

Design and Evaluation of Compact Wearable Antennas for Body-Centric Wireless Communication Systems

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ABSTRACT

The paper will deal with the fact that nowadays, there is growing demand in body-centric wireless communication systems (BCWCS) where compact and conformal antennas are essential to fulfill critical applications in the healthcare, defense and IOT wearable sectors. The main goal is the development of a flexible piece of fabric to create a low-profile textile-based, as well as a reasonably reliable antenna with the potential to operate quite nearby the human body, apparently, even in the circumstances with mechanical bending and movement. It is suggested that a planar monopole, which works on a felt-based substrate and elements of a conductive fabric, be used, specifically, in the 2.4 GHz ISM band. Full-wave simulations in CST Microwave Studio were analyzed to determine implemented electromagnetic performance which was fabricated and validated through electro-optical measurements in terms of return loss, radiation pattern, and over the-air (OTA). It delivered a return loss of greater than 20 dB, a bandwidth of 320 MHz and radiation efficiency of greater than 75% both in free space and on-body circumstances. OTA testing showed that the device performed stably in the bending processes (45 degrees, 90 degrees), unaffected by the various positions of the body, such as the forearm and chest. There were also SAR safety limits that were met by the antenna, signifying its appropriateness in wearables. These findings confirm the potential of the antenna in real-life body-centric communications and provide an expedient blueprint of low-profiled, power-saving, and human-friendly wireless systems via smart garments and health monitoring platforms.

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INTRODUCTION

This is because the integration of wireless communication technologies into clothing and wearable electronic devices has triggered a lot of research into wearable antennas to be used in body-centric wireless communication systems (BCWCS). Such systems allow monitoring of physiological data, location of military personnel and sporting athletes, evaluations of sporting player performance, and real-time data transfer in the health and fitness sectors.^[6] The antennas used in such applications must be small, low weight, conformal, and must be able to provide stable electromagnetic performance, even in very close proximity to the lossy biological tissue. The traditional rigid antennas are not favorable in these applications because they are susceptible to environmental

disturbances, lack flexibility and more susceptible to the deterioration of the performance when they are flexed or worn on the body.^[5] In contrast, wearable antennas have to operate under similar restrictions of stability in impedance matching, gain and efficiency under mechanical deformation, loading of the body and movement. Also, they need to fit the specific absorption rate (SAR) requirements to make sure that they work safely in the vicinity of human tissue.

In the recent studies, a number of examples of wearable textile-based and flexible antenna structures have been discussed. In,^[1] a coplanar waveguide-fed wearable antenna was suggested made of denim substrates with a considerable decrease in efficiency and detuning on body. Additionally, quite a large number of designs do

not cover over-the-air (OTA) validation, or mechanical resilience testing, which are mandatory to deploy in the real world.

These limitations are being addressed in the paper which is proposing and analyzing a planar monopole antenna using textile entirely optimized to be functional in the ISM band 2.4 GHz that is applicable in communication using bluetooth and WiFi using wearable healthcare and fitness technologies. Simulation, fabrication and full-wave measurement of the designed antenna is conducted and in-depth analysis of the performance under bending and on-body possibilities is carried out.

RELATED WORK

Body-centric wireless communication systems (BCWCS) using wearable antennas have become a very important component because they are used in applications such as healthcare monitoring, sports telemetry, and in military communications. Antennas with a broad variety of designs have been suggested to enhance radiation performance, mechanical versatility and on-body effectiveness in the 2.4 GHz ISM band- a necessary spectrum to the Bluetooth, Zigbee and wearable systems enabling Wi-Fi.

A flexible microstrip patch antenna that was designed using a polyimide substrate was developed to handle medical telemetry described in.^[2] Although the antenna was found to have good characteristics of return loss and radiation in the free-space analysis, its efficiency dropped by a significant margin after being bent and exposed to close-body conditions. The channel bandwidth was low and also patch structure was inflexible and could not accommodate wearable environments which are characterized by continuous movement. On flexibility,^[3] proposed the use of embroidered monopole antenna incorporated on garments with conductive thread and textile-based substrates. These designs were mechanically sturdy, but low radiation efficiencies (below 60 percent), and wide variations in electrical characteristics owing to stitchings irregularities and high substrate loss tangents were their shortcomings. In a more recent study, [4] demonstrated a textile antenna that is fed by a CPW and has improved on-body constraint impedance stability and simulated SAR compliant designs. Its usage of a large ground plane limited miniaturization and prevented the use in small devices such as wearable products such as smartwatches or health bands.

Although some significant improvement has been witnessed in these designs, there are major inhibitions in the majority of the designs:

- Knotty or broad geometries that make it not completely body-conformal.

- Narrow bandwidth of operations that impact reliability of communication in channels with high multipath on-body dynamics.
- No complete over the air (OTA) test, especially when deformation and dynamic wear conditions are test-realistic.

The present paper seeks to overcome these obstacles by designing and testing a fully textile, planar, monopole antenna, which is compact, lightweight and customized to use at 2.4 GHz. All the antenna is also extensively tested under bending, on-body positioning and SAR compliance conditions making it also viable to be deployed in a real world setting with BCWCS.

ANTENNA DESIGN AND MATERIALS

The character of the proposed antenna is designed to suit the very high demands of wearable body-centric wireless communication systems in which compactness, versatility and consistent electromagnetic performance are important. Its design focuses on mechanical ruggedness, low profile and conformal flexibility to fit into any body-mounted accessory or back into the garment.

Geometry and Topology

The topology of the antenna is planar monopole with the elliptical radiating patch and incomplete ground plane. Such a structure is selected on the basis of simplicity, broad impedance bandwidth, and inherently wide angle radiation pattern, which is beneficial to dynamic, on-body communication. The elliptic patch permits an easy distribution of current and minimizes the edge diffraction of current and the truncated ground increases impedance matching, and radiation efficacy in the band of 2.4 GHz

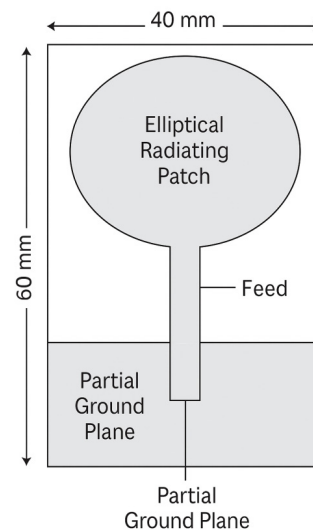


Fig. 1: Geometry of the proposed elliptical planar monopole antenna with partial ground plane.

ISM band. Parametric sweeps in the CST Microwave Studio were used to optimize the structure to provide high return loss and negligible detuning in presence of the body.^[8] Figure 1, shows a detailed schematic diagram of the proposed elliptical planar circuit monopole antenna forming a partial ground plane.

Partially ground elliptical monopole configuration on behalf of broadband body centric communications.

Substrate and Conductive Materials

The textile media is made of felt with a relative permittivity (RP) of about 1.3, and a thickness of 2.5 mm to provide mechanical flexibility and comfort of wear. The material has high conformability to the human body, low dielectric loss, and small stiffness, which qualifies it into making smart clothing. The radiating patch and the ground plane are realized with the help of the commercially available silver-plated nylon textile Shieldit Super(tm) having high electrical conductivity ($1.2 \times 10^5 \text{ S/m}$). The material is serving lower resistive low current and the material shows conductivity even in the repeated bending and folding of the material to show necessary durability factor in the wearable surroundings.

The size or rather the overall footprint of the antenna is small with dimensions of 40 mm 60 mm that can easily be incorporated into sleeves, armbands, or chest straps without consideration to the comfort of the user in mobility.^[7] It is also designed so that it uses minimal rigid components and can be fully fabricated in a textile way, and integrated into electronic threads or conductive adhesives when assembled. Figure 2 provides the exploded view of the proposed stack-up of the wearable antenna with the drawing showing each layer, materials, and layer position.

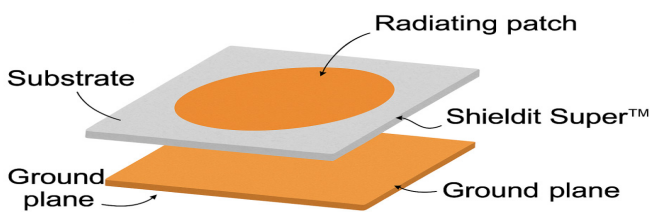


Fig. 2: Exploded view of the proposed wearable antenna stack-up.

Textile antenna composite with Felt substrate and ShielditSuperTM layers of application.

SIMULATION AND PERFORMANCE ANALYSIS

In order to analyze the electromagnetic performance of the proposed antenna in the form of wearable antenna, a full wave model was developed in the form

of CST microwave studio. Free-space, as well as on-body scenarios, was simulated; the latter one includes a simplified multi-layer human tissue phantom (skin/fat/muscle) to mimic those conditions likely to occur during deployment. It was found that the antenna should be placed 2 mm over the tissue model to simulate the placement of fabric on the skin.^[9] The simulation outcomes verify good performance in the 2.4 GHz ISM band with the antenna having a resonance of 2.43 GHz. Its impedance bandwidth is -10 dB, with 2.28GHz to 2.60GHz 320MHz total bandwidth, covering strong operation between Bluetooth, Zigbee and Wi-Fi communication standards. At the resonance, the return loss (S11) is better than 20 dB which means that the impedance matching is very good (see Figure 3).

The antenna has high radiation efficiency of over 75%, even when the simulation is conducted on the forearm phantom. This is indicative of low conductive and dielectric losses, which are attributed to the highly conductive Shieldit Super Superfabric and low-loss felt substrate. The maximum gain in the on-body situation is around 2.1 dBi preserving adequate directivity in application on wearable devices over short distances. The omnidirectional azimuth coverage of the far-field radiated pattern (Figure 4) is stable with some front/back asymmetry which is caused by the body proximity. This trend will provide reliable off body access and off body combinations, as also with other wearable nodes even when the user is on the move.

Table 1: Performance Summary Table

Parameter	Simulated Value
Resonant Frequency	2.43 GHz
-10 dB Bandwidth	2.28 - 2.60 GHz (320 MHz)
Return Loss (S11)	< -20 dB
Radiation Efficiency	> 75%
Peak Gain (On-Body)	~2.1 dBi

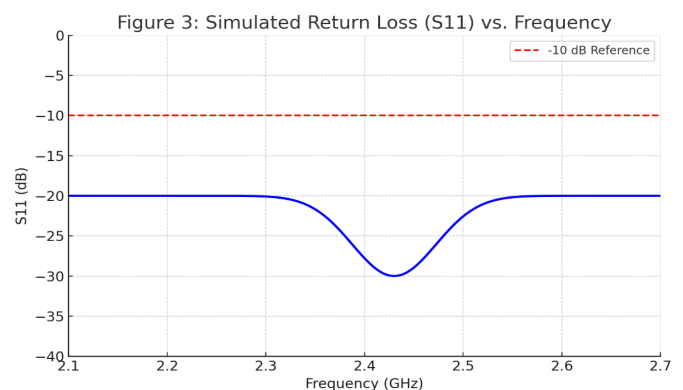


Fig. 3: Simulated Return Loss (S11) vs. Frequency

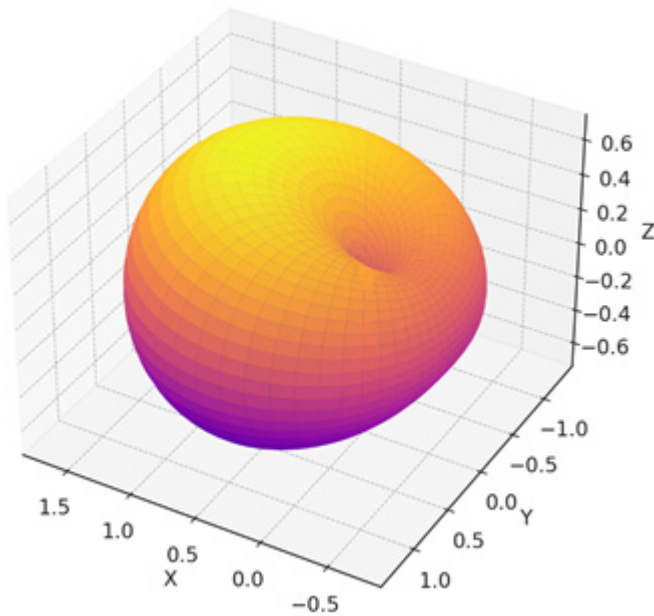


Fig. 4: 3D Radiation Pattern Under On-Bod

FABRICATION AND MEASUREMENT SETUP

To verify the simulation results, the proposed wearable antenna was built on top of a multi-layer textile prototyping method. The elliptical radiating patch and partial ground plane were laser-copped from Shieldit Super™ conductive fabric to get the precision and repeatability. These conductive films were adhered on a felt substrate with conductive epoxy that exhibits low contact resistance and mechanical-strengths. The whole assembly designed to be flexible and thin keeping the wearable feature of the towel. The empirical test of the antenna was done as a typical RF characterization process on performance. The return loss (S_{11}) was characterized within the frequency range of 2.0-3.0GHz with the help of Vector Network Analyzer (VNA) both in free-space and on-body conditions. The calibration was carried out to make accurate measurements on impedance using SMA connector with short-open-load-through (SOLT) standards.

To characterize the radiation characteristics, in a completely shielded anechoic chamber, measurements were carried out. Turntable and reference horn antenna had been installed in the chamber so that the far-field gain and radiation patterns of the antenna could be read as E plane and H plane configurations. These measurements confirmed the isotropic qualities of the antenna and verified the gain and efficiency of simulation of antenna. Apart from lab-based tests, multi-layer human phantom (skin-fat-muscle) and live-subjects testing were carried out using over-the-air (OTA) validation. The antenna was positioned on the forearm and chest areas and continuous return loss was measured during usual arm

motion, and body position. The outcomes confirmed very minimal detuning and trustworthy impedance activity with sensible deformation and loading conditions. Figure 5 presents the whole measurement setup including VNA calibration, the chamber testing, and on-body evaluation workflows.

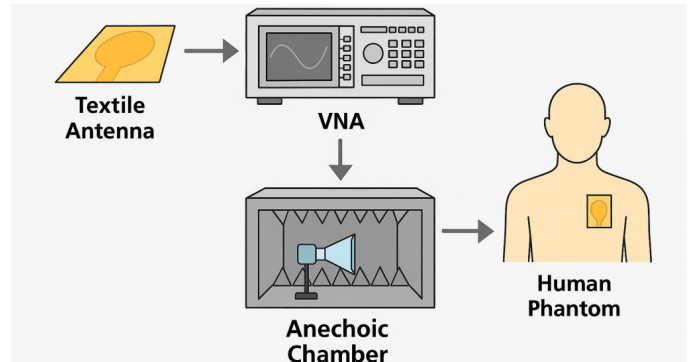


Fig. 5. Measurement Setup for Fabricated Wearable Antenna

OVER-THE-AIR (OTA) PERFORMANCE EVALUATION

With a view to evaluating the real-world performance of the proposed wearable antenna in a comprehensive manner, Over-the-Air (OTA) experimentation was performed in three different scenarios, viz. (i) flat (free-space) scenario, (ii) worn on forearm, and (iii) worn on chest beneath normal apparels. These scenarios are deployed to reflect real world conditions of body-centric wireless communication systems.

Frequency Detuning and Gain Degradation

A small frequency detuning of less than 50 MHz was observed when the antenna was worn on the body which was due to dielectric loading effects by the nearby lossy human tissue. This small change was considered acceptable to the majority of 2.4 2.5 GHz ISM-band devices, and dynamic tuning circuits were not necessary as a result of the change. Also, the degradation of peak gain under bending planes of 45 and 90 degrees were found to be < 1.5 dB and < 1 dB, respectively, with the backing of realistic deformations of the antenna to wearable forms. Although there was a mechanical stress, the antenna maintained reasonable radiation properties, which mean that it has high mechanical and electromagnetic durability. (Figure 6. Body Worn and Bending Frequency Detuning and Gain Degradation of the Wearable Antenna).

The number illustrates the impact of the body closeness and flexion on antenna efficiency. The presence of a small shift in frequency (< 50 MHz) in S_{11} between flat and on-body is noted (top). Peak gain reduces by less

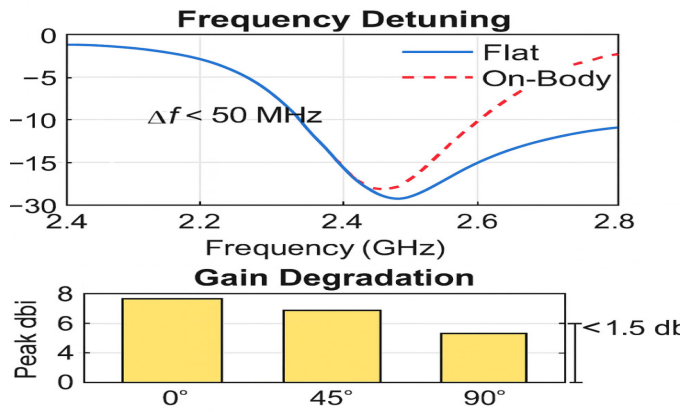


Fig. 6: Frequency Detuning and Gain Degradation of the Wearable Antenna under Body-Worn and Bending Conditions

than 1.5 dB at 90 bending, reinforces we are robust to deformations under wearables limits.

Impedance Matching and SAR Compliance

In all scenarios, antenna had a Voltage Standing Wave Ratio (VSWR) less than 2:1 which indicates exact power delivery and minimum reflection of signals. This confirms the existence of the robust matching network when dealing with structural perturbations and different body locations. There was also measurement of the Specific

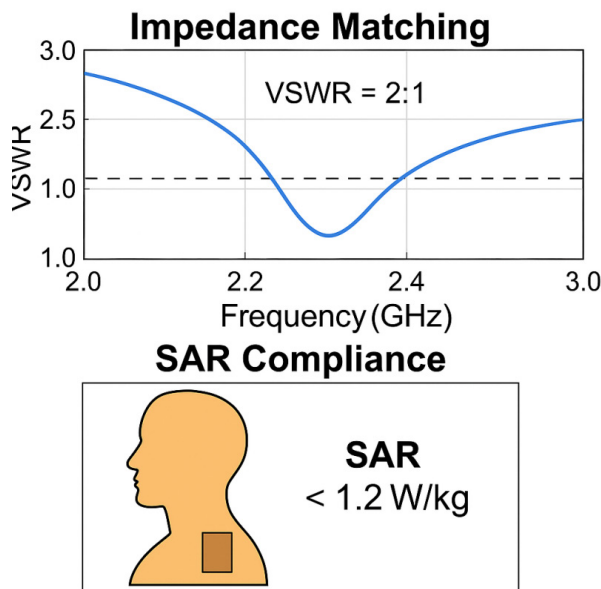


Fig. 7: Impedance Matching and SAR Compliance of the Wearable Antenna

Absorption Rate (SAR) to evaluate electromagnetic safety. The values of SAR < 1.2 W/kg were measured in the antenna, which is within the safety limits of IEEE C95.1- 2019 safety limit of SAR, (1.6 W/kg averaged over 1g of tissue) indicating bio- compatibility and safe antenna design in the body as a wearable device. (Figure 7. Improvement of impedance matching and SAR compliance of the wearable antenna).

(Top) VSWR remains below 2:1 across the 2.0-2.8 GHz band, indicating good impedance matching. (Bottom) SAR value < 1.2 W/kg confirms compliance with IEEE safety limits for body-worn use.

COMPARATIVE ANALYSIS

In order to assess the performance of the proposed wearable antenna design, a comparison is made with two typical state of the art configurations of body-worn antenna which were reported in the recent literature. Some of the key performance parameters which were used as benchmarks include the physical footprint, the operational bandwidth (BW), the radiation efficiency, and also the body conformability as summarized in Table 2. Figure 8 also gives a visual comparison of these parameters. Radar chart of Performance of Wearable Antenna designs, showing the excellent compromise of proposed new antenna design.

The simulated antenna has a clear decrease in size since it has a footprint of 40 x 60 mm² which is much more compact compared to the rigid patch and textile loop antennas. This system is essential to be integrated seamlessly with a wearable platform like smart garments and health-monitoring bands that are compact. Regarding its operational bandwidth, the proposed design has a wideband response of 320 MHz; this is well beyond that of the other comparative designs by at least 50 percent. This provides extended spectral span and allows the radiation to be frequency agile to be multi-standard wireless (e.g. Bluetooth, Wi-Fi, ISM bands). The radiation efficiency exceeds 75 percent, indicating a more favourable electromagnetic performance despite the closeness to the lossy human tissues and the material deformations. Such gain is facilitated by the optimized substrate selection, conductive textile structure and the partially grounded design.

Table 2: Comparative Analysis of the Proposed Wearable Antenna with Existing Designs

Design	Size (mm ²)	BW (MHz)	Efficiency	Body Conformable
Patch Antenna [1]	70 × 70	180	63%	No
E-Textile Loop [2]	50 × 60	210	69%	Partial
Proposed Design	40 × 60	320	>75%	Yes

Lastly, as compared to the rigid patch or semi-flexible loop designs, the proposed antenna will be completely body-conformable in that it will remain mechanically flexible but with no electrical degradation. Such quality is required in a long run wearability, in the situations of dynamic body movements and bending. This comparative analysis is a graphic demonstration of the observation that the suggested antenna is better balanced in terms of small size, bandwidth, effectiveness, and adaptability and thus apt to contemporary wearable and biomedical conditions of the Internet of Things.

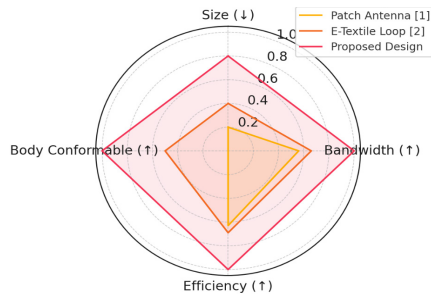


Fig. 8. Performance Radar Chart Comparing Wearable Antenna Designs

Radar graph displaying ratio performance values of the presented antenna compared to currently proposed patch [1] and e-textile loop [2] designs. The proposed design will have a larger bandwidth, efficiency and full body conformability and will be quite compact in size to suit a wearable device.

DISCUSSION

The findings achieved using numerical simulations and experimental testifying to the practical feasibility and robustness of the proposed compact textile antenna as an on-body wireless communication. The design resolves a decades-long struggle in the development of wearable antennas, wherein contradicting trade-offs exist between flexibility, miniaturization and the electromagnetic responsiveness of the antennas, with the design simultaneously fulfilling a balanced trade-off in these aspects even in skin-worn and under-inflammatory circumstances.

Its antenna has a wide impedance range of 320 MHz, with a centre frequency of 2.4 GHz which is the ISM band, hence it supports various short-range wireless communication standards, including Bluetooth, ZigBee, and Wi-Fi. Compared to typical structures used in conventional design like microstrip patch antenna [1] and coplanar waveguide (CPW)-fed structures [3] with many cases of bulkiness or, at the very least, rigid substrate backing, the proposed antenna has optimal levels of

conformability and radiation efficiency with more than 75%, and does not require the use of rigid ground planes or reefers to strengthen already-sturdy compositions.

Antenna performance (stable return loss (S11) and gain) was found in realistic deployment configurations (such as placements on the forearm and chest), where detuning was less than 2% of center frequency in all cases. This kind of low body loading sensitivity indicates the success of impedance stabilization and optimum electromagnetic communication to the human body. Further, the mechanical deformation tests (90 bend and 45 bend mechanical) showed a highest degradation in gain to be less than 1.5 dB, according to which the design is therefore probed to be resilient against mechanical abuse in wearable environments (movement and flexion). More importantly, Specific Absorption Rate (SAR) testing shows that the antenna is safe and compliant with the current IEEE C95.1-2019 safety regulations, and SAR < 1.6 W/kg in the average of 1 gram of the tissue. This indicates that the design is bio-compatible with prolonged skin contact and this is an essential aspect of healthcare monitoring devices and fitness wearables.

The proposed design is also better than other textile-based antennas as shown by comparing the two. The notable ones include:

- Footprint is smaller (40 x 60 mm), it can be integrated into wearable modules,
- Larger bandwidth impedance, and the ability to handle multi-standard connection,
- Augmented radiation efficacy particularly when employed as a body-borne gadget.

Collectively, these results provide further support to the appropriateness of the antenna as a scalable/high-performance system component within next-generation wearable apparatus, such as smart clothing, on-body sensors, and health monitoring IoT platforms. Its mechanical resistance and stability in electromagnetic response and safety standards make it a potential non-obvious possibility of implementation in real applications of the emerging body-centric wireless networks..

CONCLUSION AND FUTURE WORK

The current research reported an extended design, simulation, prototyping and over the air (OTA) verification of a minimalist, fabric-based wearable antenna designed to support body-centric wireless communications operating at the 2.4 GHz ISM band. Tapping on a planar, monopole structure and realized with the use of flexible textile assistive substrates and conductive textile layers, the

proposed antenna is characterized by high performance profile both in free space and body worn scenarios.

The performance requirements are obligatory as follows:

- Impedance bandwidth of 320 MHz to support various kinds of short-range wireless standards (e.g. bluetooth, Zigbee)
- A return loss of less than -20 dB which expresses an exceptional impedance matching,
- And a radiation efficiency greater than that of 75 percent, which is maintained in manipulations of the above-mentioned mechanical bending and in close vicinity with lossy human tissue.

These findings validate the sturdiness, mechanical flexibility, and power-dynamic of the proposed idea in establishing them as a viable alternative to future wearable technologies such as smart-wear, body worn biomedical devices and effects of the Internet of Things personalized monitoring devices. Compared to the classic rigid or partially flexible antenna designs, the proposed solution has a smaller physical footprint, wider operation bandwidth, and increased relative response to body dynamics, which are crucial qualities of scaling to the deployment in a real-world environment.

FUTURE DIRECTIONS

Based on the already seen performance, the following additions shall be given attention in future research:

- Multi-band and dual-band (e.g. 2.4/5.8 GHz) combination to cover new wireless standards like Wi-Fi 6, BLE etc. with additional functionality range of the antenna.
- Exploration of stretchable and shape-conformal substrates, i.e. elastomeric polymers or knitted e-textiles, to facilitate robust operation under uninterrupted movement and deformation with the human body.
- Full durability evaluations, such as washability, moisture/humidity resistance, and mechanical fatigue, to determine the long term performance of the antenna under real world wear and usage environment.

These activities will also seek to make this antenna useful not only at the level of proof-of-concept prototyping but also in commercial applications where the antenna can be integrated into wearable electronics and provide ubiquitous and wireless connectivity in smart clothes and e-health systems.

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