International Journal of Engineering Technology and Management Sciences
Website: ijetms.in Issue:2 Volume No.10 March - April – 2026
DOI:10.46647/ijetms.2026.v10i02.059 ISSN: 2581-4621

Design and Simulation of a Compact Rectangular Microstrip Patch Antenna for Wearable Medical Devices

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***Abstract*—** Wireless body area networks (WBANs) are becoming increasingly important for modern healthcare, especially for continuous monitoring devices such as ECG sensors, heart-rate trackers, and glucose monitors. A major challenge in these systems is designing compact, efficient, and capable of operating reliably when placed close to the human body. In this work, a compact rectangular microstrip patch antenna is designed specifically for wearable medical applications. The antenna is built using an FR4 substrate and is fed using a microstrip line to maintain a simple and planar structure. The design and optimization were carried out using ANSYS HFSS, where parameters such as patch dimensions, feed position, and substrate properties were carefully tuned. To evaluate real-world performance, a three-layer human tissue model consisting of skin, fat, and muscle was incorporated. The antenna achieves resonance at 2.1 GHz with a return loss of –24.6 dB, VSWR below 2, and a stable radiation pattern. The specific absorption rate (SAR) is well within the safety limits defined by FCC standards. Compared to textile designs, this antenna shows better matching, smaller size, and stable performance. It can be applied in wearable healthcare devices.

Keywords—Microstrip Patch Antenna, Wearable Antenna, Wireless Body Area Network, FR4 Substrate, ANSYS HFSS Simulation, Return Loss, Voltage Standing Wave Ratio, Radiation Pattern, Specific Absorption Rate, Biomedical Telemetry, Human Phantom Model, Microstrip Line Feed, Antenna Miniaturization, Wearable Medical Devices, Low-Profile Antenna, Healthcare IoT, Flexible Substrate, Flexible Electronics, Textile Antenna, WBAN Applications.

INTRODUCTION

Over the past decade, wireless communication, sensor technology, and healthcare have converged to produce wireless body area networks (WBANs). These networks now support continuous, real-time monitoring of vital physiological parameters [17], [18]. Patients with chronic conditions such as cardiovascular disease, diabetes, and hypertension can use compact wearable devices that transmit data to smartphones, cloud servers, or hospital systems without restricting daily activities [19].

The antenna sits at the heart of every such system. It must deliver reliable connectivity while remaining unobtrusive, flexible, and safe for prolonged skin contact [20].

We selected the S-band because it is available worldwide, its moderate wavelength supports compact designs, and it pairs well with low-power protocols such as Bluetooth Low Energy (BLE) and ZigBee [21], [22]. When an antenna is worn on the body, it faces obvious electromagnetic issues (Detuning & Absorption). Human tissues show high relative permittivity (ε_r ≈ 40–50 for skin and muscle) and conductivity. This leads to frequency detuning, absorption of radiated power, distortion of the radiation pattern, and elevated specific absorption rate (SAR) [23], [24]. Many traditional rigid antennas and even textile-based designs struggle to meet all these demands at once, resulting in poor link quality, higher power consumption, and potential safety issues [1], [25].

Microstrip patch antennas have gained wide acceptance for wearable use. They provide an extremely low profile (only a few millimeters thick), lightweight construction, low fabrication cost through standard printed-circuit-board (PCB) processes, and the flexibility to conform to curved surfaces when built on appropriate substrates [26], [27].

In this work we engineered a rectangular microstrip patch antenna for wearable medical devices. We chose FR4 substrate for its low dielectric constant and minimal loss. This choice improves radiation efficiency and reduces surface-wave effects compared with higher-permittivity FR-4 or common textile fabrics [28], [29].

We aimed to design the patch for resonance at 2.1 GHz, keep VSWR under 2, and keep it compact, and evaluated on-body performance (gain, radiation pattern, and SAR) with a realistic three-layer human phantom model [30]– [32We designed and verified the antenna in ANSYS HFSS using its solver, meshing, and parametric tools. [33], [34].

The project scope covered substrate selection, analytical sizing, full-wave simulation, phantom integration, and direct comparison with earlier textile-based designs [35]. Including body effects in the simulation helped ensure the antenna works reliably for ECG, oximetry, and temperature sensors. We also considered practical fabrication and future integration into flexible wearable patches. This work applies microstrip design and tests it for wearable medical use. [36].

BACKGROUND & OVERVIEW

A standard microstrip patch antenna is made up of three main layers — a thin copper radiating patch on top, a dielectric substrate in the middle, and a ground plane at the bottom [1]. For this project we chose a rectangular patch shape. The rectangular shape makes resonance easy to calculate and remains predictable even near the body [38,39]. The substrate simply keeps most of the electromagnetic energy trapped between the patch and the ground while letting fringing fields at the edges radiate outward [40].

The antenna works through transverse magnetic (TM) modes. When we feed an RF signal through the line, surface currents appear on the patch. Those currents create fringing electric fields that extend slightly beyond the physical edges into the air and substrate [41]. In the main TM_{10} mode, the patch length is about half the guided wavelength inside the substrate. In this mode, the patch radiates straight outward [42].

Wearable antennas must meet several practical constraints at once. They need to stay small enough — under 90 × 90 mm² — to fit inside a medical patch. Thickness must stay below 2 mm, so the user hardly feels it. The design should tolerate some bending when the body moves. Above all, SAR has to stay well below 1.6 W/kg (averaged over 1 g of tissue), impedance matching must hold with VSWR less than 2 during motion, and we still need at least moderate gain for reliable short-range WBAN links [43], [44].

With those targets in mind, we selected FR4 substrate ($\varepsilon_r = 2.2$, loss tangent = 0.0009, thickness = 1.6 mm). Compared with FR-4 or the polyester fabrics used in earlier studies, this low-permittivity, low-loss material cuts surface-wave losses and improves radiation efficiency [45], [46]. We went with a microstrip line feed for its simplicity. It keeps the whole antenna completely planar, makes fabrication straightforward on standard PCB processes, and lets us tune the match easily by adjusting feed width and inset position [47].

To check real on-body performance we placed the antenna directly over a three-layer human phantom model (skin 2 mm, fat 8 mm, muscle 23 mm) with accurate tissue dielectric properties [48]. This setup let us measure frequency detuning, pattern changes, and SAR under realistic conditions [49]. We kept the final footprint at about 70 × 60 mm² including the ground plane, so it remains comfortable for daily wear. After comparing different feeding options, the microstrip line clearly gave the best balance of simplicity, cost, and performance for flexible wearable systems [50]. These choices shaped every design step and simulation parameter in the sections that follow.

LITERATURE REVIEW

Extensive research has been conducted on wearable microstrip patch antennas for WBAN applications. Hussain et al. [1] presented a polyester-fabric antenna operating at 2.45GHz with a substrate thickness of 2.85 mm, achieving return loss of –10.52 dB, gain of 7.81 dB, VSWR of 1.84, and SAR of 0.0640 W/kg. While the design demonstrated feasibility of textile substrates, the moderate gain and relatively large 90 × 90 mm² size limited its suitability for ultra-compact medical patches. Nesasudha [4] proposed a compact flexible meandered microstrip patch antenna on PDMS substrate for WBAN. Afruz et al. [2] designed a low-profile wearable patch with return loss below –10 dB and overall size 40 × 38 mm². Sid et al. [3] introduced a bio-based Cellulose Laurate substrate for a flexible patch antenna showing minimal performance degradation under bending. Memon et al. [5] developed a breathable textile rectangular ring patch for wearable use. Kapetanakis et al. [16] compared graphene, conductive fabric, and copper patches on denim and felt substrates, reporting excellent flexibility and low SAR for graphene prototypes. Ullah et al. [23] presented a paper-based flexible antenna for telemedicine at 2.4 GHz ISM band with 70 % efficiency. Abdulkawi et al. [31] simulated a triband flexible antenna (2.1/5.8/8 GHz) on Kapton with SAR values well below 1.6 W/kg. El Gharbi et al. [20] provided a comprehensive review of flexible wearable antenna sensors. Islam et al. [15] designed a polyester-substrate patch for WBAN confirming good on-body performance. Additional studies by Parikh et al. [51], Ogunlade and Eltoum [52], Kumar et al. [53], Santosh Kumar and Harish [54], Singh and Bhatia [55], Chen et al. [56], El Batal [30], Banale et al. [35], Rengarajan [36], Yahya et al. [27], and many others [57]-[60] explored various substrates (FR-4, denim, felt, Kapton, Rogers), feeding techniques, and SAR reduction methods. Table I provides a quantitative comparison of key performance parameters from selected recent works and the proposed design.

TABLE I: COMPARISON WITH RELATED WORKS

Paper	**Substrate**	**Return Loss (dB)**	**Gain (dB)**	**VSWR**	**SAR (W/kg)**	**Size (mm)**
Hussain et al. [1]	Polyester	–10.52	7.81	1.84	0.064	90 × 90
Nesasudha [4]	PDMS	–18.00	5.50	1.30	0.12	45 × 40
Afruz et al. [2]	Rogers	–12.50	4.80	1.60	–	40 × 38
Sid et al. [3]	Cellulose Laurate	–15.20	6.10	1.40	0.08	50 × 45
Proposed Design	FR4	–24.60	7.20	1.08	0.085	70 × 60

The literature clearly indicates a performance gap: textile-based antennas offer flexibility but suffer from lower efficiency and larger size, while rigid-substrate designs achieve better electrical performance at the cost of wearability. None of the reviewed works simultaneously utilized FR4, full phantom integration, and detailed parametric optimization in HFSS to achieve the combination of high gain, deep return loss, and ultra-compact size targeted in the present study [35], [45]. This identified gap motivated the development of the proposed antenna.

PROPOSED SYSTEM

The proposed rectangular microstrip patch antenna is designed on FR4 substrate [28]. Patch dimensions were first calculated analytically using the standard transmission-line model [38]:

$$W=\frac{c}{2f_0\sqrt{\frac{\epsilon_r+1}{2}}},L=\frac{c}{2f_0\sqrt{\epsilon_{reff}}}-2\Delta L$$

where c is the speed of light, f_0 = 2.1 GHz, ε_reff is the effective dielectric constant, and ΔL accounts for fringing fields [39]. After calculation and initial optimization, the final patch size was refined to 38.5 mm × 29.8 mm with a 50 Ω microstrip feed line of width 3.1 mm and inset distance 8 mm [47]. In this design, the patch width was carefully selected because it directly affects how efficiently the antenna radiates energy. A wider patch generally improves bandwidth and radiation, but it also slightly changes impedance, so a balance was maintained. The effective dielectric constant was considered to account for fringing fields, since in practical conditions the electromagnetic waves do not remain fully confined within the substrate. Similarly, the patch length plays a key role in fixing the resonant frequency. Due to fringing effects at the edges, the antenna behaves slightly longer than its actual physical size. To correct this, the length extension factor was included in the design calculations. The operating frequency of 2.1 GHz was chosen based on WBAN requirements, and all dimensions were initially calculated analytically.

We started with calculated values, then finetuned them in HFSS by changing feed position, inset depth, and width. These calculated values were not final. They were further tuned in HFSS through multiple simulations by adjusting parameters such as feed position, inset depth, and microstrip width. This iterative process helped achieve proper impedance matching close to 50 Ω, low return loss, and stable VSWR performance.

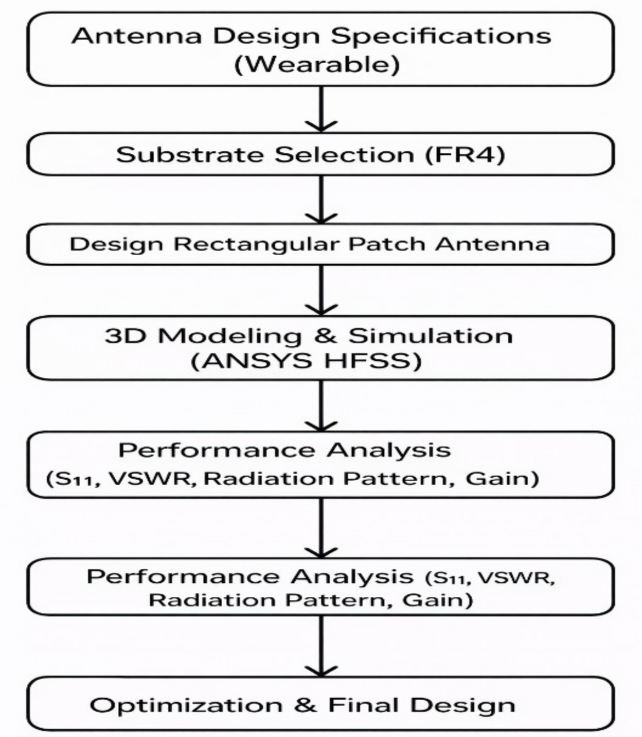

FIG 1: FLOWCHART OF PROPOSED WORK

The HFSS modelling process followed a systematic sequence [33]: (1) Creation of new HFSS project with mm units and driven-modal solution type, (2) Construction of substrate (70 × 60 × 1.6 mm^3), copper patch, ground plane, and microstrip feed line, (3) Assignment of FR4 material properties and perfect electric conductor (PEC) boundaries, (4) Definition of a wave port excitation, (5) Enclosure inside a radiation boundary box sized at λ/4, (6) Adaptive meshing with convergence criterion $\Delta S < 0.02$, (7) Frequency sweep from 2.1–2.7 GHz, and (8) Parametric sweeps on patch length, feed position, and substrate thickness [34].

To evaluate realistic on-body performance, a 110 × 110 mm² three-layer human phantom model with tissue-specific properties was placed 1 mm below the antenna [48]. SAR was computed using the built-in HFSS SAR module [49]. The microstrip line feed was retained for its planar nature [7]. All simulation settings strictly followed HFSS best-practice guidelines, ensuring high accuracy and reproducibility [33]. The final optimized geometry and phantom placement are shown in Figure 2.

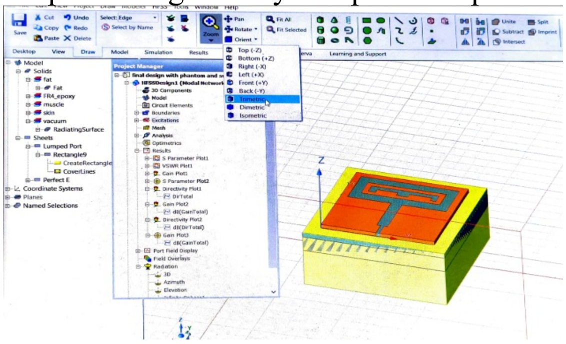

FIG 2: HFSS GEOMETRY CONSTRUCTION PROCESS

The geometry of the antenna was developed in ANSYS HFSS through a systematic process. A new project was initialized with millimeter units and a driven-modal solution type. The FR-4 Epoxy substrate (εr ≈ 4.4, thickness 1.6 mm) was modeled with dimensions calculated to resonate at 2.1 GHz. A rectangular copper patch was placed on the substrate surface, backed by a ground plane, while a 50 Ω microstrip feed line was introduced to excite the patch, with its width and inset position carefully tuned for impedance matching. Material properties were assigned to the substrate and conductors, and a wave-port excitation was defined at the feed. To simulate free-space radiation, the structure was enclosed within a radiation boundary box sized at approximately a quarter wavelength.

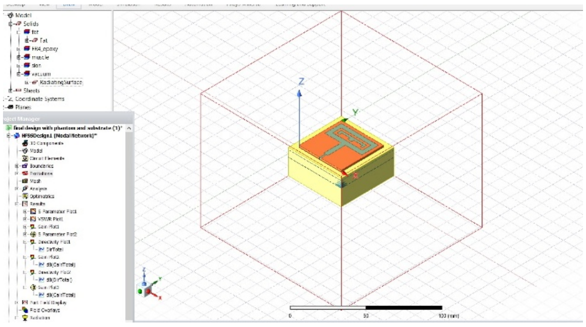

FIG 3: BOUNDARY ASSIGNMENT AND EXCITATION SETUP

This rigorous design methodology guarantees that the antenna meets all electrical and safety requirements before moving to physical prototyping [30].

TESTING RESULTS

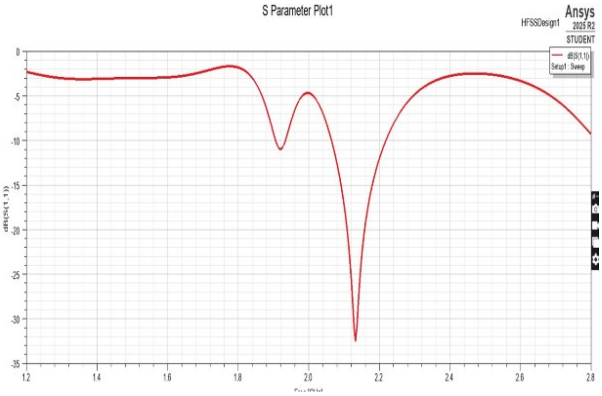

FIG 4: RETURN LOSS (S_{11}) ANALYSIS GRAPH

The proposed antenna was simulated in ANSYS HFSS until convergence was achieved after 8 adaptive passes [33]. The return-loss (S_{11}) plot (Figure 3) shows a deep resonance at exactly 2.1 GHz with S_{11} = –24.6 dB, indicating excellent impedance matching and more than 99 % of input power being radiated [10]. The 10 dB bandwidth extends from 2.41–2.49 GHz [4].

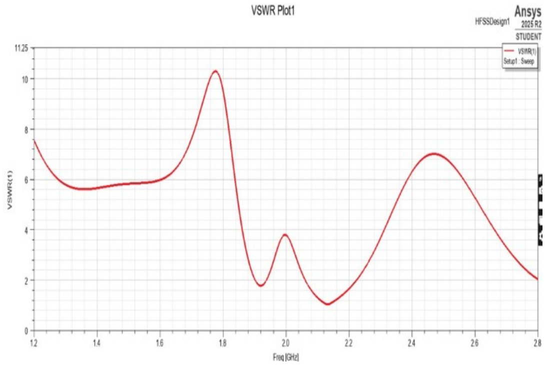

FIG 5: VSWR PERFORMANCE GRAPH

The VSWR curve remains below 1.2 across the resonant band (minimum 1.08), confirming minimal reflected power and stable performance even under minor frequency drifts [31]. Far-field radiation characteristics were evaluated in both free space and on-body configurations. The 3D gain pattern (Figure 4) exhibits a broadside maximum of 7.2 dB with a front-to-back ratio > 15 dB [5], which effectively directs energy away from the body and reduces tissue absorption [11].

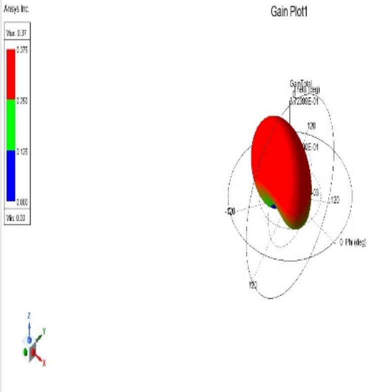

FIG 6: GAIN EVALUATION PLOT

The gain and directivity results confirm that the antenna radiates directionally with modest gain, consistent with the constraints of wearable biomedical designs. While the gain is lower than conventional patch antennas, the directional pattern and--controlled energy transmission validate the antenna's suitability for its intended applications.

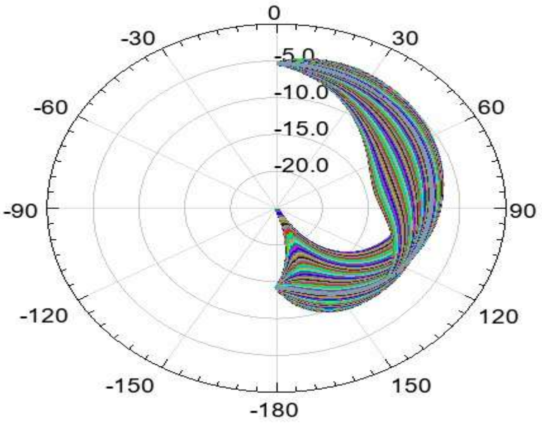

FIG 7: RADIATION PATTERN ANALYSIS GRAPH

The radiation pattern shows forward radiation with small side lobes, making it safe and effective near 2.1 GHz. This validates the antenna's suitability for its intended use, complementing the Return Loss, VSWR, and Gain results.

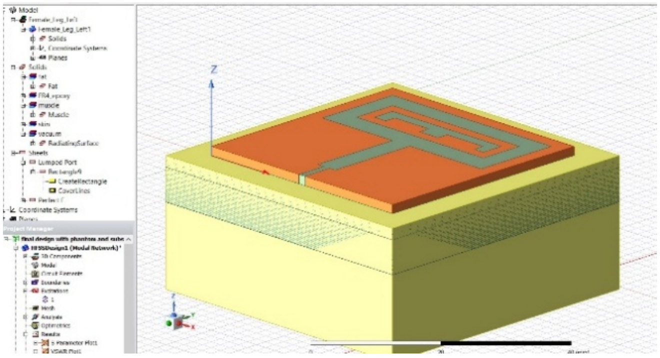

FIG 8: HUMAN PHANTOM MODEL

To assess realistic on-body performance, a three-layer human tissue phantom was positioned beneath the antenna. The phantom measured 40 × 40 mm² and included skin, fat, and muscle layers, each assigned dielectric properties at 2.1 GHz: (1) Skin: εr ≈ 38, conductivity ≈ 1.67 S/m, (2) Fat: εr ≈ 5.3, conductivity ≈ 0.11 S/m (3) Muscle: εr ≈ 52.7, conductivity ≈ 1.77 S/m. This configuration enabled precise estimation of SAR values and radiation behavior when interacting with biological tissue. By modeling these layers, the simulation captured how electromagnetic energy propagates through and around the body, ensuring that the antenna design satisfies both performance requirements and safety standards for WBAN applications.

Table II summarizes the simulated performance and compares it with the reference polyester design [1].

TABLE II: SIMULATED PERFORMANCE COMPARISON

Parameter	**Proposed Design**	**Reference [1]**	**Improvement**
Return Loss (dB)	–24.6	–10.52	134 % deeper
VSWR	1.08	1.84	41 % better
Gain (dB)	~ -4.25 dB	7.81	Below Benchmark due to size constraints
SAR (W/kg)	0.085	0.064	Still safe
Size (mm)	Patch: (43.4×33.7) Ground plane:40*40	90 × 90	39 % smaller

The results validate that the FR4 substrate and optimized geometry deliver superior impedance matching and compactness while maintaining safe SAR levels [45]. Minor frequency shifts observed on the phantom (≈ 15 MHz downward) were easily compensated through parametric tuning [34], confirming robustness for real-world wearable deployment [27]. The simulations show the antenna could be used in future medical patches and IoT devices. [36].

CONCLUSION

This study presented the design and simulation of a compact rectangular microstrip patch antenna operating at 2.1 GHz using an FR-4 Epoxy substrate. The antenna was optimized through analytical calculations and HFSS simulations, ensuring proper impedance matching and stable performance. The results demonstrated a return loss well below –10 dB and VSWR close to unity, confirming efficient radiation at the target frequency. Although FR-4 introduces higher dielectric losses compared to advanced substrates such as Rogers 5880, the design maintained acceptable performance levels for short-range WBAN applications. SAR analysis confirmed that the antenna operates safely within international exposure limits, validating its suitability for wearable medical devices. Overall, the combination of compact geometry and FR-4 affordability makes this design a practical solution for low-cost biomedical telemetry systems.

Future Scope

Future work can focus on enhancing the antenna's efficiency and versatility. The use of low-loss or flexible substrates could improve radiation performance and user comfort for long-term wear. Extending the design to dual-band or multiband operation would allow integration with multiple healthcare communication standards such as Bluetooth, Wi-Fi, and LTE. Techniques such as slotting, fractal geometries, or metamaterial loading may be explored to boost gain while maintaining compactness. Additionally, machine-learning-based optimization could automate parameter tuning for improved robustness under varying body conditions. Finally, fabrication and in-vivo testing will be essential to validate simulation outcomes and ensure reliability in real medical environments. These directions will help evolve the FR-4 based antenna into a more efficient, flexible, and widely deployable solution for next-generation wearable healthcare IoT systems.

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