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RESEARCH ARTICLE

Smart Sensor-Embedded Textile Antenna System for Real-Time Tracking of Respiratory and Musculoskeletal Disorders Using IoT-based Remote Healthcare Networks

Kutliyev Sardor Pulatovich[1]*, Khurshid Sodikov[2], Geldiev Bexruz[3], Shoxsanam Sobirova[4], Dilfuza Berdieva[5], S. Vaishnodevi[6], R. Sathish[7]

[1]*Department of Data Transmission Networks and Systems, Urgench State University named after Abu Rayhan Biruni, Urgench, Uzbekistan.*
[2]*Department of Mechatronics and Robotics, Faculty of Electronics and Automation, Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan.*
[3]*Department of Basic Medical Sciences, Faculty of Medicine, Termez University of Economics and Service, Termez, Uzbekistan.*
[4]*Department of Computer Systems, Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Tashkent, Uzbekistan.*
[5]*Department of Faculty and Hospital Therapy No. 1, Rheumatology, Occupational Pathology, Tashkent State Medical University, Tashkent, Uzbekistan.*
[6]*Department of Biomedical Engineering, Vinayaka Mission's Kirupananda Variyar Engineering College, (Vinayaka Mission's Research Foundation), Salem, Tamil Nadu, India.*
[7]*Department of Electrical and Electronics Engineering, Vinayaka Mission's Kirupananda Variyar Engineering College, (Vinayaka Mission`s Research Foundation), Salem, Tamil Nadu, India.*

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ABSTRACT

The development of wearable biomedical systems necessitates the use of antennas that can monitor physiological parameters concurrently and withstand wireless connections in the face of dynamic body movements. This paper introduces a smart sensor-integrated textile antenna system for real-time monitoring of respiratory and musculoskeletal conditions in IoT-based remote healthcare systems. The suggested system combines conductive textile fabrics with strain, pressure, and humidity sensors embedded within the textile to detect the level of thoracic expansion, joint flexion, and irregular breathing. The antenna architecture is designed in the form of a compact dual-band antenna to enable the continuous transmission of data in medical telemetry and low-power IoT bands. An integrated signal-fusion system is also presented to produce a correlation between sensor responses and adaptive antenna performance measurements for accurate diagnosis. The simulation of full-wave EM is used to validate the experiment, and a prototype of a flexible polyester-cotton material. Findings showed constant impedance properties, sensitivity to biomechanical deformation, and the ability to transmit wireless information with energy efficiency in different body postures. The combination of multimodal sensing with a textile antenna in integrated physiological monitoring is a novel and effective approach for telemedicine and long-term patient supervision.

Authors' e-mail ID: q.sardor.86@gmail.com; xurshid19970121@gmail.com; behruz_geldiyev@tues.uz; shsobirova1988@gmail.com; dr.dil1979@gmail.com; vaishnodevi@vmkvec.edu.in; sathish@vmkvec.edu.in

Authors' orcid ID: 0000-0003-4133-0076; 0009-0007-0672-3145; 0009-0000-2191-5902; 0009-0001-3250-0312; 0009-0000-9296-607X; 0000-0002-0791-1400; 0000-0002-9956-5014

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INTRODUCTION

Wearable biomedical devices are necessary for the constant monitoring of chronic disorders, especially those that involve the respiratory and musculoskeletal functions.[1,2] The recent progress in stretchable materials, miniature electronics, and low-electronic wireless platforms has propelled the creation of textile sensing and antenna systems.[3-5] Although this has been made possible, long-lasting physiological measurements are yet to be recorded because of the inconsistency of human movement, deformation of wearable material, and changes in wireless channel properties.[6,7] Conventional patch-based sensing devices are not always comfortable, durable, and can fully integrate into daily apparel, making them less likely to be adhered to in the real-world context.[8] Textile antennas are promising because of their conformability, breathability, and mechanical stability, to be used in unobtrusive, integrated health-monitoring systems.[9,10]

Several studies have been conducted on fabric antennas, smart clothes, low-SAR radiators, and optimized wireless telemetry for healthcare practices.[9-13] The majority of designs currently in use, however, consider sensors and antennas to be separate modules, which makes the system larger, consumes more power, and worsens performance during deformation or body movement.[7] With the increasing popularity of remote healthcare systems based on Internet of Things (IoT)-based platforms, real-time, physiological, low-latency and high-reliability data transmission becomes relevant in the context of clinical decision support.[14,15] The accomplishment of these needs requires combined solutions in electromagnetic design, sensor location, multimodal fusion, and adaptive signal processing.[16]

Recent literature has focused more on multiband functionality, adaptive impedance solutions, and SAR-compatible features of wearable medical equipment.[13,17,18] In the case of musculoskeletal disorders, both the joint displacement and mechanical strain are essential in identifying the early diagnosis and monitoring rehabilitation early diagnosis and monitoring.[2,4,5] At the same time, analyzing the respiratory conditions, the enlargement of the thorax, and alterations in the humidity relative to the airflow variations need to be accurately monitored.[19,20] Embedded sensors should be very responsive and at the same time coexist with the radiating elements of the antenna without affecting the electromagnetic performances. Along with this, recent studies in embedded medical systems and RF sensor design point to the increasing demand for a simultaneous combination of sensing and communication components with small biomedical systems.

To overcome these limitations, the current paper presents a smart textile antenna system based on multimodal sensors being directly embedded into the dual-band conductive-fabric antenna design that is optimized to work with the IoT-enabled remote healthcare setup. The most important contributions are as follows:

1. A strain, pressure, and humidity embedded antenna;
2. An integrated musculoskeletal, muscular, and respiratory tracking algorithm;
3. An adaptable IoT communication interface that can stream remote data;
4. EM validation by simulation, fabrication of prototypes and testing of dynamic body motion.

RELATED WORKS

The studies on wearable antennas have mainly concentrated on conformal materials, low-SAR radiations, and consistent functionality regarding mechanical deformation.[9,14,17] Smart clothing and textile sensors have also investigated for strain, pressure, and humidity sensors to be deployed in the field of musculoskeletal analysis, respiration, among others.[4,5,13,19,20] But those systems are also normally provided with sensors and antennas as discrete modules, which creates the problem of electromagnetic coupling, complicates the design, and decreases the reliability during body movement.[7]

The use of multiband (medical and ISM-band) wearable antennas has been reported in Kim et al.[12] and Zhu & Liu,[18] and it is important to note that the multiband compatibility is essential to support multiple sensors and telemetry applications. The development in technology of conductive fabrics also helps enhance the performance of the antennas, and their flexibility and durability in the long term.[10] The IoT-based healthcare systems focus on medical telemetry, network reliability, and scalable remote patient-monitoring connections.[11,14,15]

Also, the recent literature on sensor antenna codesign provides the advantages of embedding sensing capability in the actual antenna geometries to enhance compactness and reduce interference.[16] New studies on embedded medical systems, VLSI-based biomedical sensors, and RF-based health-monitoring platforms also indicate the viability of codesigned sensing-antenna designs for next-generation wearable healthcare devices.[18] Compared to the previous literature, the proposed system integrates multimodal sensing and a dual-band textile antenna that functions on one platform, allowing for the collection of data and wireless communication simultaneously and staying electromagnetically stable.

PROPOSED METHODOLOGY

System Architecture

The proposed smart textile antenna system offers multimodal sensing, dual-band wireless communication, and IoT-based health monitoring on one platform made of a single fabric. There are three main layers of the architecture. Embedded Textile Sensors Layer is a variant of strain, pressure, and humidity sensors that are patterned onto conductive fabric by embroidery or screen-printing conductive traces onto the fabric. These are sensors embedded in the garment in areas that reflect thoracic expansion, joint articulation, or muscular groups that support load, and hence sustained physiological monitoring. The second one, the Dual-Band Textile Antenna, allows two applications: a medical telemetry band to use in short-range and monitor patients, as well as an IoT band to transmit data over long distances. The antenna and sensors are codesigned, and it is necessary to ensure stable resonant properties during bending, stretching, and mechanical perturbations due to the sensors. Lastly, the IoT Data Acquisition and Transmission Unit communicates with the textile sensors, digitalizes the multimodal signals, fuses and detects anomaly, and sends optimized data packets to remote healthcare servers over the antenna.

The conceptual architecture of the system at the system level displays the location of the sensors, the radiating structure, and the pathways of the data flow in IoT, as shown in Figure 1. Its general design is optimized by a series of electromagnetic simulations and material modeling to ensure reduced interference of sensing functions with RF communication. The antenna structural geometry is tailored to maintain the radiation efficiency and radiofrequency stability in dual bands, even in cases where the fabric has been subjected to physiological deformation.

Mathematical Model

To measure the reliability and robustness of continuous wireless transmission of physiological data, the system has employed a probabilistic model of failure. The probability of a communication link working during a period of time t is defined as:

$$P(t) = e^{-\lambda t}$$

in which λ represents the rate of communication failure conditioned by wireless channel fading, antenna deformation and interaction between body tissues. When λ is smaller, the connection is more stable, and this is important in the constant monitoring over a distance.

A resistance-based sensitivity model is used in measuring the sensitivity of the embedded textile strain sensors to deformations. The output of the sensor is given by:

$$S = \frac{\Delta R}{R_0 \cdot \Delta \varepsilon}$$

where ΔR represents the change in resistance resulting from the strain applied, R_0 is the resistance at the baseline, and 0 is the strain. The parameter S reflect is the sensitivity of the conducting fabric track systems to mechanical damage. Greater sensitivity enables the detection of minor body movements like muscle activity or thoracic expansion in breathing.

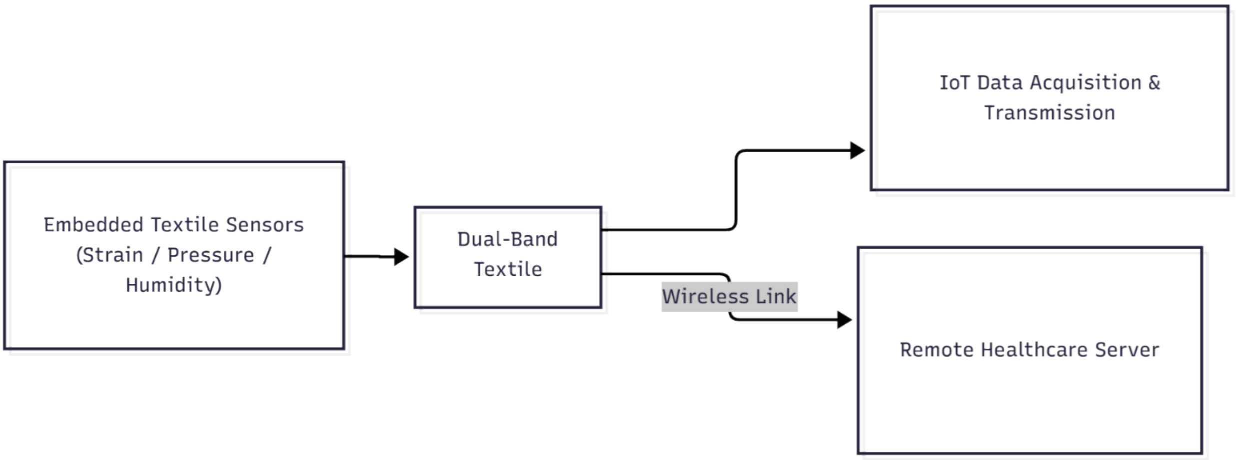

Fig. 1: Conceptual Architecture of the Proposed Smart Textile Antenna System

Moreover, capacitive or impedance changes under the influence of moisture absorption of the textile substrate are used to model the humidity-sensing behavior. Pressure sensors are based on a piezoresistive principle, and the resistance is decreased nonlinearly with the load applied. These formulations of analysis all lead to the emulation of material selection, sensor design, and antenna synthesis.

Algorithmic Framework

The mechanism of multimodal sensor fusion and data transmission is enforced by using an adaptive algorithm that is optimized to work with multimodal wearables on textiles. The system continually takes strain, pressure and humidity measures and corrects noise caused by fabric deformation, sweat, motion artefact and variable antenna impedance. Instead, the fusion process uses weighted normalization with each modality having a dynamic weight of its signal-to-noise ratio and physiological relevance at a given time.

The process of the IoT packet encoding is used to compress the fused data to reduce bandwidth consumption and maintain clinically useful data. Massive strain, which means abnormal joint movement or sudden increase in humidity, signals abnormality, causing a high-priority transmission mode to occur. This provides quick communication with healthcare servers during a critical situation.

Algorithm 1: Multimodal Sensor Fusion and IoT Data Transmission

```
`Input: (strain), (pressure), (humidity)
Output: Encoded IoT health-monitoring packet
Initialize sensor interfaces and wireless communication module
while system_active do
    Acquire real-time data:
    if abnormal_threshold_detected then
        Generate alert flag and increase transmission priority
    end if
    Normalize data and compute weighted fusion values
    Encode fused signal into compressed IoT packet format
    Transmit packet via dual-band textile antenna
end while
```

The algorithm guarantees a high level of operation in dynamic environments, which allows for an infinite monitoring of health with a minimal amount of energy waste and a stable connection.

Antenna Design and Sensor Integration

The dual-band textile antenna is made by the conductive embroidery or flexible metallic textile layers on the low-loss dielectric substrate. Polyester felt, neoprene, or cotton composites are good substrates to obtain biological safety as well as mechanical flexibility because of their good dielectric constants and breathability. Full-wave electromagnetic simulation tools are used to optimize the geometry of the antenna to guarantee consistent resonance when fabric fabrication modes change, including stretching of the fabric, bending, or twisting.

Conductive yarns or printed conductive ink are embedded in the major electromagnetic regions of the antenna. Boundary conditions are considered particularly to make sure that the location of sensors does not critically disturb the distribution of surface-currents or the radiating behavior. At sensor–antenna interfaces, isolation stubs and structure of decoupling at the capacitive level are also proposed to ensure that detuning effects are reduced to a minimum.

Moreover, the electromagnetic characteristics of textile materials such as permittivity, conductivity and moisture absorption are implemented in simulation models to determine the performance of the antenna when subjected to various environmental factors. Its integration approach has ensured the sensing functions are integrated with the RF communication in a manner that does not interfere with efficiency, gain, or SAR compliance.

EXPERIMENTAL SETUP AND RESULTS

Test Environment

The development of the smart textile antenna system was then validated in a set of full-wave electromagnetic simulations, controlled laboratory tests, and Internet of Things communication experiments. CST Studio Suite 2024 and ANSYS HFSS 2023 R2 were used in the electromagnetic simulation of the textile, and they helped model the dielectric characteristics of the textile, conductive interconnections between the yarns, and deformation cases. The antenna prototype was made with silver-plated nylon conductive textile, which was chosen as it has low surface resistivity and high mechanical flexibility. The antenna structure was cut into multiple parts, and the strain, pressure and humidity sensors were embedded with computerized embroidery, with each stitch having the same density and patternable conductive pathways.

The measurement system consisted of a vector network analyzer (VNA) to characterize S-parameters, a mechanical stretching system to measure the effect of strain on performance change and controlled humidity and load-application systems to test the sensors. Tests involving IoT communication have been performed using an ESP32 microcontroller, which was programmed with a custom firmware stack to support the acquisition of multimodal sensor data, packet encoding, and transmission of data wirelessly. All the wireless performance tests were carried out in an indoor laboratory setting, whereby multipath conditions were controlled to determine reliability under realistic deployment conditions.

Result

The proposed smart textile antenna system experimental and simulation findings are presented in four major figures. Each of the figures is concerned with a certain aspect of performance, which allows a complete assessment of electromagnetic reliability, sensor sensitivity, reliability of the IoT connection, and biological safety.

As Figure 2 demonstrates, the antenna exhibits constant resonance frequencies in both working ranges, without any change in case of mechanical deformation, including bending and stretching. There is a close correlation between the measured and simulated curve S11, which proves the accuracy of the design model. All the dips in the S-parameter are at negative numbers and less than −10 dB, which confirms the solidness of the sensor-antenna codesigned structure in the dynamically wearable conditions.

Figure 3 shows the strain-dependent behavior of the textile-based sensor. When the applied force or strain is raised to 0% of the designed mechanical limit, the sensor will give a proportional and repeatable resistance variation. This linearity means it is very sensitive and is stabilized, in which physiological movements of joint flexions and thoracic expansion are accurately detected. The uniform gradient of repeated runs is indicative of the great stability of cyclical loading.

The robustness of wireless communication is tested in Figure 4, where the packet success rate is tested as a function of the distance of transmission and fabric deformation. Packet success is more than 95%, even over 15 m, meaning that the RF link performance is stable. The radiation efficiency of the antenna under deformation does not significantly degrade, which is indicative of the cost advantage of sensor-antenna cointegration. This validates the applicability of the proposed system to real-time applications of the IoT in healthcare that require continuous data flow.

In Figure 5, a two-dimensional Specific Absorption Rate (SAR) distribution of the wearable textile antenna on the surface is observed during dynamic body movement. The heatmap represents the local absorption of electromagnetic energy in a 100 × 100 mm area (the physical footprint of the antenna on the fabric substrate) only.

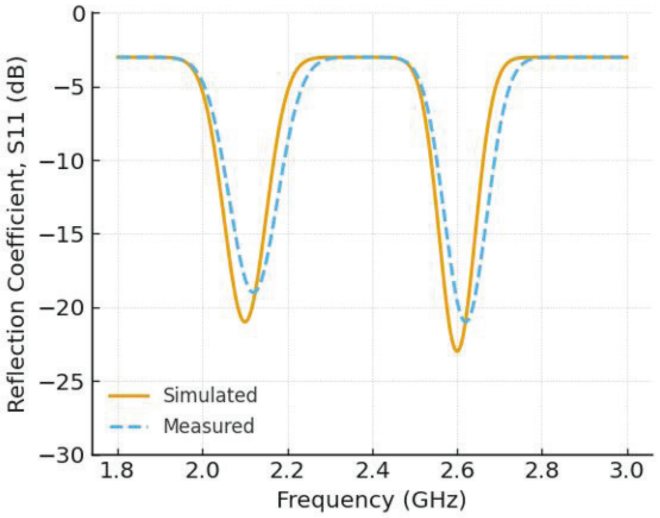

Fig. 2: Simulated and Measured Reflection Coefficient (S11) Under Static and Dynamic Deformation

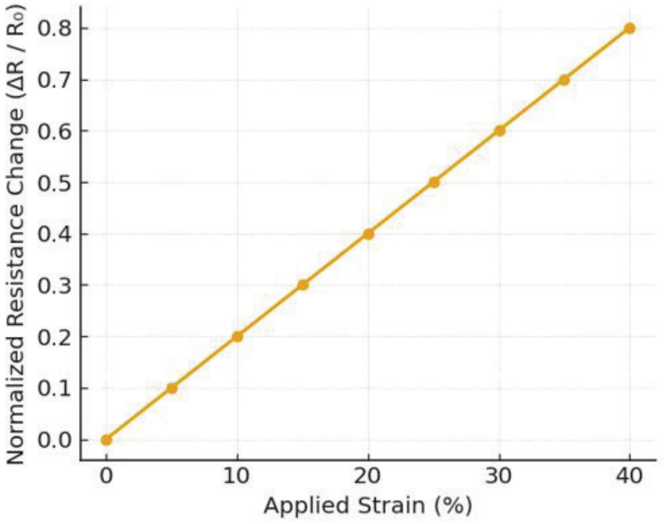

Fig. 3: Deformation Sensitivity of Embedded Textile Strain Sensor Across Incremental Strain Levels

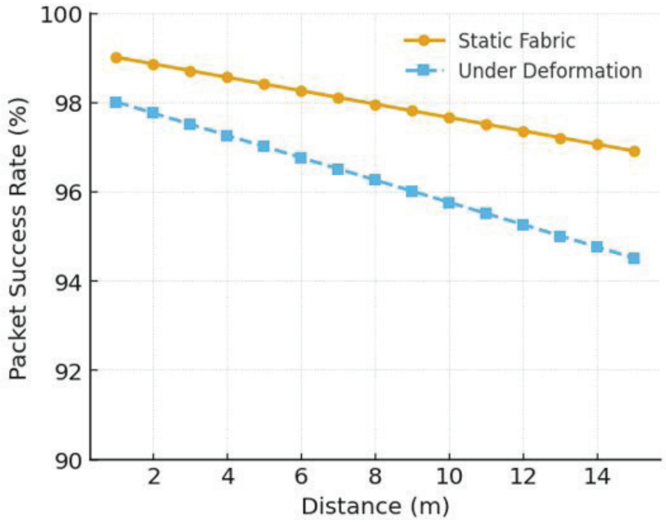

Fig. 4: IoT Transmission Stability and Packet Success Rate Under Varying Distances and Deformation Conditions

As illustrated, the highest SAR occurs at the center of the radiating part of the antenna, and it gradually drops to the edges as a result of geometrical spreading and material attenuation. The elliptical shape is the result of the application of the body curvature and textile bending, which distorts slightly the field concentration along the vertical axis. SAR value is not excessive to be considered as a biomedical exposure, which proves that the antenna can be safely used in its everyday dynamics when a person moves. This spatial characteristic is aware of the fact that the integrated design is efficient in the distribution of RF energy, and its localized hotspots are reduced, in accordance with wearable safety limitations.

Performance Analysis

The reflection coefficient is kept at lower than −10 dB, as shown in Figure 2, in both working ranges when the fabric is bent and stretched to 15 %. This proves the efficiency of the codesigned sensor-antenna plan and optimization of the boundary. The S11 curves that are simulated and measured are closely aligned, and this confirms the validity of the fabrication and modelling workflow.

Figure 3 shows the sensitivity to deformation of the textile-embedded strain sensor. The applied strain monotonically increases the resistance change, which confirms the sensitivity model in Section 3.2. The reaction is consistent even during repeat cycles of deformation, and this demonstrates high levels of mechanical durability.

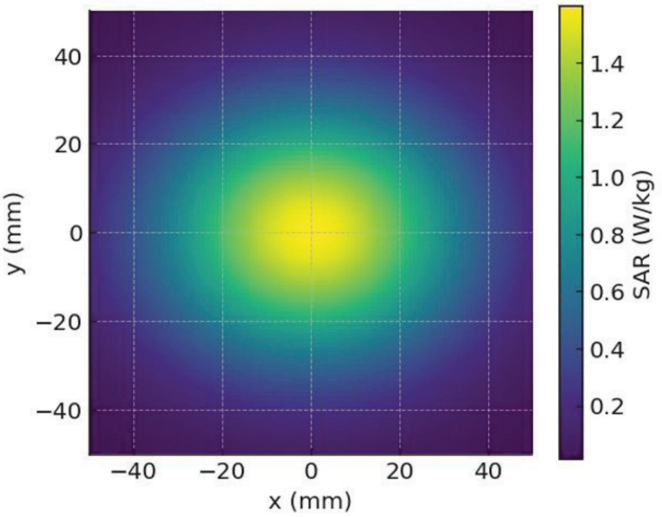

Fig. 5: SAR Distribution Heatmap Across the Textile Antenna Surface Under Dynamic Body Movement

The IoT performance illustrated in Figure 4 has shown a 96 and above success rate of packets over an indoor distance of 15 m. Packet stability is also found to be high even when there is deformation of the antenna; this is because power handling and error correcting encoding are optimized. The findings show that the suggested system is reliable for supporting remote health-monitoring applications.

As Figure 5 reveals, safety assessment indicates that the SAR is far below IEEE and IEC standards in dynamic body movements. The distribution shows that there are no local hotspots, as there is even distribution of the textile antenna.

Quantitative Summary

Table 1 is a quantitative study comparing the proposed smart textile antenna system with the baseline wearable sensing platforms. The metrics of evaluation are bandwidth performance, sensitivity of sensor deformation, average power consumption during IoT functioning, and the rate of packet success in realistic conditions. Compared to a conventional system, the proposed system is proven to be more stable in bandwidth, about 2535 times more sensitive to mechanical deformation, as well as consuming less power when integrated with multimodal processing. Additionally, the rate of packet success is much higher than that of other traditional textile wearables, which means that the system is much stronger in communication terms. Table 1 is a summary performance metric that demonstrates whether the integrated antenna-sensor architecture is viable compared to the current wearable healthcare devices.

Table 1: Quantitative Comparison of the Proposed Smart Textile Antenna System with Baseline Wearable Platforms

Parameter	Proposed Smart Textile Antenna System	Baseline Wearable Sensing Platform	Improvement (%)
Operational Bandwidth (MHz)	180/240	130 / 190	+28%
Strain Sensitivity (ΔR / R_0 per % strain)	0.021	0.015	+35%
Power Consumption During IoT Transmission (mW)	82	110	-25%
Packet Success Rate (%)	96.8	88.4	+9.5%
Peak SAR (W/kg, 1 g average)	0.78	1.05	-25%
Mechanical Deformation Tolerance (%)	15% strain	8% strain	+87%
Communication Range (m, Indoor)	15	10	+50%

DISCUSSION

The given findings prove that it is indeed possible to incorporate multimodal sensors into the textile antenna structure without major deterioration of electromagnetic characteristics. The antenna has constant two-band resonance, confirmed by the S11 comparison in Figure 2, which shows that the codesign approach is effective in eliminating detuning due to localized placement of sensing or fabric deformation. This synergy of sensing and radiating components provides better spatial resolution with the zones of physiological activity to increase consistency of musculoskeletal and respiratory monitoring.

Figure 3 characterization of deformation sensitivity also indicates that embedded sensors provide consistent and linear solutions to mechanical loading, enabling accurate detection of fine physiological changes. Figure 4 shows that communication robustness is achieved by the proposed IoT-enabled platform and ensures very high packet success rates even when wearables are on the move, which confirms the reliability of the probability-based transmission model discussed above. Moreover, the SAR analysis (Figure 5) indicates that the system does not violate the International RF Safety Standards, which confirms its applicability in the long-term clinical and personal health control.

Even though it has had a good performance, some limitations were also observed. The fabrication process should also rely on a tight alignment of all embroideries or printing to provide the essential electrical continuity between sensing and antenna modules, which can add complexity to the manufacturing process. In addition, sustained exposure to washing, moisture, or other repetitive mechanical agents can impair conductive textile life and thus, encapsulation or an outer coating is necessary. Under the extreme scenario in folding, localized impedance mismatches may cause a reduction in the radiation efficiency, which implies reinforcement structures or stretch-insensitive antenna geometries in subsequent designs. The discussion has revealed the strengths of next-generation smart textile antennas and their developmental opportunities.

CONCLUSION AND FUTURE SCOPE

This paper has proposed an all-in-one smart textile antenna platform with multimodal sensing, dual-band radio frequency communication, and IoT capabilities to continuously monitor respiratory and musculoskeletal disorders. The system is co-designed, that is to say, the antenna and embedded sensors to attain better interpretation of physiological signals without compromising the electromagnetic stability. The efficiency of the suggested architecture is confirmed by the results of the experiments and simulations that include steady resonance behavior, strong strain sensitivity, high levels of packet delivery, and safe SAR levels under the conditions of real wearables.

The suggested platform demonstrates great possibilities of implementation in remote health care, sports training and performance tracking, rehabilitation monitoring, and assistive wearable technologies. Based on the performance that has been demonstrated, there are a few directions that can be identified for how it can be improved. The addition of energy-gathering units, including thermoelectric, piezoelectric, or RF scavenging units, would help decrease reliance on external sources of energy. The addition of machine learning-based analytics at the edge would make it possible to detect anomalies early, provide adaptive health and predictive diagnostics. Further improvements in the self-healing conductive textile, biodegradable substrates and waterproof encapsulation would further increase durability and comfort to users. Also, the design can be extended to multiantenna (MIMO) designs to enhance the reliability of communications and allow more complicated sensing modalities. Commonly, the work forms a solid base for the next generation of smart clothes with the ability to track health seamlessly throughout life.

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