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DESIGN OF ARRAY FED BEAM REFLECTOR ANTENNA WITH MAXIMUM POWER RADIATED EFFICIENCY BASED ON NEAR FIELD PATTERN SYNTHESIS USING SUPPORT VECTOR MACHINE

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ABSTRACT: Radiation efficiency is one of the important parameter to describe how efficiently an antenna transmits and receives RF signals, which is defined as the ratio of the total power radiated by an antenna to the total input power received from the generator. The maximum radiation efficiency can be obtained when the feed array excitation of a reflector antenna is synthesized by the Conjugate Field Matching (CFM) method. However, the CFM method only get the strongly tapered feeding power distribution. This can lead to most of Power Amplifiers (PAs) working in low efficiency states and reduce the Equivalent Isotropic Radiated Power (EIRP) with the limited power consumption. Hence in order to solve these issues, design of array fed beam reflector antenna with maximum power radiated efficiency based on near field pattern synthesis using Support Vector Machine is presented. In this work, combining the radiation efficiency and the PA efficiency, the radiated power efficiency (RPE) is defined as the new design goal and is to be raised to achieve higher EIRP. For this reason, a method based on the near-field pattern synthesis is described. In this method, all the ON-state PAs are required to work in the highest efficiency state. Then, with well trained Support Vector Machine (SVM), the ON–OFF states of the PAs are adjusted so that the reflected focal field can be better synthesized by the near-field pattern of the feed array. Thus, the loss of the radiation efficiency will be minimized. As a result, RPE will be improved.

KEYWORDS: Antenna, Equivalent Isotropic Radiated Power, Power Amplifiers, Support Vector Machine (SVM).

I. INTRODUCTION

Connectivity technologies continue to evolve year after year to meet growing global demand for increasing data rates and number of connected devices. Indeed, today, not only are humans connected to the global network but objects, sensors, industrial machines, drones and even satellites are all connected to the same network, which is pushing further the development of new technologies that allow all these needs to be met. As such, the development of a new generation of reconfigurable antennas enabling real-time monitoring of users is necessary [1].

Communication link and target ranges for satellite communications (SATCOM) and space-based sensors (e.g. radars) vary from approximately 400-1000 km for low earth orbits (LEO) to 35,800 km for geosynchronous orbits (GEO). At these long ranges, large antenna gains are required and most legacy systems use high gain reflectors with beams that are either fixed or mechanically steered [3].

Antenna arrays are widely applied in many fields such as radar, communication, detection, and imaging due to the flexibility of their beam design. Directional high-gain antennas can be found in many applications satellites communication, radio astronomy and radar. Dish reflector antennas are suitable for these kinds of applications when they are fed with a horn antenna. However, they have a limited ability to steer the main beam only via a mechanical feed offset. Moreover, they can only provide multi beam scanning via multiple feed horns which are offset in different places. To overcome this shortcoming, array fed Reflector Antennas (RAs) have been described.

The idea is that instead of using a horn or other directional antenna as a feed, we feed the parabolic antenna with an array antenna. Hence, characteristics of the array-fed help us have flexibility, high gain and more important, radiation directions can be moved electrically and without mechanically movements. Then, optimizing the weights of array-fed elements and physical shapes of the array-fed, we expand the field of view.

Several attempts have been performed to examine the performance of these types of reflector antenna feeds. Reflector antennas are widely used in satellite communications and space radars due to their high gain and high radiation efficiency properties [5]. In order to obtain the electronically scanning beams within the restricted sector of space, the phased arrays are used as the feeds of the reflectors. RAs are a group of powerful and efficient high-gain antennas; they are highly adopted in many different conditions thanks to their numerous advantages, such as low profile, low cost, good radiation performance, and ease of manufacturing. Compared to traditional phased arrays, RA have a less complex feeding system and, thus, lead to a reduction in the losses introduced by the feeding networks [2].

By arranging the layouts and excitation signals of antenna elements, the antenna array can achieve many excellent performances that a single antenna cannot, such as higher gain, lower side lobe level, and multi-beams. In the past few decades, many optimization and synthesis methods of antenna array radiation pattern have been developed. According to the characteristics of these methods, they can be classified into mathematical optimization synthesis methods, intelligent evolutionary algorithms, and convex optimisation algorithms [4].

Although these algorithms have strong robustness in dealing with complex optimization problems, the synthesis efficiency is lower when the number of the antenna array is large, leading to large solution parameters. Meanwhile, convex optimization algorithms, as another branch of algorithms in the field of optimization, have been widely used in the optimization of antenna array radiation pattern synthesis. In addition, many researchers have tried their best to explore and develop several further deterministic and stochastic methods to deal with the antenna array radiation pattern synthesis problems.

Radiation efficiency is one of the important parameter to describe how efficiently an antenna transmits and receives RF signals, which is defined as the ratio of the total power radiated by an antenna to the total input power received from the generator. An antenna with high radiation efficiency efficiently radiates the input power to free space. In the case of low radiation efficiency, the input power is mostly dissipated because of the internal losses such as metal conduction, dielectric and magnetic losses within the antenna.

In recent years, with the progress of computer technology, machine learning technology has also been rapidly developed. Machine learning (ML) is the study of computational methods for improving performance by mechanizing the acquisition of knowledge from experience. As a modern data-driven optimization and applied regression methodology, ML aims to provide increasing levels of automation in the knowledge engineering process, replacing much time-consuming human activity with automatic techniques that improve accuracy and/or efficiency by discovering and exploiting regularities in training data.

In this work, design of array fed beam reflector antenna with maximum power radiated efficiency based on near field pattern synthesis using support vector machine is presented. The rest of the work is organized as follows: The section II describes the literature survey. The section III presents design of array fed beam reflector antenna with maximum power radiated efficiency based on near field pattern synthesis using support vector machine. The section IV evaluates the result analysis. The section ends with conclusion.

II. LITERATURE SURVEY

Ahmed M. Montaser, Korany R. Mahmoud et. al., [6] describes Deep Learning Based Antenna Design and Beam-Steering Capabilities for Millimeter-Wave Applications. In this study, a deep neural network (DNN) is implemented to soft computation of the dual-band circularly polarized bone-shaped patch antenna (BSPA) at 28 GHz and 38 GHz for 5G applications. Via a simulated database of 150 BSPAs, a DNN model is constructed on a 5-layer system using an adaptive learning rate algorithm. A fabricated BSPA operating at 28 GHz and 38 GHz is used to test and verify the DNN model. Then, the application of DNN with back-propagation algorithm and weighted MGSA-PSO algorithm is used for beam-steering the main beam pattern of the designed uniform circular antenna array with side-lobe level <=-30 dB by estimating the appropriate feeding phases of the 16 elements.

M.-M. Tamaddondar, H. Keshavarz, J. Ahmadi-shokouh et. al., [7] describes Beamsteering for Non-uniform Weighted Array-Fed Reflector Antenna. A beamsteering scheme is presented for an array-fed paraboloid reflector antenna is proposed. In this method, a non-uniform amplitude weighting strategy is used in order to demonstrate an offset fed for the reflector antenna. Steered beam is kept in shape in terms of half power beam width (HPBW) and relative side lobe level (RSLL). To do so, an analytical derivation of beam pattern is performed for the array-fed reflector antenna. Two standard non-uniform weighting techniques, Binomial and Dolf-Tschebyscheff, are employed for this reason. Finally, a multi-object optimization method is proposed to provide the best weighting. The computer simulations are performed for different multiobject optimization scenarios. The results reveal an improvement beam shape in terms of HPBW and RSLL traditional non-uniform weighing methods.

Alan J. Fenn and Jared W. Jordan et. al., [8] describes Design and Analysis of an Axisymmetric Phased Array Fed Gregorian Reflector System for Limited Scanning. An axisymmetric phased array fed confocal parabolic Gregorian reflector system is explored. The antenna utilizes a planar phased array located near the vertex of the primary reflector. Numerical electromagnetic simulations based on the multilevel fast multipole method (MLFMM) were used to analyze and optimize the antenna parameters for limited scanning. Simulations of the scanning performance of a dual reflector system with a 2 meter diameter primary reflector operating at Ku band are presented.

Nurul H. Abd Rahman, Mohammad T. Islam, Yoshihide Yamada, and Naobumi Michishita et. al., [9] describes Design of Shaped-Beam Parabolic Reflector Antenna for Peninsular Malaysia Beam Coverage and its Overlapping Feed Issues. Design and performance of a shaped beam 12.2 GHz array-fed reflector antenna for broadcasting. Initial design, employing a cluster of feed horns illuminating a parabolic reflector is initially presented for multi beam antenna (MBA) system to produce a contoured beam for Peninsular Malaysia. This analysis shows the results of the contoured beam antenna that have been achieved for beam scanned over a coverage size of approximately 0.9° long and 0.5° wide. Small variation of radiation level, which is less than 3dB within the edge of coverage (EOC), is also demonstrated in the performance analysis satellite is presented in this analysis.

Manuel Arrebola, Eduardo Carrasco, and Jose A. Encinar et. al., [11] presents Beam Scanning Antenna Using a Reflectarray as Sub-Reflector. In this work, a dual-reflector antenna based on a main parabolic reflector and a reconfigurable reflectarray as subreflector is presented for beam scanning applications. The beam deflecting is achieved by modifying the phase introduced by each element of the Sub-reflect array. The required phase distribution for each scan angle is obtained through a synthesis technique based on the analysis of the antenna in receive mode. The results show that the beam can be scanned in a range ±6° by inserting switches on the delay line to provide a 3-bit quantization.

III. DESIGN OF ARRAY FED BEAM REFLECTOR ANTENA WITH MAXIMUM POWER RADIATED EFFICIENCY

In this work, design of array fed beam reflector antenna with maximum power radiated efficiency based on near field pattern synthesis using support vector machine is presented. The Fig. 1 shows the schematic of presented approach.

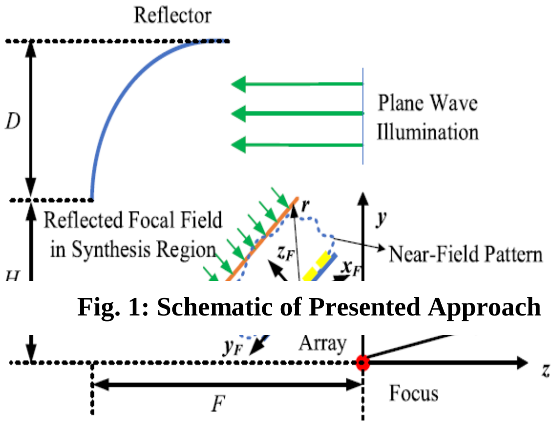

Fig. 1: Schematic of Presented Approach

The EIRP of a transmitting antenna is the product of the power transmitted by the antenna and the gain of this antenna and is given as

$$EIRP = G.P_t \quad (1)$$

The antenna gain can be calculated by the directivity D and the radiation efficiency η_r and is given as

$$G = D.\eta_r \quad (2)$$

For a reflector antenna with a fixed aperture, its directivity D is fixed. Suppose the output power of the i th (i = 1, 2, . . . ,N) PA is P_i and neglect the power of the input small signal, the total transmitted power P_t and the total power consumption P_c are, respectively.

$$P_t = \sum_{i=1}^{N} P_i \quad (3)$$

$$P_c = \sum_{i=1}^{N} \frac{P_i}{\eta_i} \quad (4)$$

Where η_i is the efficiency of the *i*th PA. Thus, with unit power consumption, the achieved EIRP is

$$EIRP = \frac{D.\eta_r.\sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} \frac{P_i}{\eta_i}} = \eta_r.\eta_{pa}$$

$$s.t.\eta_{pa} = \frac{\sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} \frac{P_i}{\eta_i}} \quad (5)$$

We refer to this factor as *RPE*. η_{pa} represents the average PA efficiency.

Near-Field Pattern Synthesis Method: A method is described based on the near-field pattern synthesis to raise the RPE. In this method, the PA efficiency reaches the maximum value by making all the ON-state Pas output the same power. This is at the cost of the reduction of the radiation efficiency of the reflector. In order to minimize the loss of the radiation efficiency, the ON–OFF states of the PAs are adjusted so that the reflected focal field is better synthesized by the near-field pattern of the feed array. The near-field pattern of the feed array is given by

$$E^{n-f}(r) = e_y \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn} E_{mn}(r) \quad (6)$$

Where A_{mn}(m, n = 1, . . . , 14) is the complex excitation coefficient of the mnth element. E_{mn}(r) is the electric field radiated by the mnth patch element at the observation point r. ey is the unit vector along y_F axis. E_{mn}(r) is composed of its θ-component and ϕ-component, which can be expressed as

$$E_{mn}(r) = E_{mn}^{\theta}(r) cos\theta_{mn} sin\varphi_{mn} + E_{mn}^{\varphi} cos\varphi_{mn} \quad (7)$$

Where $E_{mn}^{\theta}(r) = jK \frac{e^{-jkr}}{\pi r} \times \frac{\cos\left(\frac{kb}{2} sin\theta_{mn}\right) sin\left(\frac{ka}{2} sin\varphi_{mn}\right) sin\varphi_{mn}}{sin\theta_{mn} cos\varphi_{mn}}$ (8)

$$E_{mn}^{\varphi}(r) = jK \frac{e^{-jkr}}{\pi r} \times \frac{\cos\left(\frac{kb}{2} sin\theta_{mn} sin\varphi_{mn}\right) sin\left(\frac{ka}{2} sin\varphi_{mn}\right) cos\theta_{mn}}{sin\theta_{mn}} \quad (9)$$

where (θ_{mn}, φ_{mn}) are the coordinates of the observation point in the local spherical coordinate system of the mnth element. K is a constant. a and b are the width and length of the patch, respectively.

In this method, the ON–OFF states of the PAs are to be modulated to achieve a good synthesis of the focal field. Thus, the task of determining the feeding power distribution can be seen as a classification problem, in which the near-field patterns of the feed array serve as feature vectors, and the ON–OFF states of the PAs serve as classification labels. Since the feeding phase distribution is related to the beam-scanning angle, we keep it the same as that obtained by the CFM method. Among many classification algorithms, the SVM is one of the most popular ones. The main idea behind it is to compute a hyperplane as a decision boundary, which leads to the following binary prediction:

$$\hat{y} = \begin{Bmatrix} 0, when\ w^T.\phi(x) + b < 0 \\ 1, when\ w^T.\phi(x) + b \geq 0 \end{Bmatrix} \quad (10)$$

Where, *x* is the feature vector that is inputted into the SVM. ϕ(x) maps x into a higher dimensional space to make feature vectors linearly separable. w and b are the weight vector and the constant coefficient, respectively. They are obtained in the SVM training process, in which the following constrained optimization problem is solved.

$$min_{w,b,\xi} \frac{1}{2} w^T w + C \sum_{i=1}^{l} \xi_i$$

$$\text{Subject to} y_i(w^T.\phi(x_i) + b) \geq 1 - \xi_i$$
$$\xi_i \geq 0, i = 1, \ldots, l \quad (11)$$

Where ξ_i is a slack variable measuring the margin violation. $y_i \in \{-1, 1\}$ defines the classification instance, and $i = 1, . . . , l$ is the training sample number. $C > 0$ is the regularization parameter to balance the model complexity and the cost of deviations. Due to the possible high dimensionality of the vector variable ***w***, usually we solve the following dual problem:

$$min_{\alpha} \frac{1}{2} \alpha^T Q \alpha - e^T \alpha$$

$$\text{Subject to} y^T \alpha = 0$$

$$0 \leq \alpha_i \leq C, i = 1, \ldots l \ (12)$$

where e = [1,…, 1] is the vector of all ones. Q is an l by l positive semidefinite matrix with $Q_{i,j} = y_i y_j K(x_i, x_j)$, and $K(x_i, x_j) = \emptyset(x_i, x_j)$ is the kernel function. When (12) is solved, using the primal-dual relationship, the optimal vector variable w satisfies

$$w = \sum_{i=1}^{l} y_i \alpha_i \emptyset(x_i) (13)$$

Note that the decision function of the SVM is determined by the support vectors, not by the whole sample space. This can reduce the computational complexity and avoid "curse of dimensionality." In this work, the training of the SVM consists of presenting known pairs of inputs and outputs (i.e., near-field patterns and the corresponding feeding power distributions to achieve such patterns, respectively), called *training set*, so that the machine is able to extract the relationship between them and provide outputs to new inputs. The feeding powers in the training set are randomly selected within {0, 1}, which represent the ON-state and the OFF-state of the PA, respectively. Then, the corresponding near-field pattern can be calculated by (6).

It needs to be normalized with respect to the maximum amplitude before being added into the training set. In order to optimize the radiation efficiency, the near-field pattern of the feed array needs to realize a good synthesis of the focal field.
Thus, we take the focal field as the target near-field pattern and input it into the well-trained SVM. That is, the input feature vector is the vectorized focal field

$$x_{input} = (E^{focal})^{*} \quad (14)$$

The asterisk stands for the conjugate operation. It can ensure that the focal field and the near-field pattern have the same propagation direction. Similarly, x_{input} should be normalized with respect to the maximum amplitude. Then, the well-trained SVM will output the required feeding power distribution.

In this method, the synthesis region is required to cover the main part of the focal field because it is sufficient to represent the highest radiation efficiency. Since the focal fields corresponding to different scanning angles are different, different focal field synthesis regions have to be used. However, considering that the main part of the focal field has a predictable position movement with the scanning angle, these focal field synthesis regions can be obtained from each other by the corresponding movement. Here, we will determine the best synthesis region for the beam steered to 0◦ both in the elevation and the azimuth planes of the reflector. In order to maximally cover the focal field by the synthesis region with a limited size, the main part of the focal field must lie in the center of the synthesis region better based SVM.

IV. RESULT ANALYSIS

In this section, design of array fed beam reflector antenna with maximum power radiated efficiency based on near field pattern synthesis using support vector machine is implemented using MATLAB.
In order to validate the effectiveness of the presented method, some numerical results are presented in this section. The Fig. 2 shows the normalized directivity vs zeneath angle.

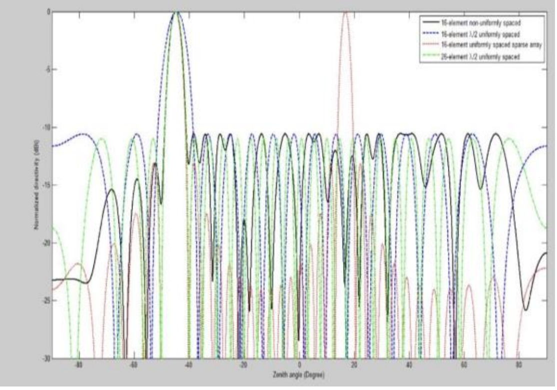

Fig. 2: Normalized directivity vs zeneath angle

In this work, the RPE is calculated based on the PA efficiency values, noticed that the output power in Fig. 2 is the normalized value with respect to the 1 dB gain compression point. Obviously, the PA efficiency will be rather low when the output power is at a low level.

ON-State PAs Output the Same Power: By using the SVM to synthesize the focal field in the corresponding best synthesis region, the best feeding power distributions for each scanning angle are obtained, respectively. Because of the symmetry of the antenna structure, the feeding power distributions corresponding to the positive angle scanning and the negative angle scanning are generally symmetrical. Here, we only give the feed power distributions of the positive angles scanning. For comparison, the feeding power distributions obtained by the CFM method are taken. The Fig. 3 shows the beam pattern.

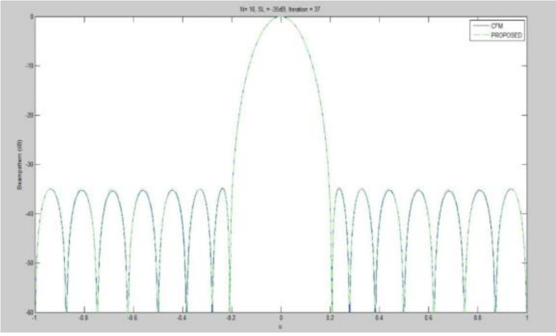

Fig. 3: Beam Pattern

From the numerical results, it is observed that the RPE is about 22% higher than that of the CFM and about 10% higher than that of the optimum CFM truncation case.

V. CONCLUSION

In this work, design of array fed beam reflector antenna with maximum power radiated efficiency based on near field pattern synthesis using support vector machine is presented. In this article, the RPE is defined as the new design goal and is to be raised to achieve higher EIRP. For this reason, a method based on the near-field pattern synthesis is proposed. In this method, the output powers of all the on-state PAs are required to be the same to maximize the PA efficiency. Then, the reflected focal field is synthesized by the near-field pattern of the feed array to minimize the loss of the radiation efficiency. This is accomplished by taking the focal field as the target near-field pattern and inputting it into the well-trained SVM and taking its output as the required feeding power distribution. Besides, the proper choice on the location and the size of the focal field synthesize region is also included. It is observed from the numerical results that the RPE is about 22% higher than that of the CFM and about 10% higher than that of the optimum CFM truncation case.

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