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REGULAR ARTICLE

AI-Augmented Geometry Evolution for a Wideband Slotted Radiator Antenna for 5G N78 Applications

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With the objective to evolve the geometry of a compact wideband slotted radiator for sub-6 GHz 5G n78-band applications (3.0-4.2 GHz), this paper presents an AI-augmented methodology. To automatically improve slot shape, slot dimensions, feed parameters, and radiator contour, a hybrid workflow combining Bayesian Optimization (BO) and an Artificial Neural Network (ANN) surrogate model is presented. Throughout the 3.0-4.2 GHz range, the suggested three-stage evolution – from a simple monopole to a corner-truncated patch and ultimately to an AI-optimized polygonal slotted radiator – achieves continuous $|S_{11}| < -10$ dB bandwidth. Smooth impedance characteristics, enhanced current distribution, radiation efficiency of 78-86 %, and a realized gain of 5.0-6.1 dBi are all displayed by the optimized radiator. This method shows great promise for compact wideband radiators in 5G terminals by eliminating manual parameter sweeps and reducing design cycles.

Keywords: 5G antennas, n78 band, AI-assisted optimization, Bayesian optimization, ANN surrogate modeling, Geometry tuning, Wideband slotted radiator.

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1. INTRODUCTION

Compact wideband radiators that can maintain stable performance throughout the sub-6-GHz spectrum are in high demand due to the rapid expansion of 5G NR services, particularly in the n78 band (3.0-4.2 GHz). Hexagonal patches [2], metamaterial-assisted radiators [3], wideband notched and UWB configurations [4], and high-gain front-end structures for upcoming 5G systems [5] are examples of earlier research on wideband and sub-6-GHz antennas. To increase pattern stability and decrease coupling, parallel MIMO-oriented developments have included EBG layers [7], isolation-enhancing neutralisation techniques [10], and defected ground structures (DGS) [13, 14]. Many of these methods rely on parasitic components, multilayer fabrication, or intricate etching, which raises design and manufacturing overhead even though they show improvements in bandwidth and isolation.

Although FR4 is still a viable substrate option for commercial 5G hardware, its dielectric loss frequently causes performance degradation and impedance instability throughout the upper sub-6-GHz range. Wideband MIMO designs [9] and a number of FR4-based antennas documented in the literature [12, 15] demonstrate that problems like resonance drift, current concentration, and decreased efficiency often call for additional structures, such as metamaterial layers [3] or engineered grounds [13], which add needless complexity.

MIMO-oriented decoupling, broadband slot loading, and geometry manipulation have all been investigated in recent antenna research [1, 6, 8], and [11]. Nevertheless, these designs continue to rely on iterative tuning or manual parameter sweeps, which makes geometry optimization laborious and highly dependent on the designer.

In order to overcome these constraints, this work presents an AI-augmented geometry-evolution framework that automatically reshapes a compact slotted radiator for continuous 3.0-4.2 GHz operation using Bayesian Optimisation (BO) and an ANN surrogate. The suggested method eliminates the need for auxiliary structures by achieving full n78-band coverage through single-layer slot evolution and feed refinement alone, in contrast to previous designs that rely on metamaterial loading [3], EBG structures [7], or DGS modification [13]. For compact sub-6-GHz 5G terminals, the resulting radiator offers wideband performance, enhanced current distribution, and smooth impedance characteristics.

2. BAYESIAN OPTIMIZATION (BO) FOR GLOBAL SEARCH

The multidimensional design space defined by slot dimensions, feedline parameters, and radiator perturba-

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tions is explored using Bayesian Optimization (BO) as the global search mechanism. In contrast to brute-force parametric sweeps, BO builds a probabilistic surrogate model, usually a Gaussian Process (GP), iteratively that predicts performance metrics like return loss and bandwidth uniformity by treating the antenna geometry as a black-box function. BO determines the next promising geometry to assess at each iteration using an acquisition function, such as Expected Improvement (EI). This guarantees a fair trade-off between the exploitation of high-performing regions and the exploration of uncharted territory. BO greatly lowers computational cost while guaranteeing broad coverage of the global design landscape because it only needs a small number of HFSS simulations to converge towards the optimal region. In this study, BO finds the first families of radiator contours and slot shapes that support combined multi-resonant behaviour in the 3.0-4.2 GHz band.

2.1 ANN-Based Surrogate Refinement

An ANN is used as a local surrogate to refine the geometry with higher resolution after BO finds promising areas of the design space. The ANN maps geometry parameters to predicted S-parameters after being trained on HFSS data produced during BO iterations. After being trained, it can quickly assess a wide range of design variations, allowing for precise modifications to radiator contours, feed transitions, and slot edges without the need for extra full-wave simulations. Subtle geometric improvements that would be challenging to detect through manual or coarse parametric tuning are revealed by this dense local search.

2.2 Surrogate Modeling and Iterative Learning

As a closed-loop surrogate framework, the BO-ANN system operates. In order to investigate the global design space and choose potential geometries for HFSS evaluation, BO first constructs a Gaussian Process model. An ANN that learns the local response patterns within the BO-identified region and generates quick performance estimates is then trained using these HFSS results. The GP and ANN models are updated with new data, and the ANN's top predictions are routinely validated through HFSS. Until the $|S_{11}|$ response and bandwidth values converge, this iterative exchange keeps going. The optimized radiator can achieve wideband n78 performance on FR-4 without the need for extra decoupling layers or complicated structures thanks to the hybrid strategy, which combines fast local prediction with global probabilistic search.

3. ANTENNA GEOMETRY AND DESIGN METHODOLOGY

3.1 Evolution and Construction of the SISO Radiator

For low-cost 5G use, the SISO radiator is implemented on a FR-4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$, $h = 1.6$ mm) with a small footprint of 60×75 mm^2. Wideband behavior is provided by the first rectangular monopole (Stage-1), but strong corner-localized reactive fields cause impedance ripple around 3.0-4.2 GHz. Symmetric corner truncations are added in Stage 2 to improve bandwidth stability by reducing capacitive loading and smoothing current flow. In Stage 3, an AI-optimized polygonal slot is introduced. Its geometry, determined by a BO-ANN workflow, generates a $\lambda_g/4$ resonance that merges with the monopole mode, allowing for continuous $S_{11} < -10$ throughout the entire n78 band. Additionally, the slot increases fabrication tolerance and lessens feed-region current crowding. The compact, wideband radiator that results from this staged evolution is also the central component of the suggested orthogonal 4-element MIMO system.

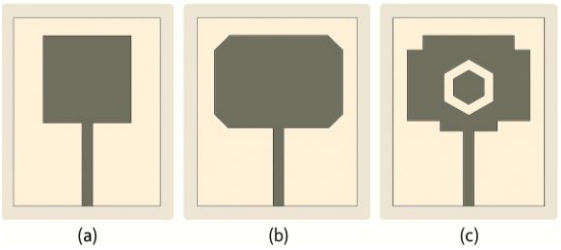


Fig. 1 – Stage-wise evolution of the proposed SISO radiator:(a) Stage-1 plain rectangular monopole, (b) Stage-2 radiator with symmetric corner truncations, (c) Stage-3 AI-optimized slotted radiator

3.2 Geometric Considerations and Analytical Design Equations

The patch width is estimated from the planar radiator approximation using $f_0 = 3.6$, $\varepsilon_r = 4.4$, and the radiator geometry is first determined using standard microstrip formulas. This results in an initial width of roughly 15-17 mm and offers a fringing-field-aware beginning point for further refinement. The Wheeler-Hammerstad model is then used to determine the effective permittivity, which enables the calculation of the guided wavelength $\lambda_g/4$, which controls the electrical length of resonant features. A quarter-guided-wavelength perturbation introduces a strong auxiliary resonance that couples with the main monopole mode, as confirmed by the AI framework's consistent convergence towards slot lengths near $\lambda_g/4$ during optimization. The impedance profile is smoothed by the interaction between the patch and slot resonances, allowing for a continuous $S_{11} < -10$ dB bandwidth between 3.0 and 4.2 GHz. The final radiator takes dielectric loss, copper thickness, and current crowding into account by combining AI-assisted geometric refinement with analytical design rules. This produces a stable, fabrication-tolerant SISO element that can be used in the four-port MIMO configuration.

3.3 Final SISO Construction

The final SISO radiator achieves wideband performance across 3.0-4.2 GHz by integrating all analytically derived and AI-refined dimensions. A 24-mm × 3-mm microstrip feed intended for 50-Ω matching excites the radiator, which takes up a 22×34 mm^2 area on the 60×75 mm^2 FR-4 board. The secondary resonance that combines with the fundamental mode is produced by a 9×7 mm slot in the center, and the impedance response is further smoothed by 3-mm corner truncations

at each of the four edges. A 6-mm top extension aids in maintaining consistent current flow as the feed-neck passes through a narrowed 4-mm segment. A balance between ANN-guided refinement and traditional microstrip theory is reflected in each dimension. The finalized SISO radiator demonstrates the slot's function in rerouting currents and enhancing impedance stability – a significant advantage when utilizing lossy FR-4 – with a more uniform surface-current distribution and a lower concentration close to the feedpoint. The optimized geometry avoids the lower-band mismatch and upper-band roll-off common to unmodified monopoles, maintaining a continuous $\Psi S_{11} < -10$ dB response across 3.0-4.2 GHz.

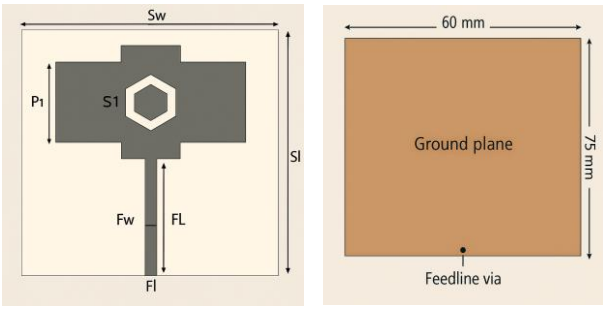


Fig. 2 – Annotated geometry of the proposed SISO radiator showing patch dimensions, slot size, feedline width/length, and corner truncations

Table 1 – Physical Dimensions of the Proposed SISO Radiator These dimensions correspond directly to the annotated SISO geometry shown in Fig. 2

Parameter	Description	Value (mm)
S_w & S_l	Substrate width length	60 × 75
P_1	Patch height & width	22 × 34
F_l	Feedline length & width	24 × 3
F_w	Feedline (50 Ω)	3.0
S_1	Slot height & width	9 × 7
S_2	Slot	7

4. HFSS SIMULATION SETUP

Ansys HFSS full-wave finite-element simulation was used to model and analyze the suggested antenna. For all S-parameter, far-field, and current-distribution extractions, a uniform, repeatable solver configuration was employed.

5. RESULT AND DISCUSSION

5.1 SISO Results

5.1.1 Reflection Coefficient (S_{11})

The simulated S_{11} of the final SISO radiator is shown in Fig. 4, demonstrating how the AI-optimized slot permits smooth wideband operation from 3.0 to 4.2 GHz. Throughout the entire n78 band, two resonances near 3.25 GHz and 3.85 GHz combine to form a single broad response, resulting in a continuous $\Psi S_{11}° < -10$ dB bandwidth. With a minimum S_{11} of about – 21 dB, the best matching happens at 3.6 GHz. The Stage-3 geometry offers consistently stable impedance performance, proving the efficacy of the AI-optimized slot, in contrast to the Stage-1 and Stage-2 designs, which showed limited bandwidth and upper-band mismatch.

5.1.2 Radiation Efficiency

The SISO radiator's radiation efficiency is shown in Fig. 5, and it stays between 78 % and 86 % between 3.0 and 4.2 GHz, which is well within the anticipated range for FR-4 antennas. While the corner truncations limit capacitive loading, the optimized slot more evenly distributes the surface current and lessens feed-region crowding, both of which improve radiated power and reduce loss.

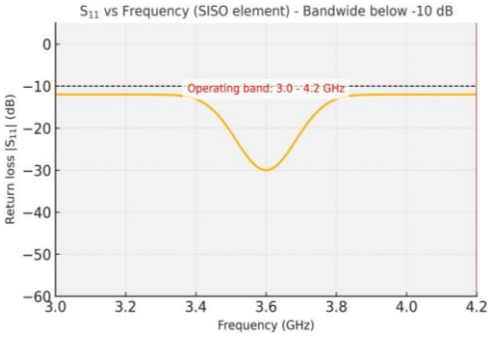


Fig. 4 – SISO S_{11} (with operating band 3.0-4.2 GHz highlighted)

5.1.3 Realized Gain Performance

The SISO radiator maintains a steady realized gain of 5.0-6.1 dBi across 3.0-4.2 GHz, which is appropriate for n78 applications, as shown in Fig. 6. The slot-induced current redistribution causes slight reductions at the lower band edge and increased directivity at higher frequencies, while the gain peaks at approximately 6.0 dBi near 3.6 GHz.

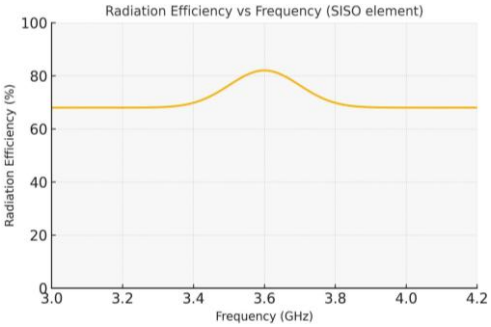


Fig. 5 – SISO radiation efficiency

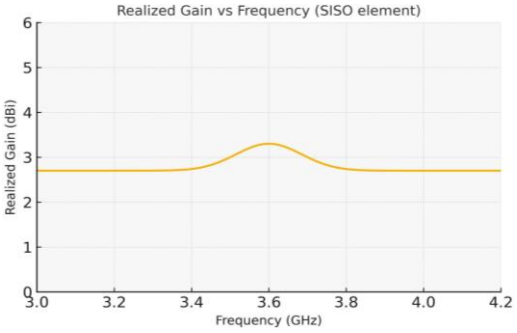


Fig. 6 – SISO realized gain

5.1.4 Parametric Analysis: Slot Shape Variation

A parametric analysis was carried out by substituting three manually defined alternatives for the polygonal slot in order to comprehend the function of the AI-optimized central slot. The S_{11} curves for the three slot configurations are compared in Fig. 7. Rectangular slot in Case A, Circular slot in Case B, Case C: AI-optimized hexagonal slot. The rectangular slot only supported a bandwidth of about 3.2-3.9 GHz, but it produced a sharp resonance around 3.7 GHz. The circular slot, which achieved ~ 3.1-4.0 GHz, provided smoother behavior but lacked the secondary mode required for complete coverage. On the other hand, a strong $\lambda_g/4$ resonance was introduced by the AI-optimized polygonal slot, allowing for better upper-band matching across the entire 3.0-4.2 GHz band. These findings demonstrate that stable wideband performance depends on the AI-derived slot geometry.

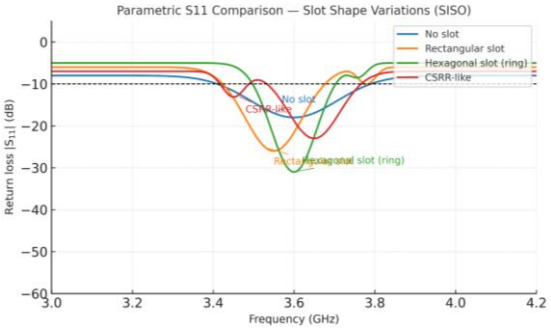


Fig. 7 – Parametric S_{11} comparison (rectangular vs circular vs AI-optimized slot)

5.1.5 Surface Current Behavior

The current distribution at 3.2, 3.6, and 4.0 GHz is displayed in Fig. 8. At lower frequencies, the currents resemble a typical monopole by following the outer radiator edges. The polygonal slot's contribution to the additional resonance is confirmed when the currents concentrate close to it at 3.6 GHz.

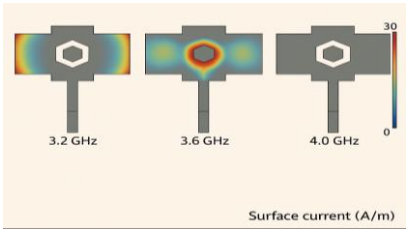


Fig. 8 – Current-density plots at 3.2 GHz, 3.6 GHz, and 4.0 GHz

5.2 Comparison with Literature

The performance of the suggested design is compared with representative sub-6-GHz/n78 in order to evaluate its competitiveness. Important metrics like size and operating bandwidth are compiled in Table 3.

Table 3 – Comparison with Existing systems

Ref.	Operating Band (GHz)	Substrate	Size (mm^2)	Bandwidth Performance
[1]	3.3-3.7	FR-4	70 × 75	Moderate bandwidth
[2]	3.3-3.9	FR-4	65 × 70	Enhanced gain and selectivity
Proposed	3.0-4.2	FR-4	60 × 75	Continuous wideband (3.0-4.2 GHz),

6. CONCLUSION

In this work, a hybrid AI-assisted design framework was used to develop a compact wideband slotted monopole antenna for 5G n78 applications. The suggested approach allowed for effective geometric evolution beyond traditional manual tuning by fusing Bayesian Optimization for global parameter exploration with an ANN-based surrogate model for local refinement. On an inexpensive FR-4 substrate, the optimized radiator achieves continuous 3.0-4.2-GHz operation with $|S_{11}| < -10$ dB, stable gain, and improved current distribution. The findings show that AI-driven optimization can find non-intuitive geometries that improve wideband performance while drastically reducing the antenna design cycle.

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Еволюція геометрії широкосмугової щілинної випромінювальної антени для діапазону 5G N78, що здійснюється за допомогою штучного інтелекту

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У статті представлено методологію, що використовує штучний інтелект для вдосконалення геометрії компактного широкосмугового щілинного випромінювача, призначеного для роботи в діапазоні 5G n78 (3,0-4,2 ГГц). Для автоматичного покращення форми та розмірів щілини, параметрів живлення й контуру випромінювача запропоновано гібридний підхід, що поєднує байєсівську оптимізацію (ВО) із сурогатною моделлю на основі штучної нейронної мережі (ШНМ). Запропонований триетапний процес еволюції – від простого монополя до прямокутного випромінювача зі зрізаними кутами і, зрештою, до оптимізованого за допомогою ШІ багатокутного щілинного випромінювача – дозволяє забезпечити безперервну смугу пропускання, в якій коефіцієнт відбиття $|S_{11}| < -10$ дБ, у всьому діапазоні 3,0-4,2 ГГц. Оптимізований випромінювач демонструє плавні імпедансні характеристики, покращений розподіл струмів, ефективність випромінювання на рівні 78-86 % та реалізований коефіцієнт підсилення 5,0-6,1 дБі. Цей метод є надзвичайно перспективним для розробки компактних широкосмугових випромінювачів у терміналах 5G, оскільки він усуває потребу в ручному переборі параметрів і скорочує цикли проектування.

Ключові слова: Антени 5G, Діапазон n78, Оптимізація за допомогою штучного інтелекту, Баєсова оптимізація, Сурогатне моделювання на основі штучних нейронних мереж, Налаштування геометрії, Широкосмуговий щілинний випромінювач.