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

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MAIN CHALLENGES

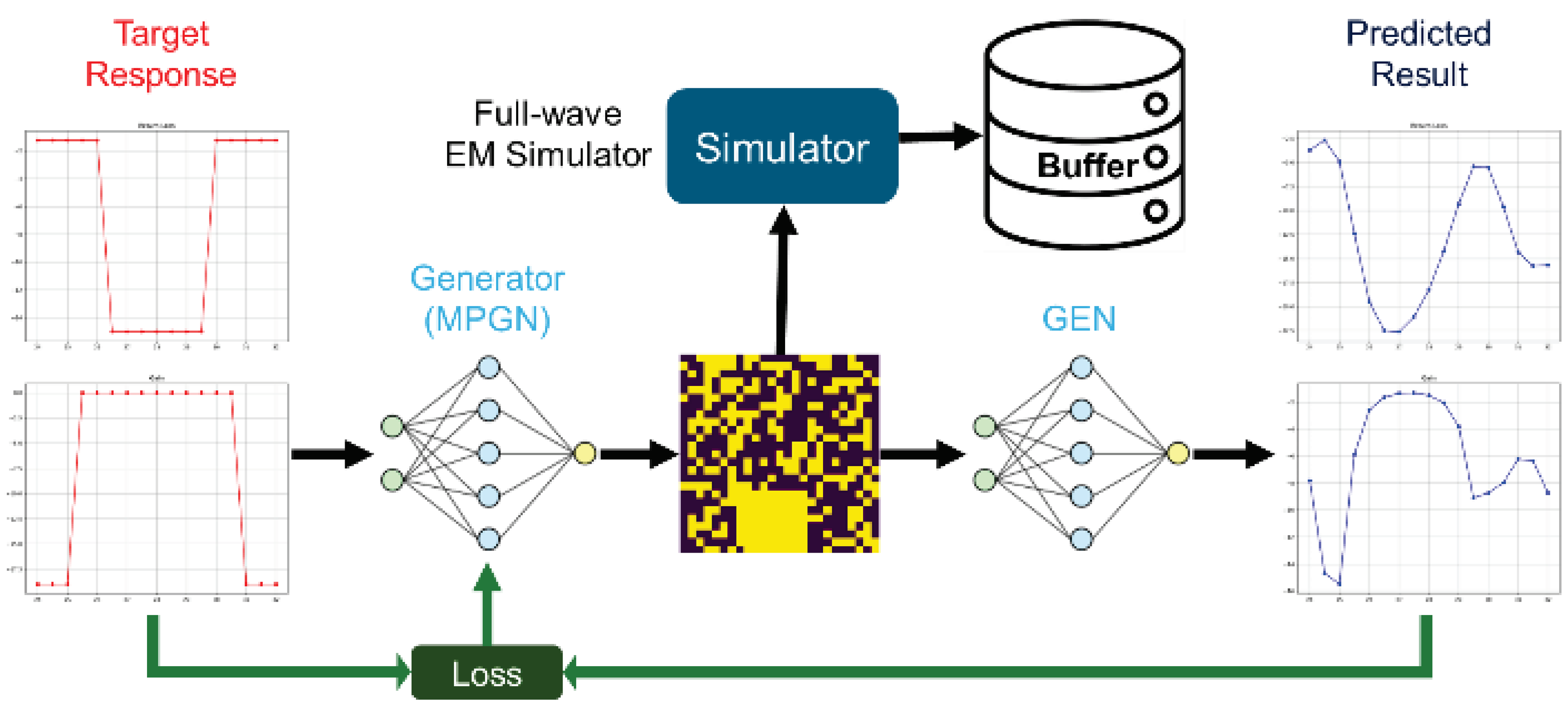
Designing microstrip patch antennas for millimeter-wave 6G systems is a high-dimensional, non-convex optimization problem.

- Evolutionary algorithms rely on expensive stochastic EM simulations.
- Dataset-based deep learning requires massive pre-collected samples.
- New specifications need a design flow that can adapt without rebuilding an offline dataset.

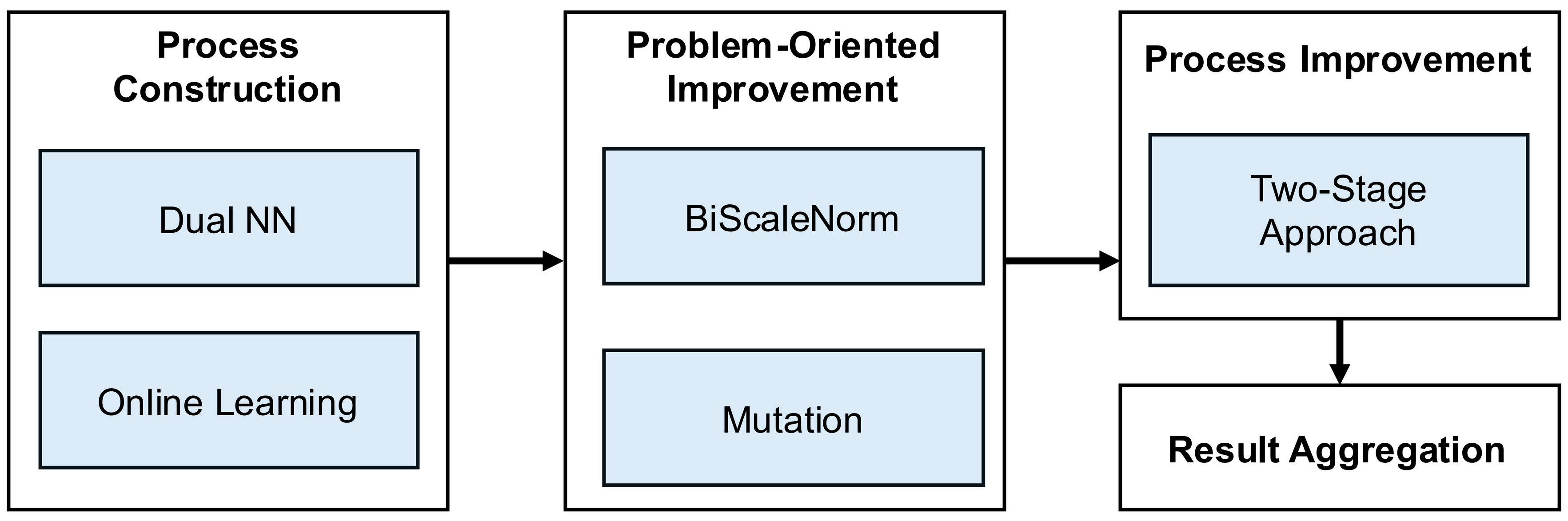
PROPOSED FRAMEWORK

The proposed framework forms a closed, data-free design loop:

- **Metal Pattern Generation Network (MPGN):** Converts the target antenna response into a binary metal pattern, which is evaluated by HFSS to obtain its physical response.
- **Gradient Estimation Network (GEN):** Learns online from HFSS-labeled samples as a differentiable surrogate and provides gradient guidance for updating MPGN, while HFSS remains the physical evaluator.



The upper diagram illustrates the core online learning loop, while the lower diagram summarizes the complete two-stage optimization workflow.



CONTRIBUTIONS

- **Fully data-free framework:** no dependence on offline EM datasets
- **BiScaleNorm:** resolving gradient saturation in binary optimization
- **Two-stage exploration strategy:** helping the model escape local optima

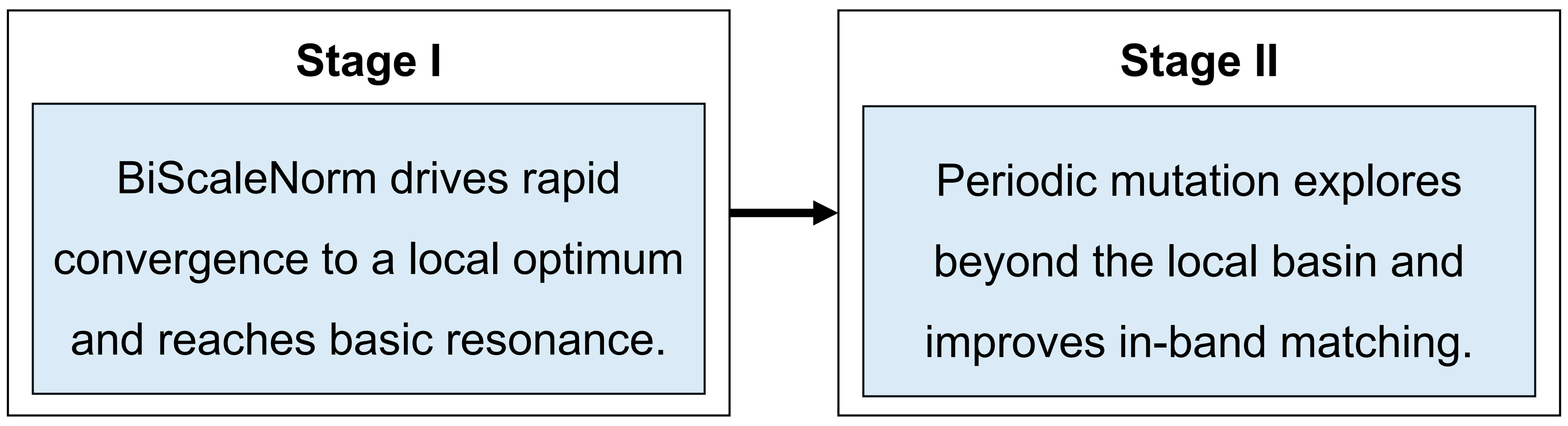
BISCALENORM

Binary metal-pattern generation suffers from a "gradient barrier" and severe gradient vanishing. BiScaleNorm independently scales positive and negative activations using running extremes (M, m):

$$\hat{x} = \begin{cases} \dfrac{x}{M}, if\ x > 0 \\ \dfrac{x}{|m|}, if\ x < 0 \end{cases}$$

This keeps activations out of saturation regions, preserving active gradients for hard binarization functions (e.g. Sign) and enabling stable training of discrete patterns.

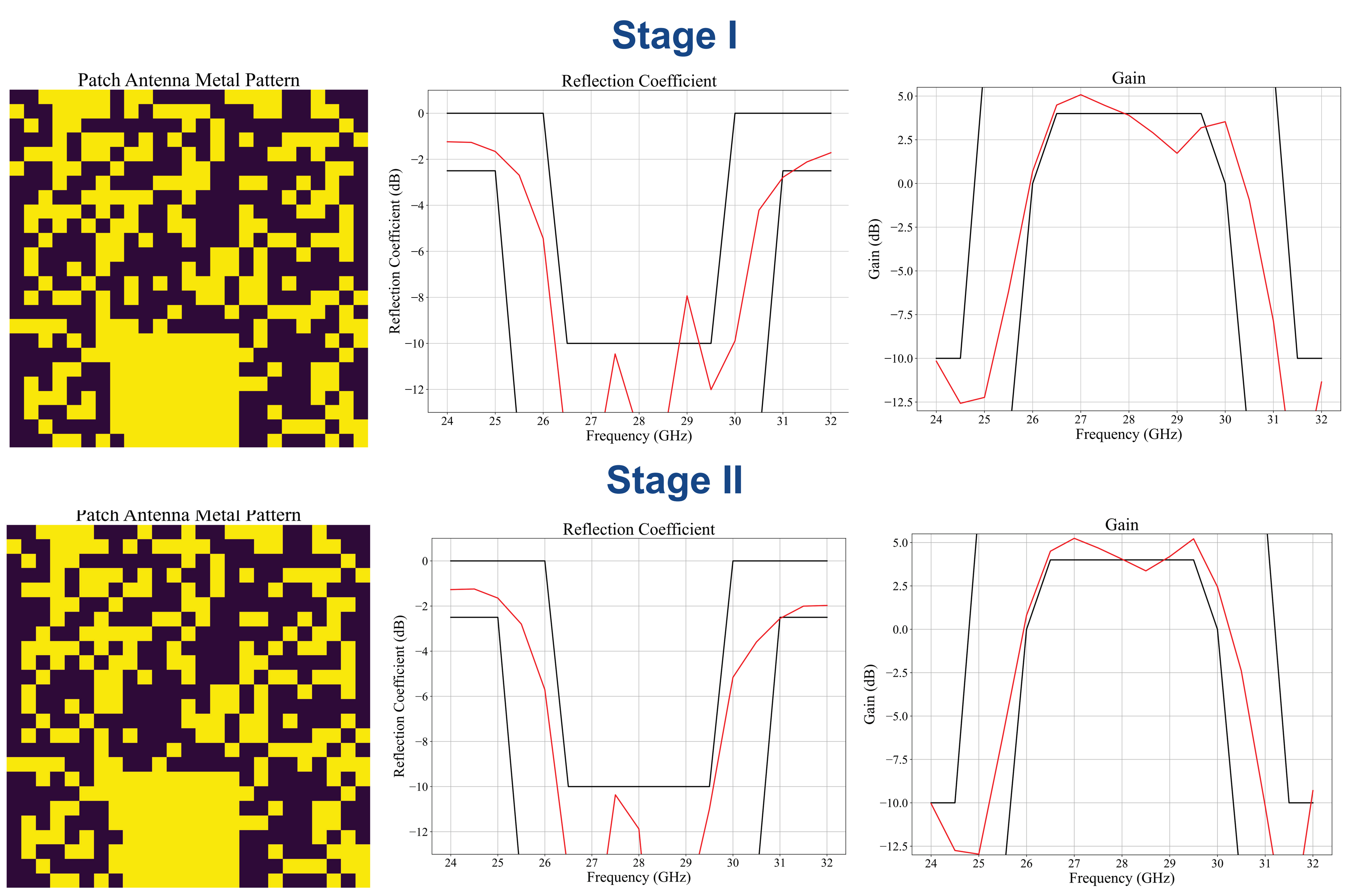
TWO-STAGE GRADIENT EXPLORATION



BiScaleNorm first stabilizes binary pattern generation and enables rapid convergence. Periodic mutation then helps the model escape local optima and further refine the design.

VALIDATION ON 5G NR N257

The validation compares Stage I and Stage II on the 5G NR n257 band (26.5 to 29.5 GHz). Stage II further improves in-band matching and maintains the desired realized gain after exploration.



Stage II mutation escapes the local basin and achieves a lower in-band reflection coefficient while maintaining the target gain.

CONCLUSION

The proposed data-free, gradient-guided framework generates valid mmWave patch antennas with reduced EM simulation effort. It can also be retargeted to other frequency bands with minimal configuration changes.

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