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Review on trends and recent development on Yagi-Uda antenna designs for 5G communication applications

Zhaira Marianne Ferrancol Ferran, Luisa Ann Tamayo Ongquit * and Edwin Romeroso Arboleda

Department of Computer, Electronics and Electrical Engineering, College of Engineering and Information Technology, Cavite State University, Philippines.

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Abstract

The Yagi-Uda antenna, renowned for its exceptional performance in radio communications and TV reception since its inception, continues to be a subject of enhancement by researchers aiming to refine its design for modern communication needs. This review examines various innovations tailored to fulfill the evolving demands of the burgeoning 5G network. By integrating multiple driven elements, expansive feeding networks, and comprehensive impedance matching techniques, a single antenna can now accommodate numerous 5G frequency bands. Efforts to miniaturize the antenna's design, crucial for maintaining performance while reducing size, include the stacking of element layers and the adoption of flexible or planar configurations. Additionally, the antenna's coverage is further optimized for 5G mobile communication through the implementation of dynamic beam steering, which employs phased arrays, Rotman lenses, and adaptive machine learning algorithms. The incorporation of active elements that allow for dynamic signal characteristic control also contributes to the enhanced performance of the Yagi antenna. Finally, the exploration of various array configurations, such as bi-Yagi and quad-Yagi, offers improvements in gain, directivity, and compatibility with 5G applications.

Keywords: Yagi-Uda Antenna; 5G applications; MIMO; Phased arrays; Antenna

1. Introduction

1.1. History and Development of Yagi-Uda Antennas

One of the key contributors to the growth of broadcasting technology was the development of Yagi-Uda antennas, or the narrower name Yagi antennas, by Hidetsugu Yagi and Shintaro Uda in 1926. The original plan was constructed on the parasitic array principle, where a riding element is coupled to other passive elements to mold the radiation pattern and achieve high directivity.

The Yagi-Uda antenna design gained its higher and higher popularity in the 1930s and 1940s, principally in the fields of radio and television broadcasting. Its simplicity and effectiveness, along with the great gain it provided and its perfect directionality, made it an antenna solution used by the majority of the point-to-point communication systems.

During the past years, the Yagi-Uda antenna has seen its innovative stages where designers and engineers have tried various changes and betterments to enhance its working capacity, bandwidth, and adaptability. These adjustments have been instrumental in the broad utilization of Yagi-Uda antennas in different wireless communication systems of the present time like cellular networks, satellite communications, and radar applications.

* Corresponding author: Luisa Ann Tamayo Ongquit

1.2. Fundamental Principles and Characteristics of Yagi-Uda Antennas

The Yagi-Uda antenna is a form of a directional antenna that is made up of two parasitic elements called directors and reflectors and a driven element which is the passive element (usually a dipole). The driven section is the one that converts the incoming electric signals into electromagnetic waves while the passive section models the radiation pattern and also enhances the antenna's directivity.

Electromagnetic coupling between the driven and parasitic elements is a key feature of the Yagi-Uda principle of operation. The length of the reflector, which is slightly longer than the driven element, sends the backward waves to the directions in which the radiation is wanted. The directors, which are shorter than the driven element, are doing the operations with the electromagnetic field to aim the beam in that particular direction.

Most important features of Yagi-Uda antenna are as follows:

- High directivity and gain, which makes it a perfect one for long-range, point-to-point communication
- Frequency-dependent performance, which can restrict bandwidth and wideband operation
- Simplicity and cost efficiency that affect widespread adaption
- Versatility in configuration, like linear, circular, or planar arrangements

The profound understanding of the fundamental principles and characteristics that lie behind the Yagi-Uda antennas is very important in the design, optimization, and implementation of these antennas in today's wireless systems, like 5G networks.

2. Evolution of Yagi-Uda Antennas for 5G Applications

2.1. Challenges and Requirements of 5G Wireless Networks

Changes in our network technology to the 5G ones have given rise to new standards and difficulties which traditional antennas including Yagi-Uda must meet. The important factors for the next generation of mobile communication will include bigger capacity and higher data rates, which are difficult to reach with narrowband Yagi-Uda. Additionally, 5G uses higher frequency bands such as millimeter waves (mmWave), requiring antenna types that can operate efficiently at these frequencies. For 5G, beamforming and beam steering capabilities are needed to increase spectral efficiency and help overcome path loss problems experienced at high frequencies. Lastly, there is a growing need for smaller, integrated antenna solutions required for 5G networks that can be adapted to mobile handsets or base stations physical restrictions.

2.2. Adaptations and Modifications to Traditional Yagi-Uda Designs for 5G

The challenges of 5G have prompted many researchers and engineers to develop alternative revisions or modifications to the traditional Yagi-Uda designs. To augment the operational bandwidth, wide band Yagi-Uda antennas have been developed through techniques such as tapered elements, additional director elements and multi-resonant driven elements. For 5G applications at mmWave frequencies, Yagi-Uda antennas are chosen due to their compact size; by using these miniaturization techniques as well as higher-permittivity substrates, development of mmWave Yagi-Uda antennas has become possible. To accommodate 5G beamforming capabilities that necessitate dynamic beam steering and reconfigurability, switchable or tunable PIN diodes or varactor diodes have been incorporated into reconfigurable and beam-steerable Yagi-Uda antennas. For 5G base stations and user equipment antenna systems that are compact but highly integrated include the use of amplifiers, phase shifters in conjunction with a yagi-uda antenna. Different changes and modifications to the usual Yagi-Uda antenna designs have guaranteed that this kind of an antenna is still in use in the 5th generation wireless market, where its distinct features and flexibility make it possible to satisfy the needs of next-generation communication networks.

3. Methodology

This review explores the current trends and developments in Yagi-Uda antenna designs for 5G communication applications. To establish the validity of findings, the researchers searched several academic online databases and journals relevant to this field, including IEEE Explore, ResearchGate, Google Scholar, and other technology-focused publications. The search results were further refined by capitalizing relevant phrases such as "Yagi-Uda Antenna," "5G applications," "MIMO," "phased arrays," and "antenna," in addition to the suitable operators. To make sure that only the essential and pertinent publications were assessed, each search result was carefully examined in accordance with the inclusion and exclusion criteria. The researchers selected peer-reviewed articles, conference papers, and reviews published between 2006 and the present, focusing on trends and current breakthroughs in Yagi-Uda antenna designs for 5G communication applications. The chosen studies were categorized into four main areas: broadband Yagi-Uda antenna designs for 5G, compact and miniaturized Yagi-Uda antennas for 5G, reconfigurable and adaptive Yagi-Uda antennas for 5G, and Yagi-Uda antenna arrays for 5G beamforming. Upon having the final list of included papers, the researchers conducted a manual and systematic assessment to extract the necessary data and information, such as the title, author, and relevant antenna parameters. This review addresses thirty-four papers deemed relevant and obtained from various databases.

4. Results and Discussions

4.1. Broadband Yagi-Uda Antenna Designs for 5G

4.1.1. Bandwidth and Frequency Enhancing Technique

Enhancing the performance of Yagi-Uda Antennas in 5G applications includes adding more parasitic elements or reflectors to get broadened operational bandwidths, loading dielectric or ferrite materials for wider frequency coverage, and using frequency selective surfaces or metamaterials for improved wideband performance.

Table 1 Comparison Table of Yagi-Uda Antennas having Bandwidth and Frequency Enhancing

Antenna	Frequency	Gain	Directivity	Dimension	Feeding mechanism	Application	Ref
Bi-band Quasi Yagi-Uda Antenna for Worldwide 5G Applications	24.25 GHz – 28.5 GHz 47.2 GHz – 48.2 GHz	Maximum Gain: 8.5 dB (higher band) 8.2 dB (lower band)	3 dB beam width: Lower Band) 42° at 25 GHz 32° at 27GHz (Higher band) 30° at 48.5GHz 32° at 50GHz	15x20 mm^2	Utilizes 50 Ω microstrip line	Worldwide 5G applications (especially in Europe, South Asia, and North America)	[1]
Bandwidth Enhancement and Generation of CP of Yagi-Uda-Shape Feed on a Rectangular DRA for 5G Applications	3.67 GHz – 4.60 GHz	6.65 dBi	Omnidirectional radiation pattern (typical for dipole antenna)	Rectangular DRA: 26.1 mm x 14.3 mm x 25.4 mm (H x W x B) Yagi-Uda Shaped Feeding Strip: Overall width: 1 mm Breadth: 1mm Gap: 2 mm Lengths (Lf1, Lf2. Lf3): 3 mm, 5 mm, and 7 mm, respectively Parasitic Patch: Height: 11.75 mm Width: 1.00 mm	Single feeding mechanism with a Yagi-Uda shaped flat surface metal strip	5G applications	[2]

Dual-Band Microstrip Quasi-Yagi Antenna Design for Free Band and 5G Mobile Communication	Lower band (amateur radio, amateur satellite): 2.3 GHz – 2.4 GHz Higher band (planned 5G mobile communication): 3.4 GHz – 3.8 GHz	Peak gain of 5 dBi	Lower band: Omnidirectional Upper band: Directional	Ws: 1.5 mm; Wle: 15.75 mm; Wa: 4mm; W1: 38 mm; W2: 38 mm; W3: 9.75 mm Lg: 5mm; L1: 19 mm; S: 0.5 mm	Microstrip fed	Drone application: Communication between drones using the amateur radio band and connects users to 5G mobile communication in disaster scenarios.	[3]
A High Gain Broadband Quasi-Yagi Dielectric Lens Antenna for 5G and Millimeter Wave Applications	Main band: 28 GHz – 38 GHz Demonstrate scaling: 60 GHz – 77 GHz)	Realized Gain: 11 dBi -13 dBi (28 GHz – 38 GHz)	High directivity	Parameters (mm) a: 4.500; b: 44.65; wf: 0.235; ws: 0.330; wp: 0.178; wd1: 0.924; wd2: 1.050; rh: 0.500; Ld: 3.350; Ld1: 2.050; Ld2: 1.050; Lp: 0.723 Gd1: 0.260; Gd2: 1.940; sx: 0.254; sz:0.254; Scaling factor: 0.508	Microstrip feeding with a U-shaped MS-to-SL balun for single-ended to differential conversion	5G communication systems (backhaul) Imaging High data-rate communication Automotive radars Millimeter-wave applications:	[6]
Gain Enhancement of Quasi Yagi Antenna Using Lens Technique for 5G Wireless Systems	28 GHz (Millimeter-wave band)	With lens: 15.5 dBi Without lens: 11.38 dBi (improvement of 4.12 dBi)	Highly directive radiation pattern with main lobe	Substrate: Rectangular (width W = 13 mm, length L = 24 mm, thickness h = 0.123 mm) Permittivity of substrate: 3 Dielectric hemisphere lens: Radius: 9 mm Material: Roger RT-5880 (ε = 2.2) Elevation from fifth director: 5.12 mm	Micro-strip line feed to a driven dipole	5G wireless communication systems	[5]
A Broadband High Gain Microstrip Yagi Antenna Array for Mm-wave Communication Systems	Designed for 28 GHz (operates from 25.8 GHz to 35.3 GHz)	Single element: 8.8 dBi at 28 GHz (average gain of 7.5 dBi across the bandwidth) Array: 15.2 dBi at 28 GHz (stable gain above 13 dBi from 22 GHz to 35.8 GHz	Primarily radiates in the direction of the dipole (broadside radiation)	Uses Rogers RT Duroid 5880 substrate with 0.254 mm thickness Array: 8-element linear arrangement with overall size of 22 x 80 mm^2 single element in mm a = 1.4; b = 1.6; h = 1.6; Wt = 0.6; Wf = 0.79; Wg = 1.4; W1 = 0.6; W2 = 0.6; W3 = 0.6; Ws = 14; Ls = 14; Lt = 1.2; L1 = 2.3; L2 = 2.6; L3 = 3.4; d1 = 1.5; d2 = 2.2; d3 = 2.6	Unequal microstrip power divider	5G and other millimeter-wave wireless communications	[4]

Machine Learning-Based Technique for Gain and Resonance Prediction of Mid Band 5G Yagi Antenna	3.5 GHz, suitable for mid-band 5G applications specially the n78 band	Maximum gain: 6.57dB Efficiency: 97% (indicating strong signal strength and coverage)	Directional, focusing its signal in a single direction to reduce interference	Compact size: 0.6420 x 0.5830	RLC equivalent circuit model is used for impedance matching,	5G communication systems, with potential use in satellite communication	[7]
Machine Learning-Based Approach for bandwidth and frequency Prediction for N77 band 5G Antenna	Designed for the n77 band (3.3 - 4.2 GHz)	7.95 dB	Directional antenna with high radiation efficiency	Dipole: D = 31 mm Reflector: R = 41 mm Directors: Dir1 = Dir2 = 27 mm Other: Ls = 52 mm, Ws = 49 mm; Wg = 49 mm; Lg = 9.50 mm; S1 = 32 mm; S2 = S3 = 8 mm; F = 3 mm	Coaxial cable	N77 band (5G)	[8]

A quasi-Yagi-Uda antenna with bi-band radiator, patterned ground, and three radiator sets achieved 8.5 dB gain in 24.25-28.5 GHz and 8.2 dB in 47.2-48.2 GHz, providing a practical 5G solution with balanced performance and simplified manufacturing [1].

A T-shaped feed was transformed into a Yagi-Uda shaped feed (antenna-B), improving impedance bandwidth and generating circular polarization. This antenna design operates from 3.67-4.60 GHz with a simulated 6.65 dBi gain, making it suitable for 5G applications [2].

Versatile Yagi-Uda antennas for 5G include a dual-band microstrip quasi-Yagi with loop resonator and dipole, covering amateur and 5G bands for drone mobile base stations [3]. Another millimeter-wave array used bow tie and arc chamfering for 46.4% bandwidth, with three directors and unequal divider to maintain stable high gain for 5G beamforming [4].

A quasi-Yagi with dielectric lens achieved 15.5 dBi gain and 2 GHz bandwidth, enhancing 5G performance in a cost-effective design [5]. The planar perforated lens maintained efficiency and low cross-polarization, using a dielectric slab waveguide for broadband operation [6].

In terms of machine learning utilization, A 3.5 GHz design achieved 6.57 dB gain, 520 MHz bandwidth, and -43.45 dB return loss using linear regression and Gaussian processes for 99% prediction accuracy [7]. Another study used Random Forest Regression to optimize an N77 band 5G antenna's bandwidth and frequency [8].

Yagi-Uda antennas have been enhanced for 5G applications through various modifications. These enhancements have enabled Yagi-Uda antennas to cover a wide range of 5G frequency bands with optimized performance characteristics predicted using machine learning techniques.

4.1.2. Multiband and Ultra-Wideband (UWB) Yagi-Uda Configurations.

Enhancing the performance of Yagi-Uda Antennas in 5G applications includes designing Yagi-Uda antennas with multiple driven elements tuned to different frequency bands for multiband operation, incorporating wideband feeding networks and broadband impedance matching to enable ultra-wideband Yagi-Uda designs, and exploring log-periodic-inspired Yagi-Uda topologies for inherent multi-octave bandwidth.

A log-periodic Yagi-Uda with coaxial feed and BALUN can operate across multiple bands, including 5G's lower frequencies. With suitable resonances, it's well-suited for diverse wireless uses, especially 5G, providing excellent FBR and gain [9].

The design consists of four quasi-Yagi antennas with bow-tie monopoles, achieving a 1.37 to 16 GHz bandwidth, suitable for 5G and other wireless applications. Its compact structure and port isolation cater to high-speed, high-capacity communication needs [10].

The UWB Yagi-Uda with NZIM, ME dipole, and coaxial feed is well-suited for 5G, including V2X. It ensures efficient, reliable 5G connectivity [11].

Printed quasi-Yagi antennas with adjustable stubs provide wideband 5G coverage, improved bandwidth/gain, stable patterns, and low cross-pol [12]. A flexible 28 GHz quasi-Yagi delivers wideband, high gain (avg 6.2 dBi, up to 10.15 dBi in array) performance even when bent [13].

A substrate lens Yagi-Uda antenna was designed for wideband sub-THz 5G operation. The optimized design offers 82 GHz bandwidth and 38 degree beamwidth, addressing the need for wideband sub-THz antennas in 5G [14].

ML-based surrogate optimization can enhance traditional Yagi-Uda for 5G. Using Kriging and adaptive sampling, the final optimized antenna achieved 9.9 dB gain and 20% bandwidth covering global 5G millimeter-wave bands, demonstrating significant performance improvements for 5G [15].

In summary, Yagi-Uda antennas have been enhanced for 5G applications through various methods, including multiband design, wideband feeding networks, broadband impedance matching, and log-periodic-inspired topologies. Examples include a log-periodic structure antenna, a super-wideband response, and a flexible quasi-Yagi antenna. Metamaterials and flexible substrates have also been explored. Machine learning techniques have been used to optimize Yagi-Uda antennas, achieving a gain of 9.9 dB and 20% impedance bandwidth.

Table 2 Comparison Table of Yagi-Uda Antennas having Multiband and Ultra Wideband Configurations

Antenna	Frequency	Gain	Directivity	Dimension	Feeding mechanism	Application	Ref.
A Log-Periodic Structure Based Quasi-Yagi Antenna for Multiband Wireless Applications	Center Frequencies: 1.795 GHz, 2.54 GHz, 3.835 GHz, 5.1 GHz, 7.11 GHz	Multi-band Values: 5.61 dBi (dominant mode), 4.91 dBi, 4.48 dBi, 3.25 dBi, 2.44 dBi	End-fire radiation pattern	Length: 75 mm (reflector) Width: 15.74 mm (driven element 1) Substrate Thickness: 3.12 mm	Coaxial feed with a balanced microstrip balun	5G (lower band) and multi-band wireless applications	[9]
A single-layer compact four-element quasi-Yagi MIMO antenna design for super-wideband response	1.37 – 16 GHz	3.5 dBi and 5.4 dBi	Directive radiation patterns with four orthogonal directional beams)	-	Microstrip line-fed bow-tie monopole element	Large capacity and high-speed communication systems covering multiple wireless bands	[10]
Stereoscopic UWB Yagi–Uda Antenna with Stable Gain by Metamaterial for Vehicular 5G Communication	3.5 GHz – 5.5 GHz	Peak gain: 8.5 dBi Flat in-hand gain: ripple lower than 0.5 dBi	Mainly unidirectional with low cross-polarization	Length: 60 mm Width: 60 mm Height: 8.5 mm	Combination of coaxial feed and ME structure using electromagnetic superposition	Vehicular communication	[11]
A wideband millimeter-wave	Wideband: 24.8 – 40	Wideband: 6.3 – 8.9 dBi	Single antenna: Omnidirection	L = 20 mm W = 23 mm	Microstrip-to-slot line feed	5G wireless cellular systems	[12]

antenna based on quasi-Yagi antenna with MIMO circular array antenna beamforming for 5G wireless networks	GHz(47% bandwidth Multiband: 27 – 29 GHz and 36 – 40 GHz bands	Multiband: 7.2 – 7.9 dBi	al radiation pattern. MIMO circular array: Steerable beam within the azimuthal plane	Substrate thickness (h) = 0.8 mm			
Flexible Quasi-Yagi-Uda antenna for 5G communication	Center Frequency: 28 GHz	Single Antenna: 5.2 dBi - 6.2 dBi (measured) Array Antenna: 9.2 dBi - 10.2 dBi (measured)	End-fire radiation pattern Radiation patterns have HPBW (Half Power Beamwidth)	Utilizes MFLEX flexible material with a thickness of 0.120 mm. Designed on a single-substrate-layer flexible printed circuit (FPC).	Grounded coplanar waveguide (GCPW) to a microstrip line and a dipole	5G communication systems	[13]
Wideband Sub-THz Substrate lens Yagi- Uda antenna for 5G Communications and beyond Communication Systems	300 GHz	The SLYA offers high gain (13.1 dBi)	Directional radiation pattern	Parameter Values h1 = 6 µm; h2 = 50 µm; li = 575 µm; wi = 300 µm; R = 300 µm; Ld = 272 µm; S = 125 µm Lens axis length = 2100 µm	Most likely a coaxial cable	Sub-THz communication such as wireless data transfer and imaging	[14]
Optimized 5G-MMW Compact Yagi-Uda Antenna Based on Machine Learning Methodology	Designed for 5G MMW bands, including FCC (27.5-29.5 GHz), ETSI (26.5-27.5 GHz), China, Japan, India and Korea bands.	Initial design: 9 dB at 28 GHz Optimized design: Maximum simulated gain: 8.1 dB at 28.5 GHz Measured gain: near 7.9 dB at 28 GHz	Directive beam pattern due to the presence of directors.	W = 23.5 mm L = 34.7mm	Microstrip fed line with Z0 = 50 Ω	5G communication (MMW bands)	[15]

4.2. Compact and Miniaturized Yagi-Uda Antennas for 5G

4.2.1. Size Reduction Methods without Compromising Performance

Designers of antennas have been searching for ways to minimize the size of Yagi-Uda antennas physically while still maintaining their gain, bandwidth, and radiation patterns. This could include techniques such as using high permittivity loading dielectrics, applying metamaterials, or integrating folding/meandering structures.

Multilayer Yagi-Uda structures have been explored, stacking antenna elements at optimized distances. This improves the antenna's performance, making it more suitable for 5G. The vertical integration allows a more compact, efficient design for IoT and other 5G devices [16]. Another multilayer dielectric substrate Yagi-Uda provides wide bandwidth and high gain, meeting 5G's requirements [17].

A miniaturized dual-band loop quasi-Yagi antenna was developed for 5G, targeting efficient spectrum use in indoor applications. It uses a virtual array to enhance gain without increasing complexity [18].

Multilayer glass packaging with low-loss polymer addresses mmWave 5G, enabling compact system-in-package. A monopole taper Yagi-Uda, in this packaging, covers all 5G NR bands [19].

In summary, Yagi-Uda antennas have been miniaturized using high permittivity dielectric loading, metamaterials, and folding/meandering structures. Examples include a multilayer structure for improved gain and bandwidth, a dual-band loop quasi-Yagi antenna design for efficient operation in various bands, and a monopole taper radiator antenna covering all 5G New Radio bands with high gain.

Table 3 Comparison Table of Yagi-Uda Antennas having Size Reduction Methods

Antenna	Frequency	Gain	Directivity	Dimension	Feeding mechanism	Application	Ref
Compact Multilayer Yagi-Uda Based Antenna for IoT/5G Sensors	24 GHz	10.9 dBi (higher than the 8.9 dBi of the planar Yagi antenna)	Vertical plane (aligned with directors)	Lengths of the lines used (in mm) Ldip = 3; Ldir = 1.68; Lref = 3.47; Lcps = 5.32; Lt1 = 1.88; Lt2 = 1.918 Widths of the lines used (in mm) Wdip = 0.80; Wdir = 0.715; Wcps = 0.25; Wmsc = 0.25; Wt1 = 0.78; Wt2 = 0.48 Other parameters (in mm) hdir = 2.286; href = 3.048; subs = 10; gap = 0.3	Coaxial feed with a balanced microstrip balun	Microstrip-to-coplanar strip line transition	[16]
Integrated Multilayer Yagi Antenna for 5G	24 GHz	Simulated gain: 10.9 dBi	Directional radiation pattern with main lobe in the vertical plane	Cubic structure side length = 10 mm Dipole length = 3 mm Gap = 0.3 mm Director length = 1.68 mm Reflector length = 3.47 mm	Microstrip section.	5G in Europe IoT Devices	[17]
Miniaturized Virtual Array Dual Band Loop Quasi-Yagi Antenna Design for 5G Application	Dual-band: Lower band: 2.4 GHz - 2.48 GHz (Wi-Fi) Upper band: 3.4 GHz - 3.8 GHz (sub-6 GHz 5G)	W/O virtual ground: Lower band: 1.59 dBi Upper band: 4.7 dBi With virtual ground: Lower band: 5.0 dBi Upper band: 6.84 dBi	-	Single antenna element: (in mm) length_1 = 10; length_2 = 4.5; Wm_1 = 10.5; Wm_2 = 8.75; dist_1 = 0.5; dist_2 = 0.5; thick = 1.5; gnd = 4.2; L1 = 22; L2 = 38 Virtual ground plate: 58 mm x 58 mm	Single-ended feeding based on the antenna design	Indoor applications in factories and shopping malls: Remote tracking and control of automated and mobile systems using 5G technology	[18]
Broadband and Miniaturized Antenna-in-Package (AiP) Design for 5G Applications	Designed for 5G NR bands: n257 (26.5-29.5 GHz), n258 (24.25-27.5 GHz),	Single element: higher than 4 dBi within the entire band (24.25 GHz to 40 GHz)	Primarily radiates in the endfire direction (0°)	Single element: 3.05 mm x 5.56 mm (0.25λ0 x 0.45λ0 at 24.25 GHz)	Unequal microstrip power divider for the array Simple coplanar waveguide	5G communication (24.25 GHz to 40 GHz bands)	[19]

	and n260 (37-40 GHz)	Array: higher than 6.2 dBi			(CPW) for the single element		

4.2.2. Planar and Printed Yagi-Uda Structures

Planar and printed Yagi-Uda antenna configurations are being developed for compact, easier-to-integrate designs. These designs exploit low profile, lightweight, and conformance capabilities, enabled by printed circuit board or thin film fabrication.

A Yagi-Uda antenna designed for 5G uses a printed monopole driver on an FR4 substrate. It achieves -36 dB return loss, and 640 MHz bandwidth, meeting 5G requirements. Its compact, high-gain design makes it suitable for 5G microwave circuits [20].

A printed Yagi-Uda antenna with corrugated dipole and capacitive extension delivers enhanced gain for millimeter-wave mobiles. Reflectors and director enable high gain and efficiency to overcome path losses. Its radiation pattern and low coupling suit MIMO, ensuring diverse signals and reduced interference. The compact design enables seamless mobile integration [21].

A microstrip Yagi antenna on FR-4 uses a corporate feed to connect two branches, achieving 9.5 dB gain. Parasitic directors and reflectors enhance performance by improving signal quality and range, essential for 5G high-frequency needs [22].

In summary, the development of planar and printed Yagi-Uda antenna configurations is aimed at providing more compact and integrated designs for 5G applications. The printed monopole antenna on an FR4 substrate achieves 6.9 dBi gain, -36 dB return loss, and 640 MHz bandwidth, making it suitable for 5G microwave circuits. Novel printed Yagi-Uda antennas with a corrugated strip dipole, capacitively coupled extension, reflectors, and director provide enhanced gain and efficiency at millimeter-wave frequencies, enabling good performance for 5G MIMO systems.

Table 4 Comparison Table of Yagi-Uda Antennas under Planar and Printed Structures

Antenna	Frequency	Gain	Directivity	Dimension	Feeding mechanism	Application	Ref.
Design of printed Yagi-antenna for 5G communication	Designed for central frequency (f0) of 3.5 GHz Bandwidth: 640 MHz (3.24 GHz to 3.88 GHz)	Average gain of 6.9 dBi in the range of 3.4 GHz to 3.6 GHz Maximum gain of 6.9 dBi at Θ=90° and ψ=270° (E-plane and H-plane)	Directional antenna with good directivity	Substrate size: 50 mm x 50 mm	Microstrip fed	5G communication systems	[20]
Dual-band (28/38 GHz) Yagi–Uda Antenna with Corrugated Radiator and Triangular Reflectors for 5G Mobile Phones	Dual-band (28 GHz and 38 GHz	Simulated: 8.84 dBi at 28 GHz, 9.97 dBi at 38 GHz Measured: 8.7 dB at 28 GHz, 9.5 dB at 38 GHz	Radiation pattern: End-fire pattern suitable for MIMO systems	Parameters (mm): La = 2.4; Lt1 = 3.62; Wr2 = 1.0; Lr2 = 3.4; Wt2 = 0.62; Lt3 = 2.5; WG = 6.72; Lext = 0.8; Wt1 = 0.5; Lt2 = 4.02; Dr = 1.95; Ld = 2.79; Wt3 = 0.35; Wr1 = 1.0; Lr1 = 7.6; Wext = 0.2	Mic strip line with a transition to a coplanar strip line	5G mobile phone MIMO antenna systems	[21]

Design and Analysis of Microstrip Yagi Antenna for Wi-Fi Application	Designed for Wi-Fi frequency range (5.15 GHz - 5.875 GHz) Operating bandwidth: 5.47 GHz - 5.57 GHz Resonant frequency of 5.8 GHz for single element design	One branch design: 6.69 dB - 6.89 dB (depending on the number of parasitic elements) Two branches (proposed design): 9.5 dB (16% improvement from one branch)	Highly directional with main lobe forward Front-to-back ratio of 17.8 dB (simulated)	Substrate size: 65 mm x 80 mm	Microstrip line feed with quarter-wave transformer for impedance matching	Wi-Fi application (IEEE 802.11 standard in 5 GHz band)	[22]

4.3. Reconfigurable and Adaptive Yagi-Uda Antennas for 5G

4.3.1. Dynamic Beam Steering and Pattern Reconfiguration

Yagi-Uda antennas enable dynamic beam steering and pattern reconfigurability. Electronic beam steering targets receivers to enhance signal quality and minimize interference - crucial for 5G beamforming and adaptive coverage. Integrating tunable components allows real-time adjustment of the radiation beam.

One system uses a modified Rotman lens to feed the array, enabling 5-way beam steering over 45 degrees with less than 1 dB power variation between ports [23].

A 26-30 GHz 5G phased array uses Yagi-Uda elements. More directors enhance performance across scanning, even with interference, for reliable 5G [24]. A phased quasi-Yagi with reflector, driver and directors enables beam steering and mobile integration, providing wide bandwidth, high gain, and meeting SAR for handhelds [25].

Another antenna has a fan-beam pattern with a wide 256.72° HPBW and 11.16 dBi peak gain. It covers ±48° using beam steering, crucial for wide 5G communication coverage. These enhancements enable effective 5G beamforming [26].

A shared-aperture quasi-Yagi has complementary pattern and polarization for 5G-NR. Combining even-odd modes enables switching between omnidirectional, broadside and tilted patterns, enabling versatile, adaptable 5G antennas [27].

Unsupervised ML can calibrate Yagi-Uda parameters. Adjusting director-driver distance controls phase to direct radiation. This reconfigurable approach allows 60-degree scattering, improving signals in complex environments [28].

Yagi-Uda antennas are being enhanced with dynamic beam steering and pattern reconfigurability capabilities, crucial for 5G systems, using techniques like modified Rotman lenses, phased arrays, and fan-beam radiation patterns. Machine learning is also being explored to achieve wide-angle beam steering, essential for high-performance, adaptable antennas required for 5G networks and devices.

Table 5 Comparison Table of Yagi-Uda Antennas under Dynamic Beam Steering and Pattern Reconfiguration

Antenna	Frequency	Gain	Directivity	Dimension	Feeding mechanism	App.	Ref.
A 28GHz beam switching Yagi Uda Array using Rotman Lens for 5G Wireless Communication	Center frequency: 28 GHz (millimeter-wave band for 5G	Simulated gain of the antenna array: Varies from 8.3 dBi to 8.7 dBi when switching beam ports.	Electronically steerable beam: Main beam: steer ±20° from broadside direction. Covers 45° angular space symmetrically Scalable to cover 360°	Parameters (in mm) w1 = 0.5; w2 = w3 = w4 = w5 = 0.4; L1 = 2.1; L2 = 2.9; L3 = 2.5; L4 = 2.3; L5 = 2.1; d1 = 1.7; d2 = 1.2; d3 = d4 = d5 = 0.8; wline = 0.34; wa = 0.48; La = 2.1, Da = 1	Rotman lens feeding an array of antipodal Yagi-Uda antennas	5G communication base stations (covering a 45° sector)	[23]
High-Performance Yagi-Uda Antenna Array for 28 GHz Mobile Communications	26 GHz - 30 GHz (28 GHz is the designed center frequency)	12 dB - 16 dB (depending on scanning angle)	End-fire radiation mode with beam-steering capability (0° to 60°)	Single Yagi-Uda element: 5.35 mm x 9 mm Entire Antenna Array: 75 mm x 150 mm	microstrip feeding mechanism based on the design on a PCB	5G smartphone antenna	[24]
MM-Wave Phased Array Quasi-Yagi Antenna for the Upcoming 5G Cellular Communications	26 GHz	4.4 dB (single element)	End-fire radiation pattern	Single element: Wsub × Lsub × hS = 60 × 120 × 0.8 mm3 (on Arlon Ad 350 substrate) Linear array: Wa × La = 9 × 40 mm2 (with 5 mm spacing between elements)	Coax-to-microstrip line with truncated crown of vias around the coaxial cable	5G smartphone antenna	[25]
Quasi-Yagi Slotted Array Antenna with Fan-Beam Characteristics for 28 GHz 5G Mobile Terminals	28 GHz (target band: 27.5 GHz - 28.35 GHz)	11.16 dBi (simulated peak gain)	Fan-beam with HPBW of 256.72° (hemispheric beam coverage in ±y direction)	a modified ground plane with the dimensions of 31 × 70 mm was considered. 1 × 8 array antenna	Microstrip feeding line	5G mobile terminals	[26]
Compact Shared Aperture Quasi-Yagi Antenna with Pattern Diversity for 5G-NR Applications	5G-N78 band (3.30 GHz to 3.80 GHz)	Monopole mode (P1 excitation): 3.15 dBi Yagi antenna mode (P2 excitation): 7.38 dBi In-phase excitation: 4.53 dBi Out-of-phase excitation: 4.92 dBi	Monopole mode: Omnidirectional with a tilt towards theta = 60° Yagi antenna mode: Broadside radiation pattern in the Y to Z plane In-phase excitation: Tilted pattern in the Y to Z	0.511 λ0 × 0.244 λ0 × 0.005 λ0 (λ0 is the free space wavelength at 3.30 GHz)	CPW-type feeding with even-odd mode excitation	5G-NR communication (microcell application)	[27]

			plane with peak radiation at -45° <u>Out-of-phase excitation:</u> Tilted pattern in the Y to Z plane with peak radiation at +45°				
Design of 5G Dual-Antenna Passive Repeater Based On Machine Learning	-	<u>Dual-antenna total gain:</u> 6.1 dB Improvement over receiving patch antenna alone: 2 to 6.1 dB (depending on transmitting power)	Directional antenna with a scattering angle of nearly 60°	<u>Microstrip Patch Antenna:</u> Patch size: 9.1 mm (X-axis) x 8.5 mm (Y-axis) Coaxial probe radius: 0.8 mm, height: 0.64 mm <u>Yagi-Uda Antenna:</u> Reflectors: 5.5 mm (X-axis) x 2 mm (Y-axis) Directors: Varied lengths based on a multiple of wavelength	Coaxial probe for the microstrip patch antenna	5G communication - specifically addressing blind spot signal coverage.	[28]

4.3.2. Integration of Active Elements and Feeding Networks

Embedding active components in Yagi-Uda allows dynamic control of signal amplitude, phase and polarization. With reconfigurable feeds, this enables adaptive radiation for changing 5G conditions.

A bi-Yagi or quad-Yagi array achieved gains over 10 dB and high F/B ratios. It integrates active elements and feeding networks to enhance WLAN/mmWave performance. The 6-element structure has a driven patch, gap-loaded reflector, and multiple directors. The feeding network excites multiple Yagi arrays in phase, boosting gain and directivity [29].

In summary, the Yagi-Uda antenna design allows for dynamic control over signal amplitude, phase, and polarization, adapting to changing 5G network conditions. A study developed bi-Yagi and quad-Yagi arrays for enhanced performance, achieving gains above 10 dB and high front-to-back ratios. The antenna structure includes six patch elements, a driven element, a gap-loaded reflector, and multiple director elements. The feeding network uses a 50Ω feedline and a quarter-wave transformer.

Table 6 Comparison Table of Yagi-Uda Antennas under Integration of Active Elements and Feeding Networks

Antenna	Frequency	Gain	Directivity	Dimension	Feeding mechanism	App	Ref.
Design of microstrip bi-Yagi and microstrip quad-Yagi antenna arrays for WLAN and millimeter-wave applications	Designed for 5.2 GHz	<u>Single microstrip Yagi array</u>: 11.6 dBi <u>Microstrip bi-Yagi array</u> : 13.4 dBi <u>Microstrip quad-Yagi array :</u> 16.1 dBi	Quasi-endfire radiation (between broadside and endfire) with maximum radiation at angles between 35° and 45° in the E-plane	Described for each element of the single microstrip Yagi array Dimensions of bi-Yagi and quad-Yagi arrays not explicitly given, but they are larger due to the additional elements	50Ω feedline transformed to a high impedance line through a quarter-wave transformer Feeding structure on the same layer as the antenna elements for simpler fabrication	Potential applications include WLAN (WiFi, WiMax) and millimeter-wave frequencies	[29]

4.4. Yagi-Uda Antenna Arrays for 5G Beamforming

4.4.1. Array Configurations and Feeding Techniques

Research on Yagi-Uda 5G arrays explores linear, planar and circular designs to improve radiation and beamforming. Enhanced feeding networks, including corporate, series and series-corporate, distribute signals effectively through the array.

A linear 2-element array, with 8 parasitic elements per element, on Rogers Duroid substrate. This microstrip Yagi-Uda combines Yagi's directivity with microstrip's compact size and easy fabrication, suitable for vehicular and 5G [30].

A microstrip-fed Yagi-Uda dipole array, designed in Antenna Magus and CST, has a driven element, directors and reflector. The microstrip feed enables a compact, lightweight design for mobile integration [31]. Another microstrip patch array antenna combines Yagi elements with corporate series feeding for 5G communications. This results in a compact, high-performance antenna suitable for the millimeter-wave bands used in 5G networks [32].

Edge-mounted arrays achieve wide 24-44 GHz TARC bandwidth with variable scan ranges and notable gains. Corner-mounted arrays are less complex but have lower peak gains. Reducing mutual coupling and optimizing element spacing is key for improving array efficiency [33].

In summary, the Yagi-Uda antenna array is being actively researched for 5G applications, with a focus on improving radiation patterns, beamforming performance, and signal distribution through various feeding network configurations. The designs offer promising results in terms of gain, bandwidth, and suitability for integration into mobile devices and 5G networks.

Table 7 Comparison Table of Yagi-Uda Antennas under Array Configuration and Feeding Techniques

Antenna	Frequency	Gain	Directivity	Dimension	Feeding mechanism	App.	Ref.
Linear array Yagi-Uda 5G antenna for vehicular application	Center frequency: 3.5 GHz (low band 5G)	Simulated gain: 10.5 dB (peak value)	Directional antenna	Overall dimensions: 110 mm x 60 mm x 1.6 mm Substrate thickness: 1.6 mm	Microstrip feed	Vehicular communication for 5G (3.5 GHz low band)	[30]
Microstrip-Fed Yagi-Uda Dipole Array Antenna At 3.6 Ghz Frequency For 5G Application	Operating frequency: 3.4 - 3.8 GHz (designed for 5G applications)	Simulated gain: 10.01 dBi Measured gain: 6.1 dBi at 3.6 GHz	Unidirectional radiation pattern with a main lobe directed along the 0° axis (similar to a Yagi-Uda antenna)	Simulated dimensions: 140.1 mm x 84.66 mm x 1.6 mm Measured dimensions: 141 mm x 85 mm x 1.6 mm (slightly larger than simulated)	Microstrip feed	5G communication devices	[31]
Four-Element Microstrip Patch Array Antenna with Corporate-Series Feed Network for 5G Communication	The target operating frequency of the antenna is 28 GHz.	Highest gain of 9.5 dB	end-fire radiation pattern	Substrate: 16 mm × 15 mm × 1.6 mm (for single element design) Overall antenna (proposed corporate series fed): 35 mm × 37 mm	Corporate series feeding technique, which combines the advantages of series and corporate feed networks.	5G communication applications	[32]
mmWave Yagi-Uda Element and Array on Liquid	22 GHz to 44 GHz (covers 3GPP	Original design: 5.4 to 6.7 dBi (25 GHz), 6 to 7.1	Steerable beam through phased array approach	Not directly specified in the text but refers to clearance	-	5G mobile terminals	[33]

Crystal Polymer for 5G	mmWave bands)	dBi (28 GHz), 7.7 to 9.2 dBi (40 GHz) Improved design with corner array: slight gain improvement over original design	(linear or arc-shaped array) Scan range limited by mutual coupling at lower frequencies, improved by decoupling modification	distances in relation to wavelength (λ) – E-plane clearance: 0.6λ at 22 GHz (minimum) – H-plane clearance: Not specified			

4.4.2. Adaptive Beamforming and Multiple-Input Multiple-Output (MIMO) Systems

Yagi-Uda antennas are being integrated into 5G adaptive beamforming and MIMO systems. By combining beamforming algorithms, MIMO processing, and Yagi-Uda's directionality, antenna arrays can dynamically steer beams for targeted coverage, interference mitigation, and capacity increase - critical for 5G.

A MIMO system uses QYUA antennas designed for mmWave to achieve high isolation and performance. The CMOS 6-layer design optimizes size and efficiency. MIMO configs with 2, 4, and 8 elements show improvements in key parameters, supporting high-rate 5G and multigigabit communications [34].

In summary, Yagi-Uda antenna arrays are being increasingly integrated into adaptive beamforming and MIMO systems for 5G, enabling sophisticated beamforming techniques through electronic control of signal characteristics. This integration allows for dynamic beam steering, targeted coverage, interference mitigation, and increased capacity – crucial for the successful deployment of 5G networks. The development of QYUA-based MIMO systems further demonstrates the potential of Yagi-Uda antennas in supporting high-performance, multigigabit 5G and beyond communication systems.

Table 8 Comparison Table of Yagi-Uda Antennas under Adaptive Beamforming and MIMO Systems

Antenna	Frequency	Gain	Directivity	Dimension	Feeding mechanism	Application	Ref.
A multiple-input-multiple-output on-chip Quasi-Yagi-Uda antenna for multigigabit communications: Preliminary study	60GHz (which is unlicensed and suitable for applications like video streaming, wireless gaming, and indoor networking)	-	Focuses on end-fire radiation, directing the energy towards the front, which is beneficial for point-to-point communication	Four elements with total length of 1.722 x 1.262 mm²	Coplanar waveguide (CPW) feeding mechanism is used, with a transition to coplanar-slot to accommodate millimeter-wave circuits	Multigigabit communication systems, particularly for short-range communications at 60GHz, relevant to 5G technology.	[34]

5. Conclusion

The evolution of Yagi-Uda antenna design has been remarkable, keeping pace with the ever-advancing field of wireless communication. With the advent of 5G technology, the diversity in requirements has spurred a wave of innovation. A plethora of methods have been developed to boost the antenna's performance and adaptability, catering to the burgeoning needs of 5G networks. These enhancements include expanding bandwidth, amplifying gain, enabling dynamic beam steering, and promoting seamless integration. Each innovation has tailored the Yagi-Uda antenna to be more adept for specific 5G applications, demonstrating its versatility and importance in modern communication infrastructure.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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