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A Data-Free Patch Antenna Generation Framework via Two-Stage Gradient Exploration and BiScaleNorm

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Designing microstrip patch antennas for millimeter-wave 6G applications presents a complex challenge due to high-dimensional, non-convex optimization landscapes. The approaches using traditional evolutionary algorithms (e.g., GA) rely heavily on computationally expensive stochastic iterative electromagnetic (EM) simulations, which consume too much time. Conversely, deep learning approaches typically require massive pre-collected datasets, which are costly to generate and lack adaptability to new design specifications. To bridge this gap, this study proposes a novel, data-free Metal Pattern Generation Network (MPGN) framework that eliminates the dependency on both offline datasets and computationally expensive brute-force searches.

To address the "gradient barrier" and severe gradient vanishing inherent in binary metal pattern generation, we introduce BiScaleNorm, a specialized non-linear normalization technique. Unlike standard methods, BiScaleNorm independently scales positive and negative activations using running extremes (M and m), as expressed in (1):

$$\hat{x} = \begin{cases} \frac{x}{M}, & if\ x > 0 \\ \frac{x}{|m|}, & if\ x < 0 \end{cases} \tag{1}$$

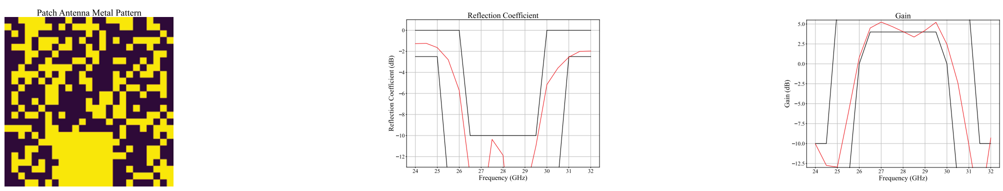
This mechanism effectively prevents activation values from drifting into saturation regions, ensuring active gradients for hard binarization functions (e.g., Sign) and enabling stable training of discrete patterns.

Our proposed Gradient Estimation Network (GEN) acts as an online differentiable surrogate, training alongside the generator to predict antenna performance in real-time. By providing gradient guidance, GEN allows the optimization to proceed efficiently, reducing the required HFSS simulations by orders of magnitude (at least in hundreds) compared to the massive iterations typical of evolutionary algorithms. To avoid local optima, we employ a Two-Stage Gradient Exploration Strategy: Stage I utilizes BiScaleNorm for rapid convergence to a local optimum, while Stage II introduces a periodic mutation mechanism to escape local basins, ensuring monotonic performance improvement.

The main contributions of this work are summarized as follows:

1. A fully data-free framework that removes dependency on expensive offline EM datasets.
2. The BiScaleNorm technique, which effectively resolves gradient saturation issues in binary optimization.
3. A Two-Stage Exploration Strategy that enables the model to escape local optima.

Validated on the 5G n257 band (26.5-29.5 GHz), our framework successfully generated a double-layer patch antenna (pattern shown in Fig. 1(a)). The results in Fig. 1(b) indicate that while Stage I achieves basic resonance, Stage II significantly deepens the reflection coefficient (S_{11}) to below -10 dB. Furthermore, Fig. 1(c) demonstrates a flat realized gain exceeding 4 dB across the passband. Comparative experiments confirm that BiScaleNorm provides superior convergence stability compared to standard baselines (e.g., LayerNorm), which failed to achieve valid resonance due to gradient vanishing. Crucially, this methodology demonstrates robust generalizability; as evidenced in our extended studies, it has been successfully adapted to design antennas for other frequency bands with minimal configuration changes, proving its viability as a generic solution for diverse mmWave components.



(a) Patch antenna metal pattern (b) Reflection coefficient (S_{11}) (c) Gain

Figure 1. Simulated reflection coefficient and realized gain of the final optimized antenna (Stage II).