

Design of Calibration Algorithms for Fully-Activated Millimeter-Wave Phased Array Antennas

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Abstract—This paper focuses on the study of the calibration technology for fully activated millimeter-wave phased array antennas. It utilizes a self-developed 1x8 array antenna module in conjunction with the M3-Force software defined radio (SDR) platform. By initiating the calibration mode with all antennas fully activated, the array antenna tuning is accomplished using the rotating element electric field vector (REV) algorithm. However, this algorithm involves the issues of ambiguity, and the paper proposes a technique to strengthen the synthesis of vectors to stabilize the estimation of antenna calibration parameters. Furthermore, an enhanced version of the REV method is introduced for incrementally joint block tuning of subarrays, facilitating the calibration of large array antennas. The paper overcomes the limitations of the traditional REV method in large array antenna calibration. Computer simulation results confirm the superior performance of this technique in overcoming issues with traditional REV methods and its applicability to large array antenna calibration. Finally, the paper validates the proposed technique through hardware testing with an array antenna and an SDR platform, confirming that the enhanced REV technology can calibrate a 1x8 millimeter-wave phased array antenna and suggesting its potential extension to the calibration of larger array antennas in the future.

Keywords—millimeter-wave phased array, rotating element electric field vector, software defined radio platform, calibration.

I. INTRODUCTION

To cope with the significant growth in the Internet of Things (IoT) and mobile devices in the current 5G era, the bandwidth in the low-frequency bands is no longer sufficient to accommodate such a large number of devices. Therefore, the application of millimeter-wave frequencies is undoubtedly a trend. Millimeter waves, i.e., high-frequency signals, induce the rapid energy attenuation with increasing distance in transmission. Directional antennas can overcome this by focusing signal power, thereby extending the transmission distance. In directional antennas, phased array antennas play a crucial role in millimeter-wave transmission. Their high directionality compensates for the substantial path loss in millimeter-wave transmission.

Typically, each antenna element in a phased array antenna has independent phase shifters and attenuators. Electronic control of phase shifters allows the effective beam to be steered in a specific direction, while control of attenuators helps form the desired radiation pattern. However, due to the small wavelength of millimeter waves, phased array antennas are highly sensitive to small deviations. Phase responses and position responses of individual antenna elements may be affected by inevitable errors and manufacturing tolerances,

and the performance of the antenna can also be influenced by temperature changes over time. If these deviations and errors are not corrected, unwanted beams may form in various directions, causing interference and limiting the gain of the antenna array as well as the overall system performance. This study addresses the issues of phase and position inconsistency among antenna elements in phased array antennas, as well as the nonlinearity of the control curves of phase shifters and attenuators. First, it explores feasible calibration techniques [1]-[7] to adjust the phase and position of antenna elements, overcoming the nonlinearity in the control curves. Next, it employs a Software Defined Radio (SDR) platform in conjunction with millimeter-wave phased array antennas for practical testing. The study validates the feasibility of the calibration technique by measuring antenna radiation patterns and confirms that this technology effectively enhances the performance of antenna beamforming.

II. EXPLANATION OF THE INTEGRATION OF MILLIMETER-WAVE ACTIVE PHASED ARRAY ANTENNAS WITH SOFTWARE-DEFINED RADIO PLATFORMS

This paper focuses on the calibration of millimeter-wave phased array antennas, with the details of the calibration technique presented in the third section. This section introduces the integration and development of the active array antenna with SDR platform. To begin with, the array antenna module employed in this thesis is a self-manufactured 1x8 millimeter-wave phased array antenna module [8] operating at 28GHz by Yuan Ze University. The physical appearance of the array antenna module is illustrated in Figure 1.

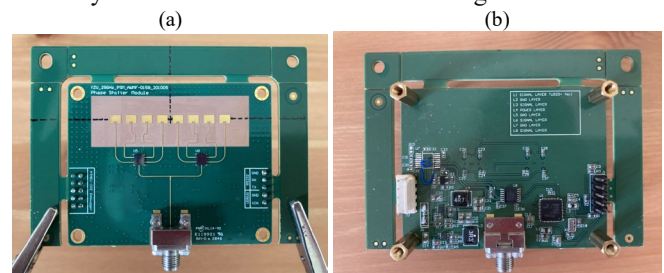


Figure 1. Homemade millimeter-wave active array module. (a) Physical front view. (b) Physical rear view.

The module incorporates an ARM (MCU) chip and an Anokiwave 0158 Beamforming IC, which is controlled by ARM to adjust the 4-bit Gain and 6-bit Phase Shifter. The array module is designed to be calibrated with SDR platform.

Next, for the explanation, the integration involves calibrating the antenna module using both a PC and the M3-

Force SDR. Based on the design module, the PCB design incorporates high-frequency microstrip circuits and low-frequency ARM control circuits. This design coexists on an eight-layer PCB. Grounding and interference elimination are crucial considerations in the design, leading to the incorporation of numerous large-area perforations in the PCB.

Regarding the development platform, it will be used to calibrate the Gain/Phase of the 1x8 millimeter-wave phased array antenna PCB mentioned above. It can execute functions related to coherent wave pointing. Traditional network analyzer calibration platforms are known to be expensive. Such platforms include probes and network analyzers integrated to measure single-frequency signals transmitted by different antennas (in switching mode). Through network analyzer computations, stable Gain and Phase values for different antennas can be obtained. This stable result is widely adopted in the industry for millimeter-wave array calibration.

Another cost-effective measurement platform is the M3-Force software defined radio (SDR) platform. This device includes two sets of AD9361 RF modules, capable of simultaneous control for four transmitters and four receivers. It supports a maximum bandwidth of 56MHz and frequencies up to 6GHz, with transmit attenuation and receive gain support of up to 40dB. When paired with MATLAB programs for signal processing, it can measure antenna phase and position. This SDR platform also incorporates millimeter-wave up/down-conversion components and a computer. Unlike traditional network analyzers (common in millimeter-wave band measurements), this platform combines physical BaseBand I/Q signals, upconverts them to millimeter-wave frequencies, retrieves the I/Q signals, calculates the Gain and Phase for the 1x8 antenna paths, and then performs compensation and calibration. This approach closely mimics the "full system calibration requirements for practical millimeter-wave communication applications." Therefore, the calibration method [8] using the SDR platform has gained recent attention. The process diagram of this SDR measurement platform is illustrated in Figure 2.

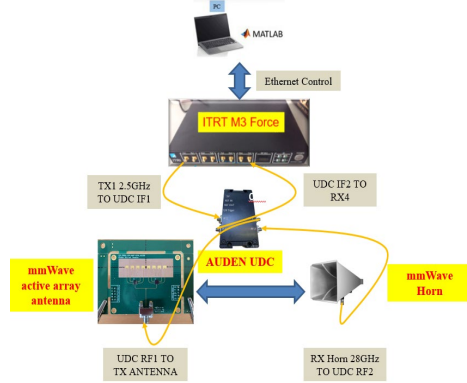


Figure 2. Flowchart of the SDR Measurement Platform.

Next, this section is dedicated to performing beam pattern measurements for the 1x8 millimeter-wave module (after compensation for calibration parameters). The measurement platform is illustrated in the following diagram, comprising the M3-Force SDR platform for signal transmission, a non-reflective chamber, and the chamber involves a 1x8 array

antenna mounted on a 360-degree rotator. This setup allows for beam pattern measurements. Moreover, after the calibration in subsequent sections, beam pattern measurements will be conducted using this non-reflective chamber setup.

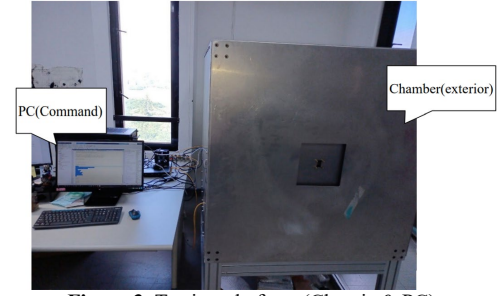


Figure 3. Testing platform (Chassis & PC).

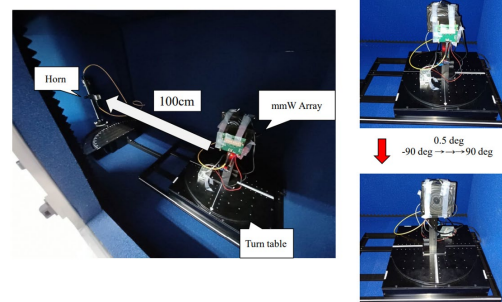


Figure 4. Internal arrangement of the chassis.

Furthermore, Figure 3 depicts the calibration chamber and the computer platform. Then, the external components, including the millimeter-wave up/down-conversion module and the M3-Force SDR platform, are connected to the calibration platform. Subsequently, Figure 4 illustrates a conceptual diagram for future testing of REV antenna inter-calibration (with a distance of more than 40cm between the Horn and Array), representing far-field testing. Finally, after antenna array calibration, Figure 4 outlines the utilization of this calibration for beam pattern measurements ranging from -90 degrees to 90 degrees.

III. RESEARCH ON ALGORITHMS FOR ESTIMATING PHASE AND ALIGNMENT OF PHASED ARRAY ANTENNAS

This section explores the research on algorithms for estimating the phase and alignment offsets of each antenna element in a phased array, aiming to obtain the calibration table for the antennas and verify the array antenna's pointing performance. Firstly, the discussion focuses on the Rotating Element Electric Field Vector (REV) method [1], which is internationally recognized for its ability to identify the phase/alignment deviations of antennas using only amplitude/power (real-number) measurement techniques. Moreover, the operational procedure for REV antenna element field measurements involves simultaneous testing of different phases across the array antenna. In other words, the REV technique incorporates real-world environmental factors into the calibration process. This includes factors such as changes in the T/R module, variations in the feed circuit, and diffraction effects caused by the antenna structure, all of which are adjusted simultaneously by the REV technique. This approach provides a more comprehensive calibration.

The REV technique involves measuring all antennas to be calibrated, but only one antenna's phase is altered to measure the overall power variation. This approach takes into account the interaction coupling factors between antennas. Such a comprehensive adjustment of all coupling factors is expected to be more widely accepted in practical applications.

Having reviewed relevant literatures, the author in reference [2] mentions that through theoretical analysis of measurement errors, the amplitude and phase differences of the excited antenna elements will decrease as the number of antennas increases, especially when combined with the full activation of REV. This indicates that the calibration measurement errors for array antennas will decrease. In reference [3], the author extends the REV method to an expanded version, where multiple antennas rotate their phases together, allowing for faster calibration. Reference [4] introduces the development of the array antenna power synthesis response using high-order Fourier series, which can enhance REV performance. Reference [5] proposes the Fast REV method, which offers the advantage of accelerating the calibration speed of REV. Commonly used simple calibration methods, such as initial calibration stages, subsequent calibration stages, near-field (far-field) calibration stages, and even the need for extensive measurement data and time-consuming processes during on-board system self-diagnostic calibration, are addressed. Therefore, there is a need for fast and accurate calibration methods [5][6] to achieve the calibration goals of array antennas.

A. Description of REV Techniques

This section aims to provide a brief overview of the core principles of the REV technology. The paper will also extend and improve the "REV confusion detection" issue associated with this technology. Furthermore, it will introduce an enhanced version of the REV tailored for large arrays.

Firstly, REV is a calibration method for synthesizing array field vectors in a specified direction. This method possesses the synthetic characteristic of summing all antenna elements. The synthesized field vector undergoes changes when one antenna element is rotated from 0 degrees to 360 degrees (controlled by a phase shifter), resulting in variations in the synthesized vector. Based on the changing amplitude values of this synthesis, the amplitude and phase of the antenna element can be determined. The behaviour of the power representation of the changing synthesized amplitude will exhibit a sinusoidal curve. The schematic diagram of REV is as follows:

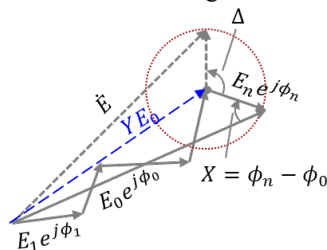


Figure 5. Schematic diagram of overall synthesized vectors in REV [1].

Figure 5 is an illustrative diagram of the synthesized vectors for all antennas. At this point, the mathematical

expression for the synthesized vector field in Figure 5 (with the n th antenna changing phase Δ) is expressed as follows [1]:

$$\dot{E} = (E_0 e^{j\phi_0} - E_n e^{j\phi_n}) + E_n e^{j(\phi_n + \Delta)} \quad (1)$$

In the above formula, E_0 represents the synthesized field of all antennas, ϕ_0 denotes the phase rotation of the all antennas and ϕ_n denotes the phase rotation of the n th element. By removing the vector field E_n of the n th element and then introducing the change in phase Δ for the n th element (with a 360-degree variation), the overall dynamic synthesized quantity $\dot{E}$ can be obtained. Next, this technique aims to determine the amplitude ratio and phase deviation between the vector field of the n th element E_n and the original synthesized vector E_0 , as expressed in the following equation [1]:

$$k = \frac{E_n}{E_0} \quad \text{and} \quad X = \phi_n - \phi_0 \quad (2)$$

Furthermore, explaining the reason for this sine wave curve, when Δ changes, there will be a variation in $\dot{E}$. At this point, the ratio (Q) relative to the original synthesized vector field E_0 can be obtained (measured), as expressed in the following equation [1]:

$$Q \equiv \frac{|\dot{E}|^2}{E_0^2} = (Y^2 + k^2) + 2kY \cos(\Delta + \Delta_0) \quad (3)$$

where $Y^2 = (\cos X - k)^2 + \sin^2 X$ and $\tan \Delta_0 = \sin X / (\cos X - k)$.

In (3), Q performs the sine wave curve when the Δ undergoes a 360-degree rotation. Moreover, (3) represent the interactive performance of Q at its maximum value with X and k . Next, further exploration is conducted on the ratio relationship between the maximum and minimum values of Q , as expressed in the following [1]:

$$r = \pm \frac{Y+k}{Y-k} > 1 \quad (4)$$

(4) has the representation indicating the need to determine whether to adopt + or adopt - in estimating X and k with confusion problem. Through the integration calculation of the aforementioned equations (3) and (4), values for k and X can be obtained (under two conditions) [1]. The explanation of the above REV technology reveals that the relative phase difference and amplitude ratio can be obtained, but there is an additional risk of confusion in judgment. A proposed method to avoid this risk is presented subsequently. The total number of measurements in the above scenario can be calculated, considering N antennas (for example, $N=8$ antennas), each having N_b bits to change the phase (for example, $N_b=6$ bits). Based on the above, it can be determined that there are $N \cdot 2^{N_b}$ changes in Q values to be measured. If $N=8$ and $N_b=6$, there are $Q=512$ ($8 \cdot 2^6 = 512$) value variations to be measured. After obtaining these Q values and considering the conditions $Y>k$ or $Y<k$ as mentioned above, the relative amplitude ratio (k) and phase difference (X) can be determined.

With these values, the relative phase calibration between antennas (i.e., $X_n - X_1$ for $n=2, 3, \dots, N$) and amplitude calibration between antennas (i.e., k_n/k_1 for $n=1, 2, \dots, N$) can be completed. These parameters form a table, which can be used for compensation and beamforming verification on the SDR and array antenna platform in the subsequent Section III.B. Further details will be explained in the following experiments.

B. Description of the Proposed Enhanced REV Technology

In the previous section, it was explained that the REV technology involves confusion issues due to the possibility of the overall synthesized vector E_0 undergoing phase cancellation or being lower in magnitude than the field vector of the n th element being tested. Conversely, the overall synthesized vector E_0 remains stable, maintaining a strength greater than the field vector of the n th element. At this point, existing literature suggests additional steps to assess the potential situations of the current synthesized vector E_0 . The author [6] proposes altering the size of the field vector of the n th element to aid in distinguishing the relationship between E_0 and the new E_n . While this approach improves the confusion issue, it indirectly increases the number of Q values that need to be measured by up to twice. As illustrated in the example explained in the previous section, it involves $Q=1024$ ($2 \cdot 8 \cdot 2^6 = 1024$) values to be measured, which results in a higher level of complexity. In this section, we enhance the energy E_0 of the REV to reduce the probability of confusion, achieving strengthened $E_0 > E_n$. This significantly diminishes the likelihood of confusion. The indirect approach we propose involves increasing the measurement E_0 by a factor of α . In other words, we can perform α measurements and summations of the overall synthesized vector, with the mathematical explanation of this summation's effectiveness provided below:

$$\begin{aligned} \dot{E}' &= (\alpha E_0 e^{j\phi_0} - E_n e^{j\phi_n}) + E_n e^{j(\phi_n + \Delta)}, \alpha > 1 \\ &= (E_0 e^{j\phi_0} - E_n e^{j\phi_n}) + E_n e^{j(\phi_n + \Delta)} + (\alpha - 1) \cdot E_0 e^{j\phi_0} \quad (5) \\ &= \dot{E} + (\alpha - 1) \cdot E_0 e^{j\phi_0} \approx \dot{E} + \alpha \cdot E_0 e^{j\phi_0}, \alpha \gg 1 \end{aligned}$$

The above formula illustrates that the original REV method had a value $\dot{E}$, which could lead to confusion. By strengthening E_0 the value α times, we can significantly achieve the result of $Y > k$, satisfying the stable estimation performance of the sum E_0 being greater than E_n . Therefore, with a high number of α , a lower probability of confusion can be obtained. The value of α can be chosen to be less than the total number of antennas. Following the explanation above, this paper chooses an enhanced REV method with $\alpha=7$, which is compared with several literature methods such as traditional REV [1], Fast REV [5], and improved confusion method [7] for stability. The criterion for determining stability is based on calculating the Mean Square Error (MSE) between the REV Beam Pattern and the Ideal Beam. If the MSE is

greater than 0.3dB, it is considered an erroneous result. For example, if the MSE for the enhanced REV is less than 0.3dB, it is considered a successful calculation; otherwise, it is considered a failure. Using this approach, we conduct 5000 simulations and calculate the error rate as error rate = number of failures/5000 $\times$ 100%. The results for different methods are presented in the following figure:

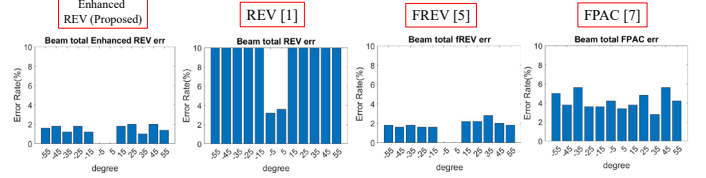


Figure 6. Comparison of stability among different methods.

The results indicate that the enhanced REV has excellent performance, while other methods show poor performance or require too many REV calculations. Therefore, the enhanced REV method proposed in this paper has a lower number of Q calculations. With $\alpha=7$, the estimation is $8 \times (2^6 + \alpha) = 512 + 56$ (only an additional 56 calculations, much lower than the previous estimate of 1024 Q values).

C. The Proposed Enhanced REV Technology for Large-Scale Arrays

Building upon the enhanced REV technology discussed above, this section extends to the array calibration of the Group-Based REV (Block-Based REV) in a Sub-Array configuration. The goal is to make it adaptable to large arrays and expedite the calibration process. Additionally, this approach considers factors related to mutual coupling between antennas, allowing for their simultaneous adjustment. The paper proposes the following two viable solutions.

1) Method 1: First, simultaneously execute the REV technique within each block, waiting for completion within each block after REV. Then, coordinate the REV adjustments between blocks outside the respective blocks.

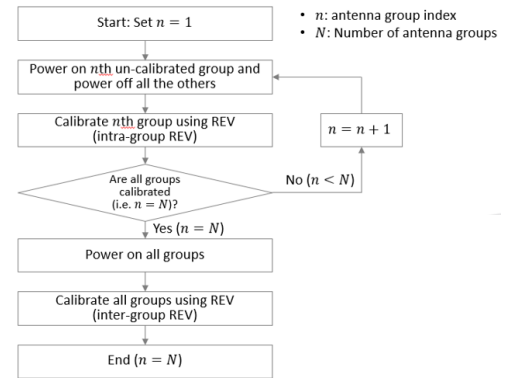


Figure 7. Adjustment process diagram for Method 1.

This method involves calibrating both the intra-block and inter-block REV. It covers the entire large array of antennas, meaning that all array antennas are divided into N blocks (for example, 4 blocks, each containing 8 sub-antennas, totalling 32 antennas to be calibrated). Each element within each sub-block must undergo calibration using the enhanced REV

method. As shown in the internal loop in the diagram of Figure 7, all internal calibrations within a group are completed. Once each group is aligned, as if integrating into a synthesized element, with N elements representing N groups, inter-group calibration is performed. Therefore, a total of $N+1$ REV operations are completed for the calibration of the entire array of antennas in that direction. The flowchart for this process is shown in Figure 7, and for the internal enhanced REV method, please refer to the explanations in Section III.B.

2) Method 2: First, sequentially execute the REV adjustments within each block, then perform the cumulative REV adjustments between blocks. This adjustment utilizes the alignment strength energy provided by the preceding block to enhance the intensity value for REV within the next group block, thereby improving the tuning efficiency in the subsequent block.

Compared to Method 1, this second method only requires N REV operations to complete the calibration of the entire array of antennas (lower than the $N+1$ REV operations in Method 1). The detailed flowchart for this method is shown in Figure 8. In this flowchart, the left loop represents the internal calibration process for Group 1, while the right loop represents the calibration process for Group 2. When calibrating Group 2, Group 1, which has already been calibrated, needs to be used for reference, and all internal calibration parameters of Group 2 are adjusted accordingly. However, the calibration table for Group 1 remains fixed, and the internal calibration for Group 2 is completed during the current REV operation. This approach allows aligning the internal calibrations of Group 2 and correcting the deviations between Group 1 and Group 2 simultaneously, providing several advantages. This process is extended to the 3rd, 4th, ..., N th groups, completing the alignment of all antenna elements.

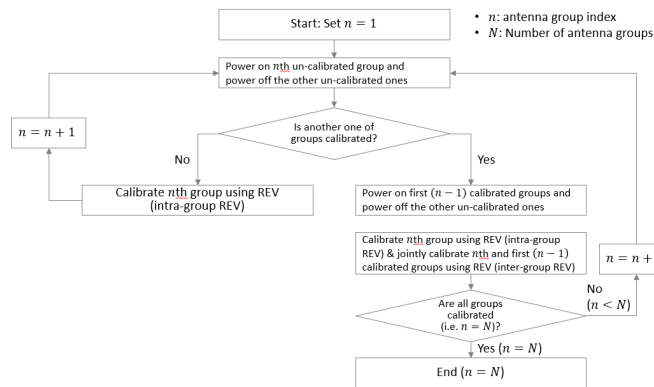


Figure 8. Adjustment process diagram for Method 2.

IV. COMPUTER SIMULATION AND HARDWARE PLATFORM TESTING

A. Computer Simulation Verification

This section focuses on computer program simulations for the Enhanced REV method proposed in Section III.B and the large array calibration method proposed in Section III.C. Firstly, the baseline antenna configuration is set with 16 antennas, inter-antenna spacing of the half wavelength, 6-bit phase shifters, 4-bit amplitude attenuators, and an SNR of

10dB. The simulation includes the influence of random variables on the amplitude and phase of each element, representing different antennas with various microstrip line distortion factors.

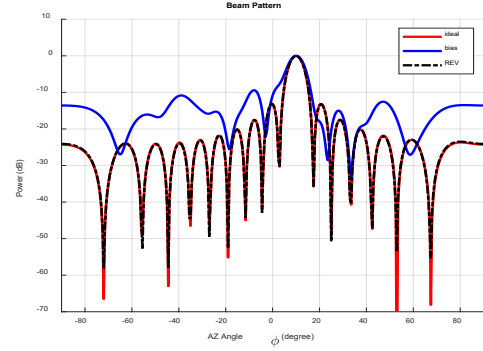


Figure 9. Simulation results of the enhanced REV method in Section III.B. After running the simulation based on the above settings, the results are illustrated in Figure 9. The red curve represents the ideal beam pattern and the black dashed line represents the beam pattern with the Enhanced REV method (close to ideal). The blue curve represents the original simulation result with added gain/phase bias and SNR=10dB effects that have not been compensated yet. In the Figure 9, it can be observed that the proposed enhanced REV method exhibits good performance.

Next, simulations were conducted to validate the two different methods proposed for the large array Group REV technology in Section III.C. Firstly, the baseline antenna parameters are similar to the explanation in the previous section, with the only difference being an increased total number of antennas to 32. This section will explain the adjustments needed for Group X and Group Y with total 32 antenna elements, where Group X involves adjustments for 1x8 antennas, and Group Y involves adjustments for 1x4 blocks, as described in Section III.C. REV X represents the adjustment method for Group X, REV Y represents the adjustment method for Group Y, namely the method 1 proposed in Section III.C. Furthermore, the simulation results include AccSub, indicating the adjustment combined with the previously adjusted Group block, as the method 2 proposed in Section III.C. The simulation results are shown in the Figure 10. Both methods, i.e., Method 1 (REV X and REV Y) and Method 2 (REV X and REV Y with AccSub), successfully calibrate the array with total 32 antennas, and the results show a well-directed beam with good performance.

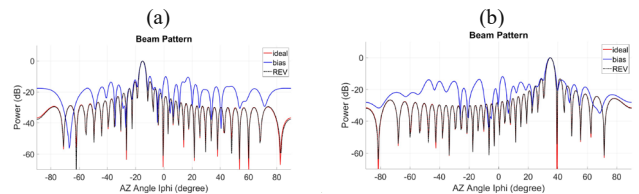


Figure 10. Simulation results in section III.C. (a) Method 1 (REV X & REV Y). (b) Method 2 (REV X & REV Y & AccSub).

Furthermore, from the above results, it can be inferred that the proposed enhanced REV calibration for large arrays, as outlined in the method 2 of Section III.C, achieves superior

beamforming performance. In particular, the beam pattern after block-wise joint calibration closely approximates the ideal beam pattern depicted in red.

B. Hardware Platform Testing

This section involves the use of the antenna array and SDR platform from Section II, along with the enhanced REV algorithm proposed in Section III for practical calibration table and beam pattern verification. In other words, the chamber platform remains the same, and the SDR with UDC (Up-Down Converter) platform is also the same. The initial step is to perform antenna array calibration at a distance of 40 cm. The calibration algorithm follows the enhanced REV method in Section III.B. Thus, the red text indicates the scenario where 1x8 antennas are fully activated. In this case, the phase of the remaining 7 antennas remains unchanged, while the phase of one antenna varies by 360 degrees (utilizing 64 states, changing every 5.625 degrees). This process is repeated for each antenna, resulting in the recording of 64 Q values for each antenna (corresponding to the peak values recorded by the SDR platform for QPSK in each packet after time synchronization). This sequence is performed for all 8 antennas, resulting in a total of $8 \times (64 + 7) = 512 + 56 = 568$ recorded Q values, including the 7 records for the enhanced state of being fully activated. Once all Q values are obtained, the REV algorithm is applied to calculate the k values and X values, representing amplitude ratio and phase difference. The phase table is then organized as shown in the table below:

TABLE 1. HARDWARE TESTING TABLE RESULTS

phase_state_table							
1	1	62	0	0	2	6	9

After obtaining the calibration table through the enhanced REV testing described above, a beam pattern diagram can be generated using a fully activated antenna array at 100 cm distance with a -90 degrees to 90 degrees rotation table, as shown in Figure 11 (pointing only towards 0 degrees).

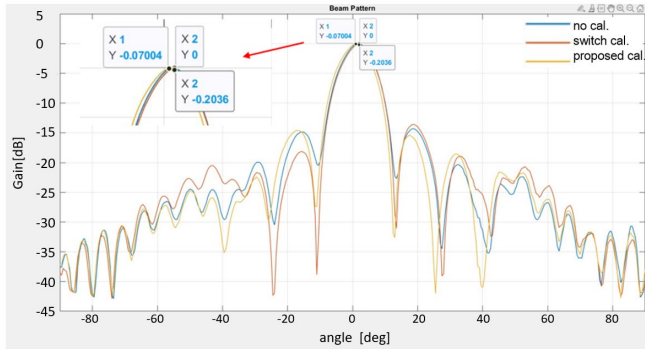


Figure 11. Diagram of field patterns from hardware testing.

From the results of this diagram, it can be observed that only the Proposed cal. (enhanced REV method) and the red Switch cal. calibration method [8] exhibit lower Null Pattern diagrams compared to the uncalibrated (original 1x8 array) beam pattern. This result confirms the feasibility of the calibration algorithm proposed in this paper, integrated with the array antennas and SDR platform. In the future, the

approach will be extended to practical calibration tests with a larger number of antennas using the method outlined in Section III.C. It is important to note that, currently, the laboratory at Yuan Ze University does not have a large array antenna, so the method described in Section III.C cannot be practically tested and verified at this time.

V. CONCLUSIONS

The algorithm development for millimeter-wave antenna calibration is crucial, and this paper has achieved significant progress. When all antennas are fully activated, the method of validating the variation of the Radiating Element Electric Field Vector (REV) using broadband signals has been implemented. This method has gained international attention as it allows obtaining phase/amplitude calibration values of antennas while considering coupling factors between antennas, with measurements relying solely on amplitude (power) and all antennas being active. However, the REV technique has inherent challenges, and in Section III, an enhanced REV algorithm was proposed to address these issues. The enhanced REV technology has been validated through simulations, demonstrating advantages such as reduced computational requirements and faster estimation compared to other algorithms from existing literature. Furthermore, the paper extends the proposed methodology to the estimation rules for large array Group-based antennas in Section III.C, showing excellent performance. Finally, in Section IV, the developed 1x8 array antenna platform, SDR platform, and calibration algorithm were jointly tested, confirming the practicality and effectiveness of the proposed methodology.

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