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Yagi-uda Antenna Design and Modeling for Gain and Bandwidth Optimization for Wifi Applications

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Research Article

Abstract

This research focuses on designing and simulating the Yagi-Uda antenna with folded dipole as a driven element for gain and bandwidth optimization. Four models were investigated to guide the designer in choosing the most suitable model for Wi-Fi applications with a resonance frequency of 2.4 GHz. The designed antenna shows promising results in terms of bandwidth, gain, reflection coefficient $|S_{11}|$*, and directivity. The proposed design produced a bandwidth (BW) of 0.33 GHz with a corresponding peak realized gain of 10.43 dB when the driven element was replaced with the folded dipole, at 2.40 GHz. The design achieved a directivity of 10.44 dBi, and a voltage standing wave ratio (VSWR) of 1.01:1. This suggests a good matching between the transmission line (TL) and the folded dipole. The high input impedance of approximately 300 Ω is another significant advantage of using a folded dipole. The* $|S_{11}|$ *of the optimized design is -52.018 dB at 2.40 GHz. This research has application in broadband services where high gain and bandwidth is of concern, such as backhauling using point-to-point and point-to-multipoint services. An appreciable gain is maintained with an improved bandwidth of 4% compared to existing works.*

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Keywords
Antenna Arrays; Yagi-Uda antenna; Endfire antenna; Wi-Fi; Bandwidth.

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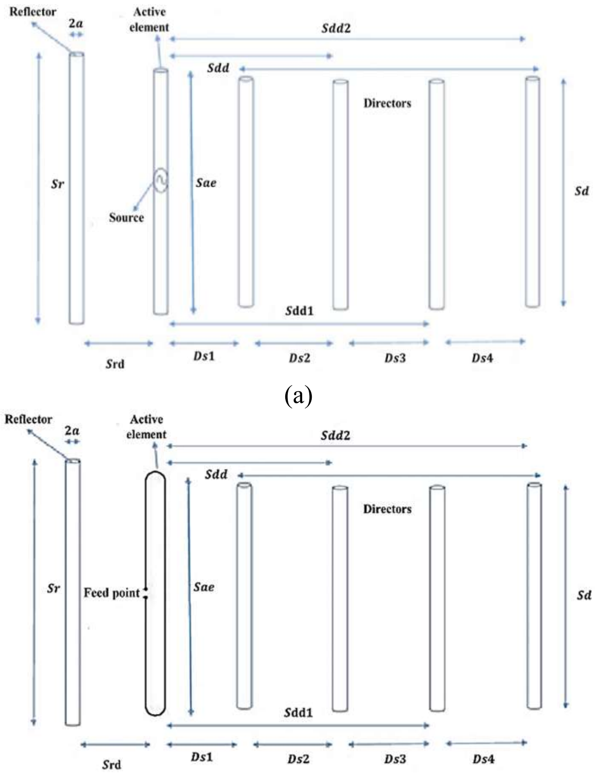
1. Introduction

Wireless communication has a wide range of applications, including wireless local area network (WLAN), wireless-fidelity (Wi-Fi), mobile phones, satellites, military, global positioning systems (GPS), medicinal, traffic radar, and aerospace applications (Farran, AlHusseini, and Kabalan, 2017), (Musril et al. 2019). One essential component of these devices is the antenna structure. The use and demand of wireless communication devices due to the high demand in data rate, antennas with higher bandwidth capabilities have received significant attention for various wireless applications (Nouri et al. 2022), (Murali et al. 2014). Patch antennas used for Wi-Fi applications have significant challenges with poor gain and weak power handling capabilities (Atabay, 2019), (Chaudhary and Purohit, 2014). These problems have been solved using the Yagi-Uda antenna (Dala, Arslan, and Saied, 2019), (Dmitriev, 2022), (Floc'h and Ahmad, 2013), (Sun et al. 2017), (Gupta and Kumar, 2023). Varieties of materials with different dielectric constants are available for the Yagi-Uda antenna (Singh, Kumar, and Kamal, 2010). Yagi antennas are frequently utilized to provide high gain in a simple installation (Pan and Dong, 2023), (Zhou, Geng, and Jin, 2022). A reflector, having one or more directors, and other driving and parasitic elements make up the antenna (Sun et al. 2017), (Farran et al. 2017). The yagi design often needs enough space on the perimeter between the reflector and the driver and between the driver and the director to work well for particular applications (Farran et al. 2017), (Bankey and Kumar, 2016). A variety of patch antennas are employed for Wi-Fi applications (Floc'h and Ahmad, 2013), (Bankey and Kumar, 2016). Numerous additional Wi-Fi standards have been developed since Wi-Fi's debut to enhance its speed and reach (Dmitriev, 2022). Since then, most routers have converted from single-band to dual-band, allowing them to send wireless signals using either of the two Wi-Fi frequency bands (Zhang et al. 2022), (Gupta and Kumar, 2023). The wireless spectrum's 2.4 GHz and 5 GHz bands, known as Wi-Fi frequency bands, are used to transmit Wi-Fi signals (Tareq, et al. 2014), (Haque, Zakariya, Singh, Rahman, and Paul, 2023). The 2.4 GHz band has more Wi-Fi coverage than the 5 GHz band. The signal may be better distributed around the house owing to the 2.4 GHz band's lower frequencies, which can more readily pass through solid surfaces (Murali et al. 2014), (electronics notes, 2017). The lesser range of the 5 GHz band is offset by the fact that it has substantially quicker Wi-Fi rates than the 2.4 GHz band (Dmitriev, 2022), (Isa et al., 2023).

The Yagi-Uda antenna also has one major problem of low bandwidth (Bankey and Kumar, 2016), (Perera, 2017), (Kullock, et al. 2020). Much effort has been put into reducing the distance between a radiating device and a ground plane to realize unidirectional radiation and greater bandwidth (Murali et al., 2014), (Perera, 2017), (Kullock et al., 2020). To attain a physically more compact size, it is preferable to lessen this size. The authors (Floc'h and Ahmad, 2013) presented a broadband quasi-yagi antenna. Results indicate that this antenna's 10 dB return loss bandwidth operates between 2.30 and 3.80 GHz with 50% efficiency. The suggested antenna in (Bankey and Kumar, 2016) spans frequencies between 2.30 and 2.50 GHz for use with Wi-Fi and Worldwide Interoperability for Microwave Access (WiMAX) applications. The reflector is swapped out for a parabolic dish, and the authors use traditional design methods with optimization. The best outcome was achieved with a rectangular shape at 0.265 GHz with a gain of 12.3 dB and a 10 dB return loss of 10%. The design, modelling, fabrication, and measurement of a four-element quasi-yagi antenna array printed on a ceramic substrate for X-band radar applications are covered by the authors in the article (Atabay, 2019). Four quasi-yagi antennas are arranged linearly to create the microstrip array antenna. It has a 3 to 5 dB gain in the frequency range and is printed on an Alumina 99.6% substrate with a 52% impedance bandwidth for a - 10 dB $|S_{11}|$ from 7.5 to 12 GHz. A small rectangular slot Yagi-Uda antenna for wireless applications is shown in (Saadh, et al. 2020). It has a size of 30 × 30 mm, fractional bandwidths of 9.03% (4.31 - 4.72 GHz), 7.86% (5.50 - 5.95 GHz), and 12.15% (4.25 - 4.80 GHz), and gains of 3.70 dB at 4.50 GHz and 6.62 dB at 5.80 GHz, respectively. In (Dala et al., 2019), the authors presented a brand-new Yagi-Uda antenna with a slotted triangular parasitic element. CST was used to carry out simulations. A better $|S_{11}|$ of -24 dB and a good directivity of 7.09 dBi ware obtained, resulting in a fractional bandwidth of 30% (74 MHz). A high gain Yagi-Uda Antenna with a frequency of 5.20 GHz was reported by (Chaudhary and Purohit, 2014) for a high data rate communication system utilizing HFSS modelling software. In (Murali et al., 2014), a size decrease was demonstrated by changing the element spacing and diameter; almost 40% of the size reduction is achieved by moving the directors and reducing the element diameter. By decreasing the spacing to 5 cm and the diameter to 6 mm, a design for 1 MHz with 6 cm spacing was given. At 6 MHz, the antenna is in use. A compact yagi antenna for Global System for Mobile Communications (GSM), WLAN, and Wi-MAX applications is demonstrated in the research (Gupta and Kumar, 2023). The suggested antenna covers frequencies with a -10 dB return loss between 2.25 GHz and 2.72 GHz for WLAN and Wi-MAX applications. For WLAN applications, the authors of (Haque et al., 2023) offer a 10-element (with eight directors) traditional Yagi-Uda antenna. The suggested antenna has a gain of 13 dB and covers frequencies between 1.80 GHz and 2.40 GHz. The suggested antenna in (Bankey and Kumar, 2016) uses eight directors to produce a gain of 13 dB while covering bands other than WLAN. The 2.40 GHz Yagi-Uda antenna was described by the authors. The specified antenna utilizes the whole 2.40 GHz Wi-Fi spectrum. The authors in (Zhou et al., 2022) developed an end-fire dual-polarized Ka-band antenna. The measured findings reveal a maximum realized gain of 16.9 dB for Horizontal Polarization (HP) and 16.0 dB for Vertical Polarization (VP). The observed 3 dB gain bandwidth for HP is 36.3% and 24.4% for VP. The authors offer a wideband Yagi-Uda phased array antenna in (Nouri et al., 2022). With 10 geometric structures, the design is implemented for fifth generation (5G) applications. The single antenna element has a 20% impedance bandwidth (IBW) from 26.0 to 34.0 GHz and a maximum measured gain of 5.5 dB at 28 GHz. A lightweight and electrically driven yagi architecture is reported by the authors in (Kullock et al., 2020). Antenna-enhanced inelastic conduction through the antenna feed gap generates light with a forward-to-backward ratio of up to 9.1 dB. Compared to a 3-element yagi antenna, the authors of (Isa et al., 2023) described a Microstrip yagi antenna with improved director elements. Twenty samples are used in the 3-element and 5-element designs (10 for three-element yagi and 10 for 5-element yagi). Compared to the 3-element yagi antenna, the 5-element yagi antenna's directivity is 1.55 dB higher and has a significant level with p (less than 0.05). However, low gain and power management capability are some issues with the patch antennas.

This paper proposed the design of a Yagi-Uda antenna for gain and bandwidth optimization for Wi-Fi applications. This paper aims to explore various design models to achieve the desired folded dipole Yagi-Uda antenna structure. A folded dipole structure is introduced as a driven element in the proposed design to address the issues of reduced gain and bandwidth. A conventional Yagi-Uda antenna was the first to be designed for reference purposes. The effects of changing various elements' spacing, length, diameter, and number of elements were investigated. The folded dipole approach is deployed to realize the proposed wideband Yagi-Uda antenna. Hence, the proposed design is suitable for Wi-Fi applications and has a wide operating frequency range of 2.12 to 2.44 GHz and a higher gain of 10.43 dB. The following contains the remaining portions of this work: The proposed design antenna structure is described in Section two (2). Section three (3) discussed the findings. Section four (4) provides the concluding remark.



(a)

(b)

Figure 1: Simulated and Measured: (a) Conventional Yagi-Uda antenna design architecture (b) Proposed folded dipole Yagi-Uda architecture. Parameters: S_r = Reflector length, S_{ae} = active element, S_d = Length of directors S_{rd} = Distance between the reflector and active element, D_s = Distance between directors, S_{dd} = Distance between Driven Element and Directors.

2. Antenna Design

The design dimension of the proposed Yagi-Uda antenna primarily deals with the diameter of the elements, lengths, and spacing between the elements, as shown in Figure. 1. Since the antenna is wire, using a cylinder of different radii depends on the design specifications. The design uses Computer Simulation Tool Studio Suite (CST) software. The CST was chosen for this project because of its application versatility and ability to handle design with a frequency in the range of Giga-Hertz (GHz) and Tera-Hertz (THz) (Tareq et al., 2014). The software simplifies the implementation and development of various antenna models, such as wire Yagi-Uda antennas, waveguides, cone antenna reflector antennas, and parabolic antennas. Thus, this paper presents four distinct design models utilizing different case scenarios. The design models are deployed to achieve the final proposed model in this paper using folded dipole structure, as outlined:

2.1 Model-I: Uniform Directors Spacing

Firstly, the wavelength λ of the antenna architecture was modelled using a closed-form Maxwell equation at speed of light $c = 3 \times 10^8 m/s$, as expressed in Equation. 1.

$$\lambda = \frac{c}{f}\ (mm) \tag{1}$$

The operating frequency f of the proposed antenna is 2.40 GHz. The antenna elements are a function of λ such that the driven element is given by $\lambda/2$, and the reflector element is 5% higher than the driven element and directors and 5% less than the driven element. Thus, $\lambda = 125\ mm$. S_{d1} to S_{d4} signify uniform spacing between the directors; 43.72 mm was chosen, and 31.23 mm was the distance between the reflector and driven element to the quarter wavelength. The proposed uniform-spaced Yagi-Uda antenna parameters with four directors are designed as:

$S_{rd} = 0.25\lambda$, $D_s = D_{s1} = D_{s2} = D_{s3} = D_{s4} = 0.35\lambda$. The S_r and S_{ae} are varied D_s is constant.

Figure. 2 depicts the structure of the uniform director spacing, and the dimensions used in the model designs are presented in Table. 1 The design is evaluated in four different cases.

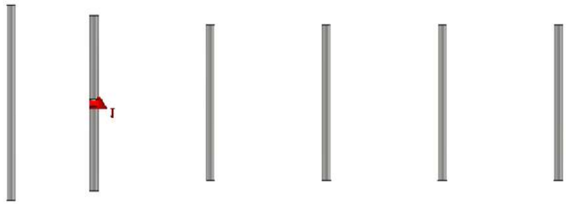


Figure 2: Model-I design with uniform director spacing.

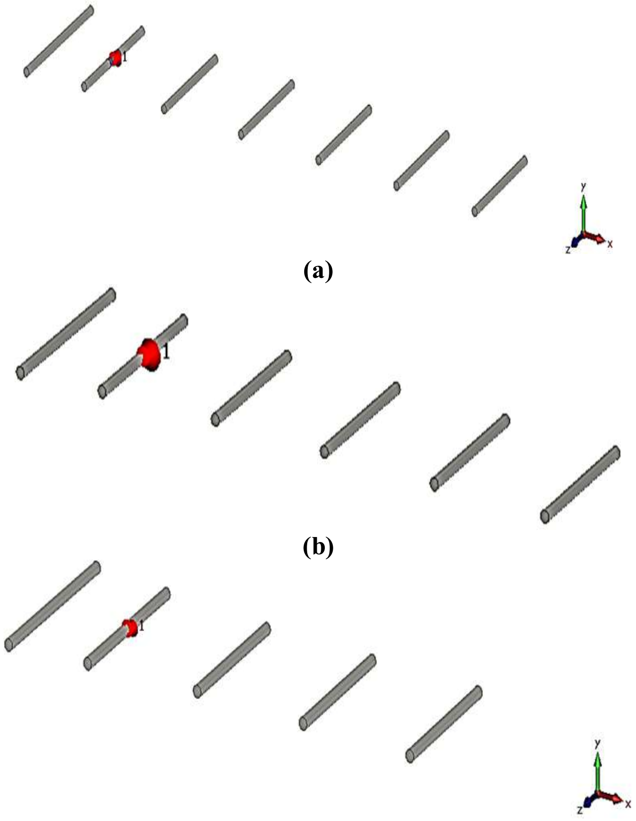
Table 1: Tabulated parameters of the Model-I design with uniform spacing.

MODEL-1	S_r	Sae	D_s
CASE-1	0.55λ	0.50λ	0.40λ
CASE-2	0.53λ	0.50λ	0.40λ
CASE-3	0.53λ	0.48λ	0.40λ
CASE-4	0.50λ	0.45λ	0.40λ

2.2 Model-II: Non-uniform Directors Spacing

The proposed non-uniform director-spaced Yagi-Uda antenna parameters using four directors is designed as:
$S_r = 0.50\lambda$, $S_{ae} = 0.45\lambda$, $S_d = 0.40\lambda$, $S_{rd} = 0.25\lambda$. Where D_s is varied, as depicted in Figure. 3.

Figure 3: Model-II design with non-uniform director spacing.



(a)

(b)

(c)

Figure 4: Model-III design using: (a) five (5), (b) four (4), and (c) three (3), different directors' elements.

Table 2: Tabulated parameters of the Model-II design with non-uniform spacing.

MODEL-II	D_s
CASE-1	0.350λ
CASE-2	0.380λ
CASE-3	0.400λ
CASE-4	0.430λ

Table 3: Model-IV parameters using folded dipole.

Model-IV	S_r	S_{ae}	S_d	D_s
CASE-1	0.50λ	0.45λ	0.40λ	0.35λ

2.3 Model-III: Varying the Number of Directors

The proposed design is achieved using three (3) different directors configurations namely: five (5), four (4), and three (3) directors configurations.

Where $S_r = 0.50\lambda$, $S_d = 0.40\lambda$, $S_{ae} = 0.45\lambda$, $D_s = 0.35\lambda$, and $S_{rd} = 0.25\lambda$, where the number of directors varied accordingly, as shown in Figure. 4a.

The dimensions used in the model designs are presented in Table. 2. The design is analyzed at four different scenarios.

2.4 Model-IV: Folded Dipole

Figure. 5 presents the folded dipole configurations, and the design parameters of ModelIV are computed as:

$\lambda = 125$ mm, $S_{rd} = 0.25\lambda$, $D_s = 0.35\lambda$, $S_r = 0.50\lambda$, and $S_{ae} = 0.45\lambda$,

Table. 3 displays the dimensions employed in the designs of the proposed Model-IV designs.

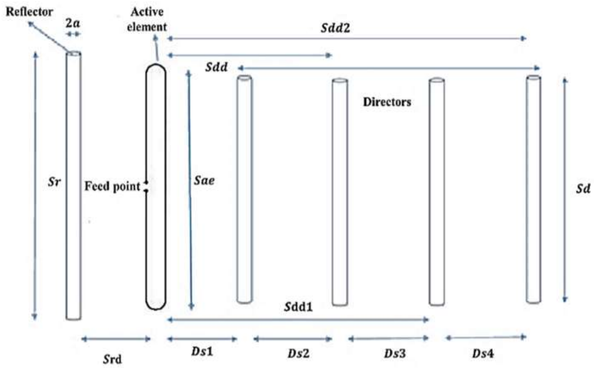
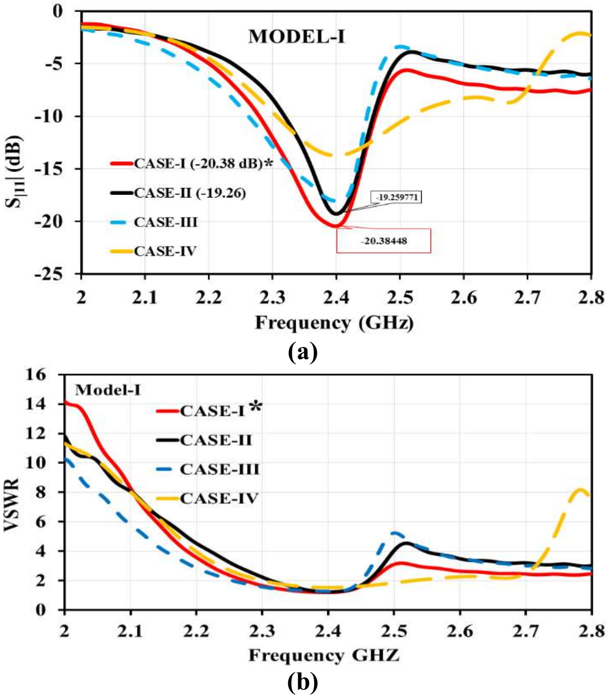


Figure 3: Model-IV folded dipole architecture.



(a)

(b)

Figure 6: Model-I results using uniform director's spacing architecture: (a) $|S_{11}|$ and (b) VSWR.

Table 4: Tabulated results of the proposed Model-I design with uniform spacing.

MODEL-I	Sr	Sae	Ds	Gain	Gain (dB)	-10 dB Interval (GHz) -10 dB Bandwidth (GHz)
CASE-1	0.55λ	0.50λ	0.40λ	10.60	10.57	2.25 - 2.41 0.167
CASE-2	0.53λ	0.50λ	0.40λ	10.71	10.68	2.30 - 2.46 0.155
CASE-3	0.53λ	0.48λ	0.40λ	11.20	11.2	2.24 - 2.42 0.173
CASE-4	0.50λ	0.45λ	0.40λ	11.30	11.21	2.26 - 2.45 0.185

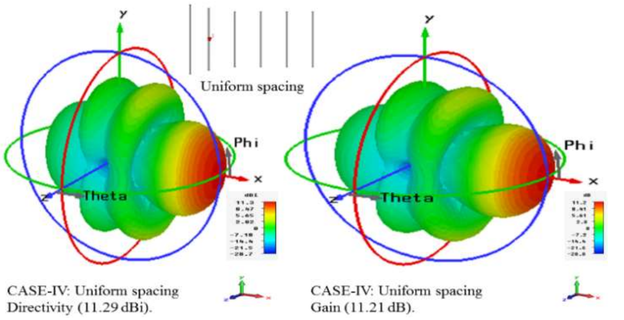
3. Results and Discussion

In this paper, PEC material is employed and analyzed at the 2.4 GHz Wi-Fi frequency band. Thus, the simulated results and findings of the proposed Yagi-Uda antenna designs at various models, based on the bandwidth (BW), reflection coefficient ($|S_{11}|$), VSWR, and gains, will be analyzed. Figure. 6a shows the simulated $|S_{11}|$ results of the proposed Model-I using uniform director spacing in four different scenarios. From the results, CASE-I shows an improved performance over the other three design scenarios. The design covers a BW of 0.167 GHz (2.25 to 2.41 GHz) at -20.38 dB resonance and realized a peak gain of 10.57 dB. Similarly, the VSWR of the proposed Model-I is depicted in Figure. 6b. The findings reveal that the CASE-I configuration successfully attains a satisfactory VSWR of 1:1.6. Table. 4 provides the summary of the MODEL-I antenna parameters. From Table. 4, the proposed antenna in Case-IV has a higher operating BW and gain, so we will focus more on it in the next model while analyzing other parameters. The 3D gain and directivity of the selected design at 2.40 GHz, is given in Figure. 7.

Figure. 8a displays the simulated $|S_{11}|$ results of the proposed Model-II, illustrating the utilization of non-uniform director spacing in four distinct scenarios. The results demonstrate that CASE-I provides better operating BW than the other three design scenarios. The design achieved a bandwidth of 0.187 GHz (from 2.26 to 2.45 GHz) with a resonance of 14.21 dB and a peak gain of 10.57 dB. The proposed Model-II's VSWR is also shown in Figure. 8b. The summary of the antenna parameters for MODEL-II is presented in Table. 5., as shown in Table. 5, the proposed antenna in Case-IV demonstrates a broader bandwidth. Thus, we will focus more on it when examining other parameters. Figure. 9. illustrates the gain and directivity of the selected design at a frequency of 2.40 GHz.

The proposed Model-III's simulated $|S_{11}|$ findings are shown in Figure. 10a, which also shows how different director elements are used in three (3) scenarios. According to the findings, CASE-III offers a more significant realized gain than the other two design scenarios. The design has a peak gain of 12.21 dB, a resonance at -28.24 dB, and a bandwidth of 0.105 GHz (between 2.31 and 2.42 GHz). The VSWR of the proposed Model-III is also depicted in Figure. 10b.

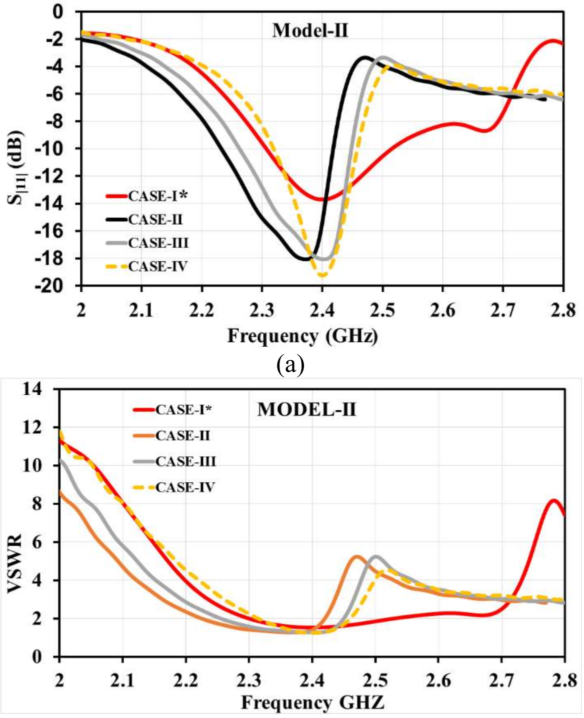
Table. 6 provides a summary of the MODEL-III antenna parameters. The proposed antenna in CASE-III exhibits an enhanced gain, as indicated in Table. 6. Thus, we concentrate more on this design to accomplish the target folded dipole design. The gain and directivity of the design at a frequency of 2.40 GHz are shown in Figure. (11a – 11c). Hence, the findings of the MODEL-III designs demonstrate that the Yagi-Uda antenna with three (3) directors has a low gain. The antenna with five (5) directors attains a maximum realized gain of 12.20 dB and a -10 dB BW of 0.105 GHz.



CASE-IV: Uniform spacing Directivity (11.29 dBi).

CASE-IV: Uniform spacing Gain (11.21 dB).

Figure 7: MODEL-I (CASE-IV: uniform spacing) realized gain and directivity at 2.40 GHz.



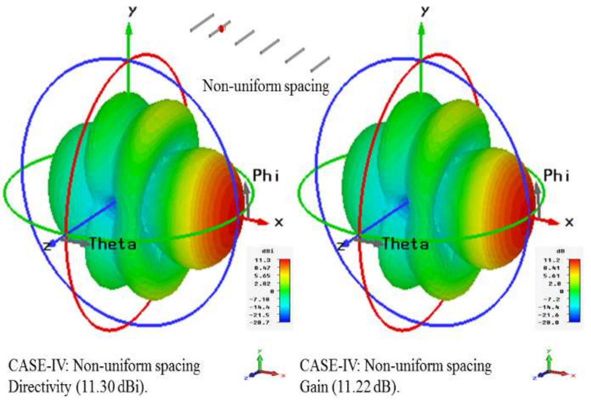
(a)

(b)

Figure 8: Model-II results using non-uniform director's spacing architecture: (a) $S_{|11|}$, and (b) VSWR.

Table 5: Results of MODEL-II design with different directors spacing.

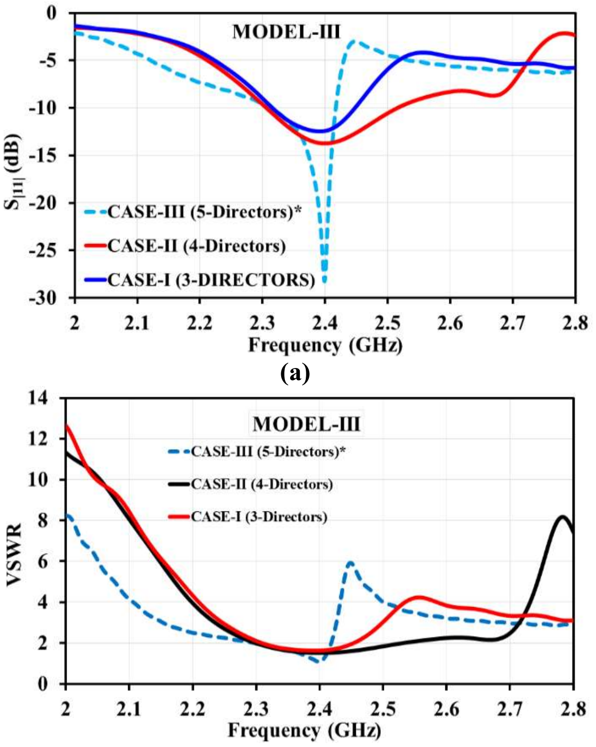
MODEL-II	D_s	**Gain**	**Gain (dB)**	**-10 dB Ranges (GHz) -10dB Bandwidth (GHz)**
CASE-1	0.350λ	11.3	11.21	2.26 - 2.45 0.185
CASE-2	0.380λ	11.71	11.54	2.23 - 2.41 0.178
CASE-3	0.400λ	11.61	10.65	2.32 - 2.49 0.175
CASE-4	0.430λ	11.5	10.61	2.32 - 2.47 0.144



CASE-IV: Non-uniform spacing Directivity (11.30 dBi).

CASE-IV: Non-uniform spacing Gain (11.22 dB).

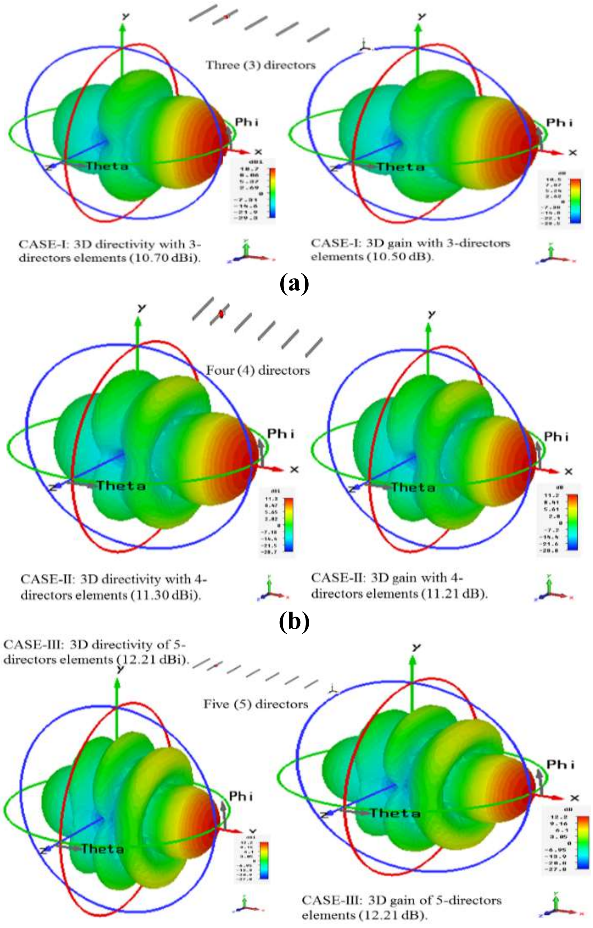
Figure 9: CASE-IV (non-uniform spacing) realized gain and directivity at 2.40 GHz.



(a)

(b)

Figure 10: Model-III results using 5, 4, and 3 director elements: (a) $|S_{11}|$ and (b) VSWR.



CASE-I: 3D directivity with 3-directors elements (10.70 dBi).

CASE-I: 3D gain with 3-directors elements (10.50 dB).

(a)

CASE-II: 3D directivity with 4-directors elements (11.30 dBi).

CASE-II: 3D gain with 4-directors elements (11.21 dB).

(b)

CASE-III: 3D directivity of 5-directors elements (12.21 dBi).

CASE-III: 3D gain of 5-directors elements (12.21 dB).

(c)

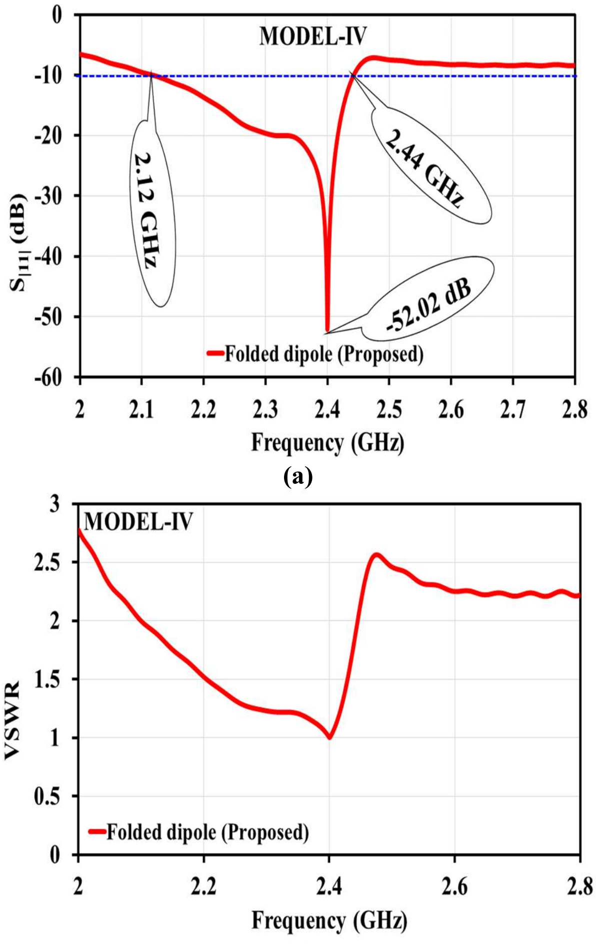
Figure 11: Model-III realized gain and directivity using: (a) Three (3) (CASE-I), (b) Four (4) (CASE-II), (c) Five (5) director elements at 2.40 GHz.

Table 6: MODEL-III using 5, 4 and 3 director elements.

No. of directors	Gain	Gain (dB)	-10 dB Interval (GHz)	-10 dB Bandwidth (GHz)
3 (CASE-I)	10.75	10.49	2.33 - .46	0.125
4 (CASE-II)	11.29	11.21	2.26 - .45	0.185
5 (CASE-III)	12.20	12.21	2.31 -.42	0.105

Table 7: Proposed MODEL-IV design parameters with the folded dipole.

MODEL-IV	*Lr*	*Lac*	L_d	*Sad*
Proposed	0.50λ	0.45λ	0.40λ	0.35λ
	Gain	Gain (dB)	-10dB Interval	-10 dB BW (GHz)
	10.44	10.43	2.12 - 2.44	0.3257



(a)

(b)

Figure 12: Proposed Model-IV results using folded dipole: (a) $S_{|11|}$, and (b) VSWR.

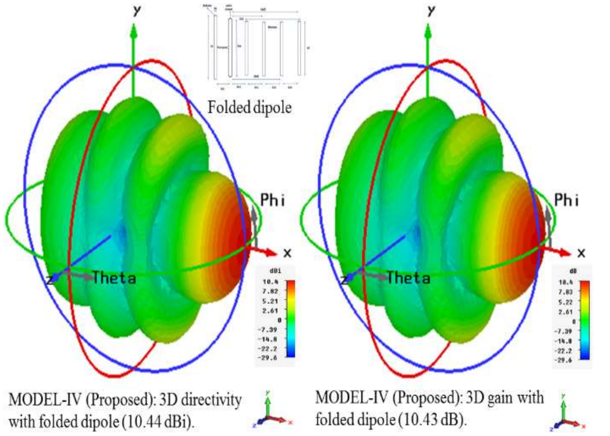


Figure 13: Proposed Model-IV realized gain and directivity at 2.40 GHz.

In MODEL-IV, a folded dipole is introduced into the design, as demonstrated in Figure. 5. The use of PEC material as conducting element and the folded dipole enhances the antenna's bandwidth and radiation efficiency due to its high input impedance functionalities, conductivity, and electromagnetic properties. Figure. 12a presents the simulated $|S_{11}|$ results of the proposed Model-IV. The proposed antenna design shows good BW, gain, and $|S_{11}|$ of -52.02 dB. Thus, the simulation results produced a BW of 0.33 GHz (between 2.12 to 2.44) with a corresponding gain of 10.44 dB when the driven element was replaced with the folded dipole. The directivity is 10.43 dB, and the VSWR of 1.01:1, which is less than 2.0, as illustrated in Figure. 12b. This indicates a good matching between the transmission line and the folded dipole, another significant advantage of using folded dipole (high input impedance of approximately 300 Ω). The $S_{|11|}$ of the improved MODEL-IV design at -52.02 dB is within the acceptable -10 dB range.

Table 8: Proposed MODEL-IV design parameters with the folded dipole.

Ref […]	Gain (dB)	-10 dB Interval (GHz)	-10 dB Bandwidth (GHz)
(Chaudhary et al. 2019)	5	8 – 12.5	4.5
(Bankey and Kumar, 2016)	10.25	2.25 – 2.35	0.102
(Dala, et. al 2019)	7.10	0.451 -0.524	0.073
(Farran et. Al 2017)	10	5.55 – 6.3	0.75
This work	10.43	2.12 - 2 .44	0.105

A comparison is made between the proposed antenna design and previously published works, in Table.8. From the results, the antenna element used for this design is the reflector, driven element, and many directors. The techniques employed are uniform director spacing, non-uniform director spacing, increasing the director numbers, and finally, replacing the driven element with a folded dipole, all using cylindrical PEC materials. Thus, the specified frequency range can be deployed for Wi-Fi applications. Hence, within the limit of the proposed design, the proposed MODEL-IV folded dipole Yagi-Uda antenna has a higher gain and broader bandwidth, as presented in Table. 7, compared to other related works from the literature.

4. Conclusion and Future Work

This study explores four (4) different models to achieve a Yagi-Uda antenna design for suitable Wi-Fi applications. A conventional Yagi-Uda antenna was the first designed as a reference antenna. The effects of modifying the spacing, length, diameter, and number of various antenna elements were explored. The proposed design incorporates a driven element using a folded dipole structure to address the challenges of lower gain and bandwidth. A high gain is maintained with an improved BW of 14% compared to existing works from the literature. The proposed MODEL-IV architecture realized a peak gain of 10.43 dB, over an $|S_{11}|$ of -52.02 dB and VSWR of 1.01:1. The findings of this study can be used in large-scale wireless communication conditions, particularly in broadband services where high BW is a challenge, such as backhauling employing PTP and PTMP services.

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