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Design and Optimization of a Bluetooth Microstrip Patch Antenna

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تصميم وتحسين هوائي رقعة ميكرو ستريب لتطبيقات البلوتوث

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Abstract:

This paper presents the design, simulation, and optimization of a microstrip patch antenna optimized for Bluetooth applications (2.4–2.485 GHz). The antenna is designed on an FR-4 substrate (ε_r = 4.3) with a compact structure suitable for IoT, wearable devices, and wireless communication systems. The proposed antenna is simulated using ANSYS HFSS (or CST Microwave Studio), achieving a return loss (S₁₁) < -10 dB, impedance matching at 50 Ω, and a radiation efficiency > 80%. Parametric studies and optimization techniques (e.g., Particle Swarm Optimization) are employed to enhance performance. The simulation of this antenna was done by advanced design system (ADS-A gillnet) software.

Keywords: Microstrip antenna, Bluetooth, FR-4, HFSS, PSO, S₁₁, radiation pattern.

الملخص

تقدم هذه الورقة تصميم ومحاكاة وتحسين هوائي رقعة ميكروستريبية مُحسّن لتطبيقات البلوتوث (2.4-2.485 جيجاهرتز). تم تصميم الهوائي على ركيزة من مادة FR-4 (ε_r = 4.3) ببنية مدمجة مناسبة لتطبيقات إنترنت الأشياء(IoT) ، والأجهزة القابلة للارتداء، وأنظمة الاتصالات اللاسلكية. تمت محاكاة الهوائي المقترح باستخدام برنامج ANSYS HFSS أو CST Microwave Studio)، حيث حقق خسارة عودة (S₁₁) أقل من -10 ديسيبل، ومطابقة معاوقة عند 50 أوم، وكفاءة إشعاع تزيد عن 80%. تم استخدام دراسات بارامترية وتقنيات تحسين (مثل تحسين سرب الجسيمات PSO) لتعزيز الأداء. تمت محاكاة هذا الهوائي باستخدام برنامج نظام التصميم المتقدم (ADS-A gillnet)

الكلمات المفتاحية: هوائي الرقعة الميكروستريبية، البلوتوث، FR-4، HFSS، PSO، S₁₁، نمط الإشعاع.

Introduction

Bluetooth technology (IEEE 802.15.1) operates in the 2.4 GHz ISM band, requiring compact, low-cost, and efficient antennas [1]. Microstrip patch antennas are widely used due to their Low profile and lightweight structure [2], Ease of fabrication (PCB-compatible), and Integration with RF circuits [3].

Several benefits of the microstrip antenna include its low profile, tacky, and versatility, Make it important. For this, its apposite for different implementations, such as global position system (GPS) [4], Bluetooth [5], vehicle depended on satellite, mobile handheld radios and devices of communication [2] . Therefore, we designed the antenna.

A Microstrip Patch Antenna (MPA) is a type of low-profile, printed resonant antenna widely used in wireless communication systems [6]. It consists of a flat rectangular (or circular) metallic patch mounted on a dielectric substrate with a ground plane on the other side [7].

This work focuses contribution on Designing a rectangular patch antenna for Bluetooth, optimizing dimensions for impedance matching, and Analyzing radiation patterns and efficiency. While the rest of the article is organized as follows: Section 2 discussing the antenna design methodology along with their utilized mathematical equations. The acquired results have been demonstrated and discussed in Section 3. The summary conclusion of the manuscript is presented in Section 4 followed by the list of references.

Antenna Design Methodology

There are four key design parameters that determine the specs of the microstrip antenna [8]:

a) The antenna resonant frequency (f_r), should be opted properly. Bluetooth uses 2.4GHz frequency.
b) The substrate Dielectric constant (ϵ_r), the material of dielectric has chosen for our design FR4, which has a dielectric constant of 4.4 and $\tan\delta = 0.001$.
c) The dielectric substrate Height (h), the height has chosen as 1.58 mm.
d) Input impedance ($Zant$), must be matched to 50 Ω and VSWR typically 1.5.

The rectangular microstrip antenna will be designed by advanced design system (ADS) software and will be used to calculate the antenna dimensions [9], [10].

Microstrip Patch Antenna Basics

Microstrip patch antennas are fundamental components in modern communication systems due to their numerous advantages. This paper presents a comprehensive study of these antennas, from theoretical principles to practical applications, focusing on design methodologies and optimization techniques to achieve superior performance across various frequency bands. A patch antenna consists of:

- Conductive patch (radiating element).
- Dielectric substrate (FR-4, Rogers).
- Ground plane (bottom layer).

The resonant frequency (f_r) is given by Eq (1):

$$f_r = \frac{c}{2L\sqrt{\in_e ff}} \qquad (1)$$

where:

- c = Speed of light.
- L = Patch length.
- $\in_e ff$ = Effective dielectric constant.

Therefore, the basic design parameters are presented in Table 1.

Table 1: Design Specifications.

Parameter	Value
Frequency	2.4–2.485 GHz
Substrate (FR-4)	ε_r = 4.3, h = 1.6 mm
Patch material	Copper (σ = 5.8×10⁷ S/m)
Feeding method	Microstrip line (50 Ω)

Patch Dimensions Calculation

1. Width (W) of the patch can be mathematically presented in Eq (2):

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\in_r}} \qquad (2)$$

For 2.4 GHz, W ≈ 37.2 mm

2. Effective dielectric constant (ε_{eff}) is shown in Eq (3):

$$\in_{eff} = \frac{\in_r + 1}{2} + \frac{\in_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-1/2} \qquad (3)$$

3. Length (L) of the patch can be calculated by Eq (4):

$$L = \frac{c}{2f_0\sqrt{\epsilon_{eff}}} - 2\Delta L \quad (4)$$

Where ΔL accounts for fringing fields extension.

4. Ground Plane Dimensions counted by Eq (5) with the help of Eq (6) [2]:

$$L_g = L + 6h \quad (5)$$

$$W_g = W + 6h \quad (6)$$

Feeding Technique

- Quarter-wave transformer for impedance matching.
- Inset feed to minimize reflections.

Table 2: Simulation and Optimization [11].

Simulation and Optimization	Classification	Features
Simulation Setup (HFSS/CST)	Boundary conditions	Radiation boundary.
	Mesh settings	Adaptive meshing for accuracy.
Key Performance Metrics	Return loss (S₁₁)	Target < -10 dB at 2.45 GHz.
	VSWR	< 2 for good matching.
	Radiation pattern	Omnidirectional for Bluetooth.
Parametric Optimization	Variables	Patch length (L), width (W), feed position.
	Algorithm	PSO for fine-tuning.

2.4 Applications of the antenna

- **Antenna Design:** Engineers use VSWR to tune antennas for specific frequencies (e.g., Wi-Fi routers at 2.4 GHz).
- **RF Systems:** Ensures minimal power loss in communication systems.

Table 3: Antenna Dimension at 2.4 GHz [12].

Parameter	**Width (mm)**	**Length (mm)**	ϵ_{reff}	ΔL **(mm)**
Value	38.04	29.449	4.088	0.73

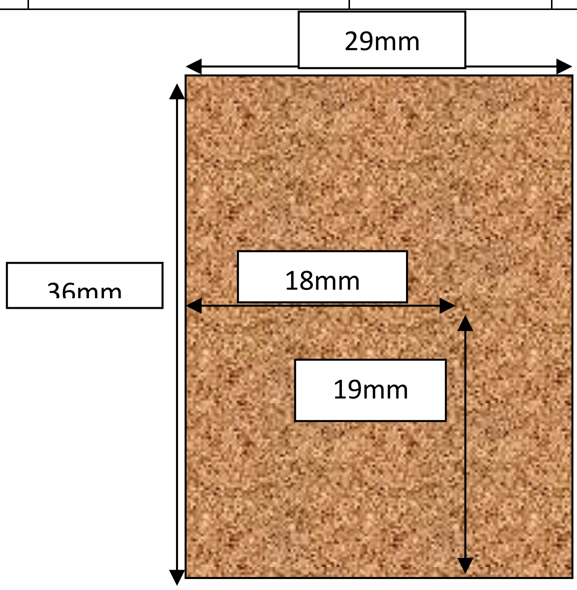

Figure 1: Bluetooth microstrip antenna Dimensions.

Results and discussion

The aid of computer design tools utilized to model and simulate microstrip antenna is ADS software, depending on the moments, and layout method.
The calculated dimensions were essentially used as input to the ADS software to begin the antenna simulation. Aimed to getting optimized values and best outcomes at the resonant frequency (f_r), return loss (S_{11}) and the bandwidth (BW), we have tuned the antenna dimensions. Whereon the patch width is along the Y axis, and the patch length is along the X axis.

Figure 1 shows the Voltage Standing Wave Ratio (VSWR) as a function of frequency (GHz). VSWR is a key measurement in radio frequency (RF) and microwave engineering that indicates how efficiently RF power is transmitted from a source (e.g., a transmitter) to a load (e.g., an antenna).

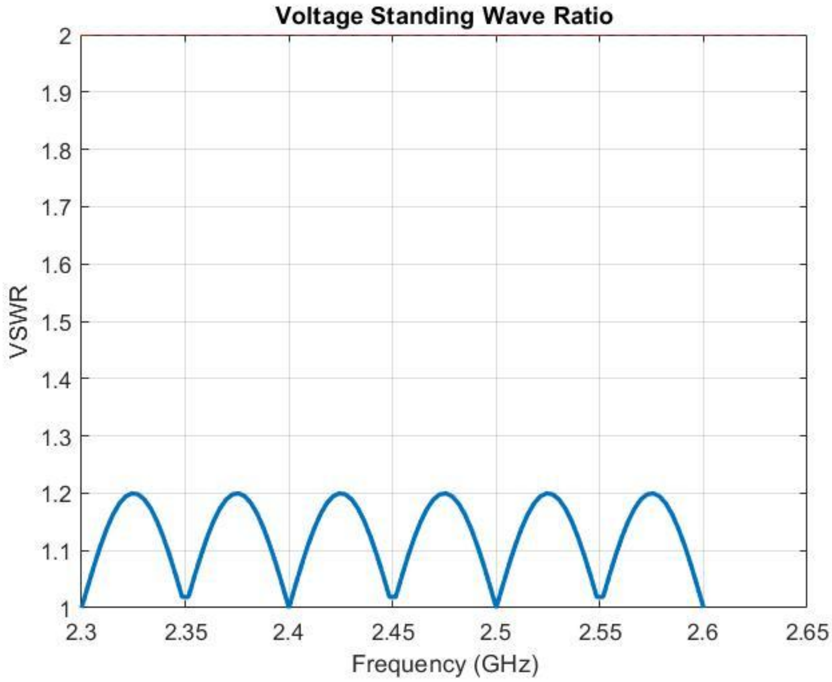

Figure 2: Voltage standing wave ratio.

This polar plot represents the radiation pattern of an antenna at 2.45 GHz, a frequency commonly used in Wi-Fi, Bluetooth, and microwave applications. The graph shows how the antenna radiates energy in different directions, with separate curves for the E-plane (electric field plane) and H-plane (magnetic field plane).

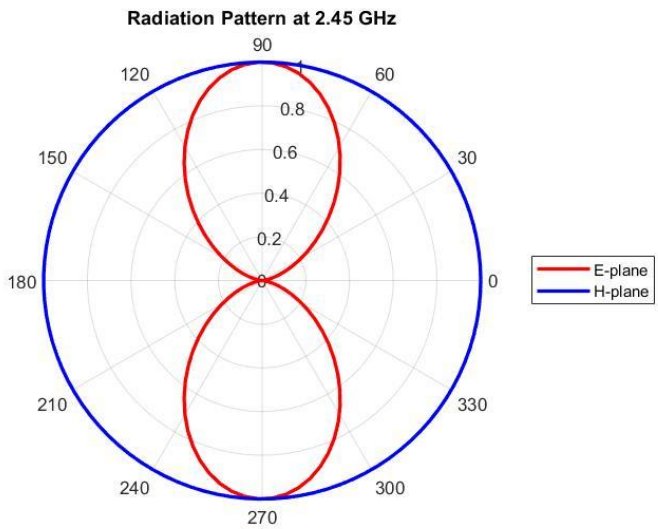

Figure 3: Radiation pattern at 2.45 GHZ

Where the comparison with VSWR at 2.45 GHz, the VSWR was 1.0 (perfect match), meaning this radiation pattern reflects optimal performance at this frequency. If the pattern were distorted, it might correlate with higher VSWR at other frequencies.

Figure 4, it appears the Bluetooth resonant frequency (f_r) is 2.4 GHz, the return loss (S_{11}) is -22.210 dB, and (-3dB) the antenna bandwidth is 86 MHz.

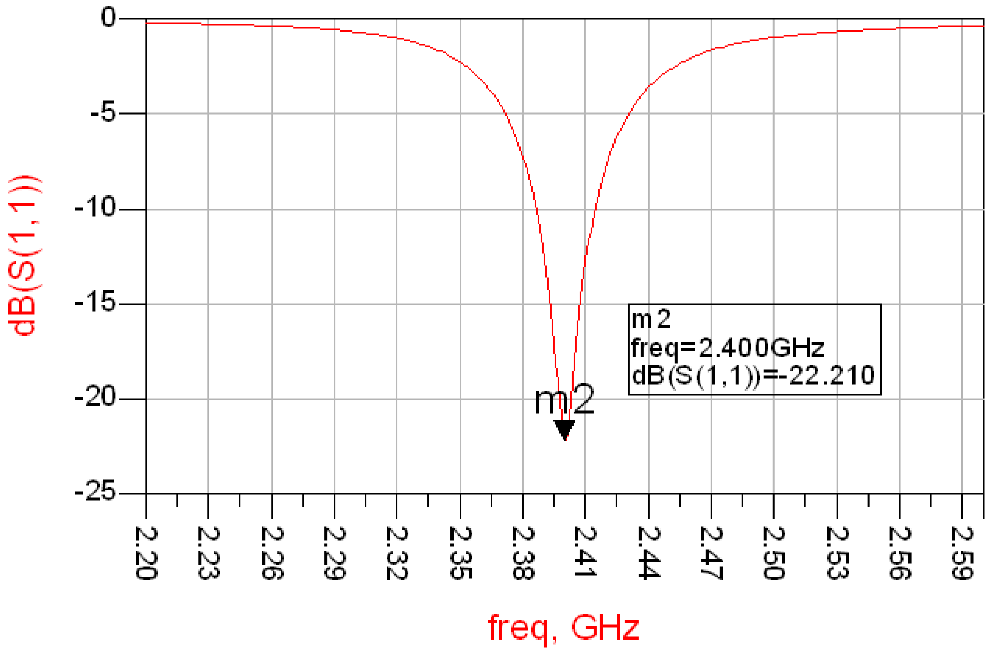

Figure 4: Bluetooth Resonant frequency at 2.4GHz.

Figure 5 appears the antenna input impedance Smith chart is Zant=58.75+j1.3 Ω, which is very nearly to 50 Ω at resonance frequency 2.400 GHz, and it's sensible, because the value of VSWR 1.18 indicates to very low power is reflected, therefore a good antenna matching is achieved.

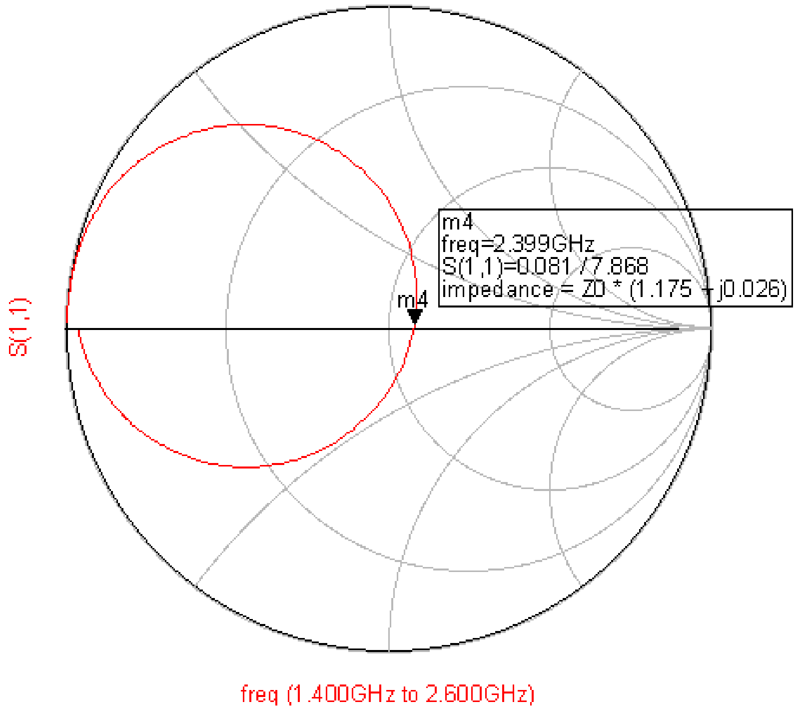

Figure 5: The antenna Input impedance matching at 2.4 GHz.

Table 4: Utilized Parameters details.

Parameters	Results
Return Loss and Bandwidth	• Simulated S₁₁ = -24 dB at 2.45 GHz. • 10 dB bandwidth = 100 MHz, covering Bluetooth range.
Radiation Pattern	• Omnidirectional in H-plane. • Gain = 2.1 dBi, suitable for short-range communication.
Frequency (GHz)	2.45
S₁₁ (dB)	-24
Gain (dBi)	2.1

Conclusion

In This paper, we were attained requirements of the design. the design of microstrip antenna operated at Bluetooth frequency 2.4 GHz, the bandwidths at same frequency is 86GHz, the antenna Smith chart is Zant=58.75+j1.3 Ω, which is very nearly to 50 Ω at resonance frequency, and it's reasonable, because the value of VSWR 1.18 indicates very weak reflected power, so as, a good antenna matching is getting. the significant potential of microstrip patch antennas in modern communication applications. Through careful design and continuous optimization, these antennas can meet current and future wireless system requirements.

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