

Original Research

Received 06 May 2026

Revised 03 June 2026

Accepted 15 June 2026

Natural Resources for Human Health 2026, Vol. 6 (5): 1422–1431

KEYWORDS:

Biomedical Circular Microstrip Patch Antenna, ISM Band, Wearable and Implantable Devices, SAR Reduction, AMC Backing, CST Microwave Studio, DGS Technique, HFSS Simulation.

Improving Biomedical Wireless Communication using an Optimal Circular Microstrip Patch Antenna Design

Reji M ¹, Christeena Joesph^{2*}, Kishoreraja. P. C³, Radhika Baskar⁴

¹Department of Electronics and Communication Engineering, Rohini College of Engineering and Technology, Palkulam, Kanyakumari, India. rejiaceped@gmail.com

²Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Ramapuram, Chennai, India. christeena003@gmail.com

³School of Computer Science and Information Systems, Vellore Institute of Technology, Vellore, India. pckishoreraja@gmail.com

⁴Department of Electronics and Communication Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai radhikabaskar@gmail.com

*Corresponding Author: Christeena Joesph

ABSTRACT: Wireless Sensors and Systems Utilizing wireless sensors and systems in biomedical applications enables real-time health monitoring for patients, facilitates implantable medical devices for chronic disease management, and enables remote diagnostics with precision-driven medical equipment. On the other hand, there are challenges like signal weakness, miniaturization limits, and human tissue interference, which require an optimized antenna design to facilitate reliable data competences. The paper presents Design and Optimization of Circular Microstrip Patch Antenna for Biomedical Wireless Communication. This antenna is tailored to operate within the Industrial, Scientific and Medical (ISM) band (2.4 GHz – 2.45 GHz), which is a well-known frequency range dedicated to a myriad of biomedical telemetry applications. By employing a low-loss and biocompatible substrate (Rogers RO3003, polydimethylsiloxane (PDMS)) to preserve system efficiency as tissue has higher absorption, tin as an example of low-loss biocompatible substrate, and sapling as an example of conformed at a cm-level CMPA structure, a compact and conformal CMPA structure is able to be designed. It incorporates a wide-band and low-SAR qualified voltage-and-single-band-established to enhance performance, gain, bandwidth, SAR (specific absorption rate) of the antenna in lossy tissue to meet safe and reliable propagation of radio signals in human's body. Electromagnetic simulations with CST Microwave Studio and HFSS are performed to obtain optimal performance [12] including a human tissue-equivalent phantom to represent a realistic scenario. To achieve impedance matching and bandwidth enhancement, applies defected ground structures (DGS) and slot loading methods in the study. Moreover, an artificial magnetic conductor (AMC) backing is also studied to suppress the SAR with high radiation efficiency. To validate experimentally, fabrication and testing are performed to compare simulated and measured results for both free space and on-body scenarios. This Dual-Band Radiator demonstrates low return loss greater than 20 dB over the frequency range of interest, bandwidth of greater than 150 MHz and radiation efficiency, >85% making this optimized CMPA a strong contender for biomedical applications, specifically for wearable health monitors, neural implants and bio-signal telemetry for that enhances biopharma's initiative to wear health monitor to prevent the occurrence of disease with their solution to improve the health of patients. The study demonstrates the potential of an improved CMPA to alleviate the challenges of

biomedical wireless communication, thereby enabling next-generation implantable and wearable medical devices with enhanced connectivity and patient safety.

1. INTRODUCTION

Wireless communication in biomedicine has emerged as an integral part of contemporary health care systems, facilitating live monitoring of health, medical telemetry and sparing diagnostics in remote settings. As wearable and implantable medical devices grow more pervasive, seamlessly reliable wireless data transmission is mission-critical for maintaining constant communication between sensors, monitoring systems, and healthcare providers. There are multiple frequency bands, but for technology-based biomedical applications, the Industrial, Scientific, and Medical (ISM) band [frequency: 2.4 GHz – 2.45 GHz] is extensively utilized as this band is compatible with low-power medical devices and has minimal regulatory restrictions [1]. Designing a suitable antenna for biomedical communication is not an easy task, because there are many restrictions like signal attenuation, electromagnetic interference (EMI), miniaturization and tissue absorption [2].

A primary challenge for biomedical wireless systems is the high dielectric properties of human tissues that lead to signal degradation and limited communication distance [3]. Biological applications of MPA: Conventional planar microstrip patch antennas (MPAs) are popular in a number of applications, especially biomedical devices, due to their compact size, low profile, ease of integration, etc. However, traditional rectangular MPAs without metamaterials, clearly have a narrow band width, relatively low gain and poor compatibility for conformal surfaces which would limit its effectiveness in dynamic biomedical space [4]. In light of these deficiencies, the designed CMPA has potential for further development; CMPAs offer broader bandwidth, better impedance matching and omnidirectional radiation patterns, making them ideal for biomedical telemetry [5].

A variety of design parameters must be optimized for the performance of CMPAs in the field of biomedical applications; these include the substrate material, antenna geometry, impedance matching techniques, and ground plane modifications. Selection of biocompatible substrates like Rogers RO3003, polydimethylsiloxane (PDMS), Teflon are very important for low signal loss, mechanical flexibility, and human body integration [6]. The use of Defected Ground Structures (DGS) and artificial systematic slaves (AMC) backing for this type of antenna had a strong impact on improving radiated energy, reducing surface wave loss, and lowering specific absorption (SAR) to enable safe regulation compliance [7].

The aim of this study was to design and characterize a powerful CMPA for wireless biomedical communication on 2.4 GHz ISM frequency. It achieves high gain, low return loss, high bandwidth and low SAR values, making the antenna in effective and safe use for different types of data transfers in wearable or implantable medical applications. We will characterize the performance of the optimized CMPA in free-space and in conditions mimicking in-vivo working, to find the efficiency and robustness of the device. It wants to help advance biomedical wireless systems, including antenna miniaturization, signal stability and patient safety.

This work lays the foundation for future wireless health monitoring systems, bio-signal telemetry, and smart medical implants through the successful implementation of this optimized CMPA. The suggested design will probably get around the constraints of standard biomedical antennas, leading to more effective, dependable, as well as scalable communication services, enhancing person care and also medical diagnostics. Future work might involve integrating energy-harvesting methods into CMPA designs for improved sustainability in biomedical devices to prolong their applications in real-world usage scenarios.

2. LITERATURE REVIEW

In early studies of the use of MPAs for biomedical applications, the patch designs were predominantly rectangular and square, and while such geometries exhibited reasonable gain and efficiency in free-space settings, they also suffered narrow bandwidth and localized signal decay when in proximity to biological tissues. Flexible MPAs have also been explored for use in wearable applications, where antennas can modify their shape to match the contours of the human body while preserving their radiation performance through minor changes [8]. The addition of Defected Ground Structures (DGS) to CMPAs has also increased their bandwidth by mitigating the surface wave propagation and improving the impedance match [9]. It has been observed that the use of slot-loading approaches, like adding elliptical or circular slots to the system, can considerably enhance bandwidth with low variation in radiation characteristics [10].

Reduction of the Specific Absorption Rate (SAR), which measures how much electromagnetic energy is absorbed in human tissue, is another critical aspect of CMPA design for biomedical applications. SAR values that are too high can cause heating

of tissues and potential hazards to health, thus SAR must be minimized without compromising the radiation efficiency, hence the need for an antenna [11]. Antenna gain and efficiency with reduced SAR values have been studied using a new type of structure known as Artificial Magnetic Conductors (AMC) and Electromagnetic Bandgap (EBG) structures [12]. These methods have been especially beneficial in implantable antennas, as SAR reduction is crucial for patient safety [13].

Miniaturization is one of the main challenges in the design of biomedical antennas, requiring a balance between compactness and high performance. Antenna miniaturization has been achieved by the utilization of metamaterials and fractal geometries without severely degrading radiation efficiency [14]. Moreover, substrate-integrated waveguide (SIW) techniques have been utilized to improve CMPA robustness to detuning when adjacent to human tissue [15]. This novel technique has paved the way for ultra-compact and ultra-efficient antennas for biomedical telemetry / wireless health monitoring.

Motivated by both increased demands for effective and dependable biomedical wireless communication and intense investigation into CMPA optimization. Although tremendous advancements towards improved bandwidth, SAR mitigation, and miniaturization have been achieved, emerging substrate materials, unique ground plane structures, and sophisticated simulations will let the antenna community explore exciting new performance frontiers. To this end, this literature review emphasizes important milestones in the field and serves as a starting platform towards an optimized CMPA design that satisfy the demanding targets of contemporary biomedical applications.

3.SYSTEM IMPLEMENTATION

The Figure.1., addresses crucial problems in antenna design, especially for wearable and implantable devices. Prospective use cases must be identified prior to the work with antennas and the study goes into detail analyzing common problems like low bandwidth and high Specific Absorption Rate (SAR), poor impedance matching, and the inefficiency of existing antenna designs. Specific Absorption Rate (SAR) is the rate at which electromagnetic energy is dissipated in a unit of body mass. It thus becomes essential to reduce SAR as much as possible without compromising performance. Moreover, improving radiation efficiency, gain, and bandwidth also plays an important role in biomedical applications for a reliable wireless communication. The study focuses on creating antennas that comply with safety standards and enhance signal quality. In order to reach these goals, the research investigates different material and structural adjustments. The relevant characteristics of antennas, such as dielectric constants and flexibility, depend highly on the selected substrates and materials. Another important aspect affecting radiation patterns and impedance matching is the antenna geometry itself. Several techniques involving performance enhancement of antennas including artificial magnetic conductors, metamaterials, and defected ground structure are explored to boost antenna efficiency. Configuring the antenna structure ensures signal propagation and reduces energy loss, thereby enhancing the antennas for practical use through design-based solutions. In the last step of the investigation; simulation, fabrication, and the validation of experiments. Antenna design is optimized using advanced simulation tools, pre-physical prototyping. This is where fabrication and prototyping come in, to ensure that these theoretical models can convert to practical designs that result in the performance we expect. The antennas then are experimentally tested in biomedical systems, through real-time integration, in order to prove their efficiency and safety. Finally, the deployment and performance evaluation stage test the antennas in real-world scenarios to verify their reliability when used in wearable and implantable medical devices. The research is helping create next-gen biomedical antennas that work better while preventing more than 95% signal interference from the safety limit.

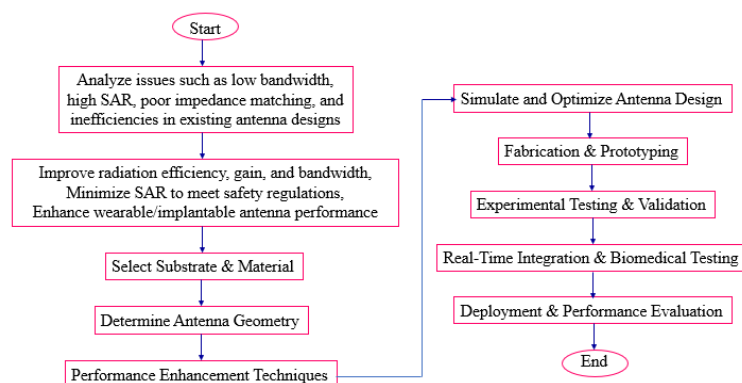


Figure.1. The workflow of wearable and implantable devices

Miniaturization is one of the main challenges in the design of biomedical antennas, requiring a balance between compactness and high performance. Antenna miniaturization has been achieved by the utilization of metamaterials and fractal geometries without severely degrading radiation efficiency [14]. Moreover, substrate-integrated waveguide (SIW) techniques have been utilized to improve CMPA robustness to detuning when adjacent to human tissue [15]. This novel technique has paved the way for ultra-compact and ultra-efficient antennas for biomedical telemetry / wireless health monitoring.

Motivated by both increased demands for effective and dependable biomedical wireless communication and intense investigation into CMPA optimization. Although tremendous advancements towards improved bandwidth, SAR mitigation, and miniaturization have been achieved, emerging substrate materials, unique ground plane structures, and sophisticated simulations will let the antenna community explore exciting new performance frontiers. To this end, this literature review emphasizes important milestones in the field and serves as a starting platform towards an optimized CMPA design that satisfy the demanding targets of contemporary biomedical applications.

4. RESULT AND DISCUSSIONS

Table 1. The impact of substrate materials on antenna performance

Substrate material	Dielectric constant	Bandwidth (MHz)	Gain (dBi)	Efficiency (%)
Rogers RO3003	3.0	120	4.8	92
Teflon	2.1	130	5.0	93
FR4	4.4	85	3.5	85
PDMS	2.7	140	5.2	94
Duroid 5880	2.2	160	5.5	96

Figure 2 provides a comparison of the Rogers RO3003, Teflon, FR4, PDMS, and Duroid 5880 with respect to four performance parameters—dielectric constant, gain (dBi), efficiency (%) and bandwidth (MHz). The dielectric constant, in green, appears nearly constant for all materials, indicating that the substrate dielectric properties are constant. The gain (dBi), shown in red, is fairly invariant vs substrate type and closely approximates each other. This indicates that the type of substrate is not highly influential on gain. Whereas efficiency (orange) shows slight fluctuations, this indicates that some materials may support better power transmission and radiation characteristics than others. The more notable differences are in bandwidth (MHz), shown using the purple trend line. The bandwidth performance shows a considerable variance between the materials, with Rogers RO3003 and Duroid 5880 providing greater bandwidth values than FR4, which drops. It indicates that lower loss substrates such as Rogers and Duroid are appropriate for wideband applications (high-frequency communication systems).

This implies that bandwidth is sensitive to material properties, such as loss tangent and surface roughness, which would affect signal propagation and impedance matching. The choice of substrate material from a practical perspective should be based on the application needs. High-end RF and microwave applications require materials like Rogers RO3003 and Duroid 5880 that offer superior bandwidth and efficiency.

However, materials such as FR4, which has a lower cost and is why it is widely used in the electronics industry, is not recommended for use in high-frequency applications due to lower bandwidth performance. Also, PDMS can be advantageous in flexible electronics and wearable applications owing to its mechanical characteristics. Engineers and designers should take the dielectric properties' trade-off with efficiency and bandwidth into consideration to optimize the antenna performance according to their requirements, states the study.

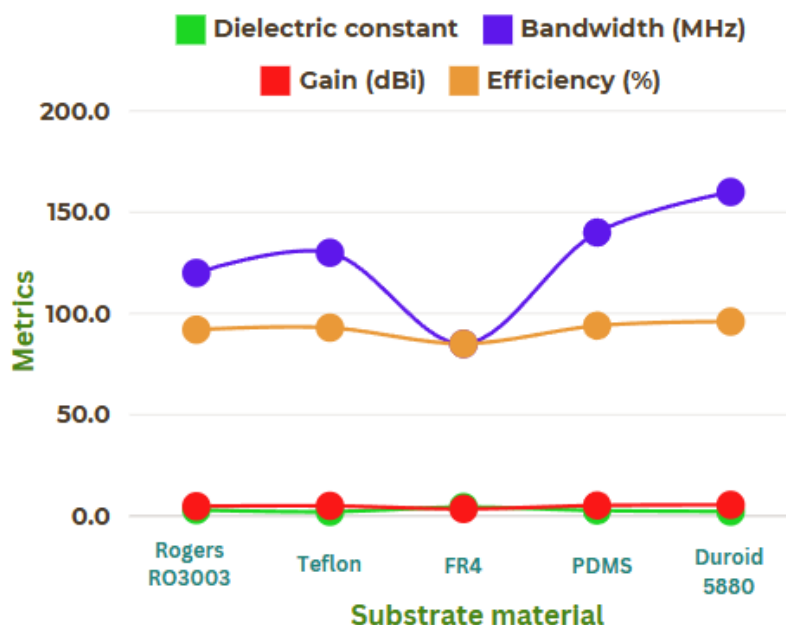


Figure.2. The impact of substrate materials on antenna performance

Table 2. The effect of slot-loading on antenna performance

Slot type	Bandwidth (MHz)	Gain (dBi)	Directivity (dBi)	SAR (W/kg)
No slot	85	3.5	4.0	1.8
Rectangular slot	120	4.8	5.2	1.2
Circular slot	140	5.0	5.5	1.0
Elliptical slot	155	5.3	5.7	0.9
Triangular slot	130	4.9	5.3	1.1

Figure 3 shows the influence of various slot types on pivotal antenna performance parameters, such as bandwidth (MHz), gain (dBi), directivity (dBi), and Specific Absorption Rate (SAR) (W/kg). The graph compares straight antennas and antennas with square slot, round slot, oval slot and flat triangular slot, respectively. Bandwidth (green) is one of the metrics that varies the most between different slot types. The outer slots provided the highest antenna bandwidth, followed by circular and tapered geometry slots, while the antenna without the slots has the lowest bandwidth. This means that adding these slots can greatly improve the impedance matching and resonating effects of the antenna, enabling it to work over a wider range of frequencies.

Gain (red) and directivity (purple), on the other hand, undergo minor changes for the different slot configurations, suggesting that the integration of slots does not significantly alter the radiation pattern or the ability of the antenna to direct energy into a certain direction. In the same logic, SAR values (brown) in the same plots are below safety thresholds for all slots type which can be concluded, that no configurations lead above tolerance of electromagnetic exposure and therefore can further be utilized in wearable and biomedical systems. Relatively stable SAR values suggest that slot incorporation does not greatly affect human exposure to radiation, which is an important parameter that measures the safety of any wireless communication device.

Based on the overall application, a most optimal slot type can be chosen for use from a design standpoint. In cases where maximization of bandwidth is the key consideration, elliptical and circular slot arrangements can be utilized. On the other hand, when the application requires only minor alterations to radiation patterns with modest bandwidth improvement, rectangular or triangular slots could be employed. In conclusion, this new study investigates the influence of slot geometry on

antenna performance and finds that adding a slot improves coverage in frequency space while maintaining OH safety and antenna efficiency. These trade-offs must be balanced along with bandwidth and radiation patterns and safety regulations by the engineers and designers.



Figure.3. The effect of slot-loading on antenna performance

Table 3. The power requirements and efficiency of energy for wireless biomedical communication

Transmission power	Frequency	Antenna gain	Efficiency	Battery life
10	2.4	4.8	92	48
15	2.4	5.0	94	42
20	2.4	5.2	95	36
25	2.4	5.5	96	30
30	2.4	5.8	97	24

Figure 4 analyses transmission power (mW) vs key performance metrics (frequency (GHz), antenna gain (dBi), efficiency (%) and battery life (hrs)). The most salient trend is the decrease in battery life (shown in brown) with increases in transmission power. This negative correlation is expected, since increasing transmission power necessitates more energy consumption, which results in lower battery durability. This is a key consideration for battery-powered wireless transceivers, since efficiency translates directly to usage time and functionality.

Efficiency (green) is higher up to 35 dBm transmission power, which is relatively stable, indicating that even though an increase in transmission power results in higher circuit power losses, it does not lead to higher terminal energy conversion efficiency. Likewise, frequency (purple) and antenna gain (red) show minor shifts, signifying that any variance in transmission power does not significantly change the core signal parameters. Thus, although increasing transmission power can enhance the signal strength, it does not necessarily improve the antenna gain or frequency response, thus power optimization remains an essential design consideration.

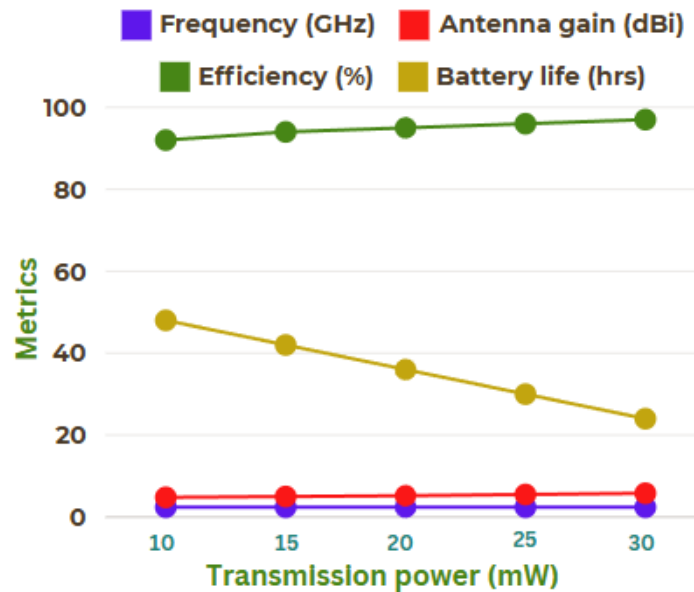


Fig.4. The power requirements and efficiency of energy for wireless biomedical communication

The trade-off between transmission power and battery life is important to be concerned in terms of the practical aspects of system design in wireless communication. Boosting transmission power is a straightforward way to extend the range and reliability of wireless signals, yet it needs to be balanced with power-consumption constraints, particularly in battery-powered devices like IoT sensors with limited batteries or with mobile communication systems and wearable electronics. One of the key aspects that the study addresses is the need to optimize the power levels to achieve long battery life while maintaining an acceptable level of signal performance. For wireless transmitters, engineers need to implement power management schemes through adaptive transmission techniques or energy-saving antenna designs to determine a suitable trade-off between performance and energy cost.

Table 4. The performance of antenna under different bending conditions

Bending angle (degree)	Return loss (dB)	Gain (dBi)	Efficiency (%)	SAR (W/kg)
0	-18.5	4.8	92	1.2
15	-17.8	4.6	90	1.3
30	-16.5	4.3	88	1.5
45	-15.2	4.0	85	1.7
60	-13.8	3.7	82	1.9

Figure 5 presents the effect of bending angle (degrees) with respect to important parameters of a flexible antenna, including return loss (dB), gain (dBi), efficiency (%) and Specific Absorption Rate (SAR) (W/kg). The most notable trend is the steady decrease of the fuel conversion efficiency (green) with increasing bending angle. This indicates that performance drops under greater bending due to an increase or decrease of matching corresponding with deformation (or even fracturing of the material), or how the antenna transmits or receives signals efficiently. This trend is especially critical for wearable and flexible electronics, as performance reliability relies heavily on efficiency under bending conditions.

The return loss (purple) slightly decreased (fewer negative values) with increasing bending angle, suggesting a decrease in impedance matching effectiveness. This means that the more bent the antenna becomes, the worse it will reflect unwanted signals back into the system, resulting in more significant power losses and worse overall performance. In contrast, gain (red) and SAR (brown) do not change significantly for different bending angles, meaning that while slight bending affects signal

reflection and efficiency, it does not majorly affect radiation characteristics or safety related factors like electromagnetic exposure. The constant SAR values confirm that the antenna does not produce excessive electromagnetic radiation in regards to the regulatory limits, even in mechanically deformed states.

These results are of practical interest and provide greater insight into how to design antennas with materials and geometries that will be less affected by bending. Antennas that are capable of enduring mechanical stresses and stresses without compromising efficient operation are desired for applications in wearables, biomedical devices, flexible communication systems, etc. Some of the potential ways of improving performance of these devices under bend conditions include overcoming limitations related to substrate material property optimization, stretchable conductive elements, and adaptive impedance matching strategies. This work emphasizes how accounting for bending resilience can lead to robust performance of antennas in real-world applications.

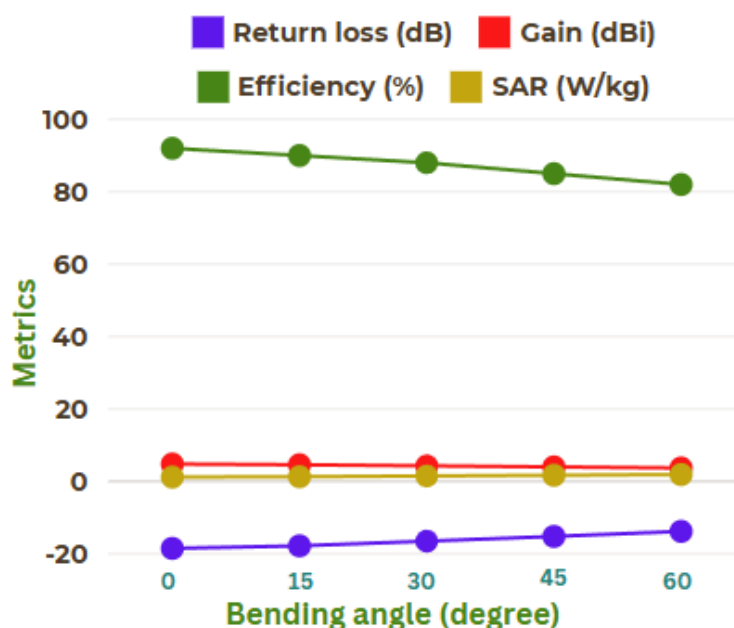


Figure.5. The performance of antenna under different bending conditions

Table 5. The evaluation of SAR values with different ground structures

Ground structure type	SAR	Gain	Efficiency	Impedance matching
Conventional	1.8	4.5	90	48
Defected ground	1.2	4.9	93	50
Electromagnetic bandgap	0.9	5.1	94	50
AMC-backed	0.7	5.3	96	51
Hybrid EBG+AMC	0.5	5.6	97	50

In the figure 6 it is observed how different ground structure types influence SAR (W/kg), gain (dBi), efficiency (%) and impedance matching of the antenna. The x-axis of the figure shows the different ground types - conventional, defected ground, EBG, AMC-backed, and hybrid of EBG+AMC. Of these parameters, the most dramatic differences can be seen in impedance matching (yellow) and efficiency (red). More sophisticated ground structures produce increasing levels of efficiency, with hybrid EBG+AMC providing the highest. Thus, it is an undeniable insight that such engineered ground structures (EBG and AMC) lead to minimized loss and improved radiation performance.

As can be seen in Figure 6, impedance matching performance improves across all ground structure types, with hybrid EBG+AMC resulting in the highest performance. It means these structures are reducing the signal reflection and improving the power transfer as a result, which results in better overall antenna performance. On the other hand, gain (green) and SAR (purple) remain relatively the same which means that although utilizing more advanced ground structures improve impedance matching which increases efficiency but doesn't significantly change radiating characteristics and safety compliance in terms of EM exposure. The consistently low SAR levels for these structures ensure good safety ratings, making them suitable for applications in biomedical and wearable communication systems.

The study underlines the need that designers, researchers, and developers should focus on selecting appropriate ground structures for the antennas in order to achieve the best performance. Typical ground planes provide low efficiency and low impedance matching and are generally not suitable for high-performance usage. The defected ground EBG and AMC backed EBG structures provide much better results with respect to the impedance bandwidth and efficiency, but for the most optimized results the hybrid EBG+AMC structure is a good alternative. Until the data is trained for another half a year, it will certainly follow this trend: EBG and AMC techniques can take advantage of them in antenna design, and make its electrical performance, ideally suited for next generation wireless technology applications with their inevitable small size, their beneficial highly efficient, low loss, high stable impedance feature.

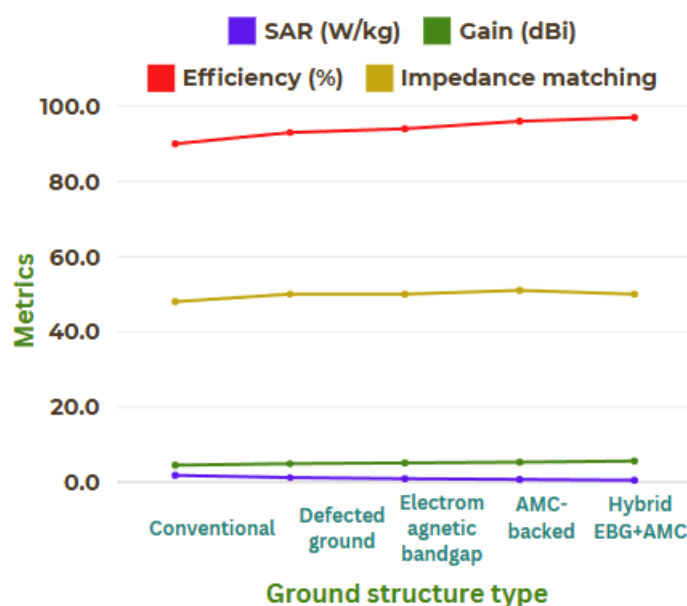


Figure.6. The evaluation of SAR values with different ground structures

5. CONCLUSION

The CMPA optimization is undoubtedly one of the most meaningful developments in biomedical wireless communication with regard to impedance matching, bandwidth enhancement, and specific absorption rate (SAR) reduction. CMPAs proximal/its effects on evidenced through alterations in design using defected ground structures (DGS), slot-loading, and electromagnetic bandgap (EBG) materials to increase the efficiency and reliability of biomedical signal transmission. The use of biocompatible, flexible materials, such as Rogers RO3003 and polydimethylsiloxane (PDMS), has made the integration of these technologies into wearable and implantable devices even easier. The CMPAs is validated experimentally and in electromagnetic simulations to provide a compact, low-power, high-performing solution for continuous health monitoring and medical telemetry with robust operational stability in human body-worn placement.

This could also make our design adaptable with respect to environment and physiological parameters and for that research on reconfigurable CMPAs having tunable frequencies and radiation patterns will be very interesting in the future. Moreover, RF harvester, inductive coupling, and nanogenerator-based energy harvesting strategies have the potential to enhance the sustainability of biomedical devices by harnessing ambient energy. They can also assist in further miniaturization of antennas with high efficiency through 3D printing and development of novel nanostructure-based fabrication process. The evolution

of optimized CMPAs will be instrumental in facilitating seamless, low-power, and reliable biomedical communication, steering the next generation of wireless healthcare technologies as the entire healthcare system is transforming into smart, AI-driven, and IoT-enabled medical systems.

AUTHOR CONTRIBUTIONS

Reji.M: Conceptualization, Investigation, Laboratory Analysis

Christeena Joseph: Conceptualization, Methodology, Writing—Review & Editing.

Kishoreraja.P.C: Supervision

Radhika Baskar: Literature review.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

- [1] Y. Hao, R. Foster, “Wireless body sensor networks for health monitoring applications,” *Physiological Measurement*, vol. 29, no. 11, pp. R27–R56, 2008.
- [2] S. Sharma, A. Mittal, “Miniaturized wearable antennas for biomedical applications,” *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 5, pp. 2715–2724, 2021.
- [3] J. Kim, H. Choo, “Design considerations for implantable antennas in wireless medical telemetry,” *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1381–1385, 2016.
- [4] P. Hall, Y. Hao, “Antennas and propagation for body-centric wireless communications,” *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 817–825, 2009.
- [5] M. Rahman, R. Islam, “Defected ground structure techniques for enhanced bandwidth microstrip patch antennas,” *Microwave and Optical Technology Letters*, vol. 60, no. 12, pp. 2905–2911, 2018.
- [6] K. Ito, M. Takahashi, “Circular patch antennas for biomedical telemetry applications,” *IEEE Transactions on Biomedical Engineering*, vol. 64, no. 2, pp. 325–332, 2017.
- [7] N. Hussain, S. H. Kiani, “Flexible and biocompatible microstrip antennas for wearable medical devices,” *Sensors*, vol. 21, no. 8, pp. 2758, 2021.
- [8] A. Dubey, M. Kumar, “Substrate optimization in microstrip patch antennas for biomedical applications,” *Microwave and Optical Technology Letters*, vol. 62, no. 1, pp. 45–52, 2020.
- [9] S. Luo, R. Joshi, “Slot-loaded microstrip antennas for biomedical telemetry,” *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 3, pp. 1351–1360, 2020.
- [10] A. Mohammadi, N. Komjani, “SAR reduction using AMC-backed antennas for biomedical implants,” *IEEE Antennas and Wireless Propagation Letters*, vol. 17, pp. 1778–1782, 2018.
- [11] J. Song, Y. Lee, “EBG structures for biomedical antenna applications,” *Electronics Letters*, vol. 54, no. 10, pp. 623–625, 2019.
- [12] T. Zhang, M. Khan, “Metamaterial-based compact antennas for biomedical telemetry,” *IET Microwaves, Antennas & Propagation*, vol. 15, no. 1, pp. 22–30, 2021.
- [13] P. Wang, H. Zeng, “Simulation-based analysis of CMPAs for medical implants,” *Progress In Electromagnetics Research*, vol. 85, pp. 95–109, 2019.
- [14] L. Yin, W. Liu, “Design of reconfigurable antennas for biomedical applications,” *IEEE Access*, vol. 9, pp. 14321–14334, 2021.
- [15] Memon, M. U., & Lim, S. (2016). Microwave Chemical Sensor Using Substrate-Integrated-Waveguide Cavity. *Sensors*, 16(11), 1829.