ANN Synthesis and Optimization of Electronically Scanned Coupled Planar Periodic and Aperiodic Antenna Arrays Modeled by the MoM-GEC Approach

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***Abstract*—This paper proposes a new formulation that relied on the moment technique combined with the equivalent circuit (MoM-GEC) to study a beamforming application for the coupled periodic and quasi-periodic planar antenna array. Numerous voltage designs are utilized to show the adequacy and unwavering quality of the proposed approach. The radiators are viewed as planar dipoles and consequently shared (mutual) coupling effects are considered. The recommended array shows a noticeable improvement against the current structures as far as size, 3-D scanning, directivity, SLL reduction, and HPBW. The results verify that multilayer feed-forward neural networks are vigorous and can take care of complex antenna problems. Even so, an artificial neural network (ANN) is ready to create quickly the results of optimization and synthesis by utilizing generalization with an early stopping method. Significant gain in the running time consumption and memory used is acquired employing this last technique for improving generalization (named early stopping). Simulation results are carried out using MATLAB. To approve this work, several simulation examples are shown.**

***Index Terms*—Radiation pattern synthesis, quasi- periodic and periodic structures, Mutual coupling effects, Artificial neural network ANN algorithm, Early stopping method.**

I. INTRODUCTION

Actually, the steering radiation pattern of coupled periodic and quasi-periodic planar structures becomes the topic of various scientific research, especially in defense and space applications, communication systems, mobile communications and electronics devices such as MIMO beamforming smart antennas, 5G Mobile Base Stations, microphone array beamforming, wireless communications, radio astronomy. Here, the main point of beamforming is the capacity to adapt the radiation pattern of the antenna array to a specific scenario. Such us, in the radio cellular communications space, many people think of beamforming as the controlling of fundamental radiation beam (main lobe of power) in a specific direction toward a user, as shown in figure (1) [11], [14].

To study the chosen coupled planar antenna arrays, the moment technique jointed to the generalized equivalent circuit (MoM-GEC) is more adopted than other numerical methods to calculate the required radiation pattern [12] in terms of calculation complexity (storage memory and time consumption). A simple technique based on the Fourier transformation used to transform electric near field (radiation from waveguide apertures) to far-field in order to scan the antenna array patterns in the desired signal directions and to put nulls in interference directions [8], [9]. At that point, to achieve the optimization technique for radiation pattern synthesis, various smart systems such that genetic algorithms and neural networks are needed. Then, to accomplish the optimization technique for radiation pattern synthesis, different insightful smart systems such that genetic algorithms and neural networks are required. Many articles have shown that a genetic algorithm (GA) was fundamentally employed for side lobe reduction in the array pattern synthesis [13]. Yet, artificial neural network (ANN) has been evaluated in many applications like example pattern recognition applications and used for input-output mapping, for system identification and adaptive prediction, etc... In this paper, we are intrigued to display the neural network's process that will be applied to the array pattern synthesis, featuring their most significant roles [4], [5], [10], [11].

This fact grows up the difficulty of the problem under setting fitting the neural network pattern, as an example, training function, design, and parameter, which would ameliorate and result in more exactness about input-output yield relations [11]. As indicated by its quick convergence, neural networks applications are having an increasingly significant role in the direction of arrivals DOA, what's more, beamforming

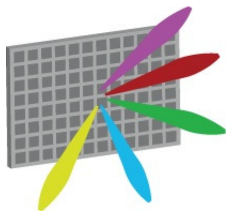

Fig. 1. 3D beamforming from a planar array example

applications [11], [14]. Subsequently, neural systems (NN) present great accordance with these necessities, and it can simply be implemented for these coupled periodic and quasi-periodic planar antenna arrays application [1], [2], [3].

The principle idea is next to construct a backpropagation neural network algorithm with supervised learning that estimates the proposed scanned array pattern's response [4], [5]. This investigation can give some essential insights about the ideal dimension of a feedforward Neural Network to stay away from over-fitting problems, particularly, when an enormous number of tests are required. Thus, sub-datasets will be examined for training, test, and validation, and then a feed-forward neural network is made and trained [10], [11].The output values will be created and regulated (denormalized), and lastly, the efficiency of the neural network will be checked in comparison to the output values with numerical target values. As a consequence, the prepared neural network will be effectively utilized for periodic and aperiodic planar antenna arrays beamforming [4], [5], [10], [11].

This work is arranged as follows: The initial step is to remind the fundamental theoretical background about the studied problem and its formulation using an integral equation built on the formalism of admittance (or impedance) operator related to Generalized Equivalent Circuit (GEC), that cited in [2], [3], [7], [8], [9], and the used Fourier representation to synthesize the required radiation with a scanned beam. Next, the fundamentals of artificial neural networks (ANN) using their main principles are recalled in the following section (III). It clarifies how to introduce artificial neural networks (ANN) using early stopping technique for synthesis and optimization, some essential networks are analysed in detail for their potential to solve simple scanned pattern synthesis problem in periodic and aperiodic antenna configurations. Then, in section (IV) numerical results are presented and evaluated for many applications. Finally, in the last section, some conclusions are described.

II. STATEMENT OF THE PROBLEM

This section presents an MoM-GEC formulation problem to modelize the coupled planar dipoles of periodic and quasi-periodic structures, that used to compute the resultant radiation pattern in any direction needed using a far-field transformation algorithm for plane-rectangular scanning [15], [16]. The picked (or considered) structure schematically appears in [2], [3] that made out of finite coupled aperiodic (or periodic) phased array planar antenna with their self excitations (arbitrarily located voltage sources). All antenna array components are shielded in waveguide composed by adequate boundaries conditions along the x and y directions which can be browsed the accompanying choices: (a) Perfect Electric boundaries, (b) Perfect Magnetic boundaries, (c) Periodic boundaries with null phases shift, and (d) a combination of these boundary conditions. The top and the bottom are respectively an open circuit and a ground plane. The considered planar circuit is lossless.

Note that periodic example (with equivalent voltage amplitude) is studied with the identical spatial formulation manner, as shown in the published work [1,2]. To explain the electromagnetic calculation, the same details given in [2], [3] are reminded. As the suggested spatial periodic design in [2], [3], we define the direct manner that extracts an integral equation to calculate the impedance matrix which constitutes also the mutual impedance in aperiodic configuration (respectively for regular periodic configuration). Next, let consider N_x non-uniform with distinct voltage amplitude sources to excite planar dipoles that belong to the whole array configuration.

The excitation fields (for elements with turn on states):$E(i,s) \in [-\frac{N_x}{2}, \frac{N_x}{2}-1][-\frac{N_y}{2}, \frac{N_y}{2}-1]$ are indicated as follows $E(i,s) = Vf(i,s)$, where $f(i,s) = \frac{1}{\delta}$ correspond to the fundamental excitations modes.

Consequently, getting back to the Kirchhoff representation and according to relations given in [2], [3], it's possible to deduce the electromagnetic states in terms of current and electric fields that verify the suggested boundary conditions of the proposed structures. It is noticed that the proposed formulation stays legitimate to study leaky waves and their supporting impacts. This investigation is chosen to clarify the periodic group of identical assembly elements placed in a one-dimensional arrangement. Then, the bi-dimensional example can without much of a stretch be given, as shown in [2], [3], [7], [8], [9].

A. Radiation pattern (using the Fourier representation)

The goal of this section is to develop a sampling representation of the radiated far EM field based on the Fourier transform. As explained in [7], [8], [9], the far-field expression is computed in comparison to far-field transformation algorithm for plane-rectangular scanning with ideal probes (or radiation from apertures by plane wave spectrum method). For more details, let consider a rectangular aperture XY of open-ended waveguide that contains a periodic planar antenna array (discontinuity plane (at z=0)), as illustrated in figure (1), where their near electric field elements are expressed in terms of $|f_{mn}^{TE,TM}\rangle$ of basis functions (the guide modes) with:

$$|E(x,y)\rangle = \sum_{m,n}\sum_{p}\sum_{q}[Z]_{pq}X_{pq}\langle f_{mn}|g_{pq}\rangle|f_{mn}\rangle \quad (1)$$

Where:

$$[\hat{Z}_{pq,st}^{upper,down}] = [\sum_{m,n}\langle g_{pq}|f_{mn}\rangle z_{mn}^{upper,down}\langle f_{mn}|g_{st}\rangle] \quad (2)$$

Then, the far radiating field in the region $z > 0$, is written as:

$$\tilde{E}_{x,y}(\theta,\phi) = \int_{-c}^{c}\{\int_{0}^{L} E_{aperture}(x,y) \quad (3)$$
$$e^{(-jk_0(sin(\theta)cos(\phi)-sin(\theta_0)cos(\phi_0))x)}dx\}$$
$$e^{(-jk_0(sin(\theta)sin(\phi)-sin(\theta_0)sin(\phi_0))y)}dy$$

Where $E_{aperture}$ is the radiating field calculated at the waveguide's aperture (discontinuity plane) through the moment method combined by the equivalent circuit (see in [2], [3], [12]).

So, this latter relation leads to denote that normalized absolute radiation pattern in dB can be demonstrated as:

$$E(dB) = 20 \times \log_{10}\left(\frac{\mid E(\theta,\phi) \mid}{\mid E(\theta,\phi) \mid_{max}}\right) \quad (4)$$

The indication of u,v specifies the unit direction:

$$u = sin(\theta)sin(\phi) - sin(\theta_0)sin(\phi_0) \quad (5)$$
$$v = sin(\theta)cos(\phi) - sin(\theta_0)cos(\phi_0)$$

The couple (θ_0, ϕ_0) is given as the beam-steering and the couple (θ, ϕ) shows the arrival direction. Here, two types of the u-v domain were considered for SLL decrease: one is regular UV space with the controlling of steering direction$(\theta_0, \phi_0) = (0, 0)$, and u,v $\in$ [-1, 1]. The other is extended u-v space where the scanned direction$(\theta_0, \phi_0) \neq (0, 0)$. Thus, the estimation value of u and v changes against the steering direction and is defined in [-2, 2] for any union of the arrival and steering directions. Given that the u-v space permits one to synthesize an array structure that confirms a beam pattern with a preferred profile for every steering direction [11].

III. ARTIFICIAL NEURAL NETWORK ANN PRINCIPLE

As explained in a past work [11], in which a detailed description of the ANN principle using early stopping technique is given to study the neural network synthesis beamforming model for adaptive planar antenna arrays [4], [5], [6].

IV. RESULTS AND DISCUSSIONS

A. Numerical results

- **Verification of the boundaries conditions through the MoM-GEC:**

To verify the boundary conditions of the proposed coupled periodic and quasi-periodic structures, various numerical results are drawn in terms of current and electric fields (calculated using the MoM-GEC method), as obtained in figures (2)and (3). In this study, the coupling effects are taken into account when the array spacing is less than or equal to $\frac{\lambda}{2}$, as proven in [2], [7], [8], [9]. The figures (2) and (3) describe an electromagnetic behavior (E,J) at the waveguide aperture for different voltage configurations examples (periodic and aperiodic structures).

- **Radiation pattern characteristics computed using the MoM-GEC:**

Based on the radiation pattern expression (4) given in the past section, many results concerning the radiation performance of the given structures are obtained. The beamforming characteristic of the array radiation patterns with directivity values in different scanning angles at 5.4 GHz is shown in figures (4) and (5). As viewed, the proposed antenna arrays has an excellent beam scanned property which is greatly efficient to cover the spherical beam-range(coverage) for electronic instruments. Figure (5) illustrates the simulated realized gains of the antenna array in the scanning range of $0°$to $+90°$. As given

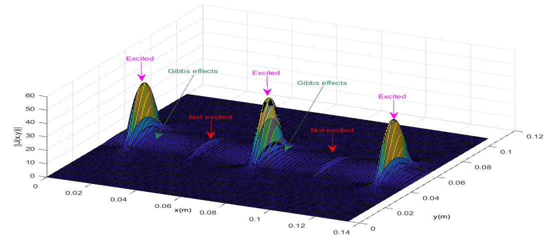

Fig. 2. Distribution of the current field for (5x1) aperiodic phased half-wavelength planar dipoles (with (1,0,1,0,1) voltage configuration) evaluated with the basis functions (guide's modes) at f=5.4 GHz (using EEEE electric walls)

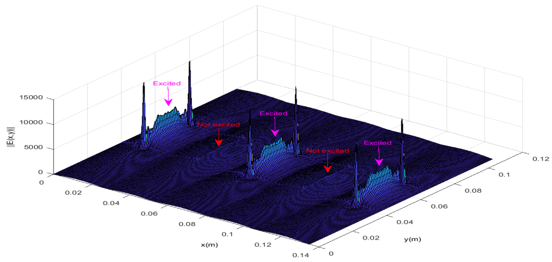

Fig. 3. Distribution of the electric field for (5x1) aperiodic phased half-wavelength planar dipoles (with (1,0,1,0,1) voltage configuration) described with the basis functions (guide's modes) at f=5.4 GHz (using EEEE electric walls)

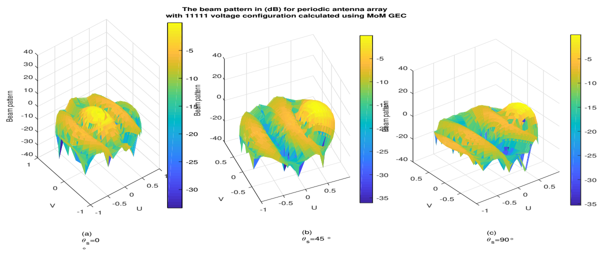

Fig. 4. Beam pattern (dB) expressed in (u,v) space for periodic planar antenna array at different scanning angles, $\theta_s = 0°, \theta_s = 45°$ and $\theta_s = 90°$

in Fig.(5), the periodic antenna array has a high orientable beam characteristic with suitable gain level at distinct steering angles.

Figure(6) shows how voltage amplitudes of array sources contribute to construct the main radiation beam, where their effects are more explained in the previously work [11] in terms of directivity, SLL and HPBW values. So, a good validation of aperiodic configurations compared to known periodic case(using electromagnetic or analytic formulations) is illustrated in figure(6).

B. ANN results

After using the neural network architecture given in [11], the mentioned periodic and quasi-periodic arrays should ab-

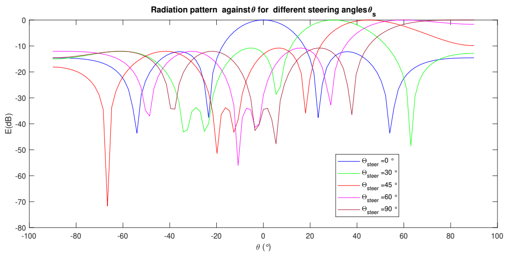

Fig. 5. Simulated radiation property of the periodic array at distinct steering angles

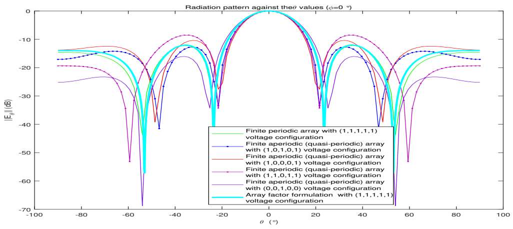

Fig. 6. Radiation pattern for distinct aperiodic configurations compared to periodic arrays using electromagnetic and analytic formulations

solutely fellow the similar network technique. After a few tests, an artificial neural network (ANN) with the following geometries was held: Two typically used strategies applied to defeat the over-training problem, to choose when to stop the training procedure, are early stopping (ES) and regularization methods. ES is sufficiently utilized because it is facile to understand and execute. Additionally, it has been accounted for to be better than regularization strategies. To use the ES method, the available radiation array pattern's data must be divided into three sets, as presented in the figure (7) : For the model building process, the available dataset consisted of 70% for the pure network learning process, 15% for validation (making decisions concerning oversizing), and 15% for testing purposes. Precisely:

- Training (preparing) group used to decide artificial neural network (ANN) weights.
- Validation group used to check the artificial neural network (ANN) execution and performance, and choose when to stop the training procedure.
- Test group used to evaluate execution performance capabilities of created artificial neural network (ANN) model.

More detailed information about the ES technique is graphically drawn in figure(8). The methodology of ES strategy can be clarified in [11].

C. ANN performance

Generally, we assessed the execution performance of the ANN model dependent on the error squared error MSE and efficiency coefficient "R" (regression plot). The MSE relation of the network is characterized as in equation 6, which is used

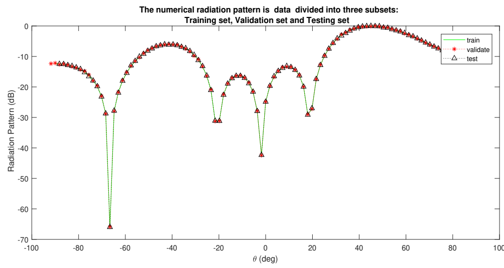

Fig. 7. Radiation patterns data partitioned into three collections: Training group, Validation group and Testing group at the scanning angles $\phi_s = 0°, \theta_s = 45°$ (aperiodic case)

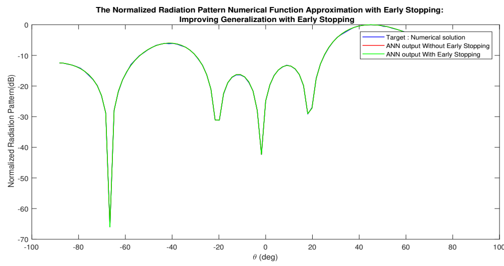

Fig. 8. Radiation pattern function estimation with Early Stopping (ES): Generalization improvement with Early Stopping (ES) at the scanning angles $\phi_s = 0°, \theta_s = 45°$ (aperiodic case)

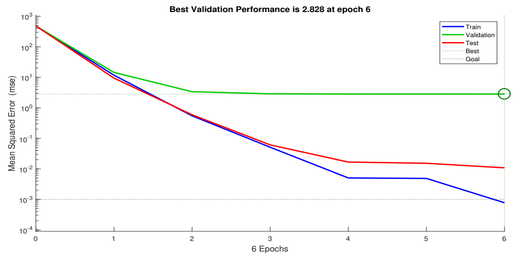

Fig. 9. Evaluation of mean squared error (aperiodic case)

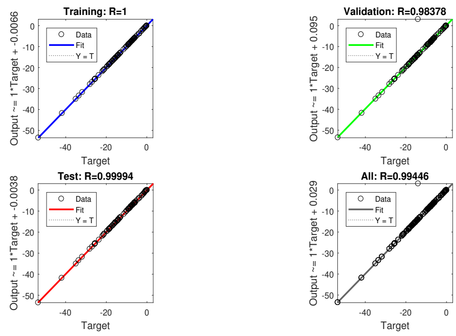

Fig. 10. Regression plot of the network (aperiodic case)

to show the performance of the network training. Performance of the best ANN is shown in figure (9), which means this model gets the lowest validation error after 6 iterations.

$$MSE = 1/2(\sum_{k=1}^{G}\sum_{i=1}^{m}[Y_j(k) - T_j(k)]^2) \quad (6)$$

Where m is the number of output nodes, G is the number of training samples, $Y_j(k)$ is the expected output, and $T_j(k)$ is the actual output. As it can be seen, the training process for artificial neural network (ANN) models is terminated at 6 training epochs when MSE reaches the value of 2.828 and the gradient descent value 0.179, with reasonable Mu value 0.0001 which would produce the convergence level of the network fast (see figure (14)). For that, it could be predicted that too little Mu value would make the network converge too gradually [6], [11].

The next step in validating the network is to make a regression plot, which shows the connection between the outputs of the network and the targets (objectives). If the training were perfect, the network outputs and the targets would be equivalent, however, the relationship is rarely perfect in reality. So, figure (10) shows the regression plot of ROP against field data. The efficiency coefficient value R of training, validation, and testing subsets shown in the diagram are R=1, R=0.98378, and R=0.99994, respectively. The overall efficiency coefficient R is 0.99446. At the testing regression result, the regression equation is:

$$output \sim= 1 * Target \pm 0.0038 \quad (7)$$

Which means the best model does not have an overfitting problem.

This proves that the developed model and the network procedure of training, testing and validation are successfully valid [4], [5], [11].

V. CONCLUSION

This work contains a novel formulation method based on the moment method jointed to the equivalent circuit (MoM-GEC) to study beamforming application for planar periodic and aperiodic structures when elements are strongly or weakly coupled. It presents the benefit of these phased arrays antenna structures to enhance the gain and the directivity pattern when the interaction effects are considered. A good validation of the proposed structures is taken into consideration in the previously published works [2] and [3].

Also, this paper is interested to synthesize the obtained radiation pattern using an artificial neural network (ANN) algorithm.

Many advantages are shown for synthesizing the calculated numerical scanned array radiation pattern using Artificial Neural Network algorithm, for example,

• The reduction of computational time and storage memory using the early stopping method which permits to remove the over-fitting problem.

• Ability to be used for coupled and complex aperiodic configuration.

• High electromagnetic performance is obtained using the finite periodic and aperiodic antenna arrays.

• Simple for implementation and coding than other optimization techniques (genetic, LMS,...etc).

• Easy to modelize complex electromagnetic calculation that taken into consideration the interaction effects.

This investigation is an essential beginning way for future research work of neural network solutions for coupled complex antenna array synthesis.

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CERTIFICATE OF PARTICIPATION

January 14, 2021

This is to certify that Bilel Hamdi from UClouvain, Belgium has attended at The 2020 IEEE Eighth International Conference on Communications and Electronics (ICCE 2020) held at Novotel Phu Quoc Resort, Phu Quoc Island, Vietnam from January 13 - 15, 2021, with the paper's information as below.

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Best regards,

Local Organizing Co-Chair

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