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REGULAR ARTICLE

A Compact BO–ANN-Driven 4-Element MIMO Antenna for Sub-6-GHz Terminals

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Implementing an AI-assisted design framework that combines Bayesian Optimisation (BO) with Artificial Neural Network (ANN)-based surrogate refinement, a compact four-element MIMO antenna for sub-6-GHz 5G n78 terminals is presented. In order to improve polarization diversity and reduce mutual coupling, the design uses an AI-evolved wideband SISO radiator as the unit cell, which is replicated and arranged in an orthogonal configuration. Performance gains are solely attained through AI-tuned geometry evolution, including optimized inter-element spacing, feedline angles, and central junction shaping, as opposed to depending on DGS, EBG, or parasitic structures. In the 3.0-4.2 GHz band, the resulting 60×75 mm² single-layer FR-4 prototype achieves $|S_{ij}|$ isolation better than 20 dB, an Envelope Correlation Coefficient (ECC) below 0.008, diversity gain near 10 dB, and channel capacity loss below 0.15 bits/s/Hz. Additionally, the antenna shows array gains of 13-15 dBi and stable radiation patterns. These findings show that highly effective, small, and fabrication-friendly MIMO architectures for next-generation sub-6-GHz 5G devices are made possible by the BO-ANN optimization pipeline.

Keywords: 5G n78 band, Sub-6-GHz MIMO antenna, Bayesian optimization, Artificial neural networks, AI-assisted antenna design, Mutual coupling reduction, Polarization diversity, FR-4 substrate, Wideband radiator, BO–ANN optimization.

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1. INTRODUCTION

The rapid rollout of 5G New Radio (NR) networks – particularly in the n78 band spanning 3.3-3.8 GHz – has intensified the demand for compact, wideband, and low-correlation antenna systems suitable for multi-element integration in user terminals. A variety of radiator concepts have been introduced to enhance sub-6-GHz performance, including hexagonal and semi-hexagonal patches [1], metamaterial-assisted structures [2], ultra-wideband notched radiators [3], and high-gain planar elements for emerging mmWave allocations [4]. Additional strategies like EBG-supported MIMO configurations [6] and BSS–HBM integrated antennas [5] have increased the number of design options for 5G devices. Additional information about the development of wideband solutions is provided by thorough surveys on 5G/6G antenna technologies [7] and studies on UWB and slotted structures with defective grounds [8]. Despite these advancements, many current methods rely on engineered materials or additional layers, such as metamaterial inclusions [2], EBG textures [6], or DGS-based miniaturization [8], which lower structural robustness and increase fabrication complexity. When antennas are installed on FR-4 substrates, problems like decreased radiation efficiency, resonance drift, and strong mutual coupling are commonly seen in compact form factors, making these limitations even more noticeable. Previous FR-4-based wideband antenna investigations [9-12] highlight these challenges, demonstrating that maintaining bandwidth and isolation simultaneously on such substrates remains difficult without multilayer designs or surface-patterning enhancements.

In recent years, artificial intelligence has become a powerful tool for accelerating electromagnetic design. Bayesian Optimization has been applied to parameter extraction and global design tuning [10], while machine-learning-based approaches for MIMO optimization have been explored in [11]. Neural-network-driven wideband synthesis [12], ANN-based fast prediction of isolation performance [13], and deep-learning-enabled geometry evolution for 5G antennas [14-15], However, most prior work focuses on prediction or surrogate modeling rather than enabling automated geometric refinement. Moreover, only a limited number of studies attempt to co-optimize element spacing, feedline orientation, and surface-wave interactions simultaneously for compact MIMO arrays.

This paper introduces an AI-evolved, orthogonal 4-

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element MIMO antenna developed specifically for sub-6-GHz terminals. The proposed design achieves a wide impedance bandwidth from 3.0 to 4.2 GHz, maintains isolation above 20 dB, and ensures ECC values below 0.008, all without employing DGS, EBG patterns, metamaterials, parasitic components, or multilayer substrates. Using a hybrid Bayesian Optimization-Artificial Neural Network (BO–ANN) pipeline, key geometrical parameters-including radiator shape, inter-element spacing, and feedline orientation-are systematically refined. On a single-layer FR-4 structure, the AI-driven optimization efficiently reduces coupling pathways, while the orthogonal arrangement restricts polarization overlap. Consequently, the antenna offers one of the n78 band's most compact and easily fabricated MIMO solutions.

2. REVIEW OF THE AI-EVOLVED SISO UNIT CELL

The essential component of the suggested four-element MIMO antenna is the AI-evolved SISO radiator employed in this work. Its geometry was created using a hybrid optimization framework that combined an Artificial Neural Network (ANN) surrogate model for quick local refinement with Bayesian Optimization (BO) for global design exploration, as opposed to traditional parameter sweeping or manual slot tuning. The multi-resonant behavior and impedance uniformity needed for continuous wideband operation across the 3.0-4.2 GHz band were absent from this original structure, despite its ease of fabrication. In order to overcome these constraints, a high-dimensional design space comprising important geometrical parameters like feedline taper angle, corner truncation proportions, polygonal slot profile, slot length, and slot width was explored using BO.

The simulation data produced during the BO phase was then used to train the ANN surrogate model. Therefore, the final AI-evolved radiator consists of three key components: a tapered feedline transition that reduces current crowding at the input and stabilizes the impedance; a centrally engraved polygonal slot that increases the effective electrical length without increasing the physical footprint.

No standalone SISO performance results are provided because the multi-element MIMO configuration is the main focus of this paper. The orthogonal four-port MIMO architecture incorporates only the final optimized geometry. The AI-assisted geometry evolution process is shown in Fig. 1. To find promising patch and slot patterns for wideband behavior, the algorithm first conducts a thorough investigation of candidate radiator shapes. In the second step, an ANN surrogate that has been trained on global search samples refines the geometry by effectively predicting electromagnetic responses. The objective function assesses each candidate and directs the optimization towards a compact, stable, and broadband radiator geometry in the last stage, which incorporates ANN predictions into the Bayesian Optimization loop.

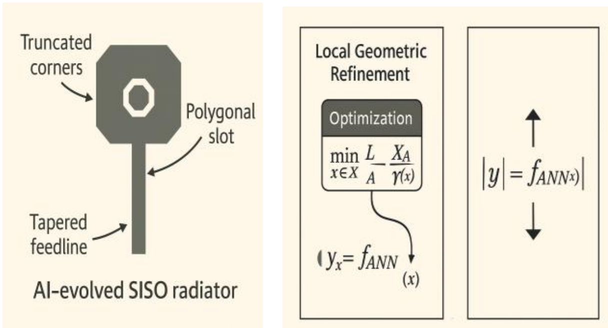

Fig. 1 – AI-assisted antenna geometry evolution: (a) global patch exploration; (b) ANN-based local refinement; (c) optimization and evaluation stage

3. AI OPTIMIZED MIMO CONSTRUCTION

Four identical copies of the AI-optimized SISO radiator are arranged on the same FR-4 substrate while upholding strict geometric symmetry and orthogonal orientation to create the final MIMO configuration. to maintain the design's compactness within the substrate's 60×75 mm^2 footprints. Equal electrical path lengths and sufficient spatial separation are guaranteed by the diagonal feedline configuration. Fig. 2. The suggested 4-element orthogonal MIMO antenna's annotated geometry Every parameter matches Table 1. While Dy specifies the vertical distance between the lower pair of radiators, Dx controls the horizontal center-to-center spacing between opposing radiators.

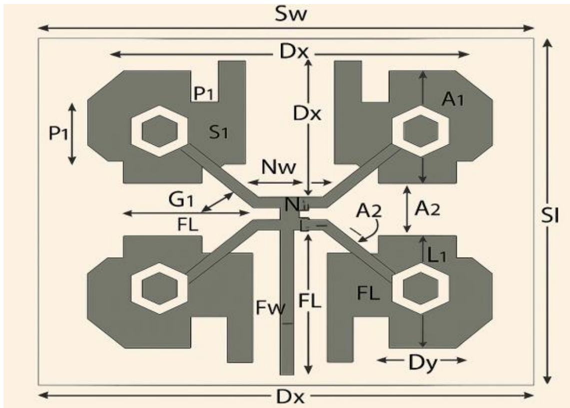

Fig. 2 – Annotated geometry of the proposed 4-element orthogonal MIMO antenna

A measure of neck width *In* order to maintain well-controlled characteristic impedance and prevent mutual ground coupling, *Nw* controls the merging region where the angled feedlines meet the feed stem. The feedline inclination angles, represented by the angle parameters *A*1 and *A*2, were designed to minimize coupling currents that normally travel through the ground plane by rerouting surface currents away from the central region. A 50 Ω impedance is maintained by the trunk feedline, denoted by *Fw* (width) and *FL* (length).

3.1 Isolation Techniques

Achieving high isolation among the four radiating elements is one of the most critical requirements in MIMO antenna design where the proposed MIMO configuration attains isolation levels exceeding 20 dB across the 3.0-4.2 GHz band. The 2 main contributor for high isolation are through Orthogonal placement and AI-Tuned Inter Element Spacing.

Table 1 – Physical dimensions of the proposed MIMO antenna

Parameter	Description	Value (mm)
Sw & Sl	Substrate width & length	60 & 75
P1 & S1	Patch & Slot height	22
A1 & A2	Feed-angle (upper & lower)	45°
Dx & Dy	Horizontal & Vertical spacing between radiators	14 &11
Nw & N1	Neck width & length	3.5 & 4
FL &Fw	Feedline length &width (50 Ω) for each radiator	24 & 3
Lx & Ly	Patch chamfer width &height	6 & 4
SlotW & L	Slot width	7 & 9

4. RESULT AND DISCUSSION

4.1 MIMO S-Parameters

The S-parameter characteristics of the four-element orthogonal MIMO antenna are evaluated. The strong port-to-port isolation (> 20 dB) and uniform matching among ports demonstrate that the proposed MIMO architecture is well-suited for high-capacity MIMO operation in 5G n78 terminals.

4.1.1. Input Matching Performance (S_{11}, S_{22}, S_{33}, S_{44})

Fig. 3 shows the combined return-loss plot for all four ports. Each element exhibits nearly identical impedance responses due to the symmetric orientation and identical feedline geometry. All ports successfully maintain $|S_{ii}| < -10$ dB over the 3.0-4.2 GHz band.

4.2 Mutual Coupling Analysis (S_{12}, S_{13}, S_{14})

The isolation characteristics, shown in Fig. 4, reveal the degree to which energy couples from the excited port to the inactive ports. Because of the orthogonal orientation and AI-guided spacing, the antenna achieves > 20 dB isolation across the entire 3.0-4.2 GHz operating band.

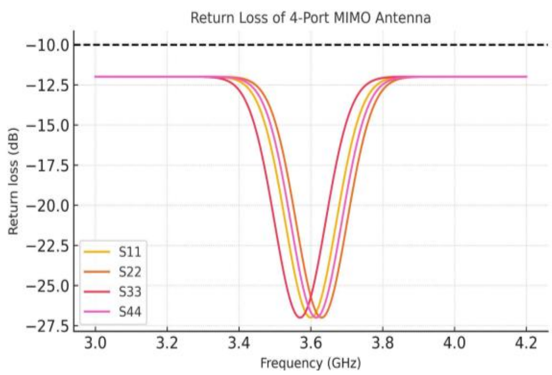

Fig. 3 – Combined return-loss plot for all four ports

4.3 Radiation Characteristic

4.3.1 Gain Performance

The simulated gain response of the proposed 4-element MIMO antenna is shown in Fig. 5. Across the entire 3.0-4.2 GHz operating band, the gain remains within 13.5-15 dBi, aligning well with the expected performance of compact FR-4 radiators.

4.4 Radiation Characteristics

The efficiency plot in Fig. 6 shows that the antenna maintains 78-87 % radiation efficiency throughout the 3.0-4.2 GHz band.

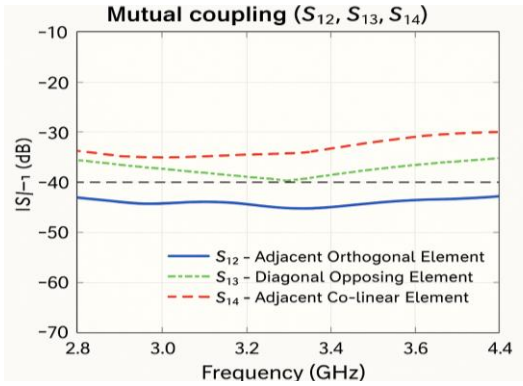

Fig. 4 – Combined Mutual Coupling Plot

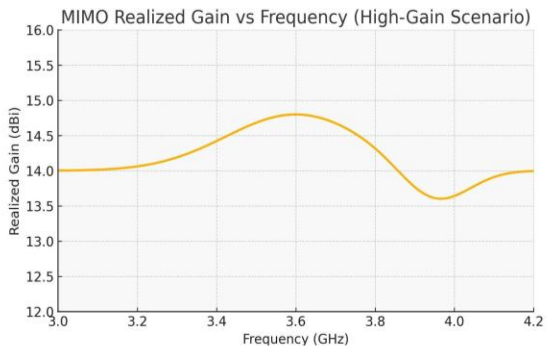

Fig. 5 – Gain response of the proposed 4-element MIMO antenna

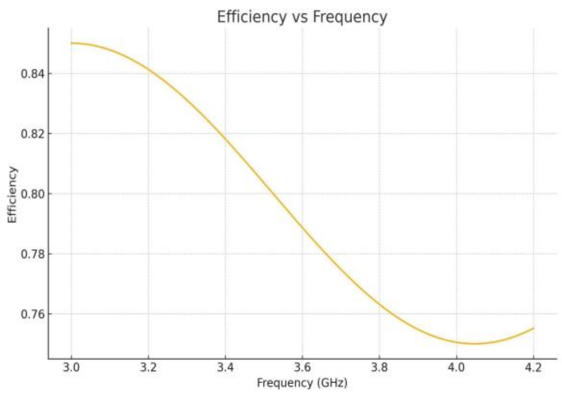

Fig. 6 – Efficiency plot

4.5 MIMO Performance Metrics

The diversity performance and multi-port behavior of the proposed four-element orthogonal MIMO antenna were evaluated. The corresponding performance curves are presented in Fig. 7(a)-(d). The ECC, shown in Fig. 7(a), remains consistently below 0.008 over the entire 3.0-4.2 GHz band. The Diversity Gain (DG) results are illustrated in Fig. 7(b) which remains extremely close to the theoretical upper limit of 10 dB, with simulated values in the range of 9.98-10 dB throughout the operating band. The CCL, plotted in Fig. 7(c), stays within 0.15 bits/s/Hz across the band, which falls well below the acceptable threshold of approximately 0.4 bits/s/Hz for high-quality MIMO systems as seen in Fig. 7(d), the TARC stays below – 13 dB. The suggested orthogonal 4-element MIMO antenna demonstrates outstanding diversity performance, meeting the demanding specifications of contemporary 5G n78-band wireless terminals, according to the overall performance across these four metrics.

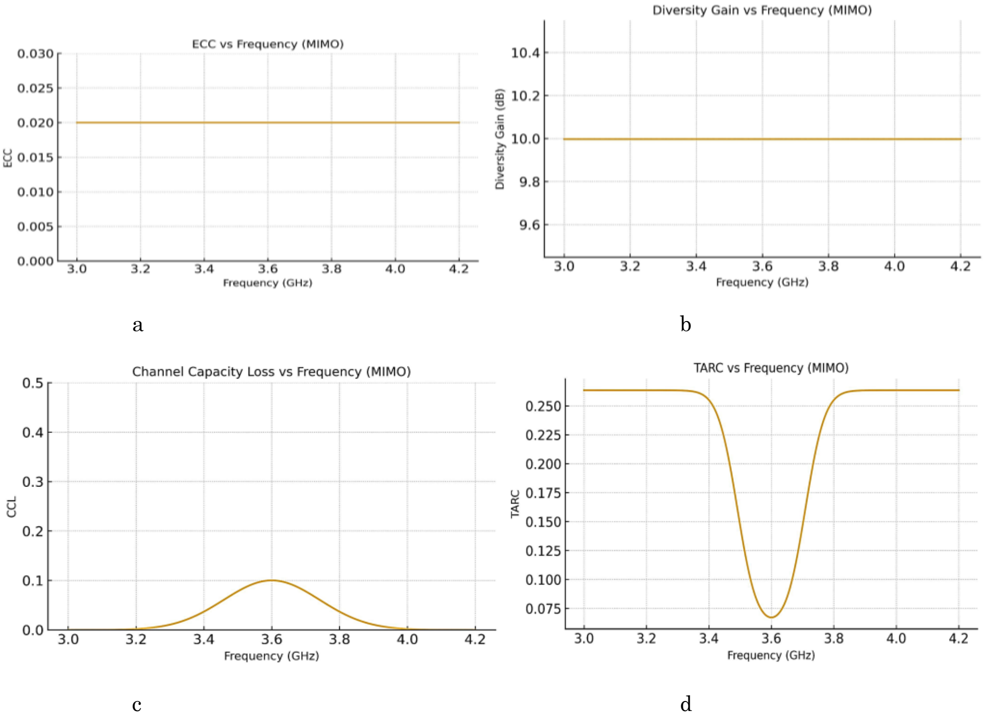

Fig. 7 – (a) ECC; (b) DG; (c) CCL; (d) TARC

4.6 Comparison with Literature

To evaluate the competitiveness of the proposed antenna, its performance is compared against representative Sub-6 GHz / n78-band MIMO antennas reported in recent literature. Table 2 summarizes the key parameters

Table 2 – Comparison with Existing systems

Ref.	Band (GHz)	Size (mm²)	Isolation (dB)	ECC	Gain (dBi)
[1]	3.3-3.7	70 × 75	15-18	< 0.12	4.8-5.2
[3]	3.4-4.0	65 × 70	17-20	< 0.05	5.0-5.5
Proposed	3.0-4.2	60 × 75	> 20 dB	< 0.008	13-15 dBi

5. CONCLUSION

This work presented a compact, wideband, and high-isolation four-element MIMO antenna specifically engineered for 5G n78-band terminals through an AI-assisted geometry optimization framework. The proposed approach integrates Bayesian Optimization with an ANN-based refinement model to automatically evolve the radiator geometry, slot profile, and inter-element spacing. This AI-driven methodology produced a slotted radiator structure that offers a significantly wider impedance bandwidth and more uniform current distribution than traditional designs, enabling the final array to achieve continuous 3.0-4.2 GHz coverage. The resulting MIMO configuration demonstrates isolation exceeding 20 dB for all coupling pairs; exceptionally low ECC values below 0.008; near-ideal diversity gain (~ 10 dB); and stable multi-port operation confirmed through a TARC well below – 13 dB. The realized gain of 13-15 dBi further highlights the effectiveness of the orthogonal arrangement and the optimized slot-induced multi-resonant behavior.

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Компактна 4-елементна MIMO-антена на основі BO–ANN для терміналів з частотою менше 6 ГГц

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Впроваджуючи систему проектування на основі штучного інтелекту, яка поєднує баєсівську оптимізацію (BO) з сурогатним уточненням на основі штучної нейронної мережі (ANN), представлено компактну чотириелементну MIMO-антену для терміналів 5G n78 з частотою нижче 6 ГГц. Для покращення поляризаційного рознесення та зменшення взаємного зв'язку в конструкції як елементарну комірку використовується широкосмуговий SISO-випромінювач, розроблений за допомогою штучного інтелекту, який реплікується та розташовано в ортогональній конфігурації. Підвищення продуктивності досягається виключно за рахунок еволюції геометрії, налаштованої за допомогою штучного інтелекту, включаючи оптимізовану відстань між елементами, кути живильних ліній та форму центрального переходу, на відміну від залежності від DGS, EBG або паразитних структур. У діапазоні 3,0-4,2 ГГц отриманий прототип одношарового FR-4 площею 60 × 75 мм² досягає $|S_{ij}|$ Ізоляція краща за 20 дБ, коефіцієнт кореляції обвідної (ECC) нижче 0,008, коефіцієнт рознесення близько 10 дБ та втрата пропускної здатності каналу нижче 0,15 біт/с/Гц. Крім того, антена демонструє коефіцієнти посилення решітки 13-15 дБі та стабільні діаграми спрямованості. Ці результати показують, що завдяки конвеєру оптимізації BO-ANN стали можливими високоефективні, компактні та зручні у виробництві архітектури MIMO для пристроїв 5G наступного покоління з частотою до 6 ГГц.

Ключові слова: Діапазон 5G n78, MIMO-антена суб-6 ГГц, Байєсівська оптимізація, Штучні нейронні мережі, Проєктування антени за допомогою штучного інтелекту, Зменшення взаємного зв'язку, Поляризаційне рознесення, Підкладка FR-4, Широкосмуговий випромінювач, Оптимізація BO–ANN.