Robust Plane Wave Generator Design in Small Anechoic Chamber Setup Using Parameterized Field Method

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ABSTRACT Plane Wave Generator (PWG) has attracted great research interest in the industry and academia for sub-6 GHz massive MIMO base station (BS) measurement, thanks to its low-cost and smaller system setup. One major concern in the small setup is its high reflectivity level inside the anechoic chamber, which might distort the quiet zone performance significantly. Meanwhile, it is critical that the quiet zone performance is insusceptible to system inaccuracies. However, these two aspects are largely overlooked in the plane wave synthesis (PWS) study in the literature. In this article, a new PWS strategy is proposed based on parametrized field distribution over an enlarged sampling area. The proposed method offers robust design and low reflectivity level. The effectiveness and robustness of the proposed PWS strategy is demonstrated in a numerical simulation.

INDEX TERMS Excitation coefficient optimization, over-the-air testing, plane wave generators, small anechoic chamber.

I. INTRODUCTION

To meet the requirement of high data rates at sub-6 GHz in the 5G communication systems, large-scale massive MIMO antennas arrays and sophisticated beamforming technology are adopted in 5G base stations (BSs). However, these new features have posed huge challenges on BSs calibration [1] and measurement, such as far-field pattern measurement and RF metrics measurement [2], owing to the large antenna aperture and high accuracy requirement of testing results. The device under test (DUT) is required to be tested under plane wave conditions, where phase and amplitude variations across the DUT are within specified tolerances. Compared with conventional direct Far Field (FF) or Compact Antenna Test Range (CATR) techniques [3], Plane Wave Generator (PWG), which approximates a plane wave in its near field region via properly control its PWG element complex coefficient excitation, has become a promising method to test 5G massive MIMO BSs, because of its merits of comparatively low cost and compact setup [4]. Over-the-air testing is expected to be the dominant testing method for massive MIMO BSs and mmWave devices, due to massive antenna configurations and integrated radio frequency front-end design [5]–[7].

One of the main research challenges for PWG design is to determine the complex coefficient excitation for each PWG element. Tapering method and constrained least squares optimization are proposed in the literature for plane wave synthesis. According to [8], tapering method determines excitation coefficients by designing a tapered current distribution, such as Tschebyscheff approximation, in order to meet some performance requirements, especially side lobe level. This method can generate a quiet zone with a wide bandwidth, with large longitudinal dimension. However, it is usually applied for an antenna array with a large array aperture, which would require a large PWG dimension, and is not suitable for our PWG in small anechoic chamber. Constrained least squares method is one kind of regression approaches. Compared with linear least squares method, constrained least squares method could avoid some overfitting cases and improve the far field performance by imposing some constraints, such as side lobe level, gain constraints [9], etc. However, it is not straightforward to relate constraints to the PWG performance in terms quiet zone quality within the quiet zone and energy outside the quiet zone.

Other algorithms reported in the literature can be grouped into two main categories, the global optimization
The remainder of the paper is organized as follows. We first state the problem in traditional regression solution. After that, the principle of parameterized field approach is introduced. In section III, the numerical simulation results of the proposed method are demonstrated. Section IV concludes the paper.
on the condition number of $F_{K \times N}$. The condition number measures the sensitivity level of the solution to small perturbations in the excitation coefficients. High condition number will probably amplify the input error and result in a distorted distribution.

In the conventional PWG method, the quiet zone is selected only to encompass the DUT, while field distribution outside the quiet zone is not considered. In the practical PWG setup, the quiet zone is rather small in small chamber, leading to an ill-conditioned transfer matrix. Additionally, phase and amplitude control in the phase-shifter and attenuator are not perfect, often suffering from quantization error and system uncertainties. Another problem in practical small setups is the reflectivity inside the anechoic chamber. Using traditional regression approach, electric field intensity outside the quiet zone might be larger than that inside the quiet zone, as reported in [14], [16]. This would inevitably cause high reflectivity.

B. PROPOSED METHOD

As mentioned above, the traditional regression method based PWS suffers mainly from two problems, ill-conditioned transfer matrix and high power distribution outside the quiet zone. The former leads to error-prone solution while the latter introduces high reflectivity in small anechoic chambers. To address these two issues, a regression method based on parameterized enlarged reference field is introduced in this subsection.

The ill-conditioned transfer matrix is caused by small data set and high relevance between data, which are consequences of small sampling area (i.e. same as the quiet zone size in the literature). To reduce the condition number of the transfer matrix, a larger reference area is expected, which will reduce data relevance and increase the number of sampling data. Furthermore, in order to avoid power diffusion outside, some constraints is needed to impose. The natural way is adding this requirement into reference field, to limit the electric field intensity outside the quiet zone. However, there is no an evaluation criteria about power outside quiet zone for PWG. To achieve it, we parameterize the new reference field distribution and apply a global search optimization, which is used to find the best reference field design. Once the best reference field is designed, the optimum excitation weights can be fast calculated by regression method.

We parameterize the field distribution, as illustrated in Fig.2. The quiet zone is located in the innermost of the sampling area. Inside the quiet zone, which is now part of the selected reference area, we still assume an ideal plane wave distribution over this zone. Outside the test area, the field distribution is parameterized by a set of parameters, such as $\{c_1, c_2, ..., c_p\}$, as shown in Fig.2. When those parameters are determined, excitation weights can be yielded immediately.

Since there are few parameters representing the reference plane to determine, several global search optimization could be applied to tackle this parameters determining problem, such as GA, PSO, ZOOpt [17] etc. In this article, we resort to PSO method to determine the parameters.

A flow chart of the proposed method implementation is shown in Fig.3. At first, PSO solver will create randomly a population of parameters set, and each set contains $P$ number of parameters. The corresponding excitation weights of each set are calculated by minimizing the expression below:

$$J(w_{N \times 1}) = \|F_{K' \times N} \cdot w_{N \times 1} - T_{K' \times 1}(C_{P \times 1})\|_2,$$

where $C_{P \times 1} \in \mathbb{R}^M$ is parameters vector representing the reference field distribution, and $K' > K$ is the number of samples in the enlarged sample area. $K$ is the number of samples in quiet zone. Hence, $F_{K' \times N}$ is the transfer matrix in the enlarged sample area, which is longer than $F_{K \times N}$. And $T_{K' \times 1}(C_{P \times 1})$ is the parameterized reference field in this area.

![Flowchart of PSO](image1.png)

![Concept of parameterized reference field](image2.png)
After that, corresponding amplitude and phase variations of each set are calculated. Amplitude variation $\varepsilon_a$ and phase variation $\varepsilon_p$ are calculated by:

$$\varepsilon_a = 20 \cdot \log_{10}\left(\frac{\alpha_{\text{max}}}{\alpha_{\text{min}}}\right), \quad \varepsilon_p = \frac{360 \cdot |\delta_{\text{max}} - \delta_{\text{min}}|}{2\pi}$$

where $\alpha_{\text{max}} / \alpha_{\text{min}}$ are the max/min amplitude inside quiet zone and $\delta_{\text{max}} / \delta_{\text{min}}$ are the max/min phase inside quiet zone. E-field inside quiet zone is calculated by equation 1 using the excitation coefficients $w_{N \times 1}$ from equation 4. $\varepsilon_a, \varepsilon_p \in \mathbb{R}^+ \cup \{0\}$ and when an ideal plane wave is generated, we have $\varepsilon_a = 0$ and $\varepsilon_a = 0$.

The next step is using an objective function to select the best parameters set from population. The objective function we use is expressed as:

$$f(C_{i \times 1}) = a_1 \cdot \varepsilon_a + a_2 \cdot \varepsilon_p$$

where $a_1, a_2 \in [0, 1]$ are scaling factor for amplitude and phase variations, respectively. They are used to normalize $\varepsilon_a$ and $\varepsilon_p$ into the same order. In practical uses, 1dB amplitude variation and 10° are acceptable. Therefore, we set $a_1$ and $a_2$ to 1 and 0.1.

PSO solver will repeat the steps above, until reaching the max iteration number. The final parameters set represents the optimum parameterized electric field design and the corresponding excitation coefficients are obtained by equation 4.

### III. NUMERICAL RESULT

We demonstrate the effectiveness of our approach on a rectangular PWG, as depicted in Fig. 1. This PWG is in the boresight direction of the quiet zone and it consists of $9 \times 14$ PWG elements. The PWG operates at 2.6 GHz with a dimension of $1m \times 1.124m$. Open-ended waveguide is used for the PWG element with a dimension of $72mm \times 34mm$ and each element’s amplitude and phase are well calibrated by face-to-face calibration method [18], [19] and mid-field calibration method [20], respectively. This PWG has a uniform configuration along $y$ axis, with an element spacing 86.5mm, but a non-uniform configuration in the $x$ axis. Spacing along $x$ axis are 0.111m, 0.121m, 0.13m, 0.137m, 0.137m, 0.13m, 0.121m, 0.111m. This nonuniform arrangement is designed to broaden bandwidth and to reduce array truncation effect [21], [22]. The distance between the PWG and the sampling area is set to $1m$, and the target quiet zone within the sampling area is set to $0.54m \times 0.9m$, which fits for 5G massive MIMO BS testing. To meet the optimal sampling distance [23], the sampling area is uniformly sampled with $30mm$ in both $x$ and $y$ axis.

The PWG element is often simplified by the point source model in [16], which might differ from reality due to mutual coupling between PWG elements in small anechoic chambers [24]. To render more realistic results, the field distribution on the sampling area per PWG element in the PWG is simulated in the CST software to generate the transfer matrix $F_{K' \times N}$.

Fig. 4 illustrates the design of desired parameterized E-field distribution in the enlarged sampling area. This design is chosen based on three reasons below. Firstly, the PWG aims to generate the plane wave field in boresight direction, most electric field energy will be radiated into the area straight ahead. Therefore, dimension of the sampling field is set to $1.02m \times 1.56m$, which is a bit larger than the dimension of the PWG. Secondly, it is difficult for amplitude and phase controller network of PWG to synthesize and maintain precisely and accurately a small energy within the quiet zone. In addition, the typical oblique incidence reflectivity of absorbing materials is only from 20dB to 30dB. The reflection signal from the small anechoic chamber lateral wall will interfere the direct wave signal, which will distort the quiet zone performance seriously. Therefore, we assume that amplitude parameters $\{c_8, c_9, \ldots, c_{13}\}$ outside the targeted quiet zone’s area is not greater than 0dB. This restriction will mitigate the multi-path reflection and avoid unwanted energy outside the quiet zone, and alleviate the required efficiency of the anechoic chamber absorbers as well [25]. Thirdly, this square-ring-shaped design is in concordance with antenna pattern. For obtaining the maximum of design freedom, each sub-area outside is set as thinner as possible. The width of them is set to 30mm, which is the same as sampling spacing. It is worth mentioning that the design doesn’t apply equally to all different cases and it is not the only way to parameterize the desired plan in this setup. We can parameterize the desired field distribution not only in spatial space, but also in angular spectrum domain.

In this article, Matlab built-in PSO solver “ParticleSwarm” is utilized. The population size for each swarm is set to $N_{\text{pop}} = 100$, maximum iterations are set to $N_{\text{iter}} = 70$ and all the other PSO parameters are set by default. The initial variables are selected randomly. It took around 63 seconds to accomplish the optimization process. Fig. 5 draw the evolution of fitness function and Table 1 lists the 13 parameters found by the PSO. It can be observed that the result converges rapidly independent of initial variables. Fast convergence guarantees that PSO will always find the best set of parameters $\{c_1, c_2, \ldots, c_{13}\}$. After that, we apply LSM to obtain the optimal excitation coefficients.
FIGURE 5. Evolution of the best fitness function value of PSO.

TABLE 1. Best reference field’s parameters.

| $c_1$     | $c_2$     | $c_3$     | $c_4$     | $c_5$     | $c_6$     | $c_7$     |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| -6.9°     | -26.5°    | -14.3°    | -55°      | -66°      | -66°      | -70°      |
| -3.3dB    | -0.67dB   | -0.45dB   | -17dB     | -20dB     | -18dB     |

FIGURE 6. (a) Amplitudes and (b) Phases of electric field distribution in main polarized direction in $1020\text{mm} \times 1560\text{mm}$ by simple LSM. The variations of amplitudes and phases inside quiet zone are $1.11\text{dB}$ and $8.5$ degrees respectively. (c) Amplitudes and (d) Phases of electric field distribution in main polarized direction in $1020\text{mm} \times 1560\text{mm}$ by our approach. The variations of amplitudes and phases inside quiet zone are $0.73\text{dB}$ and $10.2$ degrees respectively. Red dash area represents the targeted quiet zone, with a dimension $540\text{mm} \times 900\text{mm}$.

Fig. 6.(a) and 6.(b) show electric field’s amplitude and phase distributions calculated by our approach in sampling area, where the quiet zone is marked by the dash red. A quasi plane wave field is yielded with the proposed method, with an amplitude variation up to $0.73\text{dB}$ and a phase variation up to $10.2^\circ$ within the test area, respectively. It is worth mentioning that electromagnetic energy mainly emerges into the quiet zone and its proximity, which will mitigate the multi-path reflection in practice.

In comparison with our approach, we also apply a simple LSM to this problem. A plane wave is synthesized within the quiet zone, with an amplitude variation up to $1.11\text{dB}$ and a phase variation up to $8.52^\circ$, respectively. Table 2 lists some characteristics of PWG. The max amplitude of inside/outside quiet zone ratio is $0.69\text{dB}$ by our approach and $-9.1\text{dB}$ by simple LSM. In addition, the percentage of energy radiated in quiet zone is $44\%$ by our approach and $8\%$ by simple LSM. It indicates that our approach can effectively concentrate energy within the quiet zone. Furthermore, as discussed, we can effectively reduce the condition number of the transfer matrix by more than ten-folder by adopting a larger sampling area. This two factors ensures that our proposed method will be much more robust towards controller network’s uncertainties and numerical errors in practical PWG setups.

In order to show the numerical consistence, a full wave in CST 2018 is performed with the optimized excitation coefficients by our approach. Fig. 7 depicts the electric field distribution in the main polarized direction inside the quiet zone calculated by CST and our algorithm in

TABLE 2. Comparison of some PWG characteristics.

|            | Amp. variation | Phase variation | Energy ratio | Max. amp. ratio |
|------------|----------------|-----------------|--------------|-----------------|
| Simple LSM | 1.11dB         | 8.52°           | -0.69dB      | 44%             |
| Our approach | 0.73dB     | 10.2°            | -9.1dB       | 8%              |

FIGURE 7. (a) Amplitudes and (b) Phases of electric field distribution in main polarized direction in $540\text{mm} \times 900\text{mm}$ by CST. (c) Amplitudes and (d) Phases of electric field distribution in main polarized direction in $540\text{mm} \times 900\text{mm}$ by MATLAB.
MATLAB, respectively. It can be observed that those electric field distributions are quite similar. Electric field by CST are with an amplitude variation of 0.93dB and a phase variation of 12.75°, while amplitude variation by MATLAB is 0.73dB and phase variation is 10.20°. It is in the same range and the overall electric field trends are similar. As we can observe, wherever the electric field intensity is strongest or weakest in MATLAB simulation results, it will also be strongest or weakest in CST simulation. The standard deviations of amplitude variation by CST and by MATLAB are 0.2dB and 0.1dB respectively, and the standard deviations of phase variation by CST and by MATLAB are 2.53° and 2.13° respectively. The minor difference is caused by numerical truncation and numerical precision. So, that it is more likely that we can reproduce this quasi-plane wave in practical setting.

Fig. 8 depicts electric field distributions in cross-polarized direction inside quiet zone, calculated by CST and MATLAB respectively. It is observed that electric field in cross-polarized direction is below −25dB. Low cross-polarized electric intensity avoids a significant cross-polarization interference.

In addition, this controller network suffers an uncertainties about ±0.25dB on amplitude and ±2.5° on phase. Due to this reason, we add two random noises into amplitudes and phases of excitation coefficients to mimic this uncertainties and further discuss the robustness of results. The noises added into amplitude and phase terms of weights are both assumed to be a uniform distribution from −0.25dB to 0.25dB and from −2.5° to 2.5°, respectively. Eq.7 is the expression of this testing. $ea_n$ and $eq_n$ are amplitude noise and phase noise, respectively. $w_n = \alpha_n \cdot e^{i\omega_n}$ is the optimum weights by our approach and $\tilde{w}_n$ is the weights after adding noises. We put $\tilde{w}_n$ into PWG, to observe the amplitude and phase variations.

We repeat this test ten thousand times and Fig. 9 shows the robust test results by our approach and simple LSM. The amplitudes and phase variations inside quiet zone obtained by our approach are lower than those by simple LSM. Besides, it is clear that our approach is more robust towards these minor noises, compared with simple LSM. Table 3 shows statistical results of robust test, including the max, min and mean of amplitudes and phases variations in quiet zone. It is obvious that our approach surpasses simple LSM, especially in amplitude variation. The amplitude dynamic range by our approach is from 0.7dB to 1.72dB, which is lower compared with the range by simple LSM. And the phase dynamic range by our approach is from 10.11° to 15.95°, which is also better than the range by simple LSM. This test can statistically prove that our approach can yield a more robust result.

\begin{equation}
\tilde{w}_n = \alpha_n \cdot 10^{ea_n/20} \cdot e^{i(\omega_n+eq_n \cdot \pi/180)}
\end{equation}

**IV. CONCLUSION**

PWG is a good alternative technique for 5G massive MIMO BS testing in near field region thanks to its unique advantage of low-cost and compact setup requirement. Traditional PWG adopting regression method mainly suffers from two problems, ill-conditioned transfer matrix and high power distribution outside the quiet zone, making it unsuitable for practical compact anechoic chamber setups. To solve these
problems, we propose a new approach to determine complex excitation coefficients in this article. By the means of extending the reference field’s sampling area and loosening the ideal-plane wave restrictions, we effectively transform the difficult-to-solve complex coefficient optimization with hundreds of parameters into a reference field’s parameters determination problem with only few complex parameters. The proposed method can effectively reduce the condition number of the transfer matrix and furthermore limit the energy leaked outside of the quiet zone. A numerical simulation shows that our approach can approximate a more robust and better field distribution in the targeted area than the traditional regression approaches.

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