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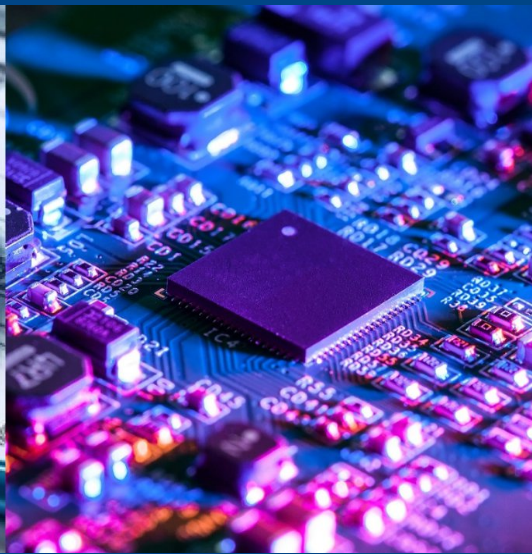

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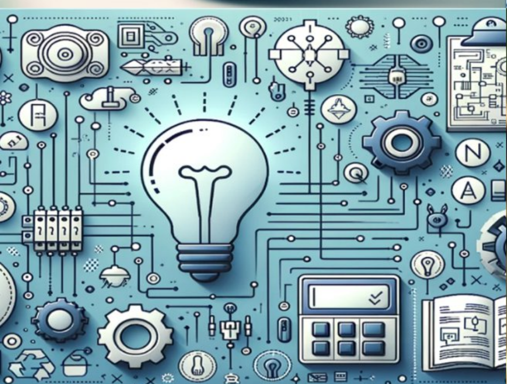

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Design and Simulation of Water Resistant Wearable Textile Antenna for Multiple Frequency Bands

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ABSTRACT: This paper presents the design and simulation of a water-resistant wearable textile antenna for multiple frequency band applications, including the 2.4 GHz ISM band used in Bluetooth, Wi-Fi, and WBAN. The antenna employs a conductive fabric patch on a flexible substrate to ensure both comfort and reliable performance. Its behavior under moisture conditions is analyzed by varying dielectric properties to simulate sweat and humidity effects. Simulations using HFSS evaluate key parameters such as return loss, gain, bandwidth, and Specific Absorption Rate (SAR). The antenna demonstrates stable performance under both dry and wet conditions, making it suitable for smart textiles and on-body IoT applications.

KEYWORDS: Wearable Antenna, Textile Antenna, Multi-Band Antenna, 2.4 GHz ISM Band, Moisture Resistance, WBAN, Smart Textiles, HFSS, SAR.

I. INTRODUCTION

The rapid growth of wearable technology has significantly increased the demand for compact, lightweight, and flexible antennas capable of supporting reliable wireless communication. These antennas are essential components in applications such as healthcare monitoring, sports tracking, and Internet of Things (IoT) systems, where continuous on-body communication is required. Unlike conventional antennas, wearable antennas are integrated into clothing and operate in close proximity to the human body, making factors such as flexibility, comfort, and safety critical in their design.

However, wearable textile antennas face several challenges due to their operating environment. Mechanical deformation caused by bending and stretching, as well as interaction with the human body, can affect antenna performance. Additionally, environmental factors such as moisture, sweat, and humidity can alter the dielectric properties of the substrate, leading to detuning, reduced efficiency, and unstable performance.

To overcome these limitations, this work focuses on the design and simulation of a water-resistant wearable textile antenna for multiple frequency bands, particularly the 2.4 GHz ISM band used in Bluetooth, Wi-Fi, and Wireless Body Area Network (WBAN) applications. The proposed antenna uses a conductive fabric patch on a flexible, low-dielectric substrate to ensure both comfort and efficient performance. The design is analyzed using ANSYS HFSS, evaluating key parameters such as return loss, bandwidth, gain, radiation pattern, efficiency, and Specific Absorption Rate (SAR). The goal is to achieve stable and reliable performance under both dry and wet conditions, making the antenna suitable for integration into smart textile systems.

II. LITERATURE REVIEW

A comprehensive review of existing research on wearable textile antennas has been carried out to understand current design approaches, performance characteristics, and associated challenges. Various studies focus on flexible antenna structures, integration into clothing, and performance under practical conditions such as bending and environmental exposure. While significant improvements have been achieved in terms of bandwidth, flexibility, and efficiency, issues

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such as moisture sensitivity, fabrication complexity, and performance degradation in real-world conditions still remain. The following table summarizes key contributions from relevant literature along with their major limitations, providing a foundation for the proposed work.

No.	Author & Year	Title	Summary	Major Limitations
1	Roy et al., 2020	Jeans-Based Flexible Textile Antenna Design	Design and analysis of textile antenna with no slot, one slot, and varying ground width; HFSS simulation; bending and body model analysis; manual fabrication and testing.	Limited bandwidth; sensitive to moisture absorption without special treatment..
2	Hertleer et al., 2009	Textile Antennas Integrated in Protective Clothing	Integrated textile antennas into firefighter clothing for reliable wireless communication in harsh conditions; evaluated textile materials and optimized antenna placement for durability and robust performance.	Complexity of textile integration; performance affected by textile properties.
3	Shakhirul et al., 2014	Embroidered Flexible Textile Antennas for Wearable Applications	Use of embroidery to construct wearable textile antennas using conductive threads; performance evaluated under bending and wet conditions for real-life scenarios.	Performance degradation when wet; fabrication complexity..
4	Roy and Chakraborty, 2019	Metamaterial-Based Dual Wideband Textile Antennas	Metamaterial-based dual wideband textile antenna with bandwidth enhancement and bending effect analysis.	Complex design; fabrication challenges.
5	Saeed et al., 2017	Flexible Reconfigurable Wearable Antennas with Artificial Magnetic Conductors	Reconfigurable wearable antenna using artificial magnetic conductor with improved radiation near body and adaptability to movement.	Increased complexity and cost; requires tuning.

III. METHODOLOGY OF PROPOSED SURVEY

Problem Statement:
Conventional wearable antennas are highly sensitive to moisture conditions such as sweat and humidity, which lead to detuning, increased losses, and unstable performance during practical use. Many existing textile antennas provide flexibility but fail to maintain consistent electromagnetic characteristics when exposed to real body environments and bending effects.

Additionally, achieving reliable performance in terms of bandwidth, efficiency, and safe Specific Absorption Rate (SAR) remains a major challenge for antennas used in Wireless Body Area Networks (WBAN), Bluetooth, and Wi-Fi applications. Therefore, there is a need to design a compact, flexible, and water-resistant wearable textile antenna that can operate stably at the 2.4 GHz ISM band while being suitable for seamless integration into smart textile systems.

Objectives:

- To design and simulate flexible, water-resistant textile antennas at multiple frequency bands using HFSS for wearable applications**.**
- To study antenna performance in dry and wet conditions by varying substrate dielectric properties and analyze parameters like S11, bandwidth, gain, and efficiency.
- To ensure stable, reliable, and safe operation for integration into smart textiles used in WBAN, Bluetooth, Wi-Fi, health monitoring, and sports tracking applications.

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- To develop a compact and lightweight antenna structure suitable for seamless integration into wearable systems.
- To analyze the effect of environmental factors such as bending, body proximity, and moisture on antenna performance.
- To optimize antenna design parameters to achieve improved impedance matching and enhanced radiation characteristics.
- To evaluate and compare antenna performance under different substrate materials such as FR-4, denim, Kapton, and felt.

Architecture Diagram and Proposed Methodology:

Proposed Method:

The proposed work focuses on the design and simulation of a water-resistant wearable textile antenna operating at multiple frequency bands, particularly the 2.4 GHz ISM band. The antenna is designed using a conductive textile patch placed on a flexible, low-dielectric substrate to ensure comfort, durability, and efficient electromagnetic performance.To enhance antenna characteristics, techniques such as defected ground structures (DGS) are incorporated to improve return loss, bandwidth, and overall efficiency. The antenna is modeled and simulated using ANSYS HFSS to evaluate key performance parameters including return loss (S11), impedance matching, gain, radiation pattern, efficiency, and Specific Absorption Rate (SAR). A major focus of the proposed method is the analysis of moisture effects. The impact of sweat and humidity is studied by varying the dielectric properties of the substrate, enabling evaluation of antenna performance under both dry and wet conditions. Different substrate materials such as FR-4, denim, Kapton, and felt are considered to optimize performance.The design process includes parameter optimization, performance validation, and comparison of results under varying environmental conditions to ensure stable and reliable operation for wearable applications.

Antenna Design:

The proposed antenna model consists of a conductive patch and a ground plane fabricated using Perfect Electric Conductor (PEC), mounted on a flexible textile substrate. The substrate materials used include FR-4, denim (jeans fabric), Kapton, and felt, selected based on their dielectric properties and suitability for wearable applications.The antenna is designed with a compact structure and optimized dimensions to operate within the frequency range of 1–10 GHz, with primary focus on 2.4 GHz. The patch geometry is modified using slot structures to enable multiband operation and improve impedance matching.The design and modeling are carried out in ANSYS HFSS, where the substrate, ground plane, and patch geometry are created and optimized. The antenna is analyzed under different conditions including bending and moisture exposure to simulate real-world wearable scenarios.Key design parameters such as substrate dimensions, patch size, slot dimensions, and feed structure are carefully selected to achieve desired performance in terms of bandwidth, gain, and efficiency. The antenna model ensures flexibility, lightweight structure, and compatibility for integration into smart textile systems used in IoT, healthcare monitoring, and wireless communication applications.

Architecture Diagram:

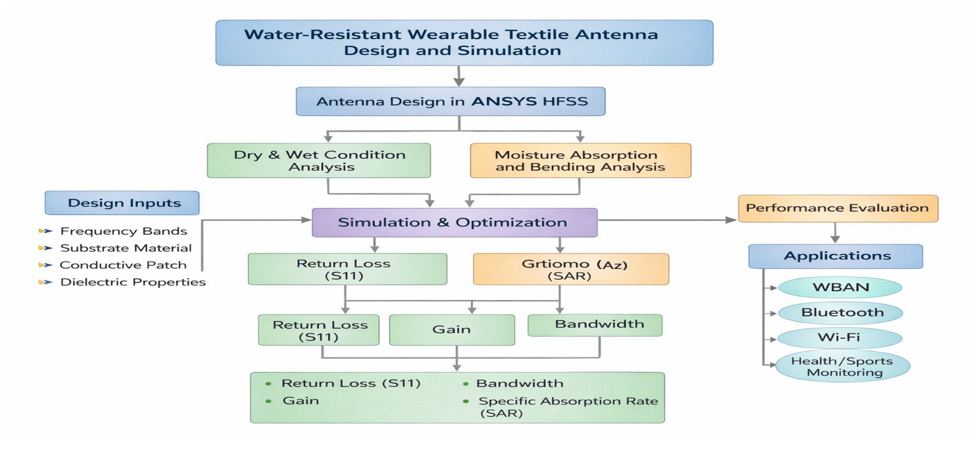

Fig1. Architecture Diagram

The proposed method implementation is structured as follows:

1. Textile Selection: A suitable textile material is selected based on flexibility, comfort, and dielectric properties. Materials such as denim, felt, Kapton, or FR-4 are considered due to their low dielectric loss and ability to support electromagnetic wave propagation. The selected material must also be durable and capable of withstanding environmental factors like moisture and bending, making it suitable for wearable applications.

2. Antenna Design: The antenna structure is designed by defining the patch geometry, substrate, and ground plane configuration. A conductive textile or Perfect Electric Conductor (PEC) is used for the radiating patch and ground plane. The design is targeted to operate at the desired frequency bands, especially the 2.4 GHz ISM band, ensuring compatibility with applications such as Bluetooth, Wi-Fi, and WBAN systems.

3. Modeling and Optimization: The antenna geometry is modeled using ANSYS HFSS. Key parameters such as patch dimensions, substrate thickness, feed line dimensions, and slot configurations are carefully adjusted. Optimization is performed iteratively to achieve proper impedance matching, desired resonant frequency, and improved bandwidth and gain.

4. Simulation in HFSS: The designed antenna is simulated using high-frequency electromagnetic analysis in HFSS. Important performance parameters such as return loss (S11), Voltage Standing Wave Ratio (VSWR), gain, radiation pattern, efficiency, and Specific Absorption Rate (SAR) are evaluated to ensure the antenna meets required performance standards.

5. Moisture Analysis: To study real-world performance, the effect of moisture such as sweat and humidity is analyzed. This is done by varying the dielectric constant and loss tangent of the substrate in simulation. The analysis helps in understanding how moisture impacts resonance, efficiency, and signal strength, and ensures the antenna maintains stable performance under wet conditions.

6. Water-Resistant Treatment: A protective waterproof coating or treatment is applied to the textile substrate to minimize moisture absorption. The challenge is to ensure that this coating does not significantly affect the electrical properties of the antenna. Proper selection of coating materials helps in maintaining both durability and electromagnetic performance.

7. Fabrication: The antenna is fabricated by placing or attaching the conductive textile or metallic patch onto the selected substrate. Techniques such as stitching, adhesive bonding, or thermal pressing are used. Care is taken to maintain accurate dimensions and proper alignment to match the simulated design.

8. Testing and Measurement: The fabricated antenna is tested using a Vector Network Analyzer (VNA) to measure parameters like S11, bandwidth, and impedance matching. Additional tests may include radiation pattern and gain measurements. Testing may also be conducted under bending or on-body conditions to evaluate practical performance.

9. Result Analysis: The experimental results are compared with simulation results obtained from HFSS. Any deviations are analyzed, and necessary design improvements are made. This step ensures validation of the design and confirms that the antenna meets the required specifications for wearable and IoT applications.

Requirements for Software and Hardware:

Software Requirements:

- **ANSYS HFSS SOFTWARE:** Used for designing, modeling, and simulating the wearable textile antenna. It helps in analyzing parameters such as return loss (S11), gain, bandwidth, radiation pattern, efficiency, and SAR.
- **Operating System:** Windows 10 or later for smooth installation and execution of HFSS software.
- **CAD Modeling Tools:** Used for creating and modifying antenna geometries before simulation.
- **Data Analysis Tools:** Tools for analyzing simulation results and generating graphs (can be integrated within HFSS).

Hardware Requirements:

- **Computer System:** A system with minimum Intel i5 processor (or higher), 8 GB RAM (16 GB recommended), and sufficient storage to run HFSS simulations efficiently.

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- **Conductive Textile / Copper Material:** Used for fabricating the antenna patch and ground plane.
- **Substrate Materials:** Materials such as FR-4, Denim (jeans fabric), Kapton, or Felt used as the dielectric substrate.
- **Vector Network Analyzer (VNA):** Used to measure antenna parameters like S11, impedance, and bandwidth during testing.
- **Fabrication Tools:** Tools such as cutting tools, stitching equipment, or adhesive bonding materials for assembling the antenna.
- **Measurement Setup:** Includes connectors, cables, and test environment for evaluating antenna performance

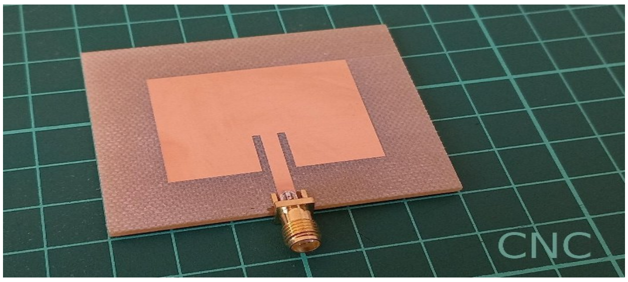

Fig. Conductive Textile Material **Fig. Vector Network Analyzer**

IV. ANTENNA DESIGN AND RESULTS

1. Circular Patch Antenna:

A circular patch antenna with a slot is used as the basic design. It provides simple structure and achieves resonance near the desired frequency band.

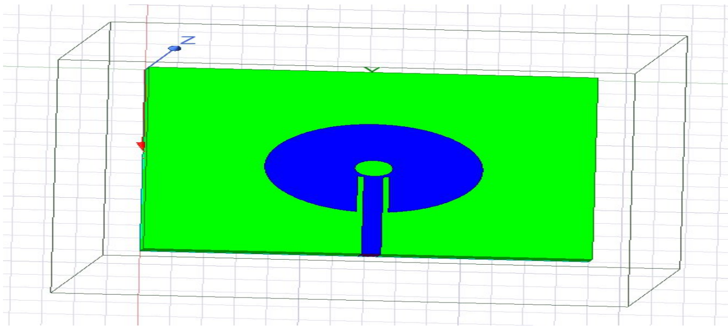

Fig 2. Circular Patch Antenna

2. Dual Band Microstrip Patch Antenna:

The patch is modified by adding multiple slots, which improves impedance matching and enables multiband operation**.**

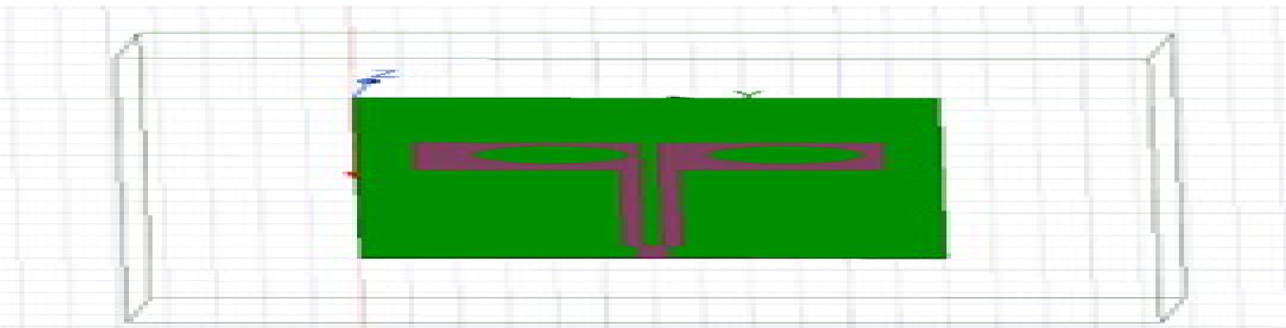

Fig 3.Dual Band Microstrip Patch Antenna

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3. **U-Shape Antenna:**
A rectangular/modified patch structure is introduced to enhance bandwidth and achieve better return loss performance.

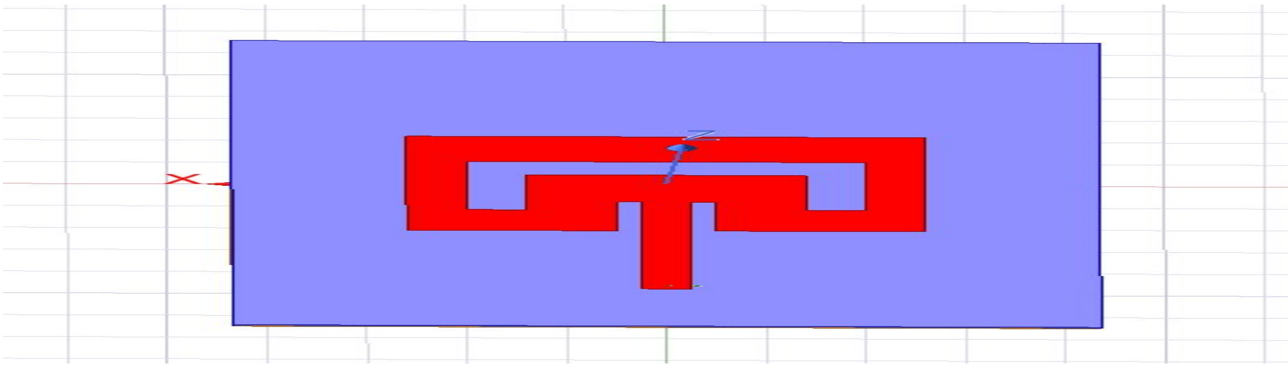

Fig 4. U-Shaped Antenna

4.E-Shaped Antenna:
An E-shaped patch with slots that increases current path, giving better bandwidth and multiband operation.

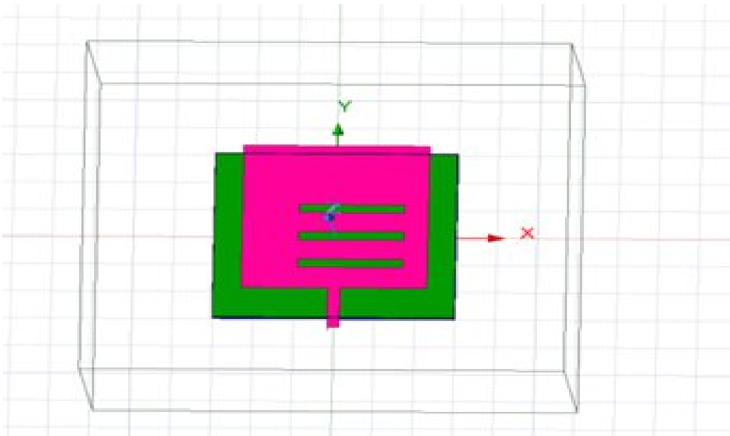

Fig 5. E-shape Antenna

V. RESULTS AND DISCUSSIONS

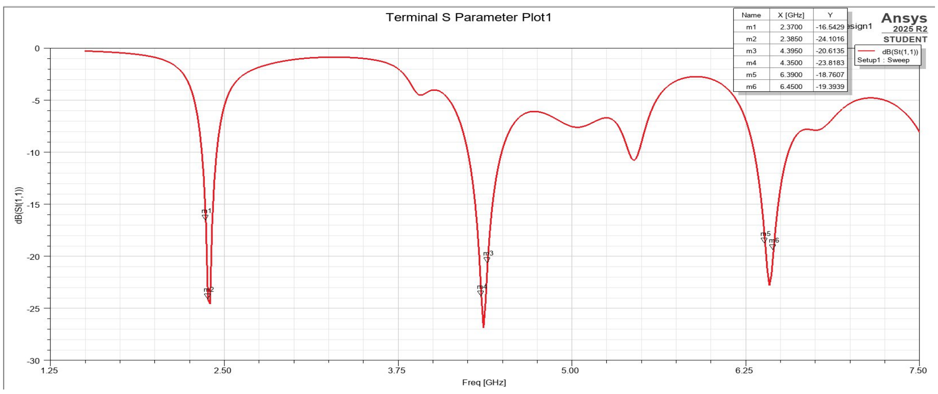

Fig 6. S11 plot for circular patch antenna

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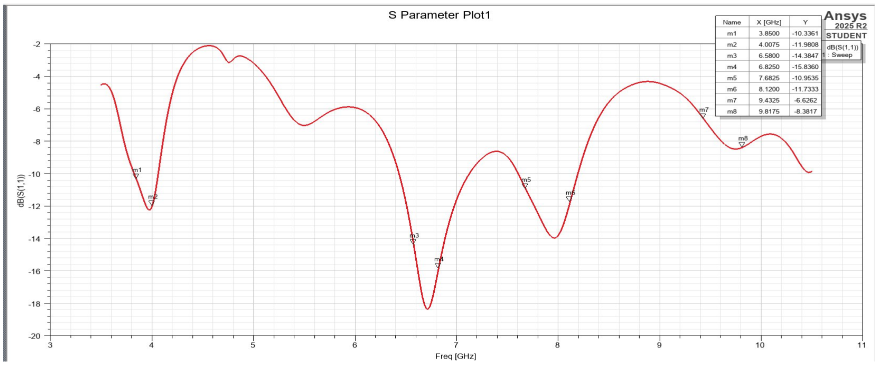


Fig 7. S11 plot for dual band microstrip patch antenna

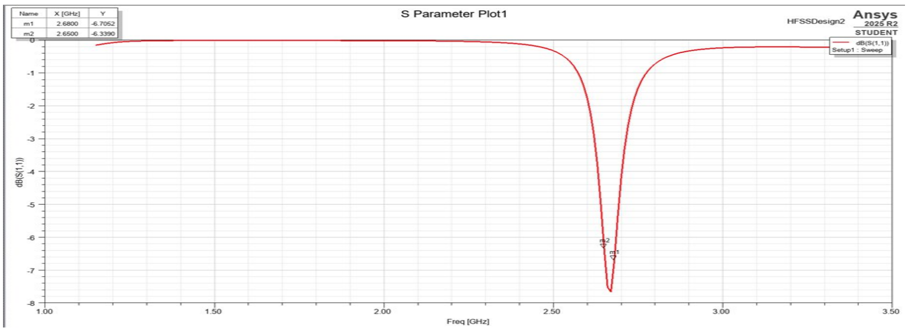


Fig 8. S11 plot for U-shaped antenna

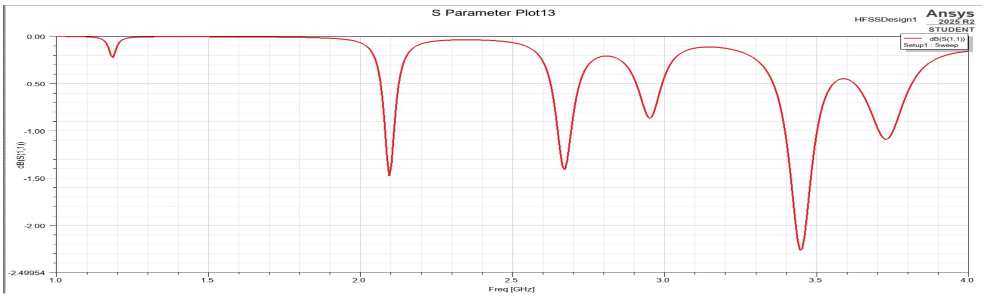
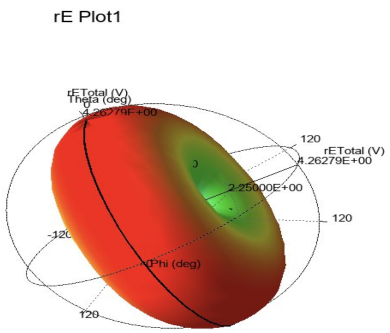


Fig 9. S11 plot for E-shaped antenna



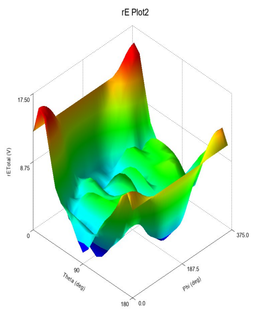


Fig 10. Gain plot for circular patch antenna Fig 11. Gain plot for dual band microstrip patch antenna

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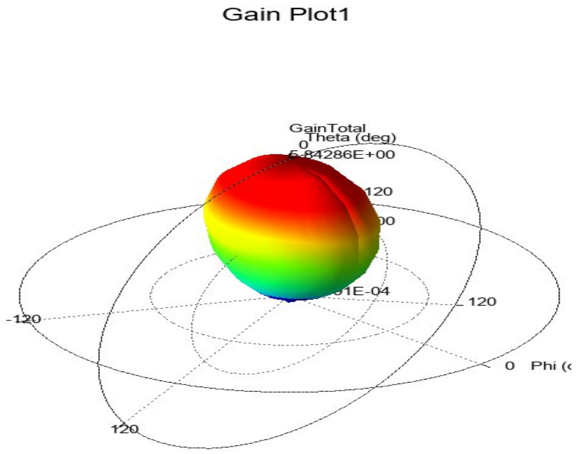

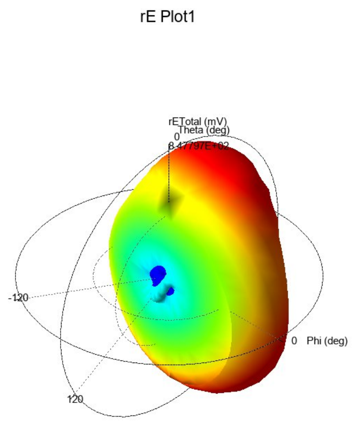

Fig 13. Gain plot for E-shaped antenna Fig 12. Gain plot for U-shaped antenna

Discussion:

The proposed wearable textile antenna designs were successfully simulated and analyzed using ANSYS HFSS, demonstrating stable resonance around the 2.4 GHz ISM band, making them suitable for applications such as Bluetooth, Wi-Fi, and WBAN. The S11 results indicate return loss values below -10 dB for all designs, confirming good impedance matching and efficient signal transmission. Modified antenna structures, including E-shaped and U-shaped designs, showed improved bandwidth and deeper resonance characteristics, enabling effective multiband operation. The antennas exhibited stable radiation patterns with satisfactory gain, ensuring reliable performance in wearable environments. Furthermore, moisture analysis revealed that the antenna maintains consistent performance under both dry and wet conditions, with only minor shifts in resonant frequency due to variations in substrate dielectric properties. The use of flexible materials such as denim, felt, Kapton, and FR-4 provided both mechanical flexibility and acceptable electromagnetic performance. Additionally, the Specific Absorption Rate (SAR) values were within safe limits, confirming the suitability of the antenna for on-body applications. Overall, the results validate that the proposed antenna designs are efficient, reliable, and well-suited for integration into smart textile and IoT-based wearable systems.

VI. CONCLUSION

A water-resistant wearable textile antenna was designed and simulated for various bands using HFSS. The antenna employed a conductive fabric patch on a flexible substrate, ensuring both durability and user comfort. Moisture conditions such as sweat and humidity were simulated by varying substrate dielectric properties to study real-world performance. The simulation results showed stable resonance at 2.4 GHz with good bandwidth, efficiency, and radiation characteristics, while maintaining safe SAR levels. The design proved suitable for smart textile integration in applications such as health monitoring, sports tracking, Bluetooth, Wi-Fi, and WBAN systems.

Furthermore, the proposed antenna demonstrates reliable performance under practical environmental conditions, making it a promising solution for next-generation wearable communication systems. The study highlights the effectiveness of flexible materials and optimized design techniques in achieving stable and efficient antenna performance.

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