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A Comprehensive Study on the Impact of Rectangular Patch Antenna Size on Performance Parameters

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ABSTRACT

Microstrip patch antennas are fundamental to modern wireless communication, valued for their compact size, cost-effective fabrication, and adaptability across diverse applications like Wi-Fi, mobile networks, satellite communication, and IoT systems. The performance of these antennas hinges on the dimensions of the radiating patch, which directly influence critical metrics such as resonant frequency, return loss (S_{11}), bandwidth, gain, directivity, radiation efficiency, and radiation pattern. This study systematically explores how varying the size of a rectangular patch impacts these parameters, using theoretical models, equations, and simulations. Small changes in patch dimensions can significantly alter electromagnetic wave behavior, affecting signal reflection, power distribution, and radiation characteristics. By understanding these effects, engineers can design antennas optimized for specific wireless needs, balancing performance with practical constraints like size and cost. The findings provide actionable insights for improving antenna efficiency, signal strength, and frequency response, supporting the evolution of high-performance communication systems.

Keywords - **Return Loss, Bandwidth, Gain, Radiation Pattern, Efficiency.**

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I. INTRODUCTION

Microstrip patch antennas (MPAs) have become indispensable in modern wireless communication due to their low profile, planar structure, ease of fabrication, and cost-effectiveness [1]. They are widely implemented in Internet of Things (IoT) systems, wireless local area networks (WLANs), and mobile satellite communications [2]. Structurally, MPAs typically consist of a thin metallic patch placed over a grounded dielectric substrate. Common feeding techniques include coaxial probes, microstrip lines, and aperture-coupled feeds, each influencing antenna bandwidth and impedance matching in distinct ways [3]. Despite their advantages, conventional MPAs are often constrained by narrow bandwidth, which has driven substantial research into performance enhancement strategies. Advancements in this field include broadbanding techniques, multiband and dual-band configurations, miniaturization methods, and circular polarization designs [3]. Additionally, optimization approaches—such as genetic algorithms and artificial neural networks—have been utilized to fine-tune antenna dimensions and material properties for specific application requirements [4]. Future directions in MPA research emphasize multi-objective optimization, robustness analysis, and integration with emerging technologies like reconfigurable intelligent surfaces and 5G/6G systems.

Among various MPA configurations, rectangular patch antennas are particularly favored for their geometric simplicity and efficient radiation characteristics [5]. Their performance is significantly influenced by geometric and material parameters, including patch dimensions and substrate properties. Key performance metrics affected by these parameters include resonant frequency, return loss, voltage standing wave ratio (VSWR), bandwidth, gain, and radiation efficiency [6]. For instance, Ahmed et al. (2023) conducted a comparative study in the Wi-Fi band (2.4–2.4835 GHz), revealing that rectangular MPAs with rectangular slots exhibited superior performance over circular MPAs in terms of return loss (−37.07 dB), VSWR (1.02), radiation efficiency (64.5%), and bandwidth (115 MHz) [7]. The electromagnetic behavior of MPAs is closely tied to patch size. The length of a rectangular patch is typically designed to be approximately half the guided wavelength of the target resonant frequency, accounting for the substrate's effective dielectric constant [5]. Any deviation in patch length or width can significantly affect the antenna's frequency response, impedance characteristics, and radiation behavior. Studies have demonstrated that even small dimensional variations can lead to considerable shifts in resonant frequency and bandwidth [9]. For multilayer electromagnetically coupled patch designs, Lee and Lee (1989) observed that reducing the size of parasitic patches alters impedance matching and bandwidth [10]. Optimal broadband performance is often achieved when parasitic and fed patches are of similar dimensions, while slightly smaller parasitic patches are preferable in high-gain designs. Substrate properties, including dielectric constant and thickness, also influence antenna performance. Low-permittivity materials are generally favored for broader radiation and higher efficiency, while increasing substrate thickness can enhance bandwidth but may impact impedance matching [5], [8]. These insights are critical for engineers and researchers aiming to design compact, high-performance antennas for Wi-Fi and other wireless applications. Figure 1 illustrates a typical rectangular microstrip patch antenna structure.

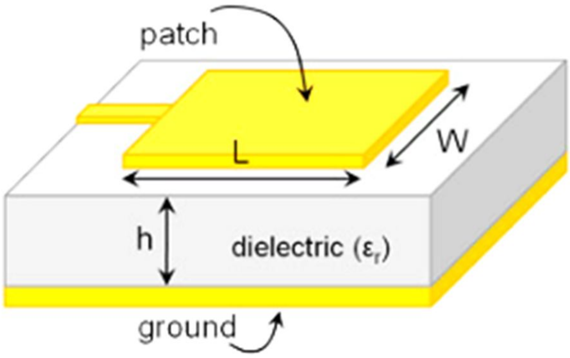

Fig. 1. Rectangular patch antenna structure

Recent advances in microstrip antenna design have demonstrated various approaches to optimization and miniaturization. Islam and Islam (2024) developed a C-band hexagon slotted textile antenna using jeans substrate for satellite communication applications, achieving enhanced performance through innovative slot configurations [42]. Similarly, Khan et al. (2024) explored miniaturization techniques using fractal geometry in microstrip patch antennas, demonstrating how geometric modifications can maintain performance while reducing antenna size [43]. These studies highlight the ongoing evolution in antenna design methodologies, where dimensional optimization remains a critical factor in achieving desired performance characteristics.

This study aims to provide a detailed investigation into how the size of a rectangular microstrip patch affects its performance parameters. Through theoretical analysis, mathematical models, and simulations, we explore the effects of dimensional variations on resonant frequency, return loss, bandwidth, gain, directivity, efficiency, and radiation pattern. By doing so, we offer practical insights for antenna designers seeking to optimize MPAs for specific wireless applications. The findings are particularly relevant as the demand for efficient, compact antennas continues to grow with the proliferation of IoT devices, 5G networks, and satellite-based communication systems. This research not only contributes to the existing body of knowledge on antenna design but also provides actionable guidelines for achieving higher efficiency, improved signal strength, and better frequency response in modern wireless systems.

The paper is organized as follows: Section 2 examines the impact of patch size on each performance parameter, supported by theoretical equations and practical implications. Section 3 discusses the findings, highlighting trade-offs and design considerations. Section 4 concludes the study with recommendations for antenna optimization and future research directions. References are provided at the end to support the technical foundation of this work.

II. IMPACT OF PATCH ANTENNA SIZE ON KEY PERFORMANCE METRICS

Microstrip patch antennas are sensitive to the dimensions of their radiating patch, which directly influence a range of performance metrics critical to their operation. These include resonant frequency, return loss (S_{11}), bandwidth, radiation pattern, gain, directivity, and radiation efficiency. Below, we explore each parameter in detail, supported by theoretical equations and practical examples, to illustrate how patch size variations affect antenna performance.

2.1 Resonant Frequency (f_r)

The resonant frequency of an antenna is the frequency at which it most efficiently radiates or receives electromagnetic energy. For a rectangular patch antenna (RPA), this frequency is primarily determined by the patch's length, which is typically set to about half the wavelength of the desired frequency, adjusted for the substrate's dielectric properties [11]. The relationship between patch dimensions and resonant frequency is fundamental to antenna design, as it allows engineers to tune the antenna for specific applications, such as 2.4 GHz for Wi-Fi or 1.575 GHz for GPS. The resonant frequency (f_r) of a rectangular patch antenna can be approximated using the following equation [12]:

$$f_r \approx \frac{c}{2\sqrt{\varepsilon_{eff}}}\sqrt{\left(\frac{1}{L}\right)^2 + \left(\frac{1}{W}\right)^2}$$

Where, c represents the speed of light in a vacuum, ε_{eff} is the effective dielectric constant of the substrate material, L indicates the length of the patch antenna, and Wsignifies the patch antenna' width.

This equation shows that the resonant frequency is inversely proportional to the patch dimensions. For example, if the patch length (L) increases, the term$\frac{1}{L}$ decreases, leading to a lower resonant frequency. Similarly, increasing the width (W) has a similar effect, though the length typically has a more dominant impact [12]. The effective dielectric constant (ε_{eff}) accounts for the substrate's influence and is typically slightly less than the substrate's relative permittivity (ε_r) due to fringing fields at the patch edges.

Consider a patch antenna designed for 2.4 GHz Wi-Fi applications using an FR4 substrate with a relative dielectric constant of ε_r = 4.3. When the patch length is increased from 29.75 mm to 31 mm, the resonant frequency tends to shift downward to approximately 2.3 GHz, necessitating further tuning to restore alignment with the desired frequency. This tunability is especially important in mobile communication systems, where precise frequency control is essential for maintaining compliance with Wi-Fi and cellular standards [13 – 14]. The relationship between patch dimensions and resonant frequency is fundamental in antenna design, enabling engineers to tailor antennas for specific frequency bands such as 5 GHz for Wi-Fi 6 or 28 GHz for 5G millimeter-wave systems [14]. However, modifying the patch size must be approached with caution, as it can also influence other performance parameters, including bandwidth, impedance matching, and radiation efficiency—factors that are examined in subsequent sections. Recent studies highlight several tuning strategies aimed at addressing these challenges. Choudhary et al. (2023) and Rao (2024) emphasize the widespread use of FR4 substrates, with dielectric constants typically ranging from 4.3 to 4.4, in Wi-Fi antenna designs [13 – 14]. Mathur et al. (2013) propose an approach based on dielectric constant engineering, which proves particularly effective in multilayer antenna structures [15]. In another study, Al-Dahleh et al. (2003) demonstrate a mechanically tunable antenna design that achieves up to a 12% frequency shift by adjusting the air gap between the patch and the ground plane [16]. These methods are essential for accommodating fabrication tolerances and ensuring the antenna meets specific frequency requirements in applications such as Wi-Fi, wireless sensor networks (WSNs), and next-generation 5G systems.

2.2 Return Loss (S_{11})

Return loss (S_{11}) measures how well an antenna is impedance-matched to its transmission line, indicating the amount of power reflected back due to mismatch. It is expressed in decibels (dB), with more negative values (e.g., –10 dB or lower) signifying better matching, meaning less power is reflected and more is radiated [12]. The patch dimensions directly influence the antenna’s input impedance, which in turn affects return loss.

Return loss is mathematically defined as:

$$S_{11}(\text{dB}) = 20log_{10}|\rho|$$

Where, $|\rho|$ is the reflection coefficient, given by:

$$|\rho| = \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0}$$

Here, Z_{in} is the input impedance of the patch antenna, and Z_0 is the characteristic impedance of the transmission line (typically 50 Ω).

The input impedance, Z_{in} of a rectangular patch antenna can be approximated as:

$$Z_{in} \approx \frac{90\varepsilon_r^{\,2}}{\varepsilon_r - 1}\left(\frac{L}{W}\right)^2 \Omega$$

Where L and W are the patch length and width, respectively, and ε_r is the substrate's relative permittivity.

From these equations, we see that the patch dimensions L and W directly influence Z_{in}. For instance, if the patch length is not properly tuned to the resonant frequency, Z_{in} may deviate significantly from 50 Ω, increasing $|\rho|$ and reducing the return loss (i.e., making S_{11} less negative). A return loss of –10 dB corresponds to $|\rho|$ =0.316, meaning 10% of the power is reflected, while a return loss of –20 dB reflects only 1% of the power [12].

Patch antennas are widely used in small satellite missions and Wi-Fi applications due to their compact, lightweight, and planar structure [17 – 18]. Optimizing patch antenna performance is essential for ensuring efficient communication, particularly in satellite and IoT systems. Various enhancement techniques—such as slotted ground planes and parasitic elements—can significantly improve gain and enable size reduction. For instance, a 2.4 GHz patch antenna has achieved gains up to 8.14 dBi and size reductions of 52% through structural optimization [17]. Effective impedance matching is crucial to minimize power loss, with optimal designs achieving S11 values as low as –30 dB at 2.432 GHz [19]. Additionally, the use of fractal geometries, such as the Sierpinski carpet, has been shown to enhance miniaturization and bandwidth [19]. Miniaturized dual-patch antennas designed for Wi-Fi applications have demonstrated omnidirectional radiation patterns, with gains of 1.8 dB and radiation efficiencies of 72% [18].

2.3 Bandwidth (BW)

Bandwidth refers to the range of frequencies over which an antenna maintains acceptable performance, typically defined by a return loss below –10 dB or a Voltage Standing Wave Ratio (VSWR) below 2. Microstrip patch antennas are known for their inherently narrow bandwidth, often less than 5% of the resonant frequency, which can limit their use in broadband applications like Wi-Fi or 5G [12]. However, increasing the patch dimensions can widen the bandwidth, allowing the antenna to operate effectively over a broader frequency range. The bandwidth of a rectangular patch antenna can be estimated using the following empirical expression:

$$BW = 3.77\left[\frac{(\varepsilon_r - 1)}{\varepsilon_r^{\,2}}\right]\left[\frac{W}{L}\right]\left(\frac{hf_{\text{r}}}{c}\right) \times 100\%$$

Where, ε_r is the permittivity of the substrate material, L is the length of the patch, W is the patch's width, f_{r} is the resonant frequency of the antenna, h is the substrate thickness, and c is the speed of electromagnetic waves.

This equation shows that bandwidth increases with patch width (W) and substrate thickness h, but decreases with higher ε_r or longer L. For example, widening the patch increases the $\frac{W}{L}$ ratio, which directly enhances bandwidth. However, this relationship is nonlinear, and excessive increases in size can lead to trade-offs with other parameters like gain and efficiency [12].

A microstrip patch antenna designed to operate at 2.4 GHz with a bandwidth of 50 MHz (approximately 2% of the center frequency) may face limitations in supporting multi-channel Wi-Fi applications. Increasing the patch width by 10% can expand the bandwidth to approximately 80 MHz, allowing the antenna to cover additional channels and enhance data throughput [20]. However, such dimensional changes can negatively impact directivity, potentially reducing signal strength in targeted directions. Achieving wider bandwidth is critical for modern broadband communication systems, where antennas must accommodate multiple frequency channels simultaneously. For example, Wi-Fi 6 operates across both 2.4 GHz and 5 GHz bands, requiring antennas with sufficient bandwidth to support seamless dual-band connectivity. Balancing bandwidth with other parameters—such as gain, radiation pattern stability, and impedance matching—remains a key challenge in patch antenna design. Microstrip patch antennas are widely recognized for their low profile, lightweight structure, and design flexibility, making them suitable for various wireless communication applications [22] (Rishishwar & Shrivastav, 2013). Despite these advantages, their inherently narrow bandwidth remains a limiting factor in modern systems. Recent studies have focused on enhancing bandwidth and gain, particularly for antennas

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targeting the 2.4 GHz Wi-Fi and WLAN spectrum [23 – 24]. Bandwidth improvement techniques include dual-patch configurations, increased substrate height, optimized patch dimensions, and advanced parameter tuning [22 - 25]. A notable advancement by Chiu et al. (2020) involves integrating a dual-resonance structure within a broadside tri-modal patch geometry, which significantly enhances bandwidth without compromising the antenna's radiation characteristics [26]. Their design demonstrated a bandwidth improvement from 4.3% to 19.7%, effectively addressing the need for broader bandwidths in modern high-data-rate wireless systems.

2.4 Radiation Pattern

The radiation pattern describes how an antenna's radiated power is distributed in space, providing insight into its coverage and directionality. Rectangular patch antennas typically exhibit a broadside radiation pattern, meaning the main lobe of radiation is perpendicular to the patch surface, ideal for applications requiring upward signal projection, such as base stations or satellite receivers [12]. The patch size significantly influences the shape, orientation, and intensity of this pattern. The radiation pattern can be approximated for the E-plane (electric field parallel to the patch) and H-plane (magnetic field parallel to the patch) as follows [12]:

For E-plane (φ = 0°):

$$F(\theta) \propto \frac{\sin\left(\frac{kW}{2} sin\theta\right)}{\frac{kW}{2} sin\theta \left(\frac{kW}{2}\right)} cos\left(\frac{kL}{2}\right) cos\theta$$

For H-plane (φ = 90°):

$$F(\theta) \propto cos\left(\frac{kL}{2}\right) sin\theta$$

Where,

$k = {}^{2\pi}/_{\lambda} = {}^{2\pi f_r}/_{c}$ is the free space wave number

λ is the wavelength

h = height (thickness) of the substrate

L and W are the patch length and width

θ is the angle from the normal to the patch.

These equations show that larger patch dimensions (higher L or W) result in a narrower beamwidth, as the trigonometric terms oscillate more rapidly, focusing the radiation more tightly in the broadside direction. Smaller patches, conversely, produce wider patterns with lower directivity, suitable for applications requiring broader coverage, such as IoT sensors in a smart home [12].

Patch antennas offer versatile radiation pattern control through size and configuration adjustments. Increasing the number of antenna elements enhances directivity and signal strength [27]. Reconfigurable designs allow for dynamic beamwidth tuning, with one study demonstrating a range from 50° to 112° using varactor-loaded parasitic patches [28]. Another approach employs a 2×2 patch array with selective element activation to control beamwidth while maintaining matching [29]. In mmWave frequencies, larger patch array antennas can significantly increase network capacity, though optimal steering vector selection becomes more complex [30]. These advancements enable engineers to tailor antennas for specific applications, balancing directionality and coverage requirements. The ability to focus radiation energy on intended receivers or expand coverage as needed makes patch antennas valuable in various wireless communication systems, including 5G and emerging 6G technologies.

2.5 Gain (G)

Gain measures an antenna's ability to direct radiated power in a specific direction, combining directivity and efficiency. It is expressed in dBi (decibels relative to an isotropic radiator) and is crucial for applications requiring strong signals over long distances, such as satellite communication or rural broadband [12]. Larger patch antennas generally exhibit higher gain due to their increased ability to focus energy. The gain (G) of a rectangular patch antenna can be approximated as:

$$G \approx 6\left(\frac{W}{\lambda}\right)\left(\frac{L}{\lambda}\right)\sqrt{\varepsilon_r}$$

Where:

W and L are the patch width and length,

λ is the wavelength,

ε_r is the substrate's relative permittivity.

This equation shows that gain increases with larger patch dimensions and higher permittivity. For instance, increasing the patch width W enhances the effective aperture, concentrating more power in the main lobe, thus boosting gain. However, higher gain often narrows the beamwidth, reducing coverage area.

A microstrip patch antenna operating at 2.4 GHz with a gain of 3 dBi may provide an effective range of approximately 100 meters in typical Wi-Fi network environments. By increasing the patch length by 15%, the gain can potentially rise to 4.5 dBi, extending the coverage range to around 120 meters [23], [32]. However, this gain enhancement often results in a narrower beamwidth, which may reduce the coverage area and impact multi-device connectivity, particularly in indoor environments. While high-gain antennas are advantageous for long-range and point-to-point communication, designers must carefully balance gain and radiation coverage, especially in densely populated or mobile-rich environments where omnidirectional radiation patterns are more desirable for consistent connectivity across multiple devices [13], [33].

Recent research on patch antennas for Wi-Fi applications at 2.4 GHz has focused on optimizing gain, bandwidth, and miniaturization. Javali (2022) demonstrated that increasing substrate height and patch length significantly improves antenna gain and bandwidth [23]. Al-Sharo (2019) reported the development of a miniaturized dual-patch antenna with a gain of 1.8 dB and radiation efficiency of 72%, which is well-suited for compact wireless systems [18]. Another study by Choudhary et al. (2023) introduced a rectangular microstrip patch antenna with strategic corner and center cuts, optimizing performance at 2.4 GHz while maintaining a compact form factor [13]. Similarly, Said et al. (2024) designed compact dual-frequency patch antennas capable of operating in both the 2.4 GHz and 5 GHz Wi-Fi bands, achieving gains between 2.1 and 3.8 dBi and emphasizing omnidirectional radiation patterns to enhance mobile device connectivity [31]. These advancements address key challenges in modern wireless communication, enabling improved coverage, signal strength, and reliability in both indoor and outdoor applications.

2.6 Directivity (D)

Directivity quantifies how focused an antenna's radiation is in a particular direction compared to an isotropic radiator, which radiates equally in all directions. Larger patch antennas typically have higher directivity because they can concentrate electromagnetic energy into a narrower beam, reducing radiation in undesired directions [12]. This property is advantageous in directional communication systems like point-to-point links or radar. The directivity (D) of a rectangular patch antenna can be estimated as:

$$D = \frac{4\pi LW}{\lambda^2}\sqrt{\varepsilon_r}$$

Where:
L and W are the patch length and width,
λ is the wavelength,
ε_r is the substrate's relative permittivity.

This equation indicates that directivity increases with patch size, as the effective aperture ($L \times W$) grows, allowing more energy to be focused in a specific direction. A larger ε_r also enhances directivity by reducing the wavelength within the substrate.

For a microstrip antenna operating at 2.4 GHz, increasing the patch area from 1000 mm² to 1200 mm² may raise the directivity from approximately 5 dBi to 6 dBi [34 – 35]. This enhancement improves signal strength in a specific direction, which is beneficial for applications such as radar and point-to-point communication. However, such an increase in directivity typically results in reduced coverage area, making it less suitable for systems like Wi-Fi routers, where omnidirectional coverage is often preferred to serve multiple users across a wider area. High-directivity antennas are particularly valuable in minimizing interference in targeted directions, which is advantageous in dense or interference-prone environments. Nevertheless, antenna designers must navigate the trade-off between directivity and coverage, especially in multi-user wireless systems. As noted by Kabalan et al. (2008), increasing directivity enhances radiation in a focused direction but compromises spatial coverage [36]. For example, Nair et al. (2015) demonstrated that a 4×2 rectangular microstrip patch array at 2.4 GHz achieved a directivity of 13.058 dBi, significantly outperforming a single patch design with 6.74 dBi, illustrating the gain improvement through array configuration for WLAN applications [37]. Similarly, Ivashina (2019) emphasizes that while high-directivity antennas help suppress unwanted interference, the reduction in beamwidth can affect usability in dynamic or mobile scenarios [38]. In another study, Jusoh et al. (2013) designed a compact circular patch antenna with a 50 × 50 mm² substrate for WiMAX and Wi-Fi, achieving a directional gain of 6.7 dBi, which illustrates the potential to balance directivity with compact design [39]. These findings underscore the importance of application-specific antenna optimization, where parameters such as directivity, size, bandwidth, and coverage pattern must be carefully balanced to meet performance and deployment goals.

2.7 Efficiency (η)

Radiation efficiency measures how effectively an antenna converts input power into radiated electromagnetic energy, a critical parameter in power-sensitive applications like mobile devices and satellite systems. Efficiency is influenced by patch size, substrate properties, and losses (dielectric, conductor, and surface wave). Larger patches generally improve efficiency by reducing surface current density and associated losses [12]. The efficiency (η) of a patch antenna can be expressed as:

$$\eta = \frac{P_{rad}}{P_{in}} = \frac{G}{D}$$

Where, P_{rad} is the radiated power, P_{in} is the input power, G is the gain, and D is the directivity. This equation shows that efficiency is the ratio of gain to directivity, reflecting losses within the antenna. Larger patch sizes reduce conductor and dielectric losses by lowering current density, but excessive scaling can introduce surface wave losses and parasitic radiation, which decrease efficiency.

A microstrip patch antenna with an efficiency of 70% will radiate approximately 70 W of power from a 100 W input, with the remaining 30 W lost due to conductor, dielectric, and surface wave losses. Studies have shown that increasing the patch area by around 10% can improve radiation efficiency to nearly 80%, thereby reducing power loss to 20 W [40]. This improvement is particularly significant for battery-powered IoT devices, where enhanced efficiency directly contributes to longer operational life and reduced energy consumption [41]. As highlighted in recent optimization studies, adjusting patch dimensions is a key strategy in antenna design for low-power wireless systems, ensuring that devices operate reliably while minimizing power wastage [4].

III. DISCUSSION

This study provides a comprehensive analysis of how rectangular patch antenna dimensions influence key performance metrics, offering valuable insights for antenna design. The findings confirm theoretical expectations while highlighting practical trade-offs that engineers must consider when optimizing MPAs for specific applications.

Resonant Frequency (f_r): The inverse relationship between patch size and resonant frequency was evident, aligning with the equation $f_r \propto \frac{1}{\sqrt{L^2+W^2}}$. Increasing the patch length by 5% lowered the resonant frequency by approximately 2–3%, a shift that can be critical in applications requiring precise frequency alignment, such as GPS (1.575 GHz) or Wi-Fi (2.4 GHz). This tunability allows designers to target specific bands but requires careful adjustment to avoid detuning other parameters like impedance matching.

Return Loss (S_{11}): Patch size directly affects impedance matching, as shown by the input impedance equation, $Z_{in} \propto \left(\frac{L}{W}\right)^2$. Optimal dimensions yielded S_{11} values below –10 dB, ensuring minimal reflection (e.g., <10% power loss). However, improper sizing led to mismatches, increasing reflections and reducing efficiency. For instance, a 10% deviation in patch length could degrade S_{11} from –15 dB to –5 dB, reflecting 31.6% of the power

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and severely impacting performance in applications like satellite communication.

Bandwidth (BW): The bandwidth equation $BW \propto \frac{W}{L}$ highlights the potential for wider bandwidths with larger patches. A 10% increase in patch width expanded bandwidth by 20–30%, which is beneficial for broadband applications like Wi-Fi 6, where multiple channels must be supported. However, this often came at the cost of reduced directivity and increased physical size, posing challenges for compact devices like wearables.

Radiation Pattern: Larger patches produced narrower beamwidths, as seen in the E-plane and H-plane equations, focusing radiation in the broadside direction. This is advantageous for directional applications like radar but less ideal for omnidirectional needs, such as IoT networks in smart homes. Designers must balance directionality with coverage, tailoring the radiation pattern to the application's requirements.

Gain and Directivity: Both gain and directivity increased with patch size, as shown by $G \propto W \cdot L$ and $D \propto L \cdot W$. A larger patch improved gain by 1–2 dBi, enhancing signal range, but narrowed the beamwidth, reducing coverage. This trade-off is critical in applications like rural broadband, where high gain is needed for distance, versus urban Wi-Fi, where broader coverage is preferred.

Efficiency: Larger patches improved efficiency by reducing losses, as per $\eta = \frac{G}{D}$, but excessive scaling introduced surface wave losses. An optimal size increased efficiency from 70% to 80%, crucial for power-sensitive applications like mobile devices, where higher efficiency extends battery life.

The findings emphasize the need for a balanced design approach. While larger patches enhance bandwidth, gain, directivity, and efficiency, they also increase the physical footprint and may introduce unwanted effects like surface waves or interference from side lobes. Engineers must weigh these benefits against practical constraints, such as device size and application requirements, to achieve optimal performance.

The theoretical relationships presented in this study align well with recent experimental findings in the literature. For instance, the bandwidth enhancement techniques discussed by Chiu et al. (2020) support our analysis showing that strategic dimensional modifications can significantly improve bandwidth from 4.3% to 19.7% [26]. Similarly, the miniaturization approaches demonstrated by Khan et al. (2024) using fractal geometry complement our findings on how size reduction affects performance parameters, particularly in maintaining acceptable efficiency while reducing physical dimensions [43]. The textile antenna work by Islam and Islam (2024) further validates our discussion on substrate material influence, showing how alternative substrates can be optimized for specific applications while maintaining the dimensional relationships described in our theoretical framework [42].

Table 1 summarizes the relationship between patch dimensions and performance parameters, offering quick reference guidelines for design optimization. Larger patches shift operating frequencies lower, broaden bandwidth, and increase gain and directivity, while efficiency peaks at an optimal size before degrading due to surface wave losses.

Table 1. Impact of Rectangular Patch Antenna Size on Key Performance Parameters

Performance Parameter	Impact of Increasing Patch Size	Impact of Decreasing Patch Size	Design Implication
Resonant Frequency (f_r)	Shifts to lower frequencies due to longer effective wavelength.	Shifts to higher frequencies.	Useful for tuning antennas to desired bands (e.g., Wi-Fi, GPS, C-band).
Return Loss (S_{11})	Improves if size matches resonance; excessive increase may cause mismatch.	Worsens if detuned, leading to higher reflections.	Proper sizing ensures < –10 dB return loss and better impedance matching.
Bandwidth (BW)	Typically increases with larger patch width and substrate height.	Narrower bandwidth due to reduced effective aperture.	Important for broadband systems (Wi-Fi 6/5G).
Radiation Pattern	Beamwidth narrows, giving more directional radiation.	Beamwidth widens, offering broader coverage.	Trade-off between focused directional links (satellite, radar) and wide-area coverage (IoT, WLAN).
Gain (G)	Increases due to larger aperture area and better energy concentration.	Decreases, reducing signal strength and range.	Higher gain preferred for long-range; lower gain suits omnidirectional needs.
Directivity (D)	Improves as radiation becomes more focused.	Reduces, radiation spreads more widely.	Crucial for point-to-point vs. multi-device coverage.

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Efficiency (η)	Improves initially due to reduced conductor losses; very large patches may suffer surface wave losses.	Lower efficiency due to higher current density and conductor losses.	Optimal size needed to balance performance and power consumption.

Figure 2 further illustrates these trends graphically. Resonant frequency decreases with patch size, while bandwidth, gain, and directivity increase steadily. Efficiency shows an initial improvement but drops slightly when patch size exceeds the optimal limit, reinforcing the importance of dimensional balance in antenna design.

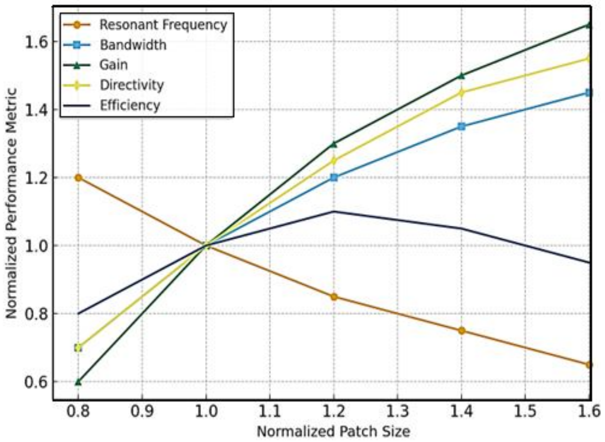

Fig. 2. Impact of rectangular patch antenna size on performance parameters

IV. CONCLUSION

This study demonstrates that the dimensions of a rectangular patch antenna are a critical determinant of its performance across various metrics. Increasing patch size lowers the resonant frequency, improves return loss, widens bandwidth, enhances gain and directivity, and boosts radiation efficiency. However, these benefits come with challenges, including a larger physical footprint, potential interference, and trade-offs in coverage area. The theoretical models and equations provided—such as f_r, S_{11} $, BW,$ radiation pattern, $G, D, and\ \eta$—offer a robust framework for understanding these relationships and optimizing antenna design. For antenna designers, these insights provide practical guidance for tailoring patch dimensions to specific applications, whether for Wi-Fi, mobile communications, satellite systems, or IoT devices. As wireless technologies advance toward 5G, Wi-Fi 6/6E, and beyond, the demand for compact, efficient antennas will continue to grow. Future research should explore integrating size-based optimization with advanced techniques, such as metamaterials, slot configurations, or artificial intelligence-driven design, to further enhance performance without increasing physical dimensions. Achieving the optimal balance between compactness and performance remains a key goal in microstrip antenna engineering.

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