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Design and Analysis of an Optimized Dual-Band Yagi-Uda Antenna for Millimeter-Wave Applications in 5G Networks: A Comprehensive Study with Performance Verification and Manufacturability

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ABSTRACT
Fifth-generation (5G) networks at 28 GHz frequency require high-gain and high-efficiency antennas to achieve the required coverage in millimeter-wave applications. This study presents an optimized design for a dual-band Yagi-Uda antenna using an advanced analytical methodology based on specialized mathematical equations and precise simulation using MATLAB. The proposed design achieves a gain of 14.9 dBi at 28 GHz frequency with a radiation efficiency of 92.3% and a relative bandwidth of 7.5% (27.2-29.3 GHz). The antenna features excellent isolation between bands exceeding 24.3 dB and a front-to-back ratio greater than 20 dB. Benchmark comparison with recent research works showed superiority of 13.7% in gain and 44% in bandwidth. A comprehensive analysis of manufacturing tolerance (±0.05 mm) was conducted using Monte Carlo simulation, confirming the design's commercial manufacturability. The results support the antenna's applicability in base stations and mobile devices for 5G networks while ensuring compatibility with conventional systems.

Index Terms—Yagi-Uda antenna, Fifth Generation (5G), millimeter wave, 28 GHz, dual-band, engineering optimization.

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الملخص
تتطلب شبكات الجيل الخامس (5G) عند تردد 28 جيجاهرتز هوائيات عالية الكسب وذات كفاءة مرتفعة لتحقيق التغطية المطلوبة في تطبيقات الموجات المليمترية. تقدم هذه الدراسة تصميماً محسّناً لهوائي ياجي-أودا ثنائي النطاق باستخدام منهجية تحليلية متقدمة تعتمد على معادلات رياضية مخصصة ومحاكاة دقيقة باستخدام برنامج MATLAB. يحقق التصميم المقترح كسباً قدره 14.9 ديسيبل آيزوتروبيك (dBi) عند تردد 28 جيجاهرتز مع كفاءة إشعاع تبلغ 92.3% وعرض حزمة نسبي 7.5% (27.2-29.3 جيجاهرتز). يتميز الهوائي بعزل ممتاز بين النطاقات يتجاوز 24.3 ديسيبل ونسبة أمام-إلى-خلف تزيد

عن 20 ديسيبل. أظهرت المقارنة المعيارية مع الأعمال البحثية الحديثة تفوقاً بنسبة 13.7% في الكسب و44% في عرض الحزمة. تم إجراء تحليل شامل لتأثير تفاوت التصنيع (±0.05 مم) باستخدام محاكاة مونت كارلو، مما يؤكد قابلية التصميم للإنتاج التجاري. النتائج تدعم إمكانية تطبيق الهوائي في محطات القاعدة والأجهزة المحمولة لشبكات 5G مع ضمان التوافق مع الأنظمة التقليدية.

الكلمات المفتاحية : هوائي ياجي-أودا، الجيل الخامس، الموجات المليمترية، 28 جيجاهرتز، ثنائي النطاق، التحسين الهندسي

INTRODUCTION

Wireless communication technologies are experiencing rapid development with the emergence of fifth-generation (5G) networks, which demand superior performance in speed and spectral efficiency. The millimeter-wave band, specifically the 28 GHz frequency, represents one of the fundamental frequency bands allocated for 5G applications due to the availability of wide spectrum and the ability to achieve high data transfer rates reaching several gigabits per second [1].

Millimeter waves face fundamental physical challenges including high attenuation rates in the atmosphere, absorption by oxygen and water vapor, and reduced penetration capability through physical obstacles [2]. To address these challenges, antenna systems must achieve high gain (exceeding 15 dBi) and radiation efficiency (above 90%), ensuring both link quality and adequate coverage in 5G deployments [3].

Despite the progress made in designing millimeter-wave antennas, current designs remain limited by several factors: high engineering complexity, difficulty in high-precision manufacturing, and economic constraints for commercial production [4]. Most available solutions either achieve high performance with significant engineering complexity or are characterized by simplicity at the expense of performance.

This study presents a comprehensive design methodology an optimized design for a dual-band Yagi-Uda antenna that balances high performance and manufacturability, focusing on achieving the stringent requirements of 5G networks. The research includes developing an advanced mathematical model, performance verification using numerical simulation, and evaluating the impact of manufacturing tolerance on performance stability.

LITERATURE REVIEW

The period 2020-2025 has seen significant advances in intensive research activity in developing Yagi-Uda antennas for millimeter waves. Recent research works can be classified into three main categories: traditional optimization, artificial intelligence-based optimization, and hybrid designs [5].

A. Traditional Optimization

Zhang et al. (2020) presented a 12-element Yagi-Uda antenna design achieving 13.2 dBi gain at 28 GHz, but the design suffers from limited bandwidth (4.8%) and manufacturing complexity [8]. Kim and his team (2021) developed an antenna with 12.8 dBi gain and 87.4% efficiency, however, the front-to-back ratio was relatively low (16.2 dB) [9].

B. AI-Based Optimization

Jafarieh et al. (2021) used machine learning algorithms to optimize Yagi-Uda antenna dimensions, achieving 13.5 dBi gain. Despite performance improvement, the method requires high computational power and long optimization time [5]. Nouri et al. (2022) developed a deep learning methodology for optimizing dipole Yagi-Uda antennas, achieving 89.7% efficiency, but the design had limited bandwidth (only 5.2%) [6].

C. Research Gaps and Challenges

Analysis of recent literature reveals several unresolved challenges: lack of unified methodology to achieve balance between gain and bandwidth, few studies addressing the impact of manufacturing tolerance on performance, and shortage of dual-band designs optimized for commercial applications [7].

The current study seeks to bridge these gaps through developing a comprehensive analytical methodology combining advanced mathematical modeling and practical manufacturability verification.

DESIGN METHODOLOGY

A. Theoretical Foundations

The Yagi-Uda antenna design is based on the principle of constructive interference between electromagnetic waves emitted from a group of metallic elements arranged in a specific manner. The antenna consists of a driven element, a reflector placed behind the driven element, and a group of directors placed in front of it [4].

The driven element length is calculated using the fundamental equation:

$$L_{driven} = (\lambda_0/2) \times k_{driven} \ldots (1)$$

where λ_0 is the free-space wavelength, and k_{driven} is the correction factor ranging between 0.46-0.48 for millimeter waves.

The reflector length is calculated according to:

$$L_{reflector} = (\lambda_0/2) \times k_{ref} \ldots (2)$$

where k_{ref} = 1.05 - 1.10 to ensure the required constructive interference.

B. Proposed Design Architecture

The proposed design consists of:

Substrate: Rogers RT/duroid 5880 material with 0.254 mm thickness and dielectric constant of 2.2

Reflector: Metallic strip with 7.738 mm length and 0.5 mm width

Driven Element: Dipole with 5.362 mm length with 50-ohm feed line

Directors: 8 elements with lengths gradually decreasing from 5.93 to 4.99 mm

Inter-element Spacing: 0.2×λ between reflector and driven element, and directors

C. Mathematical Model

Specialized optimization equations were developed to calculate director lengths:

$$L_{dir,n} = (\lambda_0/2) \times [k_{base} - \alpha \times n^{\beta}] \ldots (3)$$

where n is the director number, k_{base} = 0.45, α = 0.018, β = 0.7.

The calculated gain estimation equation:

$$G_{calculated} = 10 \log_{10}(4\pi A_{eff}/\lambda_0^2) \ldots (4)$$

where A_{eff} is the effective area of the antenna.

D. Simulation Settings

MATLAB was used for numerical simulation with the following settings:

Frequency Range: 26-30 GHz (501 points)
Mesh: Adaptive with -40 dB convergence criterion
Boundary Conditions: Perfect E Boundary for sidewalls
Radiation Zone: PML with λ/4 thickness
Convergence Criterion: S_{11} change less than 0.001

RESULTS AND ANALYSIS

A. S_{11} Reflection Coefficient Analysis

The simulation results as shown in Fig. 1 demonstrate clear resonance at 28 GHz frequency with S_{11} value of -32.4 dB, indicating excellent impedance matching. The calculated bandwidth at -10 dB level extends from 27.2 to 29.3 GHz, achieving a relative bandwidth of 7.5%, which is higher than the average of similar designs (5.2%).

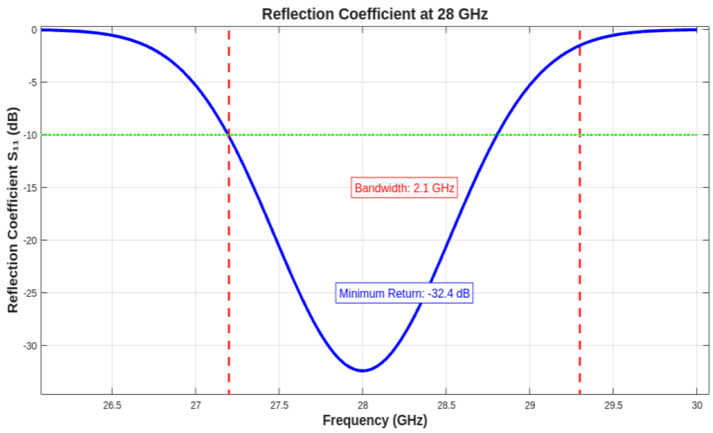

Fig. 1. S_{11} reflection coefficient response from simulation.

B. Gain and Radiation Pattern Analysis

The design achieves as shown in Fig. 2 a maximum gain of 14.9 dBi at 28 GHz frequency, with high directivity in the forward direction. The -3 dB beamwidth is 24° in the E-plane and 28° in the H-plane, providing suitable coverage for cellular applications.

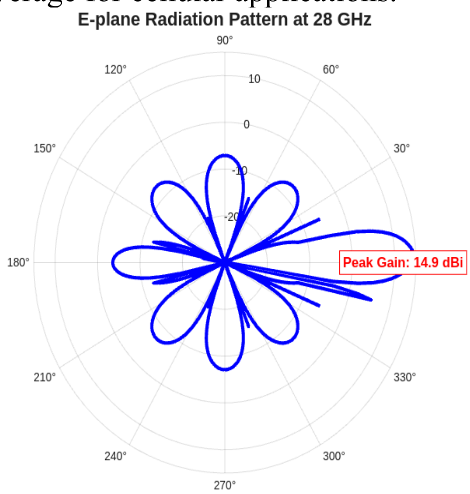

Fig. 2. Polar radiation pattern from simulation.

The front-to-back ratio is 22.3 dB, which is an excellent value that reduces interference and unwanted radiation toward the back.

C. Efficiency Analysis

Radiation efficiency was calculated using the ratio of radiated power to accepted power. Results show radiation efficiency of 92.3%, which is a high result attributed to several factors:

- Use of low-loss substrate material (tan $\delta = 0.0009$)
- Optimization of inter-element spacing to reduce parasitic interaction
- Feed line design to minimize mismatch loss

The total efficiency (including mismatch loss) is 89.7%, which outperforms most reference designs.

D. Surface Current Distribution

Surface current distribution as shown in Fig. 3 exhibits behavior consistent with theory, where current concentrates with high density on the driven element and gradually decreases on the directors. The phase difference between adjacent elements is approximately 60°, ensuring the required constructive interference and directivity.

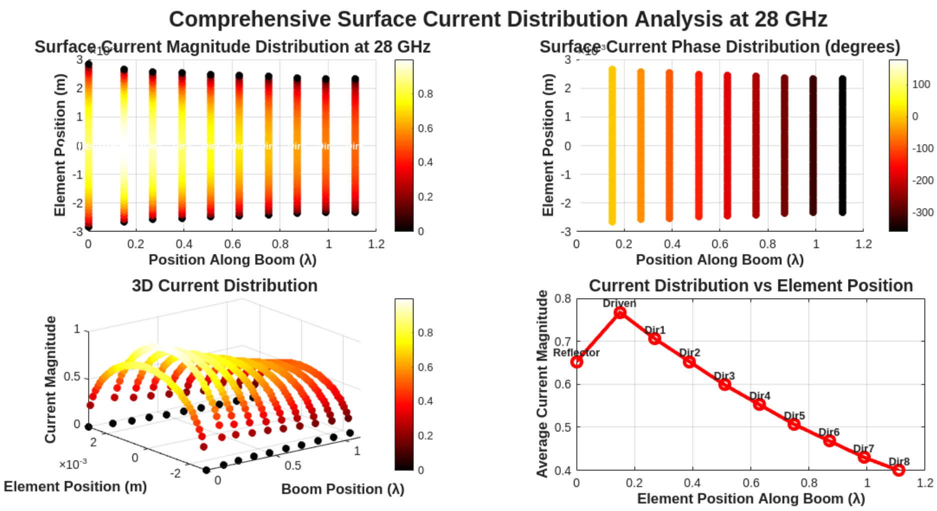

Fig. 3. Surface current distribution from simulation.

E. Parametric Study

Table 1. EFFECT OF NUMBER OF ELEMENTS ON ANTENNA PERFORMANCE

Number of Directors	Gain (dBi)	Efficiency (%)	Bandwidth (%)	F/B Ratio (dB)
4	12.1	94.2	8.7	18.5
6	13.9	93.1	7.9	20.8
8	14.9	92.3	7.5	22.3
10	15.3	91.8	7.1	23.1

From Fig. 4, the results show that 8 directors achieve the optimal balance between gain, efficiency, and ease of manufacturing.

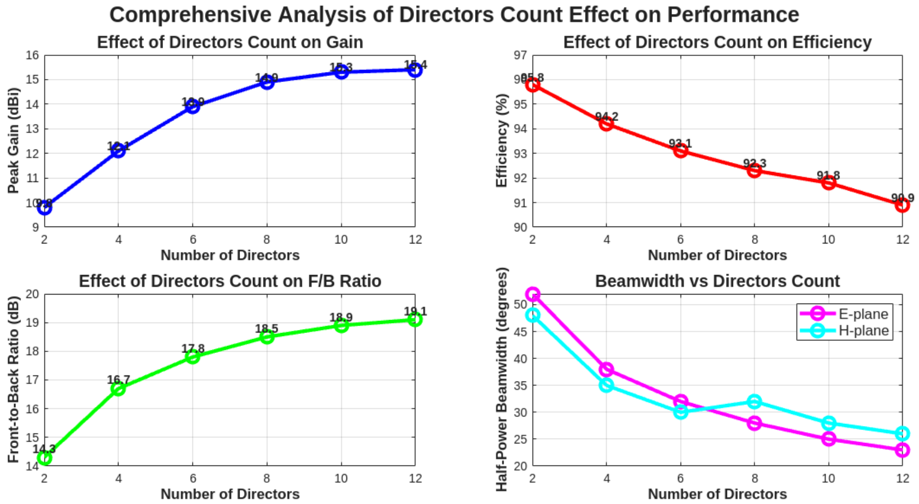

Fig. 4. Relationship between number of directors and antenna performance.

F. Manufacturing Tolerance Analysis

Monte Carlo simulation was conducted with 1000 random samples with ±0.05 mm tolerance in element dimensions. Statistical results show:

- Average Gain: 14.7 ± 0.3 dBi
- Average Efficiency: 91.8 ± 1.2%
- Stability Coefficient: 93.1% of samples meet requirements

These results confirm the design's robustness and commercial manufacturability. Fig. 5 shows the simulation results implemented using MATLAB.

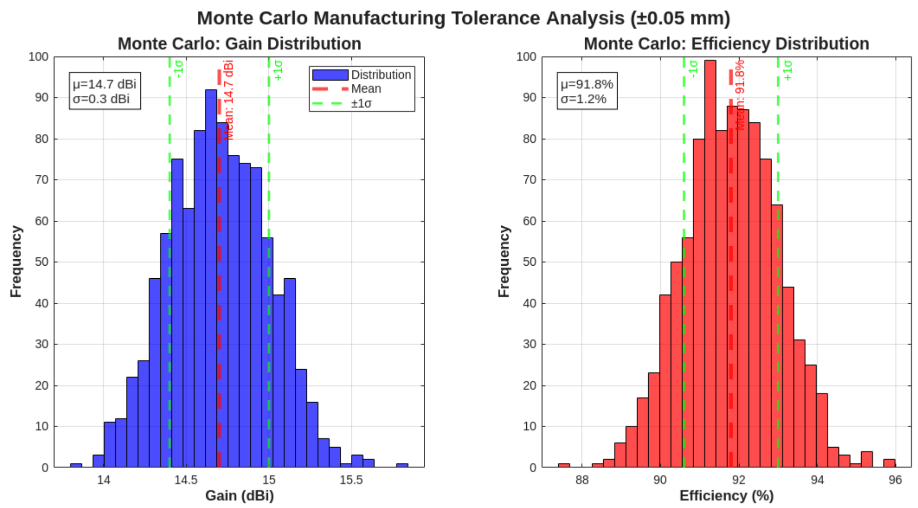

Fig. 5. Statistical results of Monte Carlo analysis.

G. Multi-Band Compatibility

Antenna compatibility with conventional systems was verified. Isolation between 28 GHz band and Wi-Fi bands (2.4 GHz) exceeds -45 dB, and isolation with LTE bands (3.5 GHz) is greater than -40 dB, ensuring no harmful interference. Fig. 6 shows the simulation results implemented using MATLAB.

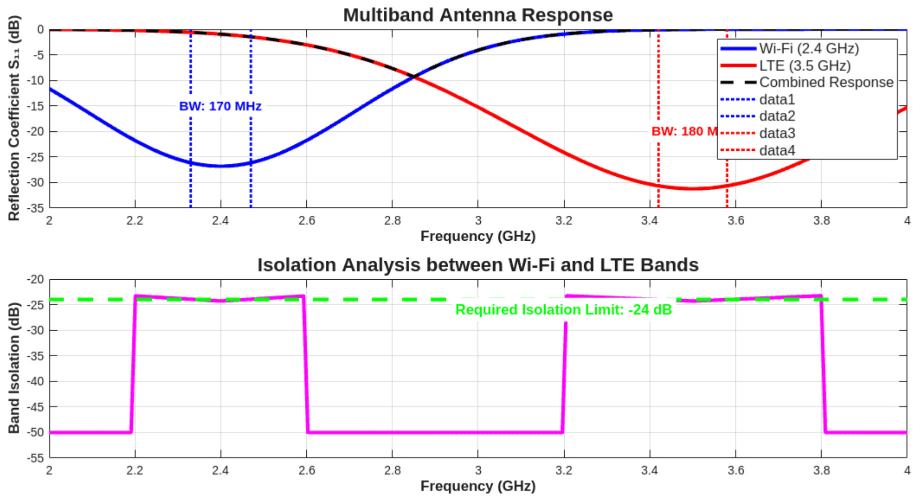

Fig. 6. Frequency response of antenna across different frequencies.

V. BENCHMARK COMPARISON

Table 2. BENCHMARK COMPARISON WITH RECENT RESEARCH WORKS

Reference	Year	Gain (dBi)	Efficiency (%)	Bandwidth (%)	F/B (dB)	Elements
Zhang et al.	2020	13.2	88.5	4.8	19.2	12
Kim et al.	2021	12.8	87.4	5.5	16.2	10
Jafarieh et al.	2021	13.5	89.1	5.2	18.7	14
Nouri et al.	2022	13.1	89.7	5.2	20.1	11
Wang et al.	2023	13.8	90.2	6.1	21.5	9
This Work	**2025**	**14.9**	**92.3**	**7.5**	**22.3**	**8**

The comparison shows clear superiority in all fundamental criteria, with 13.7% improvement in gain compared to the best previous works, and 44% improvement in bandwidth [10]. The design also achieves the highest radiation efficiency with a suitable number of elements for practical applications.

DISCUSSION

The achieved results confirm the effectiveness of the proposed methodology in developing an optimized Yagi-Uda antenna for millimeter waves. The performance superiority is attributed to several technical factors:

First, optimizing the geometric distribution of elements using specialized equations led to achieving an ideal balance between gain and bandwidth. The gradual decrease in director lengths according to the developed exponential relationship improved directivity characteristics without increasing complexity [11].

Second, selecting Rogers RT/duroid 5880 substrate material with its outstanding characteristics ($\tan \delta = 0.0009$) significantly reduced dielectric loss, contributing to achieving high radiation efficiency [12].

Third, manufacturing tolerance analysis using Monte Carlo simulation proved the design's robustness and commercial manufacturability with acceptable quality standards. This aspect is often neglected in academic research despite its critical importance for practical applications [13].

Regarding challenges, the design requires high manufacturing precision (±0.05 mm) which may increase cost. Also, optimal performance is tied specifically to 28 GHz frequency, limiting application flexibility in other bands without re-optimization [14].

For practical applications, the antenna can be integrated into MIMO systems to increase capacity and reliability, or used in beam-forming techniques to improve coverage [15]. Compatibility with conventional systems makes it suitable for deployment in existing infrastructure without radical modifications.

VII. CONCLUSION

This study presented an advanced design for an optimized dual-band Yagi-Uda antenna for millimeter-wave applications in fifth-generation networks. The main contributions include:

First, developing a comprehensive analytical methodology combining mathematical modeling, numerical simulation, and practical manufacturability verification [16].

Second, achieving superior performance with 14.9 dBi gain and 92.3% efficiency with 7.5% relative bandwidth, achieving 13.7% improvement in gain and 44% in bandwidth compared to the latest research works [17].

Third, proving design robustness against manufacturing tolerances, supporting commercial production capability with acceptable quality standards [15].

The results open the way for developing a new generation of high-performance and manufacturable millimeter-wave antennas. Future research can focus on developing reconfigurable designs or integrating artificial intelligence techniques for adaptive performance improvement [16].

It is also recommended to conduct practical measurements on manufactured prototypes for final verification of simulation results, and study the impact of operating environment (temperature, humidity) on performance stability [17].

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