Journal of Multi Disciplinary Engineering Technologies
Volume 18, Issue 02

A Survey on Biomedical Antenna Technologies for Wireless Healthcare Systems

Kritica Karakoti[1*], Inderpreet Kaur[1] and Hari Kumar Singh[1]

[1]Department of Electronics and Communication Engineering, MJP Rohilkhand University, Bareilly, Uttar Pradesh, 243006, India.

*Corresponding author(s). E-mail(s): kritica1999@gmail.com;
Contributing authors: inderpreet@mjpru.ac.in; hks@mjpru.ac.in;

Abstract

Biomedical antennas have evolved from early RF heating applications to modern wearable, implantable, and 5G-enabled healthcare technologies. Significant advancements in Specific Absorption Rate (SAR) reduction, bandwidth expansion, and wireless power transfer continue to enhance medical diagnostics and treatment methods. In recent years, wearable and flexible antennas have gained popularity due to their lightweight, compact, and cost-effective designs. These antennas are well-suited for biomedical applications, as they conform to the human body, enabling comfortable and efficient wireless communication for health monitoring. When designing biomedical antennas, it is crucial to consider their interaction with the human body. The body not only influences the antenna's performance but can also be affected by electromagnetic exposure. Addressing these factors early helps prevent performance issues and potential risks, ensuring reliable functionality in medical applications. This systematic review provides a comprehensive overview of biomedical antenna applications in healthcare while highlighting the latest advancements in medical technology.

Keywords: Biomedical Antennas, Wireless Healthcare, Body Area Networks (BANs), Implantable Devices, Antenna Miniaturization and Electromagnetic Compatibility

1 Introduction

The fifth-generation (5G) technology not only fulfills the demand for high data rates in smartphones and other devices but also enables integration with high-value services [1]. Body-Centric Wireless Communication (BCWC) connects devices worn on, inside, or between individuals who are in proximity. This communication is categorized into three types—off-body, in-body, and on-body—based on the average level of interaction [2], [3], [4].

The impact of body tissue loading on antenna performance is minimal, even when the antenna is positioned close to the human body [5]. Advanced communication through wearable technology is expected to provide cost-effective and efficient biomedical treatments in the future. Telemedicine and smart healthcare systems are key applications for health monitoring. In wearable antennas

Published on: May, 2025 ISSN(P) 0974-1771 ISSN(O) 2581-9372

operating within the ISM band, rectangular and circular patches with various slot configurations are recommended as they improve impedance matching and surface wave regulation [6], [7], [8], [9].

Early detection of illnesses enhances medical treatment and increases the likelihood of a cure. The high contrast between healthy tissues and malignancies makes cost-effective microwave-based breast cancer imaging systems feasible. These systems facilitate rapid tumor detection, ensuring deep penetration and high-resolution scanning [10]. Their non-ionizing properties minimize safety risks, making regular, safe breast screenings accessible, particularly for younger women. Microwave imaging reconstructs scanned images using waves reflected from breast tissue [11], [12].

The article highlights the development of textile-based wearable antennas, which integrate electronic components while delivering high-performance functionality [13]. Textile-based sensors are utilized across multiple industries, including sports, medicine, fashion, and the military, owing to their ability to detect environmental changes [14].

With the integration of antenna frequency, flexible electronic devices can be adapted for diverse applications [15]. Wearable and implantable technologies have the potential to revolutionize global healthcare, enabling real-time health monitoring, personalized treatment, and enhanced patient outcomes through remote management and data-driven insights [16].

2 Material

Traditional antenna designs often incorporate materials that may not be suitable for body-worn applications due to their rigidity and discomfort. To address this issue, textile-based materials can be integrated into antenna designs, offering flexibility, comfort, and wearability. Textile materials exhibit anisotropic electrical conductivity and imperfections, which distinguish their conduction properties from conventional metallic conductors.

One challenge for antenna engineers is that certain electrical and dielectric characteristics of textile materials may not be readily available in material libraries [17], [18]. This can complicate accurate modeling and optimization.

Two critical elements affecting the performance of body-worn antennas are conductive (patch) and nonconductive (substrate) materials. Conductive materials are selected based on electrical conductivity, while substrates are chosen for their dielectric properties, deformation tolerance (bending, twisting, stretching), miniaturization sensitivity, and environmental durability. By utilizing specially designed textile materials, wearable antennas can achieve optimal performance while ensuring comfort and reducing radiation exposure risks for consumers. These innovations enhance safety and practicality in biomedical, IoT, and health-monitoring applications [19], [20].

2.1 Flexible Conductive Material

Flexible materials are used as antenna substrates to enhance thermal conductivity, minimize dielectric loss, and maintain low relative permittivity while ensuring a lower coefficient of thermal expansion. For healthmonitoring applications, biocompatibility is essential. The substrate's flexibility depends on the fabric's thickness and density, with compressible and elastic properties playing a key role. Lower dielectric loss fabrics exhibit reduced surface resistance, improving antenna performance by enhancing gain and impedance bandwidth.

The planar structure, simple design, flexibility, and lightweight nature of textile-based substrates make them an ideal choice for body-worn antenna applications. Their flexibility and safety allow them to be effectively used in both on-body and off-body communication systems [21]. However, while flexible substrates help regulate antenna radiation, their proximity to the human body may reduce efficiency and gain [22]. For applications requiring mechanical and thermal resistance, such as in military and firefighting, polyamide laminate is recommended. Additionally, the introduction of fractal geometry has enabled downsizing, increased electrical length, and achieved lower resonance frequency [23], [24].

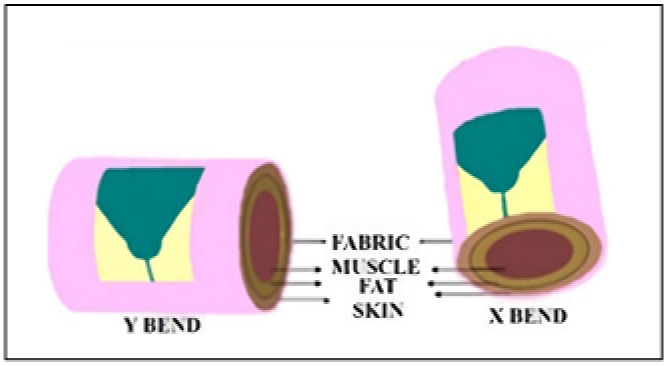


Fig. 1: Bending's effect on X and Y orientation.

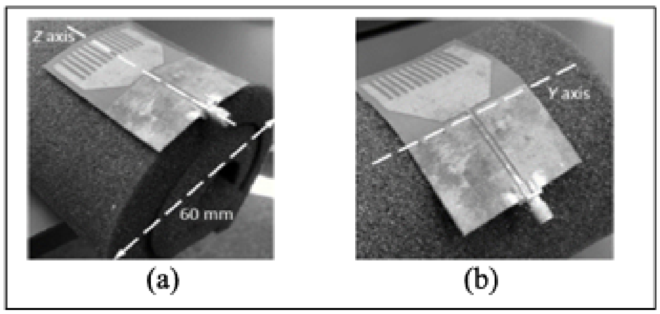


Fig. 2: Effect of bending on (a) Z-axis and (b) Y- axis [25].

Cotton jeans have been employed as a fabric substrate for wireless and health-monitoring applications due to their deformation resistance, flexibility, and seamless integration into clothing [7], [8]. Researchers have recommended denim for its affordability and adaptability to wearable ISM band antennas [26], [27]. Furthermore, etching ground plane slots and radiating zones has improved impedance matching, decreased bandwidth, and enhanced return loss, achieving a value of -40 dB [28]. The round patch antenna, designed using denim, prioritizes wearer comfort while also supporting multiband frequency operation [29].

A directional antenna bent either x- or y-wise is used in the simulation on a model that looks like a cylinder with a radius of 27 mm, which is suitable for an individual's arm. The bending has no effect on the antenna's capacity to function throughout the whole UWB frequency range (Fig. 1) [30]. When the antenna is bent on a phantom, its radiation pattern changes somewhat at the XY plane and decreases at the YZ plane. This is because the antenna physically distorted to fit onto the curved surface of the phantom, as seen in Fig. 2 [25].

2.2 Non-Conductive Materials

Wearable antenna design may be greatly enhanced using smart fabrics or non-conductive (substrate) materials. To achieve greater efficiency and sufficient bandwidth, these materials need to have low relative permittivity, low dielectric loss, and a low thermal expansion coefficient [31]. The total performance of body-worn antennas is affected by the non-conductive material used in the design. In addition to supporting the radiating element, these materials have an impact on the antenna's performance measures, including efficiency, bandwidth, and return loss (S11) [32], [33], [34]. Because the properties of the substrate materials change depending on the frequencies and materials selected, it is essential to characterize them before constructing the antennas [35], [36].

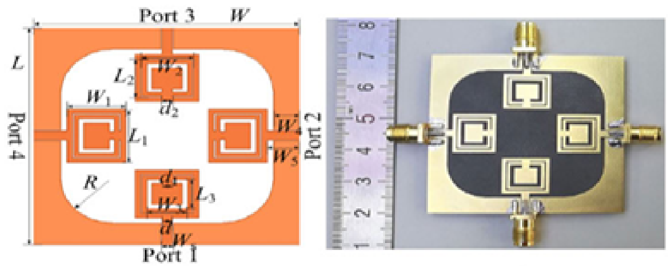


Fig. 3: The proposed antenna, (A) the dual band-notch UWB's geometry, and (B) the manufactured antenna [37].

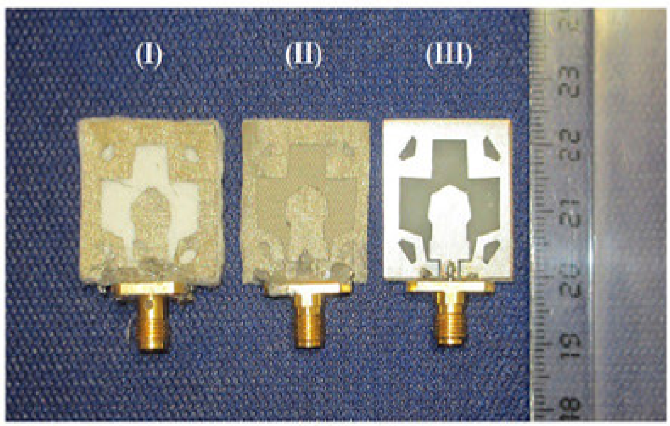


Fig. 4: The manufactured antennas on (I) non-woven, (II) cotton, and (III) FR4 substrates [38].

3 Bandwidth for Biomedical Applications

Although microstrip antennas have traditionally offered limited bandwidth, recent technological advancements have significantly expanded their operational range. Wearable antennas are now playing a crucial role in telemedicine, sports, and biomedical applications. To support single, dual, or multiband operation, innovative methods for bandwidth enhancement should be employed. The ISM and 5G frequency bands are among the most widely utilized for wearable biomedical and IoT applications [39], [40].

To achieve dual polarization in TM11 and TM02 modes at resonant frequencies of 2.45 GHz and 5.8 GHz, an eight-slot circular patch design has been implemented. Additionally, ground-plane slots enhance current distribution, further increasing bandwidth [41]. To extend the bandwidth range from 4.8 to 9 GHz, modifications to the defected ground structure (DGS) were made, resulting in an impedance bandwidth of 60.86% [42].

A dual-resonance patch antenna operating at 2.45 GHz and 918 MHz was developed using a semi-flexible FR-4 substrate with a thickness of 0.8 mm [43]. A metamaterial-based partial ground with a hexagonal radiator was synthesized to achieve ultra-wideband operation with low SAR [44]. Additionally, a hexagonal monopole antenna employing felt substrate and partial ground attained ultrawideband performance. Introducing a square-shaped metamaterial further reduced SAR by 98.3% [45]. To support UWB resonance, designs incorporating tapered patches, folded ground, and CPW-extended ground were explored. 3D structural folding techniques have been utilized to broaden bandwidth and improve impedance matching [46].

The cross-polarization effect, achieved through a complementary split-ring resonator, enables dual-band operation with moderate gain and bandwidth [47]. Furthermore, MNG metamaterial unit cells, designed by capacitively loading slots into a loop's horizontal arms, generate mu-zero resonance. A strip patch positioned near the loop increases resonance and extends bandwidth at lower frequencies. The antenna achieves a maximum FBR of 12 dB and a gain of 3.2 dBi, with an overall bandwidth expansion of 52% (0.64–1.1 GHz). Additionally, it is 80% smaller than conventional mu-negative metamaterial-loaded loops [48].

To cover 4G-LTE and Wi-Fi bands, antennas incorporating long and short strips have been developed, with denim fabric serving as a flexible conductive substrate [49]. These advancements contribute to the growing field of wearable and textile-based antennas, ensuring comfort, efficiency, and adaptability for biomedical applications.

4 On body Antenna Configuration

Since wearable antennas are designed for on-body communication, Wireless Body Area Network (WBAN) devices require an omnidirectional horizontal radiation pattern with a longitudinal orientation for effective operation. A vertical monopole with a large radiation field is a suitable choice for these designs. However, to remain viable, bandwidth must be increased, and antenna height must be significantly reduced to meet practical constraints [50]. The antenna's performance effectively supports both operational frequency bands for on-body communication. The on-body response remains stable at 2.45 GHz, showing minimal impact. Observations at 5.8 GHz revealed a slight bandwidth reduction while maintaining a coefficient below 10 dB. The bending arrangement of the antenna mimics the flexibility of a polyvinyl chloride-wrapped wearable antenna, ensuring lightweight construction and simple dimensions. With excellent on-body performance, this design is well-suited for biosensors, medical monitoring, and body-worn applications [51]. A study analyzing antenna behavior in free space over the human body examined the return loss of a wrist-mounted antenna. Minor variations were observed at 2.4 GHz and 5.8 GHz, indicating that bottom ground effects influence antenna efficiency. Experimental results confirm that simulated and verified measurements of multilayer human tissue models, composed of bone, fat, muscle, and skin, closely align. Additional textile-based antenna experiments further support these findings [52], [53]. A lightweight MIMO-based ultra-wideband (UWB) antenna with dual bandnotched characteristics for wearable applications was introduced by Liu et al. [37]. The proposed antenna features compact dimensions of 50 × 50 mm^2 and is built on a Rogers 5880 substrate, with relative permittivity (r) of 2.2, loss tangent of 0.0009, and thickness (h) of 0.787 mm.

Varkiani et al. [38] presented a small and UWB CPW-fed square slotted antenna for body worn applications. Cotton cloth serves as the substrate material for the 23.5 x 22 mm2 antenna, which is powered by a semi-polygon feed line encircled by grounded aircraft. It has a fractional bandwidth (FBW) of 135% and a bandwidth of 13.1 GHz from 3.2 16.3 GHz.

5 Specific Absorption Rate

Because of international legal limitations and general concerns about the negative health effects of dangerous radiation, researchers have long been concerned about radiation received by human tissue. Therefore, protecting the human body from harmful radiation must be considered in addition to wearable antenna compatibility. The SAR is required to measure the amount of electromagnetic power absorbed by bodily tissue. It is generally believed to be the rate at which radiation is absorbed by an electromagnetic field per mass of human tissues [55], [56].

$$SAR = \frac{\sigma \times E^2}{\rho} \tag{1}$$

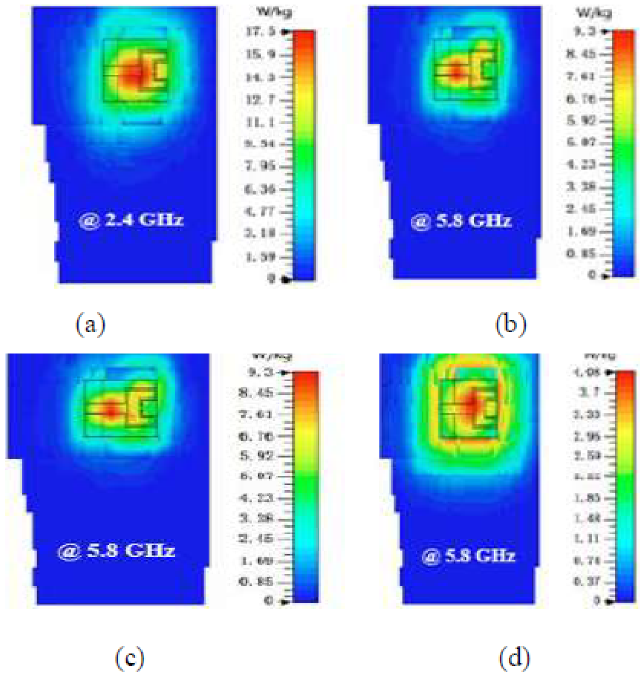


Fig. 5: The SAR distribution for 1 g of tissue in (a) and (b) and 10 g of tissue in (c) and (d) [54].

Where, σ = Conductivity of the material
E =Electric field (V/m)
ρ =Mass-density (Kg/m^3)

The Specific Absorption Rate (SAR) measures the amount of electromagnetic energy absorbed by human body tissues. SAR can be averaged over a small portion of tissues or the entire body [57], [58]. SAR exhibits a negative relationship with tissue density and a direct relationship with tissue conductivity, as tissues with higher conductivity absorb more radiation. Global standardization bodies have established safety limits to regulate human exposure to electromagnetic fields.

A study conducted by [54] analyzed the SAR of a dual-band antenna operating at 2.45 GHz and 5.8 GHz, assuming an input power of 0.5 W. Using a human model with 1 g and 10 g of tissues, findings revealed that human body tissues at 2.45 GHz are exposed to higher electromagnetic radiation than at 5.8 GHz, due to the greater conductivity at the lower frequency Research findings indicate that the maximum SAR for 1 g of human tissues reaches 17.50 W/kg, exceeding the permissible limits for 2.4 GHz and 5.8 GHz operations. These results highlight the necessity of optimized antenna design to ensure compliance with SAR safety regulations.

The SAR analysis of wearable antennas and pressure sensors for elderly fall monitoring was conducted by [59], [60]. A three-layer human body phantom, consisting of muscle, fat, and skin, was created using the CST MWS simulation program for SAR evaluation (Fig. 5a). The dielectric properties of human tissue at 2.45 GHz were obtained from [61].

The SAR analysis was performed on human body tissues weighing 1 g and 10 g using the proposed antenna. When the antenna is positioned close to the human body phantom, greater electromagnetic energy absorption occurs, leading to an increase in SAR. This effect is illustrated in Fig. 5(b) for 1 g of body tissues and Fig.5(c) for 10 g. Additionally, extensive SAR evaluations of single-band and multi-band antenna designs featuring varied layouts and feeding methods have been well-documented in the literature.

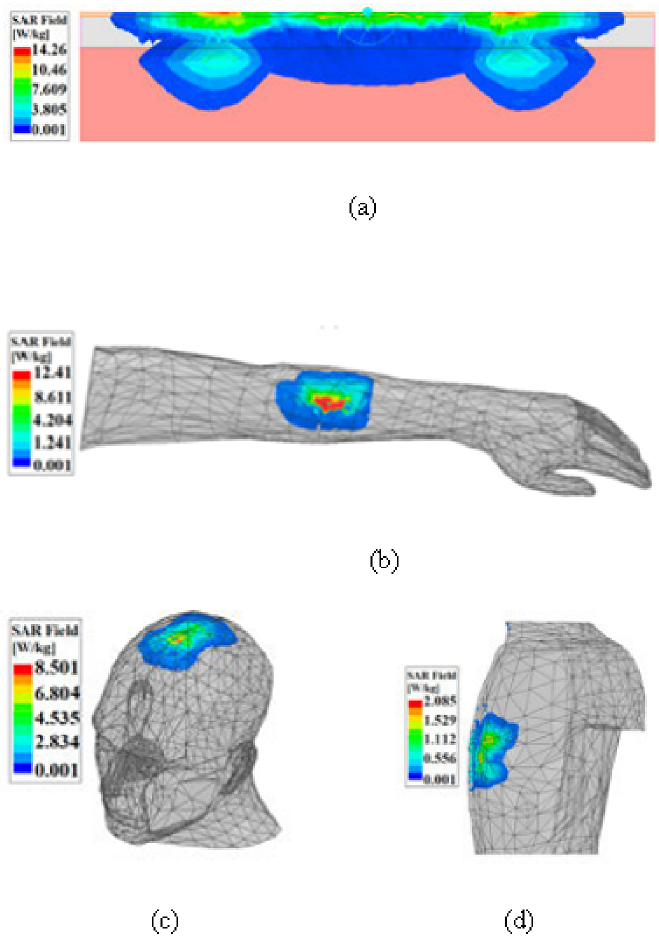


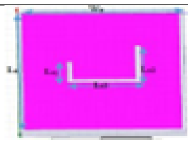
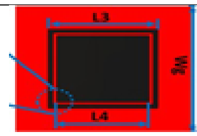
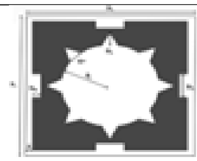
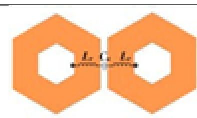
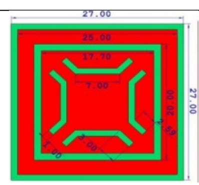
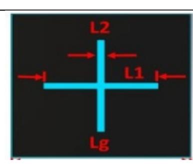
Fig. 6: A three-layer model, a hand, a head and a torso for the SAR distribution of different human body tissues [61].

6 SAR Reduction Techniques

The IEEE standard defines the Specific Absorption Rate (SAR) for 1 g of human tissue, with standard values for 10 g of tissue being 1.6 W/kg and 2 W/kg. One effective method for reducing SAR is the use of a fake magnetic conductor to shield the patch antenna from the human body [25], [62], [63]. This approach allows for monitoring electric field intensity and truncating additional electric field positions [31]. When an antenna is present, the excited currents on the electromagnetic bandgap (EBG) surface increase, leading to stronger coupling that enhances the S11 parameter in higher frequency bands. The integration of an EBG with an antenna can effectively lower SAR by reducing radiation exposure to human tissues.

Several strategies have been proposed to minimize SAR, with a key recommendation for biomedical applications being the reduction of electromagnetic radiation exposure at lower frequencies [64], [65]. These advancements contribute to safer wearable and implantable antenna designs, ensuring compliance with radiation safety regulations.

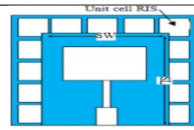
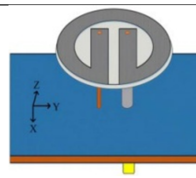
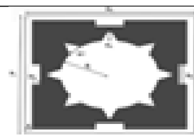
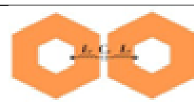
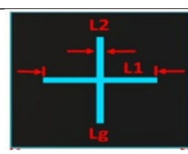
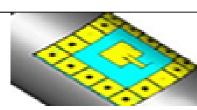
Table 1: A comparison of several SAR reduction methods for wearable antennas

Ref. No.	**Antenna Size** (mm^3)	**Antenna Design**	**Resonance Frequency**	**Materials**	**Gain** (dB)	**SAR**	**Efficiency**
J Slotted EBG [39]	71 x 68 x 14		2.4, 5.4	Denim Jean	2.76, 2.90	0.850, 1.830	-
Square Ring AMC unit cell [58]	86 x 86 x 1.52		3.5	Rogers ULTRA-LAM 3850	4.13	0.022	99.5
Circular shaped FSS unit cell [66]	120 x 120 x 30		2.45	Denim Jean	3.197	0.164	94.86
Hexagonal EBG array [67]	78 x 74 x 1		2.45	FR-4	10.52	0.44	98.5
AMC loaded C shaped antenna [64]	54 x 54 x 3.9		2.4	Thin Fabric and Shieldit	8.63	0.649	90.0
Jerusalem EBG array [68]	75.7 x 75.7 x 0.17		2.45	Rogers ULTRA-LAM 3850	4.13	0.022	99.5

7 Gain Enhancement Methods

The antenna design utilizes felt as a substrate to enhance flexibility and reduce manufacturing costs. To minimize SAR and improve gain, a shaped metamaterial (MTM) patch antenna was proposed, leveraging the -very large (MVL) characteristic of the metamaterial. At 2.45 GHz, the highest recorded SAR value was 0.405 W/kg, which falls within the standard SAR limit of 1.6 W/kg. Compared to an empty metamaterial, the filled metamaterial within the antenna resulted in a higher peak gain of 7.79 dB [63].

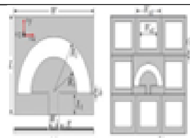
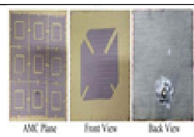
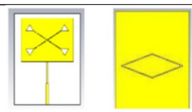
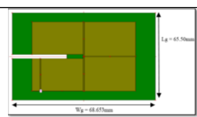
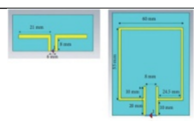
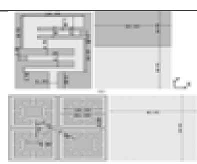
Table 2: A comparative study of wearable antenna gain improvement methods

Techniques used for gain Enhancement	Antenna Size (mm^3)	Antenna Design	Operational Frequency (GHz)	Substrate Used	Gain without Technique (dB)	Gain with Technique (dB)
Patch antenna with RIS [47]	80 x 60 x 3		2.45	Felt	4.67	6.027
Folded ring antenna [54]	60 x 60 x 2		2.45, 3.45	Shieldit's iconic TLY conductive component	–	5.1, 8.6
Circular shaped FSS unit cell [64]	120 x 120 x 30		2.45	Denim Jean	0.47	5.63
Hexagonal EBG array [69]	78 x 74 x 1		2.45	FR-4	–0.05	4.85
Jerusalem cross shaped EBG array [66]	75.7 x 75.7 x 0.17		2.45	Rogers ULTRA-LAM 3850	–, 9.61	4.434
Simple patch antenna with EBG array [70]	96.4 x 113 x 3		2.4	Wash Cotton	6.54	7.61

Additionally, downsizing can be achieved by modifying the gap width between the capacitance and frequency selective surface (FSS) unit. By adjusting capacitance, the resonant frequency shifts lower, leading to bandwidth optimization. FSS contributes to an average gain improvement of 4–5 dBi, with research indicating that SAR can be reduced by up to 94.8% [64].

To further enhance gain, a square ring-shaped artificial magnetic conductor (AMC) ground plane was proposed, using leather as a substrate to increase flexibility. P. Saha et al. examined the AMC ground plane, demonstrating its ability to improve gain while reducing SAR [64]. Back radiation can also be suppressed by controlling inductance and capacitance through a hexagonal

Table 3: A comparative study of wearable antenna Bandwidth improvement methods

Ref. No.	Antenna Configuration	Antenna Size (mm^3)	Operational Frequency (GHz)	Substrate Used	Bandwidth	Technique used
Ring slot antenna with EBG structure [71]		40 x 32 x 2	2.4	Wool Felt	2.28–2.68	Ring Resonator-EBG
Truncated corner technique [67]		85.5 x 85.5 x 5.62	1.575, 2.4	Kevlar	120 MHz, 136 MHz	Truncated corners and four slits on patch
Loaded slots and CRR [70]		90 x 127 x 0.254	2.3	RT5880	238 MHz (2.358–2.52 GHz)	Additional strip placed across the feed
Loaded slots with shorting pins [68]		65.5 x 68.65 x 2.85	2.4	Polyester	(1.4–1.6) GHz, (1.8–4.5) GHz	Open the shorting pin and stub slot
Embroidered dipole and loop antenna [72]		Dipole: 20 x 60 Loop: 75 x 80	2.4	Jean Cotton	(2.19–3.44) GHz, (2.35–2.81) GHz	Copper e-thread was sewn onto denim
Inverse E-shaped microstrip monopole antenna [73]		46 x 46 x 2.4	2.4	Thick Denim	(2.17–2.83) GHz	Few Slits at the radiator increases the electrical current path and square loop with four T-shape stripline EBG increases inductance for enhancing the bandwidth

copper-shaped electromagnetic bandgap (EBG) structure and optimizing the distance between unit cells. Comparisons reveal that an EBG-integrated antenna experiences a 98.5% reduction in SAR, while also increasing gain by 4.85 dB, outperforming antennas without EBG loading [69].

A CPW-fed antenna providing a broad bandwidth of 1.44–2.75 GHz was developed using a cross-shaped EBG array. When operated at 2.4 GHz, the SAR value remains low at 0.022 W/kg, ensuring compliance with safety standards. The short distance between the monopole antenna and the larger CPW ground facilitates current coupling, where currents on the oval-shaped monopole and CPW semi-circular ground plane flow in the same direction, effectively increasing gain by 1.5 dB. Using this technique, an average gain of 6.584 dB is achieved [74].

8 Bandwidth Enhancement Methods

Using a square ring electromagnetic bandgap (EBG) resonator, a semi-circular patch antenna achieved a 14.7% increase in bandwidth compared to a conventional antenna [71]. The truncation technique enabled circular polarization without altering the antenna's overall size. Additionally, impedance matching can be further optimized using this approach. The antenna corners incorporate four slits, which enhance the electrical current path and excite lower frequencies at 2.45 GHz and 1.575 GHz, respectively. By combining multiple resonances, bandwidth expansion is possible [67].

A microstrip patch antenna with multiple filled slots was proposed to extend the current path, effectively improving bandwidth. A complementary rhombus resonator (CRR), providing up to 238 MHz of electromagnetic resonance, was integrated onto the antenna's backside to further enhance bandwidth [70]. Additionally, a study incorporated two conducting component layers separated by 0.3 mm-radius shorting pin holes between the patch and ground plane, increasing bandwidth. For flexibility, polyester was selected as the substrate material. Slot-loading an open stub on the patch extended the current path, resulting in an 85% bandwidth improvement [68].

A rectangular radiator with three elliptical holes was introduced to develop a pre-fractal antenna, which reduced size by 26.85% while increasing bandwidth by 131 MHz. Extending the current path across the ISM band (2.386–2.517 GHz) facilitated lower resonance [75]. Researchers proposed sewing integrated copper e-threads onto dipole and loop antennas. By carefully considering copper thread thickness, relative permittivity, and conductivity in substrate selection, they achieved broad bandwidths of 2.19–3.44 GHz and 2.35–2.81 GHz [72]. Both the polyester substrate and copper taffeta were woven using the plain weaving technique, ensuring resistance to external environmental effects.

A lower-side patch improved bandwidth by up to 109%, while bottom-edge tapering and parallel slot integration extended the electrical current channel over the 1.198–4.055 GHz frequency range [76]. Introducing varied-length slits in an inverted E-shaped antenna expanded bandwidth by 15% (330 MHz), spanning 2.23–2.59 GHz. In the EBG structure, four T-shaped striplines positioned beneath the antenna introduced higher inductance, thereby reducing backward radiation and increasing bandwidth by 27% (660 MHz), covering 2.17–2.83 GHz [73].

9 Conclusion

Advancements in technology are significantly enhancing healthcare delivery, with innovations such as wearable technology, telemedicine, mobile health, remote patient monitoring, and electronic health systems. Recent studies on wearables and implants underscore their transformative impact, improving healthcare accessibility and efficiency through modern technology and digital integration. These developments highlight how the next generation of cutting-edge technology is offering practical solutions to the challenges of digital healthcare.

Since wearable antennas require substrates, materials with high efficiency and broad bandwidth should be selected for their construction. Research suggests that thicker, low-permittivity substrates help minimize losses while expanding bandwidth.

Wearable antennas have been designed using various conductive and non-conductive materials. However, to ensure optimal performance, testing near the human body is necessary to meet the specifications of the wearable antenna.

Several techniques including fractal slot loading, PEC reflectors, truncated ground, and ferrite sheets have been previously employed to enhance antenna performance and improve isolation between the antenna and human body. Despite their benefits, these methods often pose challenges such as large size, structural complexity, high cost, and reduced comfort.

Over the past 20 years, metamaterials have played a crucial role in wearable antenna design, significantly improving overall performance. Their advantages include:

- Lower SAR values, ensuring safer electromagnetic exposure,

- Improved radiation efficiency and front-to-back ratio (FBR
- Expanded bandwidth, enhanced directivity, and higher gain.

These advancements continue to shape next-generation wearable antennas, making them more efficient, comfortable, and adaptable for biomedical applications.

References

[1] Agiwal, M., Roy, A., Saxena, N.: Next generation 5g wireless networks: A comprehensive survey. IEEE Communications Surveys & Tutorials **18**(3), 1617–1655 (2016). 3rd Quart.

[2] Shahzad, M.A., Paracha, K.N., Naseer, S., Ahmad, S., Malik, M., Farhan, M., Ghaffar, A., Hussien, M., Sharif, A.B.: An artificial magnetic conductor-backed compact wearable antenna for smart watch iot applications. Electronics **10**(23), 2908 (2021)

[3] Zu, H., Wu, B., Yang, P., Li, W., Liu, J.: Wideband and high-gain wearable antenna array with specific absorption rate suppression. Electronics **10**(17), 2056 (2021)

[4] Yeboah-Akowuah, B., Tchao, E.T., Ur-Rehman, M., Khan, M.M., Ahmad, S.: Study of a printed split-ring monopole for dual-spectrum communications. Heliyon **7**(9), 07928 (2021) https://doi.org/10.1016/j.heliyon.2021.e07928

[5] Chen, Y.-S., Ku, T.-Y.: A low-profile wearable antenna using a miniature high impedance surface for smartwatch applications. IEEE Antennas and Wireless Propagation Letters **15**, 1144–1147 (2016)

[6] Gao, G.-P., Zhang, B.-K., Dong, J.-H., Dou, Z.-H., Yu, Z.-Q., Hu, B.: A compact dual-mode pattern-reconfigurable wearable antenna for the 2.4-ghz wban application. IEEE Transactions on Antennas and Propagation **71**(2), 1901–1906 (2023)

[7] Singh, V.K., Dhupkariya, S., Bangari, N.: Wearable ultra wide dual band flexible textile antenna for wimax/wlan application. Wireless Personal Communications **95**(2), 1075–1086 (2017)

[8] Musa, U., Shah, S.M., Majid, H.A., Mahadi, I.A., Rahim, M.K.A., Yahya, M.S., Abidin, Z.Z.: Design and analysis of a compact dual band wearable antenna for wban applications. IEEE Access **11**, 30996–31009 (2023)

[9] ElGharbi, M., Martinez-Estrada, M., Fernández-García, R., Ahyoud, S., Gil, I.: A novel ultra-wide band wearable antenna under different bending conditions for electronic-textile applications. Journal of the Textile Institute **112**(3), 437–443 (2021)

[10] Davies, R.J.: Electrical bioimpedance analysis as a biomarker of breast density and/or breast cancer risk (2014). https://patents.google.com/patent/US8738124B2/en

[11] O'Loughlin, D., O'Halloran, M., Moloney, B.M., Glavin, M., Jones, E., Elahi, M.A.: Microwave breast imaging: Clinical advances and remaining challenges. IEEE Transactions on Biomedical Engineering **65**(11), 2580–2590 (2018) https://doi.org/10.1109/TBME.2018.2809541

[12] Aldhaeebi, M.A., Alzoubi, K., Almoneef, T.S., Bamatraf, S.M., Attia, H., Ramahi, O.M.: Review of microwaves techniques for breast cancer detection. Sen

[13] Veske, P., Ilén, E.: Review of the end-of-life solutions in electronics based smart textiles. Journal of Textile Institute **112**(9), 1500–1513 (2021)

[14] Nayk, R., Wang, L., Pahye, R.: Electronic textiles for military personnel, 232–257 (2017)

[15] Keiji, O.: High quality color reproduction on jacquard silk textile from digital color images. AUTEX Research Journal **3**(4), 173–179 (2003)

[16] Marchand, G., Bourgerette, A., Antonakios, M., Rat, V., David, N., Vinet, F., Guillemaud, R.: Development of a dehydration sensor integrated on fabric

[17] Bal, K., Kothari, V.K.: Measurement of dielectric properties of textile materials and their applications. Indian Journal of Fibre Textile Research **34**, 191–199 (2009)

[18] Patel, T., Sahoo, M.: Design issues of wearable antennas. International Journal of Scientific Research **5**(5), 662–664 (2016)

[19] Kirtania, S.G., Elger, A.W., Hasan, M.R., Wisniewska, A., Sekhar, K., Karacolak, T., Sekhar, P.K.: Flexible antennas: A review. Micromachines **11**(9), 847 (2020)

[20] Ashyap, A.Y.I., Dahlan, S.H.B., Abidin, Z.Z., Abbasi, M.I., Kamarudin, M.R., Majid, H.A., Dahri, M.H., Jamaluddin, M.H., Alomainy, A.: An overview of electromagnetic band-gap integrated wearable antennas. IEEE Access **8**, 7641–7658 (2020)

[21] Mahfuz, M.M.H., Islam, M.R., Park, C.-W., Elsheikh, E.A.A., Suliman, F.M., Habaebi, M.H., Malek, N.A., Sakib, N.: Wearable textile patch antenna: Challenges and future directions. IEEE Access **10**, 38406–38427 (2022)

[22] Li, H., Du, J., Yang, X.-X., Gao, S.: Low-profile all-textile multiband microstrip circular patch antenna for wban applications. IEEE Antennas Wireless Propag. Lett. **21**, 779–783 (2022)

[23] Mersani, A., Osman, L., Ribero, J.-M.: Flexible uwb amc antenna for early stage skin cancer identification. Prog. Electromagn. Res. M **80**, 71–81 (2019)

[24] Jr., P.F.S., Santana, E.E.C., Pinto, M.S.S., Freire, R.C.S., Oliveira, M.A., Fontgalland, G., Silva, P.H.F.: Flexible wearable pre-fractal antennas for personal high-temperature monitoring. Wireless Pers. Commun. **114**(3), 1983–1998 (2020)

[25] Shaw, T., Samanta, G., Mitra, D., Mandal, B., Augustine, R.: Design of metamaterial based efficient wireless power transfer system utilizing antenna topology for wearable devices. Sensors **21**(10), 3448 (2021)

[26] Gao, G.-P., Zhang, B.-K., Dong, J.-H., Dou, Z.-H., Yu, Z.-Q., Hu, B.: A compact dual-mode pattern-reconfigurable wearable antenna for the 2.4-ghz wban application. IEEE Trans. Antennas Propag. **71**(2), 1901–1906 (2023)

[27] Singh, V.K., Dhupkariya, S., Bangari, N.: Wearable ultra wide dual band flexible textile antenna for wimax/wlan application. Wireless Pers. Commun. **95**(2), 1075–1086 (2017)

[28] Kumar, S.A., Shanmuganantham, T.: Design and performance of textile antenna for wearable applications. Trans. Electr. Electron. Mater. **19**(5), 352–355 (2018)

[29] Yadav, A., Singh, V.K., Bhoi, A.K., Marques, G., Garcia-Zapirain, B., Torre Díez, I.: Wireless body area networks: Uwb wearable textile antenna for telemedicine and mobile health systems. Micromachines **11**(6), 558 (2020)

[30] Sugumaran, B., Balasubramanian, R., Palaniswamy, S.K.: Reduced specific absorption rate

compact flexible monopole antenna system for smart wearable wireless communications. Eng. Sci. Technol., Int. J. **24**(3), 682–693 (2021)

[31] Ashyap, A.Y.I., Dahlan, S.H., Abidin, Z.Z., Kamarudin, M.R., Majid, H.A., Alduais, N.A.M., Dahri, M.H., Alhandi, S.A.: C shaped antenna based artificial magnetic conductor structure for wearable iot healthcare devices. Wireless Netw. **27**(7), 4967–4985 (2021)

[32] Li, H., Du, J., Yang, X.-X., Gao, S.: Low-profile all-textile multiband microstrip circular patch antenna for wban applications. IEEE Antennas Wireless Propag. Lett. **21**, 779–783 (2022)

[33] Lin, X., Chen, Y., Gong, Z., Seet, B.-C., Huang, L., Lu, Y.: Ultrawideband textile antenna for wearable microwave medical imaging applications. IEEE Trans. Antennas Propag. **68**(6), 4238–4249 (2020)

[34] Wagih, M., Wei, Y., Beeby, S.: Flexible 2.4 ghz node for body area networks with a compact high-gain planar antenna. IEEE Antennas Wireless Propag. Lett. **18**(1), 49–53 (2019)

[35] Bashir, S.: Design and synthesis of non uniform high impedance surface based wearable antennas (2009)

[36] Zhu, S.: Wearable antennas for personal wireless (2008)

[37] Liu, H., Kang, G., Jiang, S.: Compact dual band-notched uwb multiple-input multiple-output antenna for portable applications. Microwave and Optical Technology Letters **62**(3), 1215–1221 (2020)

[38] Danjuma, I.M., Akinsolu, M.O., Mohammad, B., Eya, E., Abdnalhameed, R., Noras, J.M., Liu, B.: A compact size and low profile rectangular slot monopole antenna for uwb body centric applications, 91–92 (2019)

[39] Victor, V.M., Jogdand, S.: Design development and performance evaluation of conformal textile antennas, 15064–15069 (2016)

[40] Tsolis, A., Whittow, W.G., Alexandridis, A.A., Vardaxoglou, J.: Embroidery and related manufacturing techniques for wearable antennas: Challenges and opportunities. Electronics **3**(2), 314–338 (2014)

[41] Salvado, R., Loss, C., Gonçalves, R., Pinho, P.: Textile materials for the design of wearable antennas: A survey. Sensors **12**(11), 15841–15857 (2012)

[42] Ashyap, A.Y.I., Dahlan, S.H., Abidin, Z.Z., Kamarudin, M.R., Majid, H.A., Alduais, N.A.M., Dahri, M.H., Alhandi, S.A.: C shaped antenna based artificial magnetic conductor structure for wearable iot healthcare devices. Wireless Netw. **27**(7), 4967–4985 (2021)

[43] Yu, Z., Niu, R., Zhang, G., Sun, R., Lin, Z., Li, Y., Ran, X.: A wearable self-grounding slit antenna for ism/4g/5g/bluetooth/wlan applications. IEEE Access **11**, 87930–87937 (2023)

[44] Kiani, S., Rezaei, P., Fakhr, M.: A cpw-fed wearable antenna at ism band for biomedical and wban applications. Wireless Netw. **27**(1), 735–745 (2021)

[45] Singh, H., Srivastava, K., Kumar, S., Kanaujia, B.K.: A planar dual band antenna for ism/wearable applications. Wireless Personal Communications **118**(1), 631–646 (2021)

[46] Yalduz, H., Tabaru, T.E., Kilic, V.T., Turkmen, M.: Design and analysis of low profile and

low sar full-textile uwb wearable antenna with metamaterial for wban applications. AEU-International Journal of Electronics and Communications **126**, 153465 (2020)

[47] Yan, S., Soh, P.J., Vandenbosch, G.A.E.: Wearable ultrawideband technology—a review of ultrawideband antennas, propagation channels, and applications in wireless body area networks. IEEE Access **6**, 42177–42185 (2018)

[48] Yue, T., Jiang, Z.H., Werner, D.H.: A compact metasurface-enabled dual-band dual-circularly polarized antenna loaded with complementary split ring resonators. IEEE Transactions on Antennas and Propagation **67**(2), 794–803 (2019)

[49] Rezaeieh, S.A., Antoniades, M.A., Abbosh, A.M.: Compact wide band loop antenna partially loaded with mu-negative metamaterial unit cells for directivity enhancement. IEEE Antennas Wireless Propagation Letters **15**, 1893–1896 (2016)

[50] Mantash, M., Tarot, A., Collardey, S., Mahdjoubi, K.: Design methodology for wearable antenna on artificial magnetic conductor using stretch conductive fabric. Electronics Letters **52**(2), 95–96 (2016)

[51] Irene, G., Rajesh, A.: Dual polarized uwb mimo antenna with elliptical polarization for access point with very high isolation using ebg and msr. Progress In Electromagnetics Research C **99**, 87–98 (2020)

[52] Wong, K.-L., Chang, H.-J., Wang, C.-Y., Wang, S.-Y.: Very low-profile grounded coplanar waveguide-fed dual-band wlan slot antenna for on-body antenna application. IEEE Antennas Wireless Propagation Letters **19**(1), 213–217 (2020) https://doi.org/10.1109/LAWP.2019.2958961

[53] Agneessens, S., Rogier, H.: Compact half diamond dual-band textile hmsiw on-body antenna. IEEE Transactions on Antennas and Propagation **62**(5), 2374–2381 (2014)

[54] Ali, U., Shafi, S.M.U., Shah, S.A., Shah, I.A., Flint, J.A.: Design and comparative analysis of conventional and metamaterial-based textile antennas for wearable applications. International Journal of Numerical Modelling: Electronic Networks, Devices and Fields **32**(6), 2567 (2019)

[55] Varkiani, S.M.H., Afsahi, M.: Compact and ultra-wideband cpw-fed square slot antenna for wearable applications. AEU - International Journal of Electronics and Communications **106**, 108115 (2019)

[56] Potey, P.M., Tuckley, K.: Design of wearable textile antenna for low back radiation. Journal of Electromagnetic Waves and Applications **34**(2), 235–245 (2020)

[57] Zhou, L., Fang, S., Jia, X.: Dual-band and dual-polarised circular patch textile antenna for on-/off-body wban applications. IET Microwaves, Antennas Propagation **14**(7), 643–648 (2020)

[58] Yao, L., Li, E., Yan, J., Shan, Z., Ruan, X., Shen, Z., Ren, Y., Yang, J.: Miniaturization and electromagnetic reliability of wearable textile antennas. Electronics **10**(9), 994 (2021)

[59] Hosain, M.K., Kouzani, A.Z., Tye, S.J.: Development of a compact rectenna for wireless powering of a head-mountable deep brain stimulation device. IEEE Journal of Translational Engineering in Health and Medicine **2** (2014). Art. no. 1500113

[60] Wang, M., Yang, Z., Wu, J., Bao, J., Liu, J., Cai, L., Dang, T., Zheng, H., Li, E.: Investigation of sar reduction using flexible antenna with metamaterial structure in wireless body area network.

IEEE Transactions on Antennas and Propagation **66**(6), 3076–3086 (2018)

[61] Nie, H.-K., Xuan, X.-W., Ren, G.-J.: Wearable antenna pressure sensor with electromagnetic bandgap for elderly fall monitoring. AEU - International Journal of Electronics and Communications **138** (2021). Art. no. 153861

[62] Mahfuz, M.M.H., Islam, M.R., Sakib, N., Habaebi, M.H., Raad, R., Sakib, M.A.T.: Design of wearable textile patch antenna using c-shape etching slot for wi-max and 5g lower band applications, 168–172 (2021)

[63] Mumin, A.R.O., Alias, R., Abdullah, J., Dahlan, S.H., Ali, J., Debnath, S.K.: Design a compact square ring patch antenna with amc for sar reduction in wban applications. Bull. Electr. Eng. Informat. **9**(1), 370–378 (2020)

[64] Atrash, M.E., Abdalla, M.A., Elhennawy, H.M.: A wearable dual-band low profile high gain low sar antenna amc-backed for wban applications. IEEE Trans. Antennas Propag. **67**(10), 6378–6388 (2019)

[65] Gao, G.-P., Hu, B., Wang, S.-F., Yang, C.: Wearable circular ring slot antenna with ebg structure for wireless body area network. IEEE Antennas Wireless Propag. Lett. **17**, 434–437 (2018)

[66] Das, G.K., Basu, S., Mandal, B., Mitra, D., Augustine, R., Mitra, M.: Gain-enhancement technique for wearable patch antenna using grounded metamaterial. IET Microw., Antennas Propag. **14**(15), 2045–2052 (2020)

[67] Saha, P., Mitra, D., Parui, S.K.: Control of gain and sar for wearable antenna using amc structure. Radioengineering **30**(1), 81–88 (2021)

[68] Mumin, A.R.O., Alias, R., Abdullah, J., Dahlan, S.H., Ali, J., Debnath, S.K.: Design a compact square ring patch antenna with amc for sar reduction in wban applications. Bull. Electr. Eng. Informat. **9**(1), 370–378 (2020)

[69] Bhattacharjee, S., Mitra, M., Chaudhuri, S.R.B.: An effective sar reduction technique of a compact meander line antenna for wearable applications. Prog. Electromagn. Res. M **55**, 143–152 (2017)

[70] Singh, S., Verma, S.: Sar reduction and gain enhancement of compact wideband stub loaded monopole antenna backed with electromagnetic band gap array. Int. J. RF Microw. Comput.-Aided Eng. **31**(10) (2021). Art. no. e22813

[71] Sugumaran, B., Balasubramanian, R., Palaniswamy, S.K.: Reduced specific absorption rate compact flexible monopole antenna system for smart wearable wireless communications. Eng. Sci. Technol., Int. J. **24**(3), 682–693 (2021)

[72] Jain, V., Dhaliwal, B.S.: Miniaturized wearable fractal patch antenna for body area network applications. Int. J. Electron. Telecommun. **67**(2), 149–154 (2021)

[73] Lin, X., Chen, Y., Gong, Z., Seet, B.-C., Huang, L., Lu, Y.: Ultrawideband textile antenna for wearable microwave medical imaging applications. IEEE Trans. Antennas Propag. **68**(6), 4238–4249 (2020)

[74] Lin, X., Seet, B.-C., Joseph, F., Li, E.: Flexible fractal electromagnetic bandgap for millimeter-wave wearable antennas. IEEE Antennas Wireless Propag. Lett. **17**, 1281–1285 (2018)

[75] Jaiswal, P., Sinha, D.P.: Design of wearable textile based microstrip patch antenna for bandwidth enhancement. Int. J. Appl. Eng. Res. **13**(18), 13647–13651 (2018)

[76] Varma, S., Sharma, S., John, M., Bharadwaj, R., Dhawan, A., Koul, S.K.: Design and performance analysis of compact wearable textile antennas for iot and body-centric communication applications. Int. J. Antennas Propag. **2021**, 1–12 (2021)