

Quantized 2-Bit Synthesis Control of Antenna Arrays Using Multi-Layer Perceptron-Based Machine Learning

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This paper presents a synthesis approach for controlling a phased antenna array, formulated as a multi-objective optimization problem that accounts for quantization error. To achieve effective control of the radiation pattern while minimizing quantization effects, a dithering quantization method is integrated into a Multi-Layer Perceptron (MLP) model, enabling robust 2-bit quantized control.

Index Terms—Antenna array synthesis, Dithering quantization, Multi-layer perceptron, Quantized control.

I. INTRODUCTION

CONTROLLING phased antenna arrays is crucial and challenging in satellite communications. Control can be continuous or quantized [1],[2],[3],[4], where quantized control limits the phase and amplitude of each antenna element to discrete levels, introducing noise which can degrade array performance. Therefore, a robust method is essential to ensure high performance despite these quantization effects.

II. PROBLEM FORMULATION

For a planar antenna array in the OXY plane illustrated in Fig.1, the synthesized far field in each direction (θ, ϕ) can be expressed as a linear superposition of the field in this direction from all antenna elements. The array factor (AF) is expressed in (1) as :

$$AF(\theta, \phi) = \sum_{i=1}^P w_i e^{jk_0 \Psi_i} \quad (1)$$

Where $P = M \times N$ represents the total number of antenna elements, with M and N being the number of elements along the x-axis and y-axis, respectively. The complex excitation of each element, w_i is given by:

$$w_i = I_i e^{j\beta_i} \quad (2)$$

where I_i and β_i are the amplitude and phase of the i^{th} element respectively. $k_0 = 2\pi/\lambda$ represent the wave number with λ

being the wavelength. The term Ψ_i accounts for the position of each element and is defined as:

$$\Psi_i = x_i \sin(\theta) \cos(\phi) + y_i \sin(\theta) \sin(\phi)$$

where x_i and y_i are the coordinates of the i^{th} element along x and y axis, ϕ the azimuth angle and θ the elevation. The normalized array factor is expressed as:

$$RP(\theta, \phi) = 20 \log_{10} \left| \frac{AF(\theta, \phi)}{AF_{\max}(\theta, \phi)} \right| \quad (3)$$

The synthesis problem is to find the set of complex excitation $\mathbf{w} = [w_0, \dots, w_i, \dots, w_{P-1}]$ so that the radiation pattern $RP(\theta, \phi)$ satisfies the desired radiation pattern $DP(\theta, \phi)$.

III. METHODOLOGY

A. Multi-layer perceptron (MLP) structure

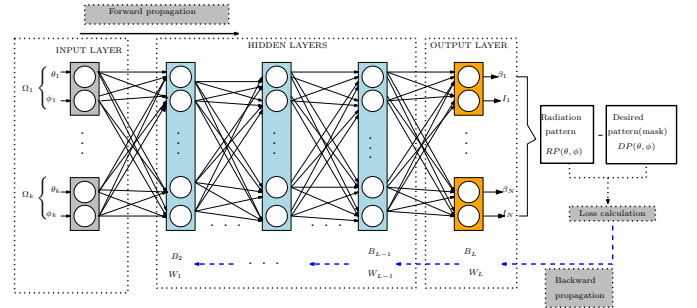


Fig. 2. The proposed multi-layer perceptron structure.

To optimize an antenna array, we propose framing the task as finding a mapping inverse function, $\mathcal{Y}^{-1}(\cdot)$ where $\mathbf{w} = \mathcal{Y}^{-1}(\Omega_0)$ with Ω_0 representing the beam direction and $\mathbf{w}$ the complex excitation vector. Using a multi-layer perceptron (MLP), we develop a machine-learning framework that takes the beam direction as input and outputs the amplitude and phase excitations. The MLP (see Fig.2) has $N_L + 2$ layers: one input, N_L hidden layers, and an output layer with $2P$ perceptrons (for P antennas). ReLU is used in the hidden layers, while "tanh" and "sigmoid" are used in the output layer to match the desired phase $[-1, 1]$ and amplitude $[0, 1]$ ranges.

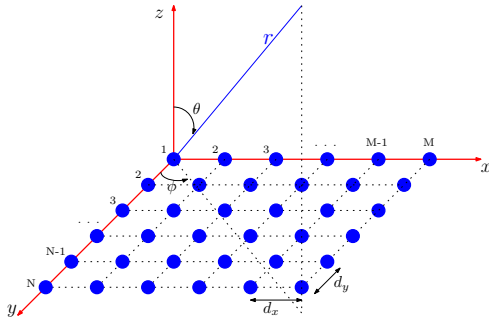


Fig. 1. Planar antenna array.

During training, forward propagation computes the predicted output, and backpropagation with gradient descent updates weights and biases based on the calculated loss, using (4).

$$\begin{cases} W_L = W_L - \mu \frac{\partial loss}{\partial W_L} \\ B_L = B_L - \mu \frac{\partial loss}{\partial B_L} \end{cases} \quad (4)$$

Where μ is the learning rate, W_L and B_L are the weights and the biases of the perceptron in the layer L respectively.

B. Loss function

The MLP-based antenna array optimization framework uses a mask function to regulate side lobes and directivity in the predicted radiation pattern. This mask function defines the pattern boundaries, specifying main lobe direction, side lobe levels, and interference suppression requirements. The pattern loss function is formulated as the Euclidean norm of the difference between the mask function $DP(\theta, \phi)$ and the predicted radiation pattern $RP(\theta, \phi)$, obtained from the complex excitation at the output of the MLP.

$$loss_P = \frac{1}{N_\theta N_\phi} \|\max(0, RP(\theta, \phi) - DP(\theta, \phi))\|_2^2 \quad (5)$$

Where N_ϕ and N_θ are the total number of azimuth and elevation angles respectively.

To enhance quantization performance, a dithering technique is applied by adding Gaussian noise with mean 0 and standard deviations $\alpha\Delta\phi$ and $\gamma\Delta I$ for phases and amplitudes, respectively at the MLP outputs. α, γ are the noise factor in the range $[0, 0.1]$. A quantization loss term is then incorporated, resulting in the overall loss function:

$$loss = c_1 loss_P + c_2 loss_Q \quad (6)$$

$loss_Q$ is the loss function of the quantization process using the dithering method and $loss_P$ is the pattern loss function. $loss_Q$ is expressed by:

$$loss_Q = c_3 loss_{amp} + c_4 loss_{phase} \quad (7)$$

With

$$loss_{phase} = \frac{1}{P} \sum_{i=0}^{P-1} (\beta_i - \hat{\beta}_i)^2 \quad (8)$$

$$loss_{amp} = \frac{1}{P} \sum_{i=0}^{P-1} (I_i - \hat{I}_i)^2 \quad (9)$$

where β_i and I_i denote the target phase and amplitude, and $\hat{\beta}_i$ and $\hat{I}_i$ represent their quantized values using dithering technique.

IV. RESULTS

This section presents the successful synthesis of a 12×12 antenna array radiation pattern, achieving a main lobe with reduced side lobes and introducing nulls for interference suppression. Simulations were conducted using the PyTorch framework on a personal computer. Fig.3 and Fig.4 compare radiation patterns based on the optimized w values versus uniform 2 bit quantization of w.

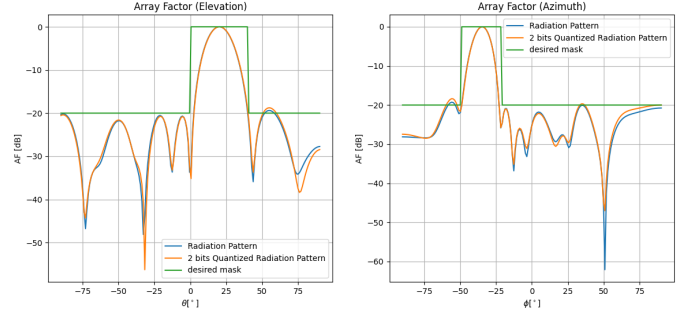


Fig. 3. Comparison of optimized and 2 bit quantization array factor in both azimuth and elevation pointed at $(-35^\circ, 20^\circ)$.

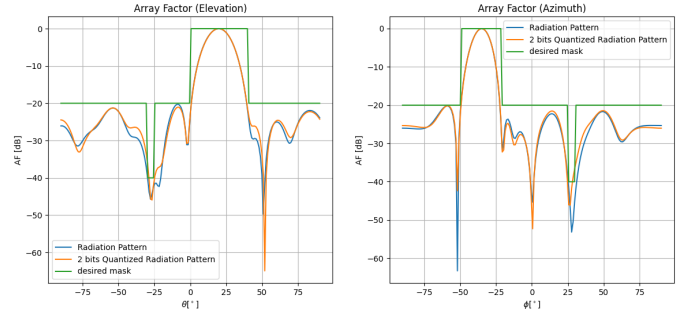


Fig. 4. Comparison of optimized and 2 bit quantization array factor with interference region in both azimuth and elevation pointed at $(-35^\circ, 20^\circ)$.

V. CONCLUSION

The proposed method offers a promising approach to reducing hardware complexity and power consumption while ensuring high-performance beam steering, precise signal targeting, and effective interference suppression for satellite applications.

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