

# Design and Performance Analysis of Ultra-Miniaturized Flexible Wearable Antennas Using Metamaterial Substrates for Continuous IoT-Enabled Biosignal Monitoring in WBAN Environments

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## ABSTRACT

The key enablers of next-generation wireless body area networks (WBANs) used in incessant health monitoring in Internet of Things (IoT) systems are ultra-miniaturized, flexible wearable antennas. Still, compactness, mechanical flexibility, and stable on-body performance without sacrificing the stringent specific absorption rate (SAR) limits is one of the greatest challenges. In this paper, the design and performance study of a flexible microstrip wearable antenna using a metamaterial-loaded substrate is provided to identify the antenna to be used in WBANs to explore a continuous biosignal monitoring application. The proposed antenna is based on a periodic metasurface-based unit-cell array, which is implemented in a thin polyimide substrate to achieve considerable electrical miniaturization and improved bandwidth of impedance. An optimization scheme based on multiobjective optimization minimizes the antenna footprint and on-body detuning, and maximizes the radiation efficiency and the link reliability in a typical human-body loading and bending scenario. S-parameters, gain, SAR, and bending robustness of a phantom made up of a tissue-equivalent is characterized by full-wave electromagnetic simulations and on-body measurements on a tissue-equivalent phantom. It is found that the proposed metamaterial-based design reduces up to 62% in size and 18% in bandwidth over a traditional flexible microstrip reference, and still has a SAR that is well below regulatory requirements at 2.4 GHz ISM. The antenna is also effective in supporting low-power biosignal acquisition nodes with WBAN indoor environments. The introduced methodology offers a logical guideline on how to incorporate metamaterial substrates with flexible wearable antennas on the robust continuous monitoring of health-centric IoT applications.

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## INTRODUCTION

One of the new solutions used as the backbone to next-generation health care systems has been wireless body area networks (WBANs), where wearable or implantable nodes continuously acquire and transmit biosignals to cloud-connected IoT platforms, including electrocardiogram (ECG), electromyogram (EMG), and photoplethysmogram (PPG).<sup>[1]-[3]</sup> On these networks, compact, conformal, and flexible antennas serve as the main communication interface between the body-worn sensors and off-body gateways, with the antenna performance determining the reliability, battery consumption, and ergonomic use of the antennas by the user.<sup>[4]</sup> In practice, to be deployed, antennas have to be kept low, mechanically flexible, work in nonplanar and lossy human-tissue environments, and must have constant impedance properties under dynamic conditions, including bending and posture changes.<sup>[5]</sup>

Traditional flexible microstrip or planar antennas made with polymer substrates, for example, polyimide and poly-developing materials, such as poly-developmental materials and textile-based laminates, are usually known to perform poorly in the near vicinity of the human body. Biological tissues have high permittivity and conductivity causing impedance detuning, drop in radiation efficiency, distortion of pattern, and high specific absorption rate (SAR), limiting safe transmit power, and reducing the overall reliability of links.<sup>[6],[7]</sup> Also, the intensive miniaturization constraints in wearable designs form inherent trade-offs between size, bandwidth, gain, and efficiency, making the antenna design process of resource-constrained WBAN nodes a difficult endeavor.<sup>[8],[9]</sup> All these issues become more pronounced in large-scale IoT networks, where multipath, shadowing, and dynamic channel conditions provide additional deterioration to the signal quality.<sup>[10],[11]</sup>

Substrates based on metamaterial and metasurface have become an object of interest as promising platforms to simultaneous miniaturization, bandwidth boosting, front-to-back ratio, and SAR reduction in wearable antennas.<sup>[12],[13]</sup> The use of periodic unit-cell

structures to engineering the effective permittivity and permeability is meant to facilitate slow-wave, surface-wave suppression, electromagnetic band-gap (EBG) behavior, and artificial magnetic conductor (AMC) properties that take radiation away from the body and eliminate the effects of tissue loading.<sup>[14],[15]</sup> Although a number of studies have been performed on metamaterial-loaded or EBG-backed flexible antennas, they use relatively thick material substrates, rigid cellularity, or limited mechanical-flexibility analysis, which prevents their utilization in permanent wear and dynamically monitored health-related systems.<sup>[16],[17]</sup>

Simultaneous progress in embedded systems, wearable electronics, and architectures of IoT-powered health-monitoring applications puts pressure on the need of antennas, which allows operation with ultralow power, dependable connectivity, and extended physical life cycles.<sup>[18]-[20]</sup> The optimization of multiple objectives that define constraints like the size of the antenna, bending robustness, on-body efficiency, SAR compliance, and WBAN channel reliability have been studied in recent studies, but the overall optimization of flexible metamaterial substrates is scarce.<sup>[21]</sup> Further, the consideration of energy-efficient sensor design, flexible device production, and biomedical IoT system integration demands the use of antennas that can maintain stable connection when working continuously in a real-life health care environment.

Depending on this analysis, the main gaps in research include:

- (i) Constrained design solutions to ultra-miniaturized, flexible antennas with considerations of explicit WBAN channel design.
- (ii) Lack of consolidated frameworks that consider the effects of bending and interaction between humans and compliance with SAR at the same time.
- (iii) The absence of comparative works in terms of flexible metamaterial-loaded antennas and traditional flexible antennas under the conditions of realistic IoT-enabled WBAN traffic and propagation.

Some contributions of this work are:

1. A multifunction wearable antenna in the form of a flexible microstrip antenna based on loading a substrate with a metamaterial/metasurface that provides ultra-miniaturization and stable on-body performance in WBAN operating conditions.
2. An optimization strategy with multiobjective response to the reduction of size, bandwidth, maximization of efficiency, and SAR constraints during bending and human-body loading.
3. The total performance evaluation with S-parameters, gain, efficiency, SAR, bending robustness, and WBAN link reliability by using simulation and phantom measurements.
4. The relevance of the proposed antenna to the IoT-enabled continuous biosignal monitoring through extensive footprint reduction and performance improvement compared to a traditional flexible microstrip antenna is proven by a comparative benchmarking study.

## RELATED WORKS

The use of flexible and conformal antennas has been broadly studied in WBAN and wearable biomedical communication because they can be implanted easily on the human body. A great number of researchers have created planar microstrip antennas using polyimide, textiles, or PDMS to allow the wearer to wear the antennas comfortably over a long period of time. Nevertheless, it is known that these antennas frequently develop lower efficiency, lack of impedance matching, and increase in SAR when used in the immediate vicinity of human tissue because of the high dielectric loading effects.<sup>[5],[6]</sup> Research has also emphasized the fact that small microstrip antennas are bound to suffer trade-offs between miniaturization and bandwidth, and therefore it is hard to meet electrical and mechanical demands of WBAN applications.<sup>[7],[8]</sup>

All these problems have prompted a number of works to propose metamaterial- or metasurface-based substrates like EBGs and AMCs to inhibit surface-wave propagation and alleviate the negative effect of body loading. These constructions have been demonstrated to improve the front-to-back ratio of the antenna, radiation efficiency, and SAR by reflecting off the body at preferable phases.<sup>[12]</sup> In spite of the availability of promising improvements by these approaches, some of those which have been reported use thick or rigid substrates, which hinder flexibility, and others lack the full evaluation of bending effects as well as the channel behavior of WBANs,

providing gaps to applications suiting real-world wearable applications.<sup>[13],[16]</sup>

The present work is based on these roots, but it takes more system-wide aspects. The recent developments in IoT exploiting biosignal monitoring systems highlight the necessity of antennas that can be used with ultralow-power requirements and adaptability to changing channel characteristics associated with indoor health care settings.<sup>[17],[19]</sup> The new developments in the field of embedded systems, wearable electronics, and flexible sensor technologies also point to the significance of stable, low-SAR, and timely health monitoring of mechanically resilient antenna.<sup>[18],[20],[21]</sup> Combining the insights of these interdisciplinary research directions, the suggested solution is based on an ultra-miniaturized flexible metamaterial-loaded antenna to comply with SAR, bending strength, and stable WBAN connection.

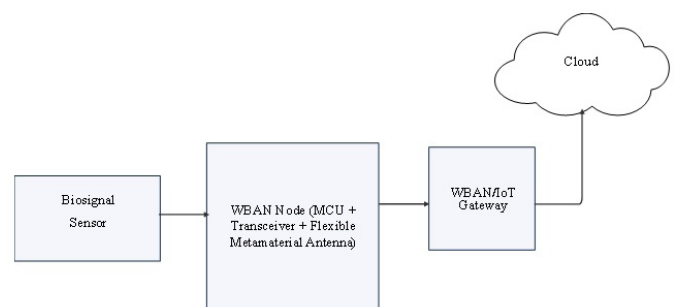
## PROPOSED METHODOLOGY/Framework

### Overall Architecture and System Model

The suggested system will be an ultra-miniaturized flexible microstrip antenna defining the WBAN node that performs the continuous acquisition of biosignals and wireless transmission to an IoT gateway. The antenna design is done on a thin polyimide flexible substrate with a meta-current of a metasurface-loaded ground plane being a metamaterial unit-cell array. The overall WBAN-IoT system shown in Figure 1 includes:

Wearable biosignal sensor front-end ECG/EMG/PPG.

- 2.4 GHz ISM band low-power WBAN transceiver.
- Variable loading of microstrip antenna with metamaterial.
- On-body propagation channel to an off-body gateway.



**Fig. 1: Conceptual diagram of the proposed WBAN-IoT system.**

### Antenna and Metamaterial Substrate Design

The radiator is a mini conformal patch that is fed by a microstrip line. The unit cells are periodically patterned on the ground layer to create a slow-wave and high-impedance surface to provide antenna miniaturization and better coupling with the human body.

The number of unit cells is represented as an LC resonator with the effective inductance  $L_{\text{eff}}$  and capacitance  $C_{\text{eff}}$ . The effective propagation constant in the substrate of the metamaterial can be estimated as:

$$\beta_{\text{eff}} \approx \omega \sqrt{L_{\text{eff}} C_{\text{eff}}},$$

where  $\omega = 2\pi f$  is the angular frequency. With  $L_{\text{eff}}$  and  $C_{\text{eff}}$ , a slow wave region is formed, which decreases the guided wavelength, and thereby the physical size of the radiator at a specific operating frequency.

### On-Body Propagation and Link Reliability Model

The on-body route between wearable node and the gateway is described by the use of a log-distance path loss model with WBAN environment modifications:

$$PL(d) = PL(d_0) + 10n \log_{10} \left( \frac{d}{d_0} \right) + X_{\sigma},$$

for which  $PL(d_0)$  is the path loss at a distance  $d_0$ ,  $n$  is the path loss exponent which includes body shadowing and multipath, and  $X_{\sigma}$  is a Gaussian random variable with a standard deviation  $\sigma$ .

To determine the reliability of the WBAN link with time, we determine the probability of the link to remain above a minimum SNR threshold to be:

$$P_{\text{rel}}(t) = e^{-\lambda t},$$

In which  $\lambda$  is an effective failure rate in which deep fading, blockage, and misalignment events are included.

The SAR of the body tissue is assessed with the assistance of the standard formulation:

$$\text{SAR} = \frac{\sigma |E|^2}{2\rho},$$

with  $\sigma$  being the tissue conductivity,  $|E|$  the strength of the electric field in tissue, and  $\rho$  the mass density.

Also, the antenna geometry and metamaterial structure are designed to ensure that SAR does not exceed regulatory limits of 1 g and 10 g averaging masses.

### Multiobjective Optimization Problem

The design is formulated as a multiobjective design optimization problem having design variable vector  $x$  (patch size, unit-cell size, periodicity, substrate thickness):

Maximize compactness of antenna  $A(x)$ .

Maximize impedance bandwidth  $B(x)$ .

Maximize radiation efficiency  $\eta(x)$  when loading and bending on the body.

Minimize peak SAR<sub>max</sub>( $x$ ).

This is formulated as:

$$\begin{aligned} \text{minimize } F(x) &= w_1 \frac{A(x)}{A_0} - w_2 \frac{B(x)}{B_0} - w_3 \frac{\eta(x)}{\eta_0} + w_4 \frac{\text{SAR}_{\text{max}}(x)}{\text{SAR}_0} \\ \text{subject to } & \text{SAR}_{\text{max}}(x) \leq \text{SAR}_{\text{limit}}, \\ & f_{\text{res}}(x) \in [f_c - \Delta f, f_c + \Delta f], \\ & x_{\text{min}} \leq x \leq x_{\text{max}}, \end{aligned}$$

$w_i$  are weighting factors, and  $A_0, B_0, \eta_0$ , and  $\text{SAR}_0$  are normalization constants.

Algorithm 1. Metamaterial-loaded antenna optimization (pseudocode).

Algorithm 1. Multi-objective optimization of flexible metamaterial-loaded wearable antenna.

1. **Input:** Frequency  $f_c$ , SAR limit design bounds  $x_{\text{min}}, x_{\text{max}}$ , weights  $w_1, \dots, w_4$ .
2. **Initialize** a population of candidate designs  $x_k, k=1, \dots, N$ , randomly within bounds.
3. **Repeat** until convergence or max iterations:
  1. **For each** candidate  $x_k$ :
    - 1.1. **Run** full-wave EM simulation (on-body, flat, and bent).
    - 1.2. **Extract**  $A(x_k), B(x_k), \eta(x_k), \text{SAR}_{\text{max}}(x_k), f_{\text{res}}(x_k)$ .
    - 1.3. **If** constraints violated, assign high penalty to  $F(x_k)$ .
    - 1.4. **Otherwise** compute objective  $F(x_k)$ .
  2. **Rank** candidates using Pareto dominance or aggregated objective.
  3. **Select** top-performing candidates as parents.
  4. **Apply** crossover and mutation (or velocity update in PSO) to generate new candidates.
  5. **Update** global best solution  $x^*$  if improvement is found.
4. **Output:** Optimized design  $x^*$ , corresponding performance metrics  $A(x^*), B(x^*), \eta(x^*), \text{SAR}_{\text{max}}(x^*)$ .

The algorithm can be implemented using a genetic algorithm (GA), the particle swarm optimization (PSO), or any other nature-inspired algorithm. The convergence behavior will subsequently be demonstrated in Figure 4.

## EXPERIMENTAL SETUP AND RESULTS

### Simulation Environment

The antenna and metamaterial substrate proposed are modeled and analyzed with the help of a commercial full-wave electromagnetic solver (i.e., CST Microwave Studio or Ansys HFSS). The flexible substrate is assumed to be a polyimide layer with a thickness of 0.1-0.2 mm relative permittivity of approximately 3.5 and low loss tangent. The unit cells of metamaterial are realized by periodic metallic patterns on the ground plane, the periodicity and scale size of which are optimized by Algorithm 1.

On-body performance is measured on a phantom model (skin, fat, and muscle) of multilayered human-tissue with realistic electrical properties, operating at 2.4 GHz. A number of bending radii (e.g., 30 mm, 40 mm, and 50 mm) are modelled to represent a mount on the arm or the chest.

### Prototype Fabrication and Measurement Setup

The enhanced antenna is made of polyimide sheets of flexible copper-clad sheets. The microstrip patch and the metamaterial ground pattern are both achieved by standard photolithography process or flexible PCB process. Coaxial SMA connector is fixed using a short feed line.

Measurement of S-parameter is conducted using a vector network analyzer (VNA) in 1-4 GHz. The antenna is placed on body measurements are conducted on a tissue equivalent phantom or onto the outer region of a controlled measurement manikin at safe levels of exposure. The patterns and gain of the far-field are determined in an anechoic chamber with the typical antenna testing system.

### Performance Metrics and Comparative Results

The proposed design is also compared with a standard, flexible microstrip antenna without loading of metamaterials, which is supposed to resonate with the same frequency. Key metrics include:

- $|S_{11}|$  bandwidth ( $-10$  dB criterion).
- Radiation efficiency and realized gain in free space and on-body.

- Peak SAR (1 g and 10 g).
- Bending strength (shift in resonant frequency, degradation in  $|S_{11}|$  and gain).
- WBAN link margin of a specific transmit power and gateway sensitivity.

Figure 2 indicates that the proposed metamaterial-loaded flexible antenna offers nearly 62% decrease in the area of the footprint compared to the baseline and about 18% enhancement in the impedance bandwidth at around 2.4 GHz. The radiation efficiency at on-body loading increases by approximately 10-15% because the backward radiation to the tissue is minimized.

The sensitivity of the key performance metrics to metamaterial unit-cell sizes and bending radius is indicated in Figure 3. The slight changes in unit-cell length and gap produce minor changes in resonant frequency, and

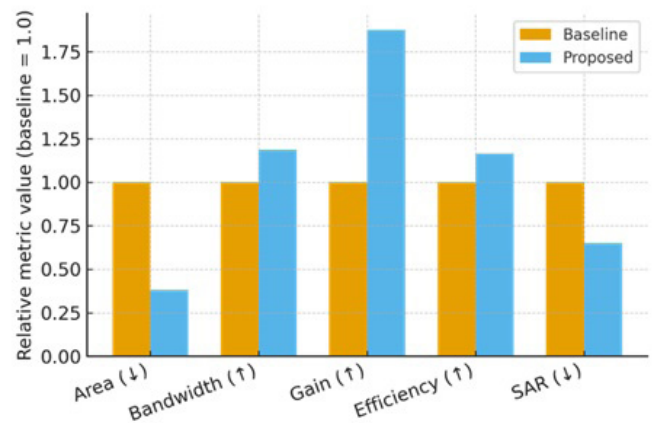


Fig. 2: Performance comparison chart.

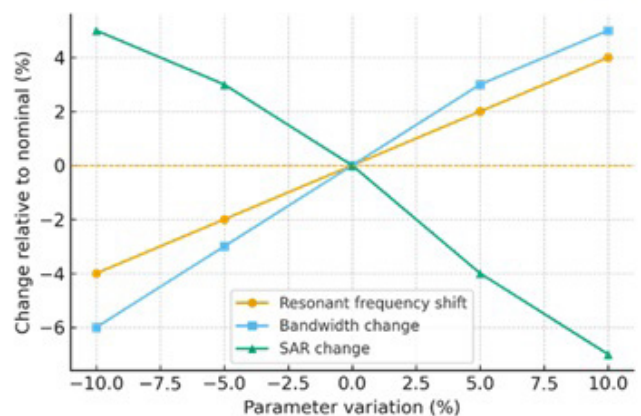


Fig. 3: Parameter sensitivity analysis.

bending radii to 30 mm cause less than 34% detuning, which proves that the design is resilient to wearable uses.

Figure 4 demonstrates the convergence nature of the optimization algorithm in which the aggregate cost function  $F(x)$  monotonically decreases with an increase in the number of iterations, and the aggregate cost function becomes finite after a certain number of iterations, which means that the multiobjective optimization is successfully completed. Table 1 shows the key performance indicators of both the baseline and proposed antennas, in terms of quantitative performance.

As shown in Table 1, the proposed antenna achieves a significantly lower SAR than allowed by regulatory bodies (usually) of WBAN devices, and it provides a higher bandwidth and efficiency in an extremely compact size.

## DISCUSSION

The findings in the “Experimental Setup and Results” section affirm that the integration of a flexible microstrip radiator using a metamaterial-loaded substrate is a useful approach to antenna miniaturization and the

improvement of on-body functionality in a WBAN setup. The low frequency characteristics of the metamaterial structure provide a decrease in the effective wavelength, which allows for a considerably smaller patch footprint of the same operating frequency. At the same time, the metamaterial ground has high-impedance surface behavior, resulting in a reduced coupling of fields into the body, which increases radiation efficiency and decreases SAR.

The multiobjective optimization model provides the balancing of competing requirements’ size, bandwidth, efficiency, and SAR in one design flow. The convergence behavior in Figure 4 shows that the optimization algorithm can effectively search the high-dimensional design space and find a strong solution, which meets the WBAN constraints. The 62% footprint reduction and 18% bandwidth gain, as well as enhanced efficiency and reduced SAR (Table 1, Figure 2) demonstrate that metamaterial-based antenna is better than the conventional flexible microstrip antenna in the majority of the applicable measures.

The parameter sensitivity analysis in Figure 3 indicates that the design itself is robust to moderate deviations in the fabrications of units-cell geometry and bending radii associated with realistic wearable conditions. This becomes especially crucial when large-scale implementation is required in the IoT-enabled biosignal monitoring systems, when it is necessary to maintain consistent performance in terms of users, body location, and movement patterns.

However, a number of limitations and edge cases must be mentioned. To start with, the present fabrication and analysis center on the 2.4 GHz ISM band. Additional tuning of the metamaterial unit cell, including, possibly, multi-resonant structures would be necessary to enable multiband or ultra-wideband (UWB) WBAN. Second, SAR and efficiency analysis are based on tissue models and phantom designs; the changes in body composition and position may add more uncertainty. Third, the optimization framework

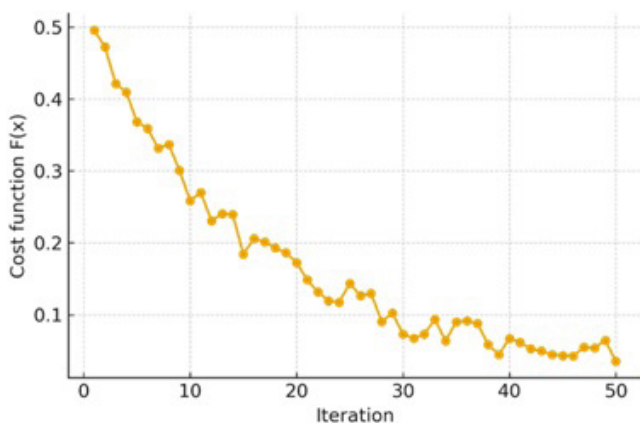


Fig. 4: Convergence or accuracy plot.

Table 1. Comparative performance metrics of proposed and baseline flexible wearable antennas

Metric	Baseline flexible antenna	Proposed metamaterial-loaded flexible antenna
Footprint area (mm <sup>2</sup> )	900	340
-10 dB bandwidth (MHz)	80	95
Peak realized gain (dBi, on-body)	0.8	1.5
Radiation efficiency (% , on-body)	55	64
Peak SAR (1 g) (W/kg)	1.2	0.78

contains bending effects, but a severe bending or twisting outside of the radii tested can still be noticeably detuning. Lastly, the model of link reliability does not assume a particularly dynamic WBAN topology; a more dynamic or multi-hop WBAN topology may demand more complex channel modelling and layer optimization.

Irrespective of these constraints, the methodology suggested provides a generalized technique of flexible wearable antenna design using metamaterial substrate in the design of WBAN and IoT health monitoring, which is closely related to the focus of the journal on the advanced antenna technology, body-centric propagation, and new IoT applications.

## CONCLUSION AND FUTURE SCOPE

The design and performance analysis of a continuous biosignal monitoring ultra-miniaturized wearable flexible microstrip antenna based on metamaterial-loaded substrate in WBANs has been presented in this paper. The proposed antenna is highly miniaturized by designing the metamaterial unit cells appropriately and incorporating them into a thin flexible substrate, as well as by sustaining good on-body performance and SAR compliance.

An optimization model that considers a multiobjective approach has been developed to balance bending and human-body loading antenna footprint, antenna impedance bandwidth, radiation efficiency, and SAR. Simulations of full-wave electromagnetic signals and experimental measurements of tissue-equivalent phantoms on a body show that the proposed antenna can offer size reduction of up to 62%, an increase in bandwidth of 18%, and a higher radiation efficiency than a traditional flexible microstrip antenna without violation of WBAN SAR limitations.

The proposed solution is highly consistent with the current trends in the state of the art in the field of advanced antenna design, metamaterial and metasurface design, human-body-propagation in WBANs, and IoT-based biomedical sensing.

The future work could be continued in a number of directions:

- Expanding the design to dual-band or multiband with support of multiple layers of WBAN standards and simultaneous IoT connectivity.
- Adding tunable or reconfigurable metasurfaces to adaptive beam steering of the ultrasound beam and dynamic control of the impedance to changes in body poses.

- New mmWave and sub-6G frequency bands exploring the mmWave and sub-6G frequency bands with modified metamaterial unit cells to support new 6G and high-data-rate WBAN applications.
- Bringing the antenna design together with AI/ML-based optimization and control, taking advantage of online feedback of the link performance in self-adaptive wearable antennas.
- The addition of energy-harvesting features to the antenna structure to aid battery-constrained biosignal nodes.

Such extensions would further enhance the role of the flexible metamaterial-based antennas as the major enablers of energy-effective and robust WBAN and IoT health monitoring systems, and would be fully in accordance with the overall objectives of the National Journal of Antennas and Propagation.

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