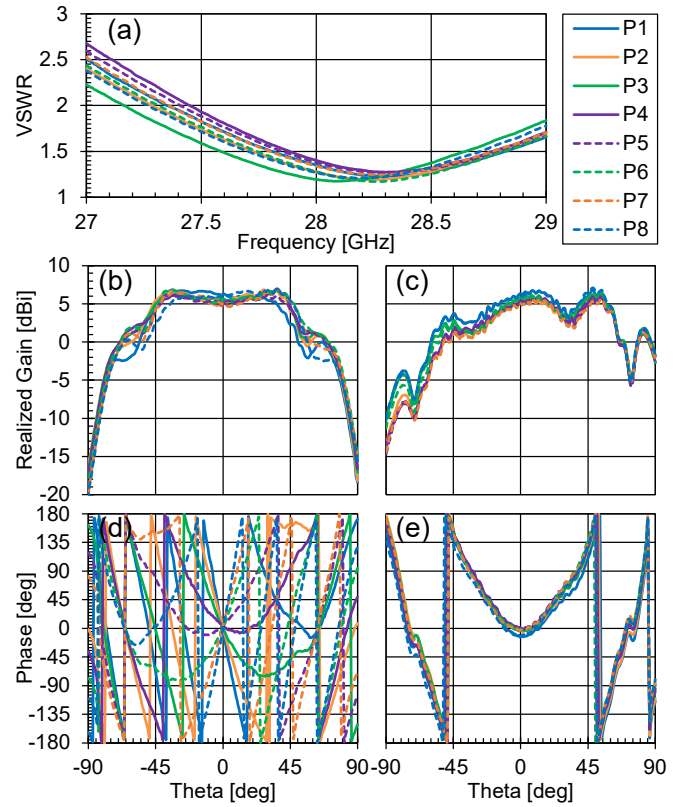


Figure 4. (a) VSWR from 27 to 29 GHz. Gain patterns of the 28 GHz patch antenna elements for the (b) horizontal and (c) vertical directions. Phase patterns of the elements for the (d) horizontal and (e) vertical directions.

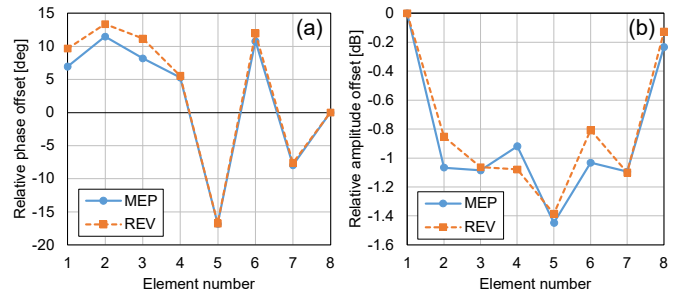


Figure 5. Relative (a) phase and (b) amplitude offset values of each antenna element port of the ULA determined by MEP and REV calibration.

current and the edges of the reflector. For the antenna element patterns in the horizontal direction, flat and high gain of about 5-6 dBi has been achieved in the range of $-45^\circ \leq \theta \leq 45^\circ$.

B. Phased Array Calibration

Due to mechanical errors and feed network characteristics, the amplitude and phase of each element may be different from the desired values. We adopt two different phased array calibration methods, MEP and REV, for comparison. For the detailed technical background of these two calibration methods, see [8] and [9]. In order to explore difference in offset values between MEP and REV, we show relative phase and amplitude offset values as a function of antenna port number for each method in Figure 5. Both phase and amplitude values for MEP are in good agreement with the ones for REV. Since MEP

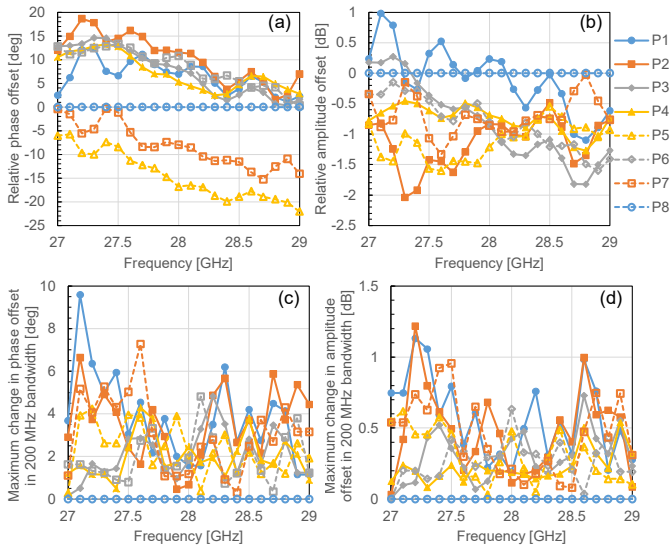


Figure 6. Relative (a) phase and (b) amplitude offset values and Maximum change in (c) phase and (d) amplitude offset values in 200 MHz bandwidth of each antenna element port as a function of frequency determined by MEP method.

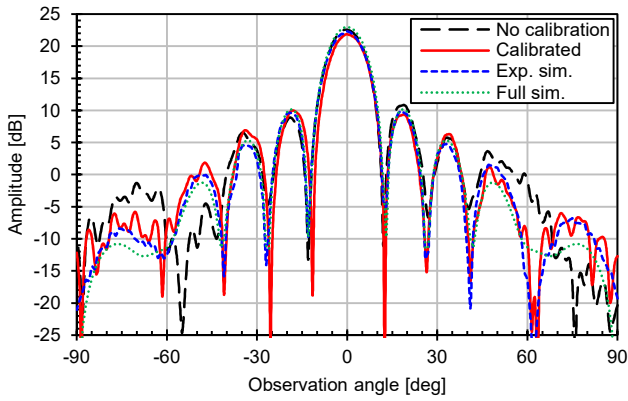


Figure 7. Summary of antenna array patterns with and without calibration along with the simulation results obtained by measured element patterns and by the electromagnetic simulator.

method requires less number of measurements than the conventional REV method if the vector network analyser is available, all the measurements in this work use the MEP method for phased array calibration. The calibration is conducted by subtracting these offset values in 5.625° unit for phase by 6-bit phase shifter and in 0.5 dB for amplitude by 5-bit gain controller from the desired excitation values.

Furthermore, frequency dependence of the phase and amplitude offset values from 27 to 29 GHz is measured and summarized in Figure 6(a) and 6(b). From these results, we further analysed the maximum change in the offset values in 200 MHz bandwidth for each port by taking the difference between the moving maximum and the moving minimum with the window of 200 MHz with respect to the frequencies from 27 to 29 GHz as presented in Figure 6(c) and 6(d). Since the offset values fluctuate within the order of one tunable step, i.e.,

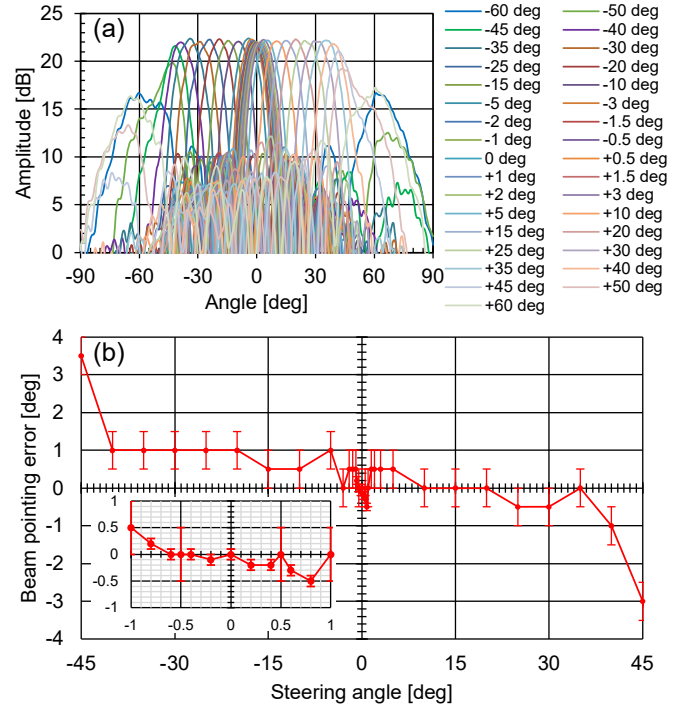


Figure 8. (a) Measured RX beam patterns pointing to the different steering angles from -60 to +60 degree. (b) Beam pointing error defined by the deviation of the actual beam pointing angle from the steering angle with the inset of enlarged view around the origin.

5.625° for phase and 0.5 dB for amplitude, in 200 MHz bandwidth, where 5G NR prescribes as the wideband communication, the offset values are regarded to be robust against frequency in our analog beamformer. However, for wider bandwidth over 200 MHz and for other than the center frequency of 28 GHz, the calibration values may not be constant in the bandwidth. The calibration method over the entire bandwidth would be further study.

C. Comparison between Calibrated Pattern and Simulation

Figure 7 summarizes the synthesized array beam patterns measured with and without calibration together with the simulation results. “Exp. sim” data means the simulation obtained by calculating the composite electric field vector from the experimental element patterns shown in Figure 4(b) and 4(d). “Full sim” data indicates the result obtained by the composite vector from the element patterns calculated by the electromagnetic simulation of each antenna element. The calibrated array pattern “MEP” reproduces the sidelobe structure of “Exp. sim” pattern well over the entire range of observed amplitude and angle, and thus, the measured calibration values are verified.

D. Beam steering

Fine beam steering is achieved as can be seen in Figure 8(a), where the envelope curve of observed beam patterns reflects the averaged element gain pattern. The beam pointing error defined by the deviation of the main lobe peak from desired steering angle is plotted in the range of $-45^\circ \leq \theta_s \leq 45^\circ$, since larger steering angles produce grating lobes, as shown in Figure

8(b). The root mean squared value of the beam pointing error is evaluated to be $\delta\theta_{\text{RMS}} = 0.23^\circ$ for $-1^\circ \leq \theta_s \leq 1^\circ$ and $\delta\theta_{\text{RMS}} = 0.90^\circ$ for $-45^\circ \leq \theta_s \leq 45^\circ$. The value of $\delta\theta_{\text{RMS}} = 0.23^\circ$ around boresight direction indicates the ULA is fully calibrated as predicted in [13], where the reference suggests that the pointing error is reduced to $\delta\theta_{\text{RMS}} \sim 0.3^\circ$ by calibration.

IV. CONCLUSIONS

This work presented the results of an over-the-air measurement of the uniform linear antenna array for 28 GHz band. First, we showed the experimental results of VSWR, the phase and gain patterns in the horizontal direction for each antenna element and verified that flat high gain of about 5-6 dBi has been achieved in the range of $-45^\circ \leq \theta \leq 45^\circ$. In order to achieve higher accuracy of the beam steering, two conventional phased array calibration methods, i.e., rotating element electric field vector method and multi-element phase-toggle method, were performed and confirmed calibration validity by comparing the result with each other. Both calibration methods realize the beam steering accuracy of $\delta\theta_{\text{RMS}} = 0.23^\circ$ around boresight direction, indicating our phased array antenna system is sufficiently calibrated according to the previous work [13]. In addition, we confirmed the robustness of the calibration values against frequencies within up to 200MHz wide around 28 GHz whose bandwidth is expected to be used as the wideband communication in 5G NR or beyond 5G.

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Tetsuya Iye (M'19) was born in Tokyo, Japan, in 1986. He received a B.S. degree in physics from Waseda University, Tokyo, Japan, in 2009 and M.S. and Ph.D. degrees in physics from Kyoto University, Kyoto, Japan, in 2011 and 2014, respectively. From 2013 to 2014, he was a Research Fellow of the Japan Society for the Promotion of Science. He joined Kozo Keikaku Engineering, Inc., Tokyo, Japan, as a System Engineer in 2014. His current research interests include millimeter-wave communications, antennas and propagation, beamforming, and the software-defined radio (SDR).



Kensuke Tsuda received B.S. and M.S. degrees in theoretical physics from Osaka University, Osaka, Japan, in 2000 and 2002, respectively. He joined Kozo Keikaku Engineering, Inc., Tokyo, Japan, as a Computational Electromagnetics Application Engineer. His research interests include the development of a real-time multi-GNSS signal generator and virtualized 5G/6G radio access networks, based on the software-defined radio (SDR) technology.



Yoshimi Fujii (M'19) received B.S. and M.S. degrees in computer science and communication engineering from Kyushu University, Fukuoka, Japan, in 1989 and 1991, respectively. Since 1991, he has been working as a Software Engineer in the telecommunication field with Kozo Keikaku Engineering, Inc., Tokyo, Japan. His research interests include various layers of wireless communication technology, especially lower layers such as the physical layer and media access layer. Currently, he is involved in a series of projects related to the implementation of wireless communication PHY layer using a software-defined radio (SDR) approach. In addition to telecommunication, he is interested in the implementation of GNSS signal generators and receivers with an SDR.