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Design and simulation of microstrip phased array antenna for 2.0–2.8 GHz

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ABSTRACT

This study aims to create and test a microstrip array antenna with eight elements that works in the 2.0–2.8 GHz frequency range. We use CST Studio Suite to run simulations that check performance metrics like return loss (S11), VSWR, gain, and radiation pattern. The results show that the antenna has a return loss of -24 dB and a VSWR of 1.13 at a frequency of 2.4 GHz, which means the impedance is very well matched. However, the radiation and total efficiencies at 2 GHz and 2.8 GHz are still low, so the design can't handle the highest frequencies in the working range. The 126 MHz bandwidth should be able to cover channels 1 to 13 in Band 40 (2300–2400 MHz), but the antenna needs to work better at frequencies above 2.4 GHz to be helpful for all applications. Compared to other studies, this antenna's gain and efficiency are still not as good as those of other phased array antennas. This study is the first step towards creating a possible digital beam steering system that adaptively aligns signals to user movement to reduce interference in mobile environments.

1. Introduction

Wireless communication technologies have grown so quickly that they have changed how people get and share information. Long-Term Evolution (LTE) 4G has made the internet faster, less laggy, and better for users. However, network providers still have trouble keeping signals strong and stable and making most of the spectrum in densely populated urban areas where user demand and data traffic keep rising [1], [2]. Advanced antenna systems, especially phased array antennas, have become a promising way to solve these problems. Electronic beam steering with phased array technology can send energy to specific users without moving parts [3], [4]. This feature boosts the signal-to-noise ratio (SNR) and spectral efficiency and cuts down on co-channel interference, all of which are important for the performance of modern cellular networks. In 4G LTE networks, phased array antennas can change the shape of their beams on the fly to follow moving users, improve coverage,

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and make it easy to switch sectors [5]. Even with these advantages, designing an antenna system that meets technical requirements like low return loss (S11), optimal Voltage Standing Wave Ratio (VSWR), small size, and high radiation efficiency in the 2 –2.8 GHz band is still a complex engineering task. Engineers also need to ensure that the impedance of all the array elements is the same so that power loss and signal reflection are kept to a minimum [6].

Microstrip patch antennas made on FR-4 substrates are popular in wireless applications because they are cheap, light, and not too hard to make [7], [8]. However, FR-4 materials have higher dielectric losses and a narrower bandwidth than more advanced substrates. This means careful design optimization is necessary, especially when high gain, directivity, and efficiency are needed [9]. Despite these challenges, few studies have tackled optimized microstrip phased array antennas using FR-4 substrates for the 2.0–2.8 GHz range, particularly for effective beam steering and adequate bandwidth to support LTE Band 40. Therefore, our work bridges this gap by designing and simulating an 8-element microstrip phased array antenna on FR-4, fine-tuning it for low return loss, reliable beam steering, and compatibility with LTE Band 40 needs.

In this study, we design and simulate a new 8-element microstrip phased array antenna tailored for the 2.0–2.8 GHz range, which is perfect for 4G LTE networks. By using digital beamforming, we aim to boost signal strength, widen coverage, and cut down on interference. Our work stands out from earlier research, like Gupta and Srinivasu [10], who explored patch arrays with different element counts at sub-6 GHz, or Abdel-Rahman et al. [11], who focused on an 8-element slot-loop array for much higher frequencies (21–23.5 GHz). Our design tackles the tricky task of fine-tuning phase and amplitude for LTE-specific arrays.

We also build on insights from Jokinen et al. [12], who used USRP software-defined radio platforms to showcase phased antenna arrays. Their work shows how crucial precise synchronization and calibration are for steering beams accurately, even with basic hardware. Plus, we draw inspiration from Oh et al. [13], who worked on multibeam segmented beamforming arrays at mmWave frequencies. They showed that combining several low-order modulated beams can create secure, power-efficient high-order QAM signals.

For our study, we use CST Studio Suite to run detailed electromagnetic simulations, tweaking phase and amplitude calibration methods based on the latest 5G and mmWave research. Our goal is to craft an antenna that shines in the 2.0–2.8 GHz band and can seamlessly fit into 4G LTE networks. By blending theoretical analysis with practical simulations, we test our design thoroughly. This work is a big step toward creating flexible, efficient, and interference-resistant phased array antennas, paving the way for more reliable wireless networks in the future [14], [15].

The results showed that the antenna's performance in the 2.4 GHz band was very close to what was simulated, with only a slight difference in VSWR and impedance matching parameters [16]. This testing type helps us determine what the FR-4 substrate does, like how much dielectric loss it causes and how much room it needs for fabrication. Other research has also shown how vital spectral analysis is for testing array-based antennas, especially when measuring frequency response, sidelobe level (SLL), and gain accuracy in a phased array system [17]. Even at higher frequencies like X-band, a Spectrum analyser helps find signal distortion caused by bad connectors and transmission lines [18]. Systematically using these tools is a great way to ensure that the electromagnetic simulation data matches how the antenna works in real life.

2. Literature review

Phased array antennas are hard to work with because they have many radiating elements arranged in a linear, planar way. You can electronically control the signal's phase going to each component and the direction of the primary radiation beam. This means that mechanical steering is no longer necessary. For military and commercial purposes, it is essential to steer the beam quickly [3]. Initially, phased arrays were mainly used in radar and defence systems. However, because of technological advances, this technology is now used in civilian communication systems, such as 4G LTE cellular networks. Phased array systems are beneficial in cities where there is a lot of interference, people move around a lot, and coverage is hard to get because they can change based on where the user is and what the environment is like [4]. Zhang and Chen [1] said that beamforming techniques in phased arrays and massive MIMO architectures improve spectral efficiency and reduce interference in places with many users. Nicolaescu and Stoica [2] also pointed out that phased array antennas can change the beam's direction in real time, making wireless communications more reliable and faster.

Several recent studies have backed the creation of phased array antennas for specific frequency bands and uses. For instance, Resky et al. [5] made a 1×16 linear array for S-band 3D radar systems with great beam control and directivity. Syamsuddin and Sugondo [6] investigated a 4×4 planar array that could steer beams in two dimensions. This is very useful for wide-area surveillance. These setups cover more ground than linear arrays, especially in cities or rugged terrain. Rakhmadani and Setiawan [7] investigated a 1×4 phased array that worked in the X-band and used FR-4 substrates. Their work showed how important it is to choose the right substrate material, match the impedance, and space the elements correctly to get low return loss and good radiation performance. The study also stressed the importance of carefully designing the feed network with quarter-wave transformers and T-junctions to keep the power balance across the array of elements.

CST Studio Suite is now one of the best tools for modelling and simulating electromagnetic fields. It lets you test antenna designs in detail. CST can study how electromagnetic fields act in complicated 3D shapes by using Finite Integration Techniques (FIT) and Time Domain Solvers. Designers use CST to accurately measure essential factors like S11, VSWR, gain, and radiation patterns. This helps them make the best antenna designs before making them [8], [9]. CST lets you look at different array configurations, feeding techniques, beam behaviours, and bandwidth or polarization characteristics. This cuts down on development time and costs while ensuring the final design meets the standards for modern wireless systems.

In short, the research shows that phased array antennas are possible from a technical point of view and have clear benefits, such as being able to be used in 4G networks. There are still problems to solve, especially when making designs that are small, cheap, and easy to add to existing commercial systems. This study looks at these problems by doing a design and performance analysis of an 8-element microstrip phased array that works in the 2.0–2.8 GHz band, standard in 4G LTE networks [10]–[13]. The goal is to make an antenna that works well in this frequency band, not just support 4G. Jokinen et al. [16] showed that using Universal Software Radio Peripheral (USRP) platforms to control a planar four-element linear phased array in a real-world setting was possible. They achieved effective beamforming by carefully calibrating and synchronizing the variety. This shows that even small arrays can steer beams, which is helpful for applications that need to be small.

Researchers have also recently investigated 8-element microstrip phased arrays to improve gain, bandwidth, and beam steering. Lee et al. [18] developed an 8-element patch array that works best for mid-band applications. It has both a wide bandwidth and a high gain. Chen et al. [19] also used artificial neural network optimization to make a low-profile 8-element phased array that scans beams better for frequencies below 6 GHz. Park et al. [20] made a small 8-element linear array on an FR-4 substrate that is good for LTE systems because it is small and has good radiation performance. Also new research has kept improving phased array designs in this frequency range. Wang et al. [21] made an 8-element phased array for use below 6 GHz that has the best side lobe suppression. Liu et al. [22] looked into phase-only beamforming methods for small phased arrays for better scanning range and gain. Zhao et al. [23] came up with a new feeding network to improve impedance matching and lower return loss in 8-element arrays that work in the 2.0–2.8 GHz range.

3. Material and method

This study uses a simulation-based approach to design and test a microstrip phased array antenna for the 2.0–2.8 GHz frequency range. The research process involves a few key steps: reviewing existing literature, designing the antenna, running simulations with CST Studio Suite software, and analyzing the antenna's performance. First, we dive into the literature on phased array antennas and beamforming techniques, which are widely used in modern wireless communication systems. This review helps us set clear design goals and performance standards to guide the project [10], [11]. Next, we design a linear microstrip antenna array with eight elements, using an FR4 epoxy substrate that's 1.6 mm thick with a relative permittivity of $\varepsilon r = 4.4$.

Our goal is to achieve a return loss (S11) below −10 dB and a voltage standing wave ratio (VSWR) of 2.0 or less. These metrics ensure the antenna and transmission line are well-matched, allowing efficient power transfer with minimal signal reflection [13], [14]. To figure out the antenna's dimensions—like its length, width, and spacing between elements—we rely on design formulas and data from recent studies. This helps us optimize the antenna's radiation performance while keeping it compact enough for modern wireless systems [19–22]. Several equations are used to calculate various antenna parameter quantities, including patch widh W in Eq. (1), patch length L in Eq. (2), Effective Dielectric Constant ε_{eff} in Eq. (3), fringing field extension (ΔL) in Eq. (4), ground plane dimensions W_g and L_g in Eq. (5) and Eq. (6), feedline width for 50 Ω (Wf) in Eq. (7), feedline length (*Lf*) in Eq. (9), and T-Junction feedline for impedance matching in Eq. (10).

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{3\ x\ 10^8}{2\ x\ 2.7\ x\ 10^9}\sqrt{\frac{2}{5.4}} \approx 35.2 \text{ mm} \tag{1}$$

$$L = \frac{c}{2\, f_r \sqrt{\varepsilon_{eff}}} - 2\Delta L \approx 27.1 \text{ mm} \quad (2)$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\,(1 + 12\,\frac{h}{W})^{-0.5} = 2.7 + 0.85\left(1 + \frac{12\ x\ 1..6}{35.2}\right) \approx 4.05 \quad (3)$$

$$\Delta L = 0.412\,.\,h.\frac{(\varepsilon_{eff} + 0.3)\,(\frac{W}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{W}{h} + 0.8)} \approx 0.76 \quad (4)$$

$$W_g = W + 6h \approx 35.2 + 6\ x\ 1.6 = 44.8 \text{ mm} \quad (5)$$

$$L_g = L + 6h \approx 27.1 + 6\ x\ 1.6 = 36.7 \text{ mm} \quad (6)$$

$$Wf \approx 3.06 \text{ mm} \quad (7)$$

$$\lambda_0 = \frac{c}{f} \approx 111\ mm\,, \lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \approx 55.2\ mm \quad (8)$$

$$L_f = \frac{\lambda_g}{4} \approx 13.8 \text{ mm} \quad (9)$$

$$Z_{in}^2 = Z_1 Z_2, Z_1 = \sqrt{50\ x\ 100} = 70.71\ \Omega \quad (10)$$

where c denotes the speed of light (3 x 10^8 m/s), εr denotes dielectric constant, f_r denotes the center frequency (2.7 GHz), ε_{eff} denotes effective dielectric constant, h denotes the substrate thickness (1.6 mm), W denotes patch width (mm), L denotes patch length (mm), Lg denotes groundplane length, and Wg denotes groundplane width. Shiows the summary of microstrip antenna specifications.

There are 8 radiating elements in a straight line that make up the microstrip phased array antenna. CST Studio Suite 2025, a professional electromagnetic simulation program widely used in the antenna research community, was employed for the design process [24]. We chose this linear arrangement because it enables effective beamforming, providing precise control over the direction of the radiation pattern. This ability to steer beams is crucial for enhancing signal quality and minimising interference when operating in the 2.0–2.8 GHz frequency band, which is prevalent in modern wireless communication systems, including but not limited to 4G LTE networks [25]. To make sure that all of the antenna elements get the same amount of power and keep the right impedance, a signal distribution network was set up. This network uses T-junctions and quarter-wavelength transformers to evenly split the power and adjust the impedance in a way that works well. This kind of feedline system cuts down on signal reflections and lets each element send out coherent radiation, which helps the array's beamforming ability [26], [27].

The antenna is made to work in the 2.0–2.8 GHz frequency range, which is the same as the LTE band spectrum. This means it will work with existing 4G infrastructure and can also be used for other wireless applications in the same band [28]. It has a structure made up of rectangular patch elements that are arranged symmetrically and connected by microstrip transmission lines. These lines spread the RF signal evenly and let you control the phase of the whole array, which is very important for steering the beam [29], [30].

Fig. 1 shows the antenna's detailed shape and layout. The design makes sure that each patch element is about half a guided wavelength (λ/2) apart. This helps with constructive interference during beamforming. This setup helps reduce side lobes and improve directivity, which in turn makes communication better in the desired direction [30].

Table 1
Microstrip antenna specifications.

Parameters	Value (mm)
Patch width (W)	35.2
Patch length (L)	27.1
Ground width (Wg)	44.8
Ground length (Lg)	36.7
Feedline width 50 Ω	3.06
Feedline length 50 Ω	13.8
Lebar feedline 70.7 Ω	1.7

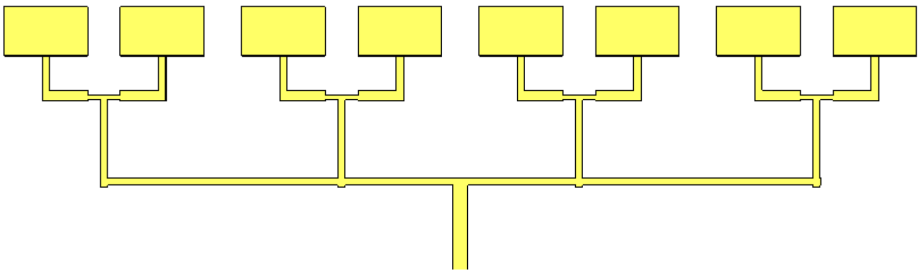

Fig. 1. Microstrip phased array antenna design, the antenna is made of FR4 Epoxy, which has a relative permittivity of εr = 4.4 and is 1.6 mm.

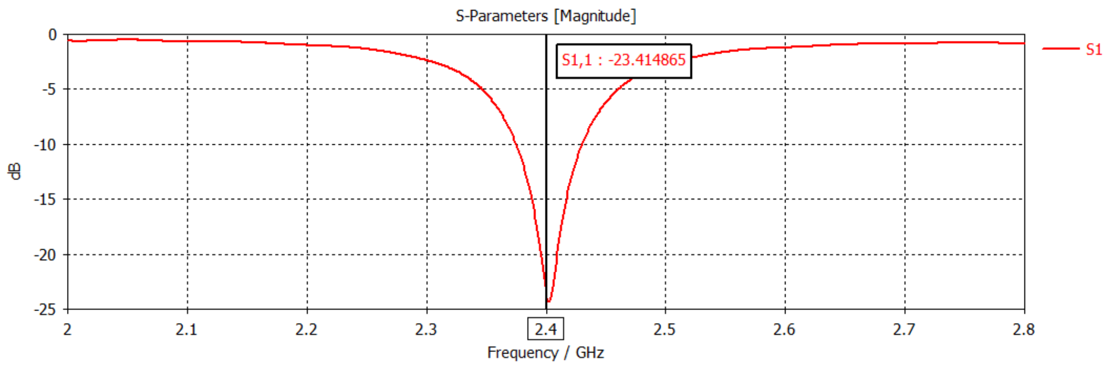

Fig. 2. Return loss simulation results.

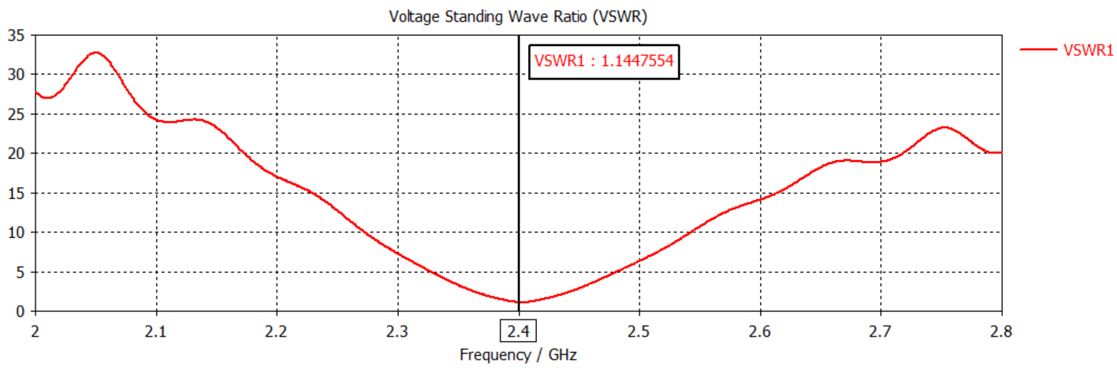

Fig. 3. VSWR simulation results.

4. Results and discussion

4.1. Results and analysis

This section presents the results of measuring the scattering parameters (S-parameters), focusing on the S11 parameter, for the antenna element in the phased array system. The S11 parameter indicates the amount of power reflected at the antenna's input port, directly showing how well the antenna matches a standard 50-ohm transmission line. Fig. 2 illustrates the simulated S11 parameter (return loss) as a function of frequency, ranging from 2.0 GHz to 2.8 GHz. The red curve represents the impedance match between the microstrip antenna and the 50-ohm transmission line, reaching its lowest point at 2.4 GHz with an S11 value of -23.41 dB, indicating the antenna's optimal resonant state. An S11 value below -10 dB is generally considered acceptable, as it ensures 90% or more of the RF power is delivered to the antenna, with only about 0.45% reflected at -23.41 dB. This demonstrates excellent impedance matching, minimizing power loss due to reflection. The S11 curve also shows stable bandwidth around the 2.4 GHz frequency, ensuring effective performance within this range. Additionally, the S11 value of -23.41 dB corresponds to a VSWR of approximately 1.14:1, confirming a near-perfect impedance match. This performance indicates that the antenna design meets the stringent RF requirements for highly efficient wireless communication systems with minimal power reflection.

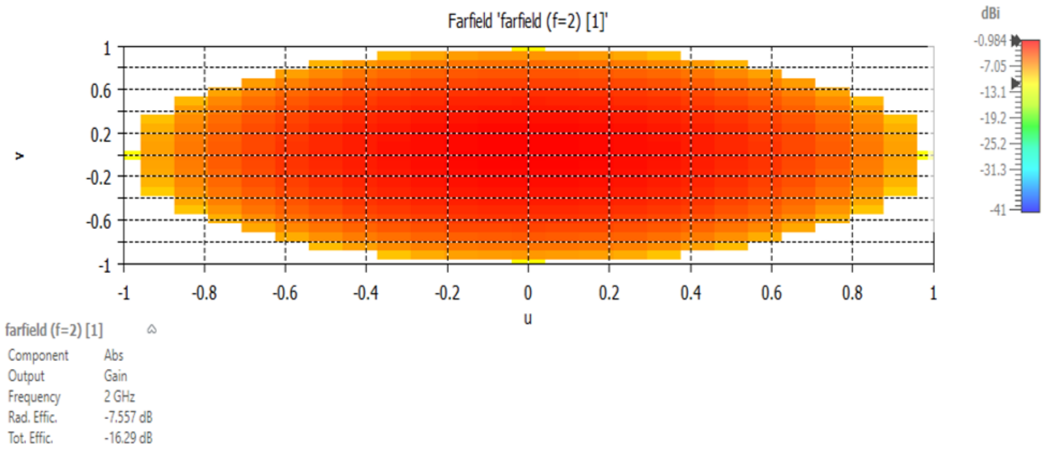

Fig. 4. 2D far-field radiation pattern frequency 2Ghz.

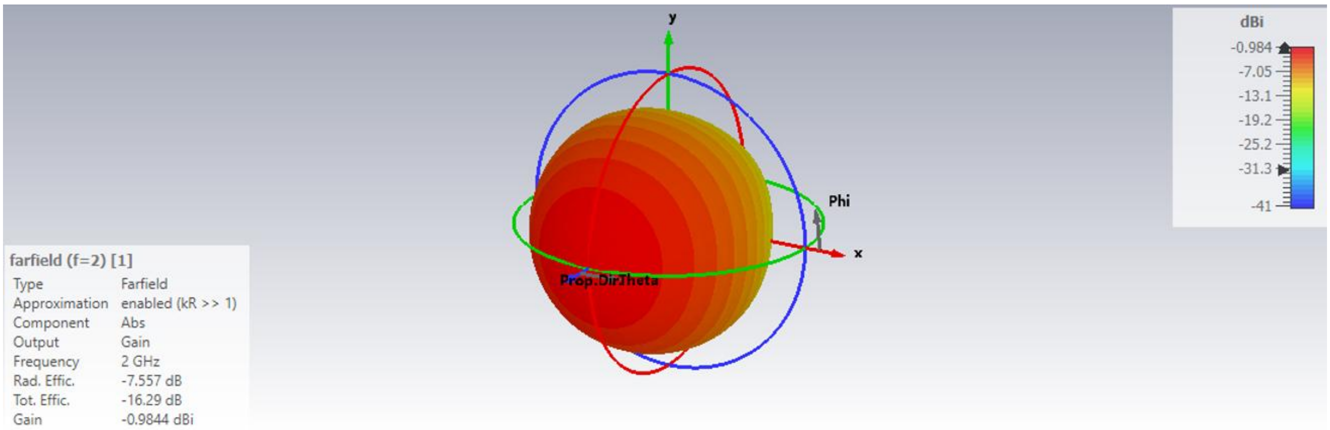

Fig. 5. 3D far-field radiation pattern for frequency 2Ghz .

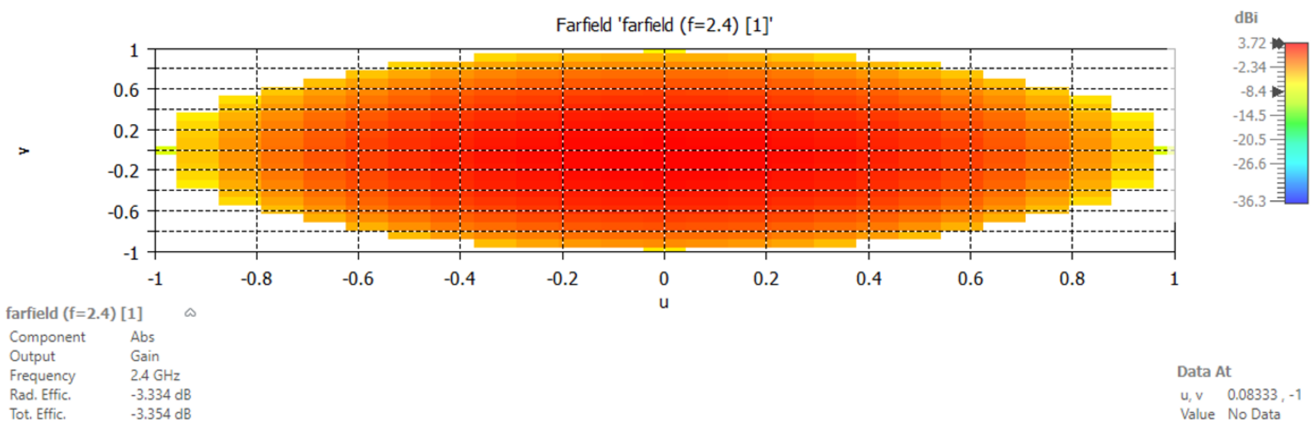

Fig. 6. 2D far-field radiation pattern frequency 2.4Ghz.

Fig. 3 shows the voltage standing wave ratio (VSWR) curve as a frequency function between 2.0 and 2.8 GHz. This graph shows how well the antenna and the transmission line match impedance. The red curve labeled "VSWR1" shows the standing wave ratio when power is reflected from the antenna. The best VSWR value is 1:1, meaning all power goes to the antenna without being reflected. The lowest point on this graph for VSWR is about 2.4 GHz, which is 1.1447554. This number is very close to the ideal condition, meaning the antenna matches the impedance well at that frequency. This shows that the antenna's central resonant frequency is 2.4 GHz.

Fig. 4 displays the antenna’s 2D far-field radiation pattern at 2 GHz. The normalized (u) and (v) coordinates show the direction of the electromagnetic signal in free space, with a color map indicating gain levels in dBi, ranging from blue (-41 dBi) to dark red (near 0 dBi).

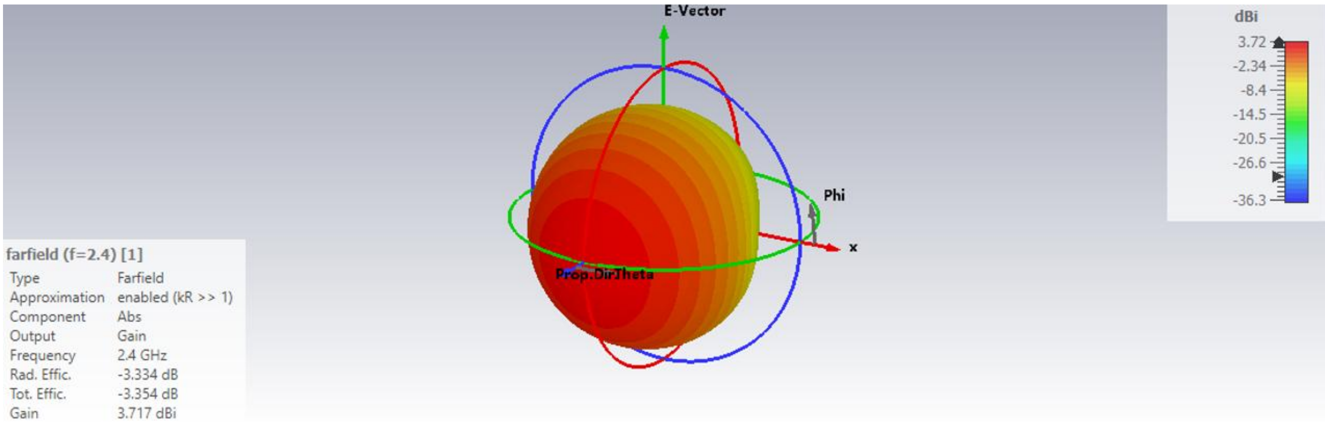

Fig. 7. 3D far-field radiation pattern frequency 2.4Ghz.

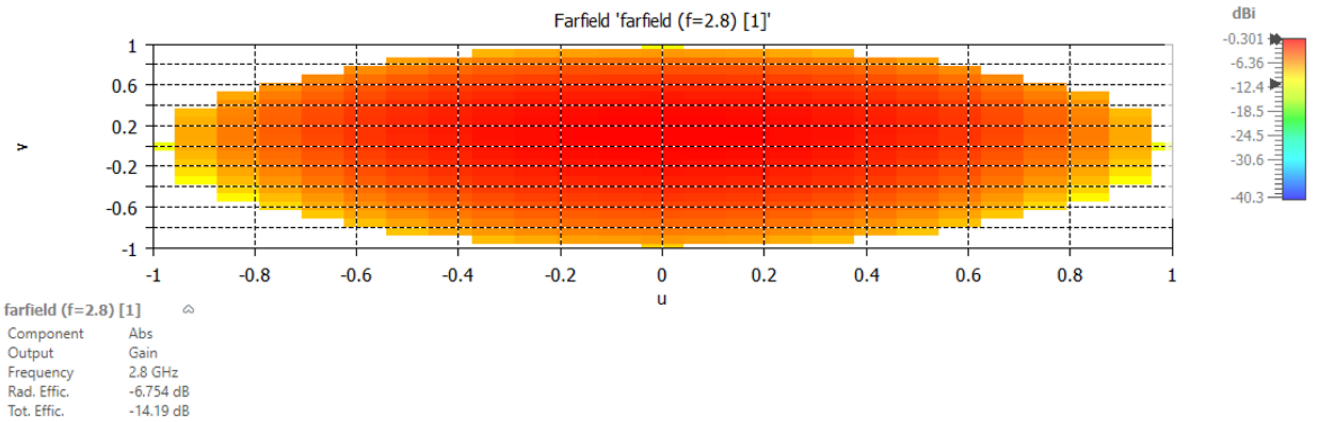

Fig. 8. 2D far-field radiation pattern frequency 2.8 Ghz.

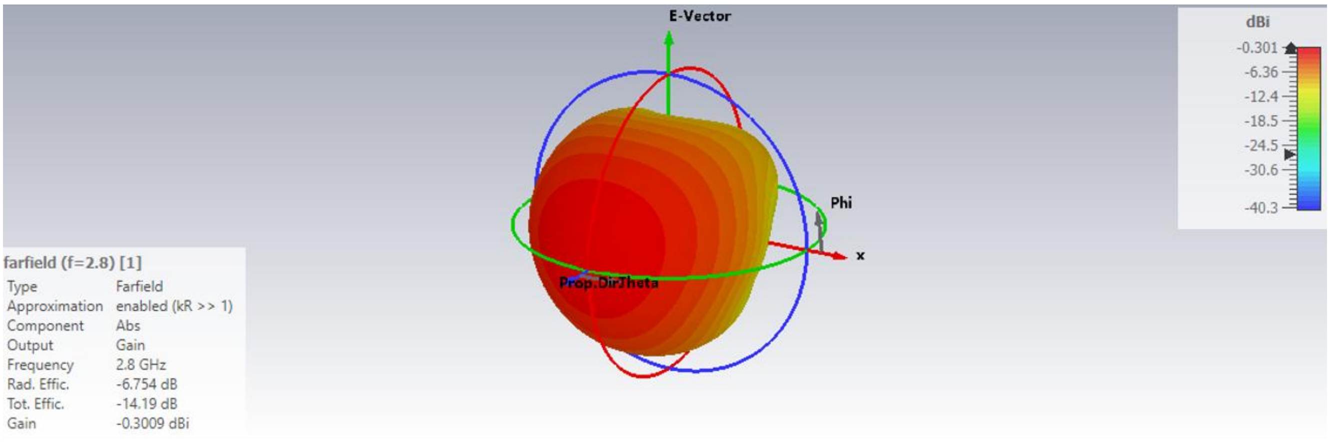

Fig. 9. 3D far-field radiation pattern frequency 2.8Ghz.

The pattern forms an elongated ellipse along the horizontal axis, showing uniform radiation in the E-plane and symmetry around the central axis, with the strongest signal in the lateral direction (broadside pattern). With a maximum gain of -0.984 dBi, the antenna has low directivity, typical for single patch antennas without arrays or reflectors. Its radiation efficiency (-7.557 dB) and total efficiency (-16.29 dB) reveal significant power losses due to dielectric, conduction, or impedance mismatch issues. This pattern suits short-range applications in a single horizontal plane, like IoT devices, module-to-module communication, or RF sensors in open spaces. However, for long-distance or directional use, the antenna needs design tweaks, such as adjusting the element structure, array layout, or adding reflectors to boost gain and efficiency.

Fig. 5 and Fig. 6 show the antenna's 3D far-field radiation patterns at 2 GHz and 2.4 GHz, respectively. Both patterns are nearly spherical, with a maximum gain of -0.984 dBi, indicating low-power omnidirectional radiation. The radiation efficiency (-7.557 dB) and total efficiency (-16.29 dB) highlight substantial power losses from impedance mismatch and material limitations.

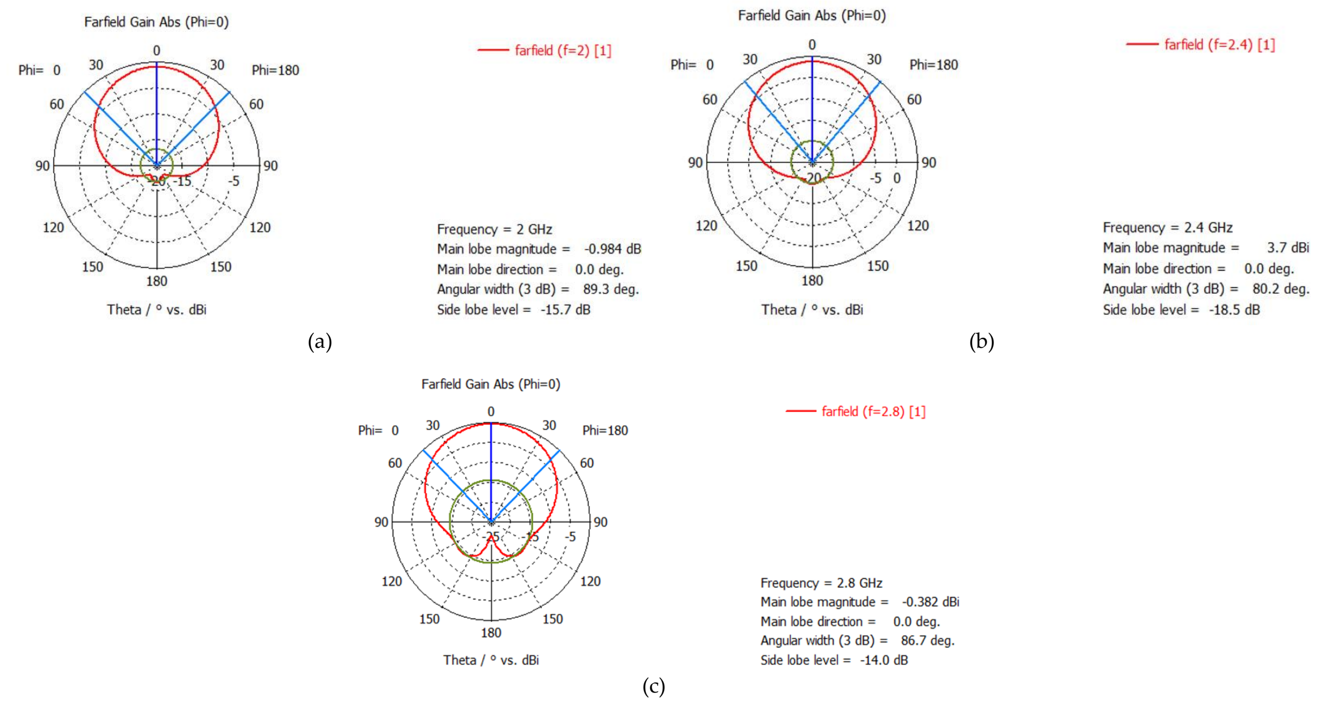

Fig. 10. Beam stering results for: (a) frequency 2Ghz, (b) frequency 2.4 Ghz, and (c) frequency2.8 Ghz.

Table 2
Steering angle

Frequency	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	360°
2 Ghz	0°	~15°	~28°	~45°	~60°	~75°	90°	~-75°	~-60°	~-45°	~-30°	~-15°	0°
2.4 Ghz	0°	~17°	~30°	~47°	~63°	~78°	90°	~-78°	~-63°	~-47°	~-32°	~-17°	0°
2.8 Ghz	0°	~18°	~32°	~49°	~65°	~80°	90°	~-80°	~-65°	~-49°	~-35°	~-18°	0°

In contrast, Fig. 7 presents a simulated 3D pattern at 2.4 GHz, showing the absolute gain distribution. The central red region marks the strongest beam at 3.717 dBi, with a color gradient from red to yellow and green indicating decreasing gain. This quasi-omnidirectional pattern has a prominent main lobe in the broadside plane, with radiation efficiency (-3.334 dB) and total efficiency (-3.354 dB) suggesting decent electromagnetic performance and acceptable power losses.

Fig. 8 and Fig. 9 illustrate the antenna's radiation patterns at 2.8 GHz. Fig. 8 shows a broadside pattern with a maximum gain of just -0.301 dBi, a total efficiency of -14.19 dB, and a radiation efficiency of -6.754 dB, indicating significant power loss and poor performance for 2.8 GHz applications. Fig. 9 reveals a nearly omnidirectional pattern with a gain of -0.301 dBi and the same radiation efficiency, offering even but weak power distribution. This makes it suitable for broad coverage but less effective for directional applications.

Fig. 10 compares beam steering results at 2 GHz and 2.4 GHz. At 2 GHz, the main lobe is at 0 degrees with a 3 dB beamwidth of 89.3°, a maximum gain of -0.984 dBi, and a side lobe level of -15.7 dB, showing limited directional focus and omnidirectional tendencies with efficiency hampered by material and feed losses. At 2.4 GHz, performance improves significantly, with a maximum gain of 3.7 dBi, a narrower 3 dB beamwidth of 80.2°, and a lower side lobe level of -18.5 dB, reflecting better focus of transmit power and reduced interference. The antenna excels at 2.4 GHz, making it ideal for Wi-Fi, IoT, and other 2.4 GHz ISM band applications. However, at 2 GHz, the patch design, array configuration, and feed system need optimization to enhance gain and efficiency for applications like 4G LTE bands.

Table 2 shows the results of a simulation of the main lobe direction of the phased array antenna when the phase is gradually changed from 0° to 360° between the array elements. As for the explanation, it is as follows:

1. 0° Phase Shift: A straight ahead (broadside) beam shows the main beam direction at 0° for all frequencies. This is what happens when you don't steer.
2. 30° to 180°: The progressive phase gradually moves the beam direction to the right, from about 15° to 90°. This shows that the antenna can be steered to the right front with increasing precision as the frequency increases (as λ gets smaller).

3. From 210° to 330°, the main beam starts to move to the left (negative) from about -75° to -15°. According to phasor theory, phase shifts above 180° make the beam go the other way.
4. 360°: The beam pattern goes back to 0°, completing one full cycle. This is in line with the wave phase's periodic nature.

4.2. Discussions, findings, and implications

The 8-element microstrip phased array antenna performs best at 2.4 GHz, with a return loss of -24 dB and a VSWR of 1.13, indicating excellent signal efficiency for applications like Wi-Fi, IoT, and LTE Band 40 (2300–2400 MHz) [1], [16]. However, its efficiency drops significantly at 2.0 GHz and 2.8 GHz, with radiation efficiencies of -7.557 dB and -6.754 dB, respectively, and total efficiencies of -16.29 dB and -14.19 dB, limiting its use across the full 2.0–2.8 GHz range [10]. Beam steering is effective, adjusting the main lobe from -75° to +90°, with optimal directivity at 2.4 GHz (3.7 dBi gain, -18.5 dB side lobe level) compared to 2.0 GHz (-0.984 dBi, -15.7 dB) [16]. The FR-4 substrate, while affordable, introduces dielectric losses, reducing efficiency compared to low-loss substrates like Rogers, as noted in prior studies [7], [17]. Adding digital beam control, as demonstrated by Jokinen et al. [12], could improve adaptability for dynamic 4G environments.

A key challenge in this design is balancing cost and performance for practical deployment. Compared to Lee et al. [16], who achieved higher gain (around 5 dBi) with an optimized feed network, this antenna's simpler T-junction design sacrifices efficiency for cost savings, making it less competitive for high-performance LTE systems [18]. Wang et al. [19] suggest that advanced side lobe suppression techniques could improve directivity, but implementing these on FR-4 is complex due to material limitations. This trade-off highlights the need for further optimization, such as refining the feed network or exploring hybrid substrates, to enhance bandwidth and efficiency while keeping costs low for real-world applications [21].

The findings of this research are summarized as follows. The antenna excels at 2.4 GHz with a -24 dB return loss, 1.13 VSWR, and 3.7 dBi gain, making it ideal for Wi-Fi, IoT, and LTE Band 40 applications. However, low efficiency at 2.0 GHz and 2.8 GHz restricts its broadband capability. Beam steering performs well, particularly at 2.4 GHz, but FR-4's dielectric losses and the lack of digital control limit adaptability in dynamic settings.

As a result, this antenna is a cost-effective solution for 2.4 GHz applications like Wi-Fi and IoT but needs improvements for broader LTE use. Using low-loss substrates [17] or integrating digital beam control [12] could enhance performance, supporting 4G and potential 5G sub-6 GHz applications. These findings encourage further research into balancing cost and efficiency for practical, scalable antenna designs.

Conclusions

This study designed and tested an 8-element microstrip phased array antenna on an FR-4 substrate for 4G LTE in the 2.0–2.8 GHz range, showing strong potential for affordable wireless systems like Wi-Fi and IoT. It effectively operates within a 126 MHz bandwidth, ideal for LTE Band 40, and offers reliable beam steering to boost signal focus and reduce interference. However, the antenna's efficiency drops at the band's edges, limiting its use for broader LTE applications, and the FR-4 material causes energy losses that hinder performance. While cost-effective, the design needs enhancements, such as better materials or digital controls, to handle high-capacity networks and possibly support future 5G systems.

The research is limited by its reliance on simulations without real-world testing, which leaves performance in actual conditions unverified. The FR-4 substrate's losses and lack of digital beam control also restrict adaptability in dynamic settings, and the bandwidth doesn't fully cover the 2.0–2.8 GHz range. Future work should focus on building a physical prototype to confirm results, exploring higher-quality substrates, adding digital beam steering for real-time flexibility, and refining the feed network to improve efficiency and bandwidth for advanced 4G and 5G applications.

Declaration statement

Kurnia Wati Pascitra Handayani: Conceptualization, Methodology, Writing-Original Draft, Collecting data. **Sopian Soim, Nurhajar Anugraha**: Writing-Review & Editing.

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Disclosure statement

There is no conflict of interest, either directly or indirectly, with anyone with a financial stake in the topic of this assignment. I also don't have any business ties, like a job, consulting, owning stock, getting or giving research grants, filing or getting patents, royalties, honoraria, or any other kind of payment that could affect how objective the content of this assignment is. I say this honestly and responsibly because I believe in academic honesty and scientific openness.

Funding statement

No one pays for the research or work that goes into this assignment, not even the government, private, non-profit, or business sponsors. The author is responsible for paying the cost of completing this task. This statement is being sent in to ensure the work is transparent and objective from an academic point of view.

Data availability statement

The manuscript and/or appendices that go with this assignment contain all the data used to write it. The author can give more information if needed, but only if it's a reasonable request. There is no private or restricted data that third parties can't see. This statement is meant to back up the ideas of openness and being able to repeat scientific experiments.

AI Usage Statement

The author says that this assignment only uses artificial intelligence (AI) in a small way to help check grammar and organize sentences. The author's thoughts are the basis for the content, analysis, and conclusions. Using AI responsibly doesn't change the originality of this work.

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