A 5GHz Flexible Compact Microstrip Patch Antenna for WBAN Applications: Design, Simulation and Performance Analysis

Md. Samiul Islam, Md. Akramul Alim and Abu Zafor Md. Touhidul Islam

Department of Electrical and Electronic Engineering, University of Rajshahi, Rajshahi-6205, Bangladesh

ABSTRACT

This paper introduces the design and performance analysis of a compact flexible rectangular microstrip patch antenna for wireless body area network (WBAN) applications. In order to provide flexibility, the proposed antenna is designed to operate at 5 GHz band using 1 mm thick polyimide substrate with relative permittivity of 3.5 and the inset-fed technique is used for better impedance matching. The patch antenna having dimensions of 23 mm ×22.72 mm × 1 mm is designed to cover Wi-Fi services of 5G band and is simulated using CST Microwave Studio. Parametric studies are conducted to investigate the antenna performance and its suitability for WBAN applications. The designed antenna resonates at 5 GHz and exhibits –10 dB impedance bandwidth of about 3.52% (5.085-4-909 GHz) and covering a total bandwidth of 176 MHz. The antenna achieves good impedance matching with directivity of 5.716 dBi, directional radiation pattern, and a high radiation efficiency of 89% at the 5 GHz resonant band. By locating the proposed antenna on a phantom human body model, it maintains positive gain, efficiency, and acceptable specific absorption rate (SAR) at the resonant frequency. The results of this study demonstrate the potential of the proposed design to enhance the performance and efficiency of the proposed patch antenna and can be a suitable candidate for WBAN applications in the 5 GHz band 5G wireless communications.

KEYWORDS

Inset-fed, Patch antenna, Wearable, WBAN, SAR, Phantom

1. Introduction

In recent years the progress in smart handheld devices, their cloud-based applications and device to device communication has resulted in an increase in the demand of high data rate. New technologies like VANET, IoT, M2M are counting more overhead concurrently to the presently growing demand [1]. The recent IoT services have to do performance trade-offs to get the finest from the current wireless technologies like Bluetooth, Wi-Fi, Zigbee, 3G and 4G. With 5G wireless technology, a fully connected network around the world will be apparent that can have a vibrant role in providing high speed connections, wide bandwidth, low latency and high reliability [2,3]. Because of the availability of a large amount of unutilized bandwidth, the future 5G network is likely to work in the mm-wave band (between 3GHz to 300GHz).

For providing Wi-Fi services the 5 GHz band has been widely used around the world as unlicensed band for use in indoor and outdoor environment [4-6]. As the popular 2.4 GHz ISM band is already overcrowded using existing WiFi and Bluetooth wireless technologies, the researchers are now intentionally designing antenna not to resonate at 2.4 GHz for avoiding probable interference of electromagnetic signals. In recent years, the5 GHz band, with its wide

DOI : 10.5121/ijasa.2023.11401

bandwidth and high data rate, is chosen specifically for use WBAN applications, military communications and telemetry applications.

Microstrip patch antennas have many advantages and widely used due to their lesser in cost, smaller size, lower weight, and easier to fabricate, wider bandwidth and flexible feed line. They are suitable for applications in GPS, WiFi, Wi-Max, WLAN, WBAN and satellite communication. The employment of inset-fed technique (planar feed configuration) for excitation of patch antenna, it can provide impedance matching of the antenna to the feed line [7-10]. The movement of the inset-fed feed point from the edge of the patch antenna towards its center results in the decrease of the input impedance and it becomes zero at the center of the patch. For better performance, the feed line is usually connected to the point inside of the patch where the feed line and patch will have equal impedance characteristics ant the input impedance is 50**Ω**.

Recently, the WBAN has achieved attention across different areas of applications such as sports, health, security, and the military [11-13]. The WBAN enabled devices must possess high data rate, low cost, low power consumption and ability to respond changes in the human body conditions [14]. Because of the human body is involved, antenna design for WBAN applications have drawn considerable attraction among the researchers [15-19]. The effects of the antennas on human body must be examined based on the analysis of its Specific Absorption Rate (SAR) limits provided by the Federal Communications Commission (FCC) and International Commission on Non-Ionizing Radiation Protection (ICNIRP) standards [20-22]. With the development of wireless communication, flexible and wearable antennas with the properties of low loss, lightweight, low profile, stable gain and easy processing are now widely used in WBAN applications [23]. The 5 GHz frequency band is becoming potential communication band for wearable antenna based WBAN applications [24].

This work presents the design and analysis of a compact size, flexible wearable microstrip patch antenna for WBAN applications for enabling enhancement in radiation properties at the resonant 5 GHz ISM band frequency. The inset-fed feeding technique is used for impedance matching. The antenna is initially designed and simulated to resonate at 5 GHz and analyzed the performance parameters under the off-body conditions. The simulation and optimization of the proposed antenna is performed using CST microwave studio. The antenna’s performance and SAR limits under the on-body conditions are also tested for confirming its suitability for WBAN applications.

Hereafter, the order of paper is as follows: Section 2 describes antenna design topology, Section 3 presents off-body antenna performance, Section 4 demonstrates on-body antenna performance on a human phantom model, and finally conclusion is presented in Section 5.

2. ANTENNA DESIGN TOPOLOGY

The design parameters of a rectangular microstrip patch antenna are the: resonant/operating frequency, dielectric constant of substrate, height of the dielectric substrate, width of the patch, Length of the patch, width of the ground plane, and length of the ground plane. In the of the patch antenna, the following parameters were considered to be known: resonant frequency as 5 GHz, substrate material as Polyimide whose $\varepsilon_r = 3.5$, patch material as copper (annealed), a loss tangent, $\tan\delta$ of 0.002 and speed of light as 3×10^8 m/s. The transmission line model is used in this work for the design of the rectangular microstrip patch antenna. The antenna dimensions (length and width of the patch) are calculated using the set of equations described in [25]. The calculated values of the design parameters of the proposed antenna are summarized in Table1.

The proposed flexible patch antenna structure was designed and simulated using a commercial electromagnetic simulation software CST Microwave Studio Suite 2018 Software. Initially, the proposed antenna is designed and simulated for a conventional patch antenna using parameter values listed in Table 1 to resonate at 5 GHz which is composed of a rectangular patch and inset microstrip feed line on a flexible polyimide substrate with a thickness of 1 mm. Then to obtain better performance, the parameter values of the rectangular patch are optimized. At 5 GHz, the optimized values of patch lengthis15.72 mm and the patch width is 20 mm, the ground length (and substrate length) is 22.72 mm, the ground width (and substrate width) is 23 mm. The optimized dimensions of the proposed antenna are thus 22.72 mm × 23 mm × 1 mm as shown in Fig. 1.

Table 1. Dimensions of the proposed antenna structure.

Parameter	Value
Resonant frequency	5 GHz
Substrate width	23 mm
Substrate Length	22.72 mm
Patch width	20 mm
Patch Length	15.72 mm
Length of the inset	3.5 mm
The width of the microstrip feedline	2.28 mm
The gap between the patch and the inset-fed	1.92 mm
Dielectric constant of the substrate	3.5
The height of the dielectric substrate	1 mm
The height of the conductor	0.035 mm

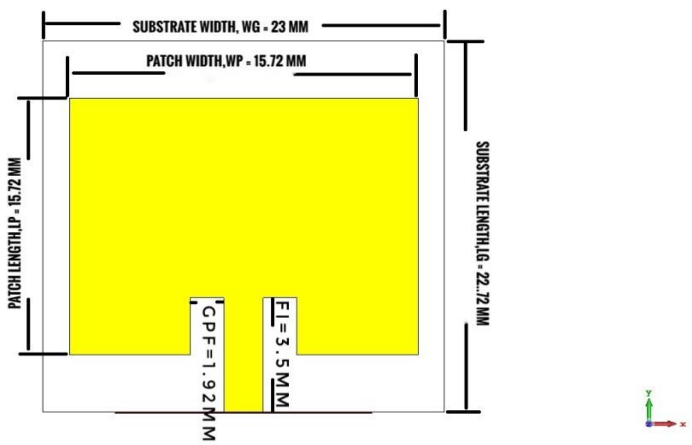


Fig.1 The structure of the proposed designed flexible patch antenna with inset-fed feeding.

3. Off-Body Simulated Results and Discussion

The performance of Microstrip Patch antennas can be discussed into two stages. Firstly, the wearable antenna is examined in off body condition at 5 GHz. Secondly, the wearable antenna is placed on the human body to investigate the performance and SAR near to the lossy human body at 5GHz. The simulated performance results of the designed antenna at 5 GHz under the off-body conditions is presented below.

3.1. Return Loss

The return loss (or S parameter) explains the relationship between the antenna system's terminals and input-output ports. The S parameter represents the amount of power reflected back from the antenna's input port, as well as the remaining power that is radiated by the antenna [26]. In practical applications, the return loss should be less than or equal to -10 dB for an antenna to operate efficiently in a specific frequency band. For the proposed flexible antenna, the S parameters have been calculated and the result is shown in Fig.2. The value of return loss is found as -22.253dB which is good.

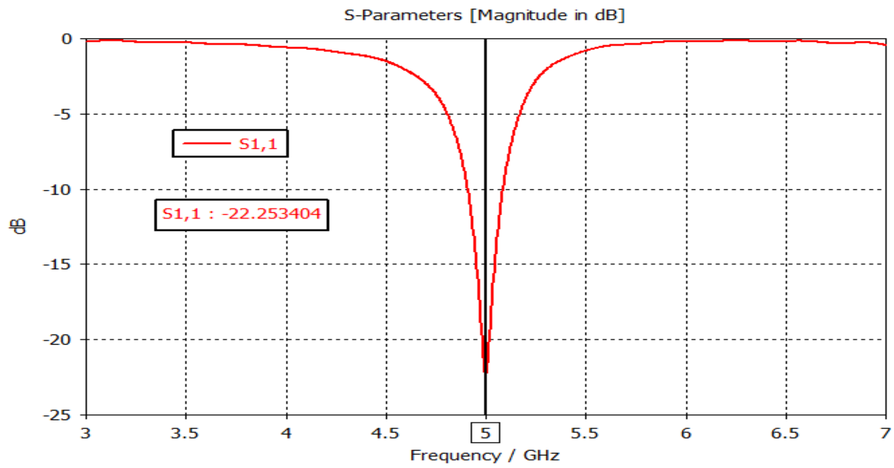


Fig. 2 Return lossversus frequency plot.

3.2. Voltage Standing Wave Ratio (VSWR)

The calculation of impedance mismatch is described by VSWR (Voltage Standing Wave Ratio) [27]. For a good designed antenna, the VSWR should lie in the range of 1-2 near the operating frequency value. The VSWR value of the proposed antenna is found as 1.167 as shown in Fig.3, which fits good for this antenna.

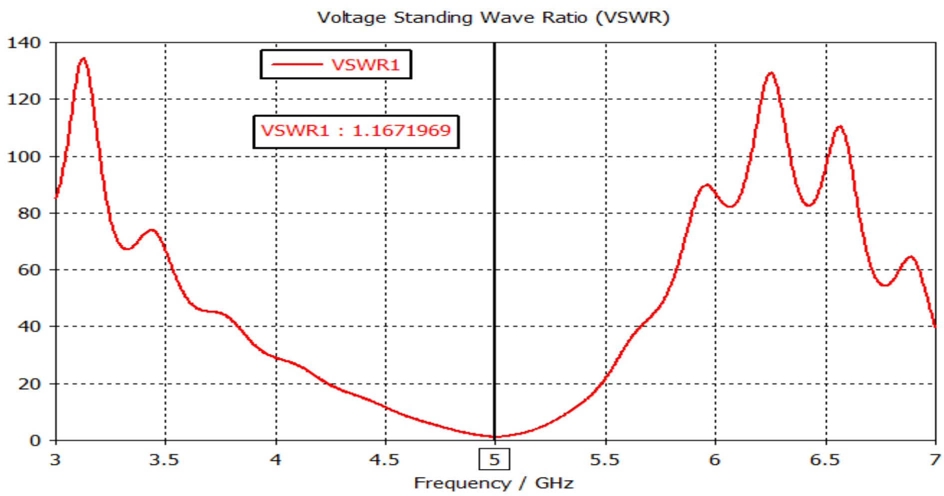


Fig. 3 VSWR versus frequency plot.

3.3. Bandwidth

Bandwidth is the range of usable frequencies within which the performance of the antenna meets the desired specific characteristics [28].Bandwidth of antenna can be calculated from the return loss graph. The following Fig.4 indicates the bandwidth of the designed antenna is 176 MHz (5.0853-4.9091 GHz) covering the ISM band and also validating its suitability for Wi-Fi services in 5G band. The antenna exhibit –10 dB impedance bandwidth of about 3.52% (5.085-4-909 GHz). Thus, the antenna is covering a total bandwidth of 176 MHz with 88 MHz on both the sides of the resonant frequency which implies that the antenna is suitable for Wi-Fi services in 5G band.

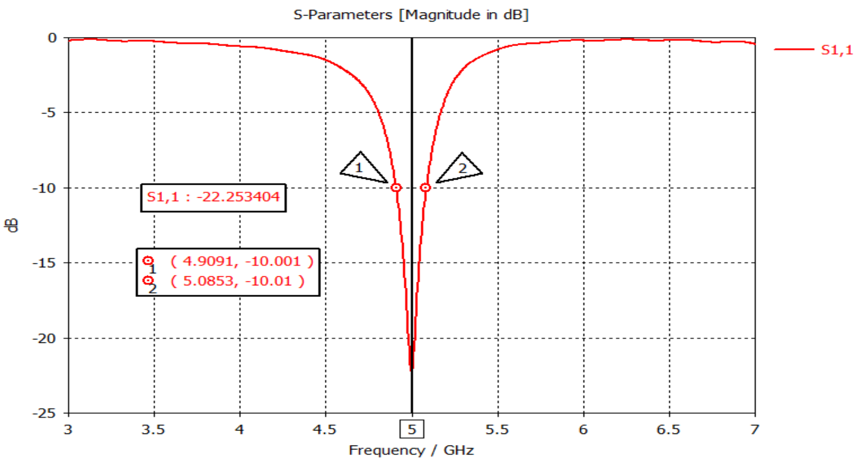


Fig.4. Return loss versus frequency plot showing bandwidth.

3.4. Antenna efficiency

The surface integral of the radiation intensity over the radiation sphere divided by the input power is known as the antenna efficiency. Figure 5 shows the efficiency of the designed antenna. The simulated radiation efficiency and total efficiency of the designed antenna is found to approximately 89.26 % and 88.73%, respectively. The proposed antenna is thus providing reasonable efficiencies at the resonating frequency.

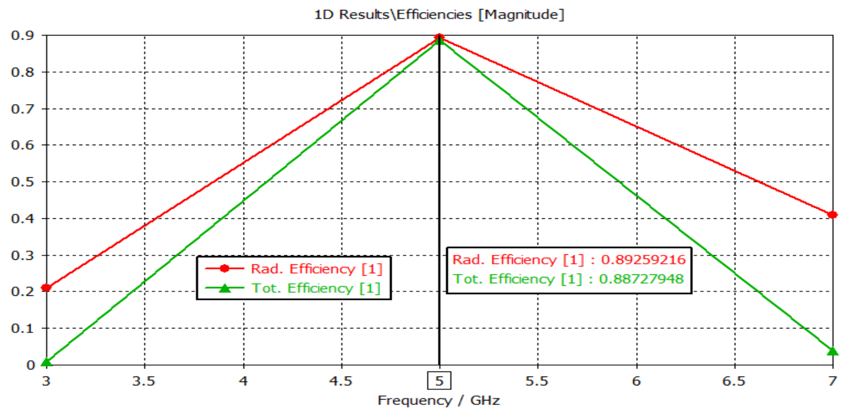


Fig.5 Efficiency versus frequency of the proposed antenna.

3.5. Surface Current Distribution

The surface current indicates the actual electric current induced by an applied electromagnetic field at the input port of the antenna. The surface current density is directly proportional to the electric field and the proportional constant is the conductivity of the material. The surface current distribution was analyzed at 5 GHz as shown in Figure 6. From the figure, it is observed that the surface current flows from the microstrip line feed and mostly distributed through the antenna which indicates the whole antenna contributes to resonate at 5 GHz.

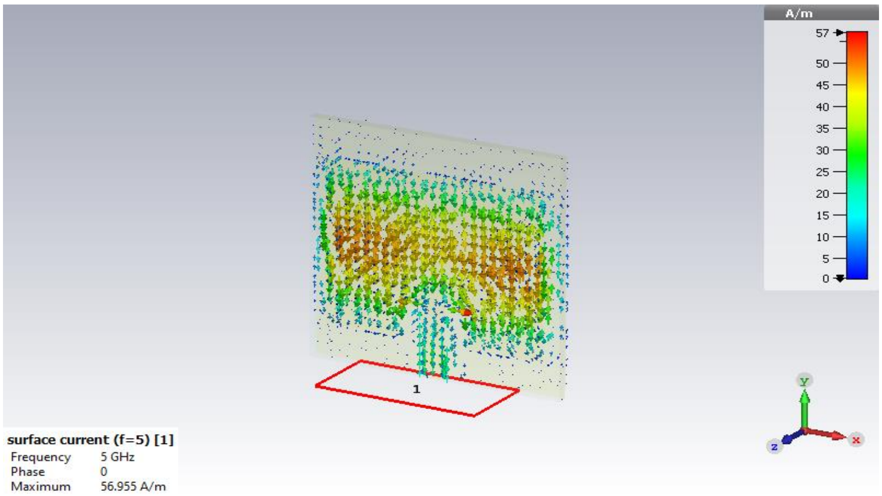


Fig.6 Surface current distribution of the designed flexible antenna at 5 GHz.

3.6. Gain

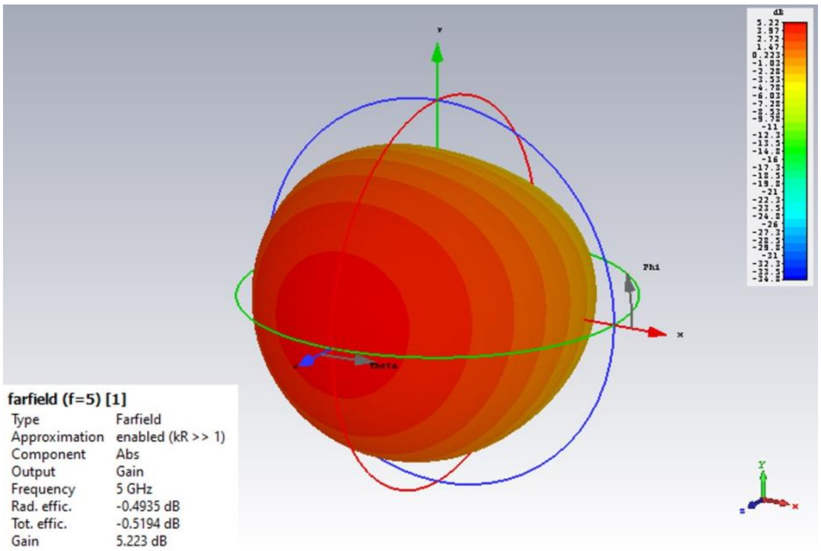
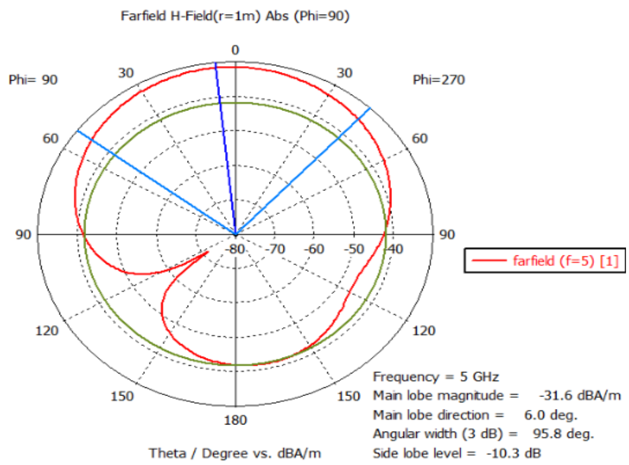


Fig. 7 Simulated 3D plot of far-field gain at 5 GHz.

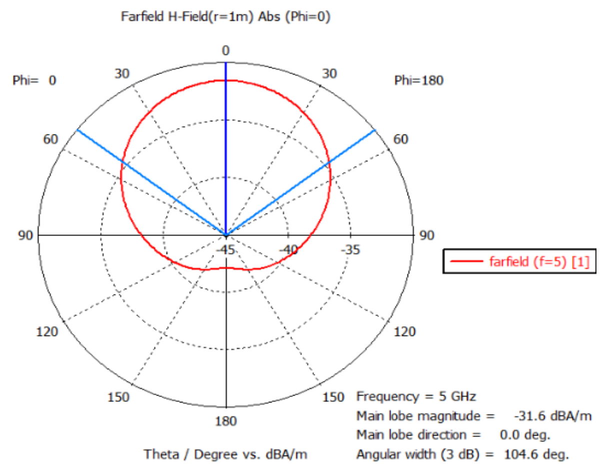
The input power is converted into radiated power and surface wave power. A small portion of the input power is dissipated due to dielectric and conductor losses of the materials used of the antenna [29]. The parameter gain is defined as the ratio of the radiated power to the input power. It measures the degree of directivity of the antenna's radiation pattern. The simulated 3D plot of the far-field gain obtained from the designed antenna is shown in Fig. 7. The antenna has a maximum realized gain of 5.223 dB at the operating frequency of 5 GHz. The designed antenna achieves a maximum far-field directivity of 5.716 dBi at the frequency of 5 GHz.

3.7. Radiation Pattern

The radiation pattern of the antenna characterizes its radiated energy. Figure8 shows the simulated 2D radiation pattern at 5 GHz. It can be seen that the designed antenna exhibits directional radiation pattern in both the E-plane and H-plane with a little back lobe at 5 GHz, implying its suitability for external WBAN applications.



(a)



(b)

Fig. 8 2D radiation pattern at 5 GHz. (a) farfield H-field pattern at phi = 90 degree
(b) farfieldH-field pattern at phi=0 degree.

Figure9 shows a simulated 3D view of the far E-field radiation pattern of the proposed antenna at the resonant frequency of 5 GHz. The red color denotes the most radiation, while the blue color denotes the lowest radiation, and the yellow and green colors show the ranges in between. The radiation pattern indicates a maximum value of the E-Field is 19.97 dBV/m.

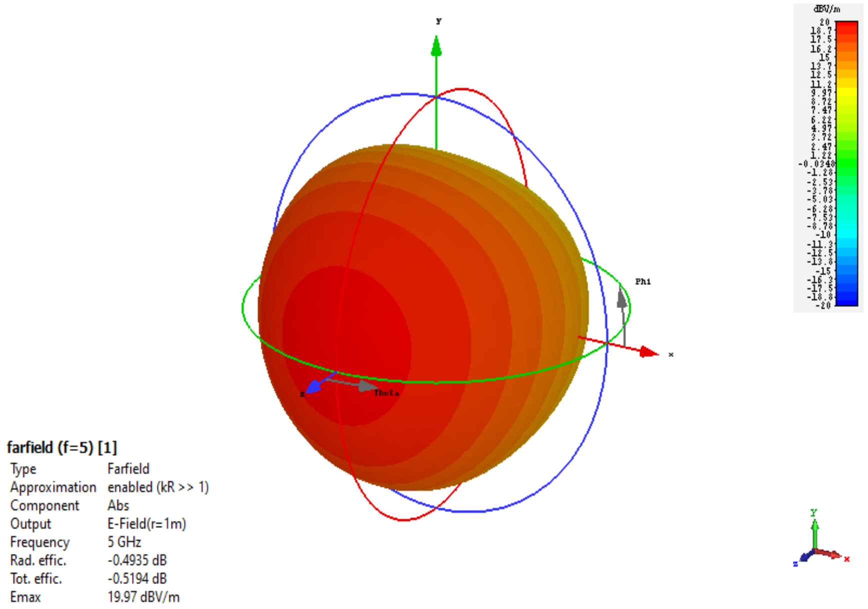


Fig.9 3D plot of far field E-field pattern at the operating frequency of 5 GHz.

3.8. Smith Chart

Smith chart of an antenna can be defined as the graphical representation of its normalized characteristic impedance and admittance. The smith chart represents how the antenna impedance varies with frequency. The smith chart plot of the proposed antenna is shown in Fig. 10. From the simulation result, it is observed that the characteristic impedance value is 48.11Ohm at 5 GHz.

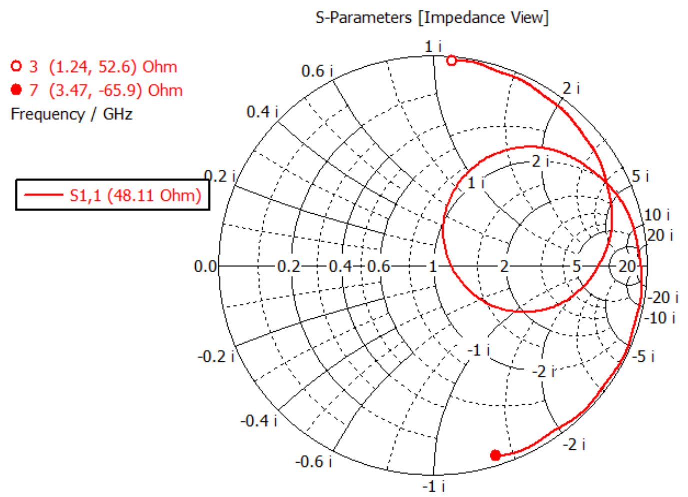


Fig.10 Smith chart of the proposed antenna.

3.9. Summary of Off-body Antenna Performance

A summary of the off-body performance of the proposed antenna is presented in Table2.

Table 2. Off-body simulation results.

Parameter	Value
Resonance frequency	5 GHz
Return loss	-22.253 dB
Bandwidth	176 MHz
VSWR	1.1672
Radiation efficiency	89.26%
Total efficiency	88.73%
Gain	5.223 dB
Realized Gain	5.197 dB
Directivity	5.716 dBi

3.10. Comparison of Proposed Antenna with Literature

A comparison of performance of the proposed designed antenna in this work with a few related designs reported in published literature is summarized in Table 3. By comparing various parameters, it may conclude that the proposed antenna features small dimensions and significantly improves the gain and efficiency.

Table 3. Comparison between the proposed antenna with some of the previously reported works.

References	Substrate materials	Resonant Frequency (GHz)	S_{11} (dB)	VSWR	Directivity (dBi)	Gain (dB)	Efficiency (%)	Patch Surface (cm^2)
[16]	Polyimide	2.45	-12.66	1.608	---	3.249	47%	13.71 (without slot)
[24]	Polyimide	3.5	-32	1.05	3	4	---	2.88 (with slot)
This work	Polyimide	5	-22.25	1.167	5.716	5.223	88.73%	3.14 (without slot)

4. Antenna performance after placing on Human Body Phantom Model

As the antenna is designed for WBAN applications, its overall performance is analyzed both in free space off-body condition and on human body phantom model. Since wearable antennas work close to the human body, the interaction between the antenna and human body tissues is an important issue to be considered. This interaction may affect the antenna performance parameters such as impedance matching, radiation pattern, realized gain and directionality. Moreover, the separation between antenna and phantom was varied and different antenna parameters such as gain, SAR, and radiation patterns were analyzed. It is observed that the performance parameters are improved when the proposed antenna is placed at a certain minimal separation of 2 mm from the human body.

To evaluate the SAR effect of the antenna on the human body, a phantom model was created in the CST simulation program as shown in Fig. 11.The body model consists of four layers which are skin, fat, muscle and air with the thickness of 2-, 5-, 20- and 2-mm, respectively [26]. The properties of each layer of human body are summarized in Table 4 [30]:

Table 4. Characteristics of Human body tissues.

Tissues	**Thickness (mm)**	**Permittivity (ϵ_r)**	**Conductivity(S/m)**	**LossTangent**	**Density(Kg/m^3)**
Skin	2	35.93	3.72	0.2835	1100
Fat	5	4.90	0.15	0.19382	910
Muscle	20	48.49	4.96	0.24191	1040
Air	2	1	0	0	1.204

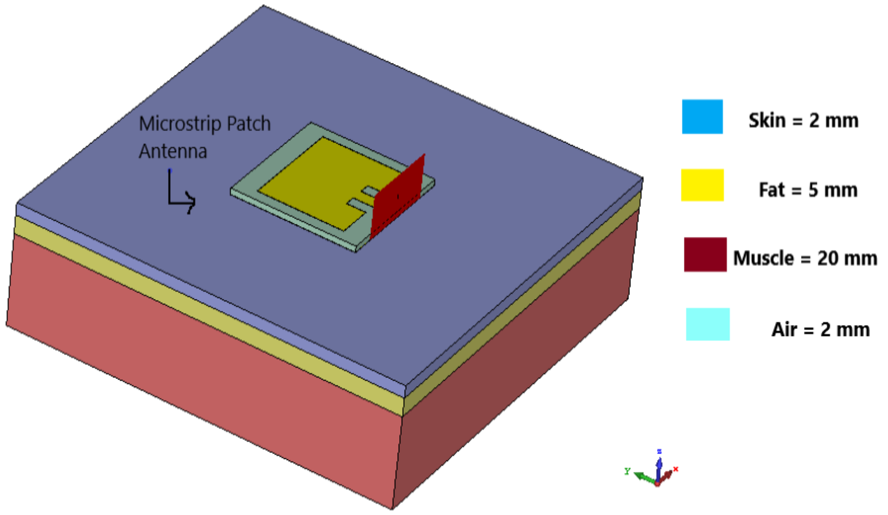


Fig.11. Designed Microstrip patch antenna on human body.

The placement of the proposed antenna very close to the human body results in shifting its resonance frequency. Based on this observation, rather than in direct contact with the human body, a 2 mm air gap is adopted in this study between the designed antenna and the human body skin.

When the antenna was placed at a separation of 2 mm from the human body phantom model, a shifting of the off-body performance parametric values was observed. The dimensions of the designed antenna were optimized to attain satisfactory results. The optimized values of the design parameters of the antenna for on-body conditions are presented in Table5.

Table 5. Optimized design parameters of the antenna for SAR analysis.

Parameter	Value
Resonant frequency	5 GHz
Substrate width	23 mm
Substrate Length	22.72 mm
Patch width	18.9 mm
Patch Length	15.70 mm
Length of the inset	3.5 mm
The width of the microstrip feedline	2.2779 mm
The gap between the patch and the inset-fed	1.92 mm
Dielectric constant of the substrate	3.5
The height of the dielectric substrate	1 mm
The height of the conductor	0.035 mm

4.1. On-Body Simulated results and discussion

A summary of the off-body and on-body performance of the designed antenna operating at 5 GHz is presented in Table 6. Although the antenna gain is almost identical at 5 GHz, the efficiency of the proposed antenna for on-body condition is significantly reduced in magnitude than the off-body condition. It may happen due to some absorption of electromagnetic energy in the tissue layers of the phantom at these operating frequencies. The return loss value under the on-body conditions is observed to be higher than the off-body condition value but it is well below -10 dB. The observation of higher return loss resulting from a poor impedance matching due to reactive loading by the body. Other possible reasons behind this observation are that when the antenna was closely placed, the input impedance of the antenna might be changed due to the fringing effect which might change the effective width of the antenna structure and thus shift the resonant frequency. Overall, a good impedance matching and a positive gain magnitude at the resonant frequency of the antenna for the on-body condition make the antenna a reasonable candidate for WBAN applications.

Table 6. Summary of the Off-body and On-body performance of the proposed antenna.

Parameter	Off-body	On-body
Return loss	-22.253 dB	-17.346 dB
VSWR	1.167	1.314
Gain	5.223 dB	5.139 dB
Realized Gain	5.197 dB	5.058 dB
Directivity	5.716dBi	6.670dBi
Total Efficiency	88.72%	68.99%

4.2. SAR Analysis

Specific absorption rate (SAR) is a measure of the allowable level of electromagnetic wave radiation to be produced by communication antenna in wireless devices. The SAR also measures EM wave penetration in human body tissues i.e., the absorption of EM power per unit mass of human body. Wearable antennas show relatively higher SAR in human body because of their unwanted radiations towards human body which needs to be controlled. The maximum safe limit of SAR specified by the US agency, the Federal Communications Commission (FCC), standard is 1.6 W/kg for 1 g of tissue and the European agency, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), has set maximum level of SAR as 2 W/kg for any 10 g of tissue.

To analyze the effects of the proposed antenna on the human body, the SAR value is analyzed at the resonant frequency. The SAR value is calculated based on the IEEE C95.1 standard and averaged over 1 or 10 g of biological tissue. The simulation results of SAR values of the proposed antenna are shown in Figs. 12 and 13 for 1 and 10 g of biological tissue, respectively. The result shows that the SAR value is 1.160 W/kg for 1 g of biological tissue and 0.486W/kg for 10 g of biological tissue at 5GHz. Overall, the obtained SAR values at the resonant frequency are far below the limits defined by the US agency, the FCC, and the European agency, the ICNIRP.

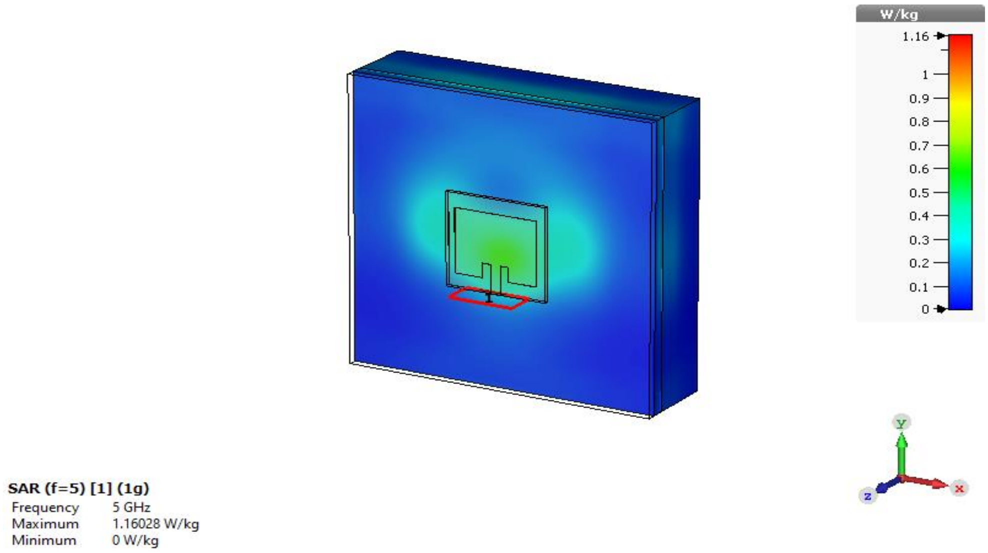


Fig.12. Simulated SAR value of the proposed antenna at 5 GHz for 1g of biological tissue.

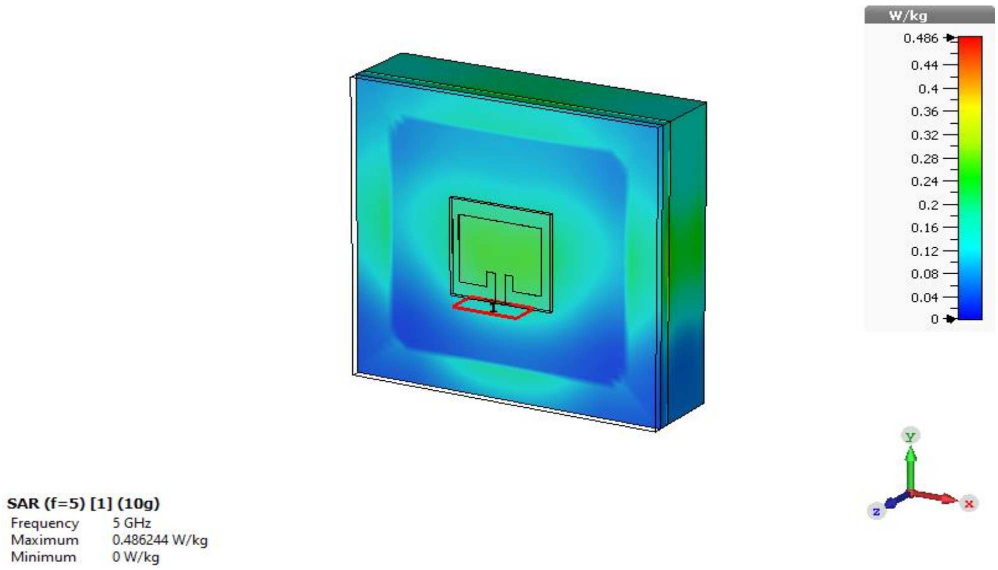


Fig.13 Simulated SAR value of the proposed antenna at 5 GHz for 10 g of biological tissue.

5. CONCLUSIONS

In this paper, a compact flexible wearable rectangular microstrip patch antenna having dimensions of 23 mm × 22.72 mm × 1 mm for WBAN applications at5 GHz wireless communications is presented. Inset-fed method is used for better impedance matching. The performance of the designed antenna is analyzed based on various parameters like return loss, VSWR, bandwidth, gain, directivity, radiation pattern and efficiency. The antenna exhibits good impedance matching at 5 GHz with return loss of -17.346, VSWR of 1.314, total bandwidth of 176 MHz, gain of 5.223, directivity of 5.716 dBi, directional radiation pattern, and a high radiation efficiency of 89%.The SAR value of 1.160 W/kg for 1 g or 0.486 W/kg for 10 g of biological tissue at 5 GHz lies far below the safe limit and it is confirmed that the proposed antenna meets the requirements of international standards and is harmless to the human body. These simulation results implies that the designed antenna achieves efficient performance and can be a suitable candidate for WBAN applications in the5 GHz band 5G wireless communications.

REFERENCES

[1] Y. Yang, and K. Hua, “Emerging technologies for 5G-enabled vehicular networks,” IEEE Access, vol. 7, pp. 181117–181141, November 2019.
[2] N. Saeed, A. Bader, T. Y. Al-Naffouri, and M. S. Alouini, “When wireless communication faces COVID-19: Combating the pandemic andsaving the economy,” arXiv preprint arXiv:2005.06637, May 2020.
[3] G. Ancans, V. Bobrovs, A. Ancans, and D. Kalibatiene, “Spectrum considerations for 5G mobile communication systems,” Procedia ComputerScience, vol. 104, pp. 509–516, 2017.
[4] 5G High-Level Forum (2018), “Making India 5G Ready,” New Delhi: Department of Telecommunications, Ministry of Communication, Governmentof India.
[5] G. Naik, J. Liu, and J. M. J. Park, “Coexistence of wireless technologies in the 5 GHz bands: A survey of existing solutions and a roadmap for future research,” IEEE Communications Surveys & Tutorials, vol. 20, no. 3, pp. 1777–1798, 2018.
[6] Enabling 5G in India- TRAI white paper: https://main.trai.gov.in/notifications/press-release/traireleases-whitepaper-enabling-5g-india.
[7] W. S. Chen, and Y. C. Lin, “Design of 2×2 microstrip patch array antenna for 5G C-Band access point applications,” IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM), pp. 1-2, 2018.
[8] C. A. Balanis, Antenna theory: Analysis and Design. John Wiley &Sons, 2015.
[9] M. A. Matin, and A. I. Sayeed, “A design rule for inset-fed rectangular microstrip patch antenna,” WSEAS Transactions on Communications, vol. 9, no. 1, pp. 63–72, Jan 2010.
[10] International Journal of Recent Technology and Engineering (IJRTE) ISSN: 2277-3878, Vol. 2, Issue3, July 2013.
[11] H. Yalduz, T. E. Tabaru, V. T. Kilic, and M. Turkmen, ‘‘Design and analysis of low profile and low SAR full-textile UWB wearable antenna with metamaterial for WBAN applications,’’ AEU Int. J. Electron. Commun, vol. 126, Art. no. 153465, Nov. 2020.
[12] G.-P. Gao, Z.-H. Dou, Z.-Q. Yu, B.-K. Zhang, J.-H. Dong, and B. Hu, ‘‘Dual-mode patch antenna with capacitive coupling structure for on-/off-body applications,’’ IEEE Antennas Wireless Propag. Lett., vol. 21, no. 8, pp. 1512–1516, Aug. 2022.
[13] N. Ziaei and A. Avokh, ‘‘Relay selection, clustering, and data aggregation routing in wireless body area networks,’’ Int. J. Commun. Syst., vol. 34, no. 10, p. e4837, Jul. 2021.
[14] C. Mao, P. L. Werner, D. H. Werner, D. Vital, and S. Bhardwaj, ‘‘Dualpolarized armband embroidered textile antenna for on-/off-body wearable applications,’’ in Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting, pp. 1555–1556, Jul. 2019.
[15] R. Sánchez-Montero, C. Camacho-Gómez, P.-L. López-Espí, and S. Salcedo-Sanz, ‘‘Optimal design of a planar textile antenna for industrial scientific medical (ISM) 2.4 GHz wireless body area networks (WBAN) with the CRO-SL algorithm,’’ Sensors, vol. 18, no. 7, p. 1982, Jun. 2018.

[16] A. Yadav, V. K. Singh, A. K. Bhoi, G. Marques, B. Garcia-Zapirain, and I. de la Torre Díez, ‘‘Wireless body area networks: UWB wearable textile antenna for telemedicine and mobile health systems,’’ Micromachines, vol. 11, no. 6, p. 558, May 2020.

[17] U. Musa, S. M. Shah, H. A. Majid, Z. Z. Abidin, M. S. Yahya, S. Babani, and Z. Yunusa, ‘‘Recent advancement of wearable reconfigurable antenna technologies: A review,’’ IEEE Access, vol. 10, pp. 121831–121863, 2022.

[18] A. Y. I. Ashyap, S. H. B. Dahlan, Z. Z. Abidin, S. K. A. Rahim, H. A. Majid, A. S. M. Alqadami, and M. El Atrash, ‘‘Fully fabric high impedance surface-enabled antenna for wearable medical applications,’’ IEEE Access, vol. 9, pp. 6948–6960, 2021.

[19] S. Hussain, S. Hafeez, S. Ali, and N. Pirzada, ‘‘Design of wearable patch antenna for wireless body area networks,’’ Int. J. Adv. Comput. Sci. Appl., vol. 9, no. 9, 2018.

[20] H. S. Savcı and F. Kaburcuk, ‘‘FDTD-based SAR calculation of a wearable antenna for wireless body area network devices,’’ Int. J. Microw. Wireless Technol., vol. 14, pp. 1–7, Dec. 2022.

[21] H. Savci, H. Sajjad, S. Khan, and F. Kaburcuk, ‘‘A compact multi-band antenna on textile for wearable body area network devices,’’ Balkan J. Electr. Comput. Eng., vol. 9, no. 3, pp. 255–260, Jul. 2021.

[22] R. Wu, J. Dong, and M. Wang, ‘‘Wearable polarization conversion metasurface MIMO antenna for biomedical applications in 5 GHz WBAN,’’ Biosensors, vol. 13, no. 1, p. 73, Jan. 2023.

[23] Kai Zhang, Guy A E Vandenbosch and Sen Yan,A Novel Design Approach for Compact Wearable Antennas Based on Metasurfaces, IEEE Trans. Biomed. Circuits Syst., vol. 14, pp. 918–927, 2020.

[24] H. Yang, X. Liu and Y. Fan, Design of Broadband Circularly Polarized All-Textile Antenna and ItsConformal Array forWearable Devices. IEEE Trans. Antennas Propagat., vol. 70, pp. 209–220, 2022.

[25] F. Hirtenfelder, ‘‘Effective antenna simulations using CST MICROWAVE STUDIO®,’’ in Proc. 2nd Int. ITG Conf. Antennas, p. 239, 2007.

[26] Karuna Kumari1 and Prof. P. V. Sridevi, “Design and Analysis of Microstrip Antenna Array Using CST Software,”International Journal of Scientific and Technology Research(IJSTR), vol. 9, Issue 1, pp. 3907-3911, 2020.

[27] Miss Anjali Majaleand Mrs. S. R. Mahadik, “Rectangular Microstrip Patch Antenna for 2.45 GHz Wireless Applications,”International Journal of Scientific Research and Development (IJSRD), Vol. 3, Issue 08, 2015.

[28] C.A.Balanis,“AntennaTheory:AnalysisandDesign”,JohnWiley&Sons, Inc.,1997.

[29] Md Ziaur Rahman andMohammed Mynuddin, “Design and Simulation of High Performance Rectangular Microstrip Patch Antenna Using CST Microwave Studio,” (2020).

[30] U. Musa, S. M. Shah, H. A. Majid, Z. Z. Abidin, M. S. Yahya, S. Babani, and Z. Yunusa, ‘‘Recent advancement of wearable reconfigurable antenna technologies: A review,’’ IEEE Access, vol. 10, pp. 121831–121863, 2022.