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Design and classification of implantable antenna for biomedical on body and off body communication

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***Abstract*—In today's society, a significant global population depends on implantable medical devices as vital tools to maintain and improve their overall quality of life. Implantable antennas assume a crucial role in a myriad of applications, ranging from pacemakers and artificial organs to temperature monitors and blood-glucose sensors. Their substantial contribution significantly propels the progress of human well-being. In the field of biomedical applications, communication primarily relies on the use of Medical Implant Communication Services (MICS) and the Industrial, Scientific, Medical (ISM) band, ensuring seamless connectivity. This paper is dedicated to providing a thorough exploration of diverse design structures, classifications, and challenges associated with implantable antennas. Embedded within medical implants, these antennas function as integral components, enhancing human life in various applications. The discussion delves into intricate details regarding implantable antenna designs and classifications, shedding light on the nuanced challenges encountered by researchers and developers in this intricate domain. Ultimately, the overarching objective is to emphasize the transformative impact of implantable antennas on human life, fostering a comprehensive understanding of their versatile uses and applications in the field of biomedical.**

***Keywords*—Implantable Antenna; Biomedical; In body; On body; Off body; MICs; ISM; Medical Body Area Network System (MBANS); Medical Device Radio Communication Service (MDRC); Radio Frequency (RF)**

I. INTRODUCTION

TODAY age of advancement one of the fastest growing fields of the technology is biomedical engineering [1]. Wireless healthcare monitoring gadgets are requires the components such as sensors, antenna etc [2]. The antenna plays a pivotal role in wireless communication systems, serving as a fundamental component that significantly influences design. Among the various types of antennas utilized in wireless communication, the microstrip patch antenna stands out as one of the most commonly employed. [3]. In designing microstrip patch antennas, the substrate plays a key role in determining the antenna's performance and suitability for its application. The basic components of an antenna design include the ground plane, substrate, patch, feed line, and connectors [4].

With recent advancements in biomedical devices, on-body and off-body wireless communication is growing rapidly. Implantable and wearable antennas are widely used in biomedical applications because of their compact size, lightweight design, low profile, portability, self-powered capability, and effective wireless communication and sensing [5-7]. Fig. 1 shows various applications of antennas in biomedical fields.

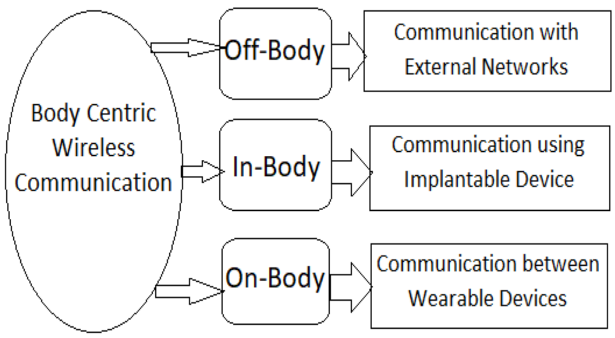

Fig. 1. Various application of antenna for biomedical communication

According to the RF spectrum allocations in US, below 100KHz frequency spectrum is allocated for inductive implant medical devices, In MDRC 401-402MHz and 405-406MHz frequency range are allocated for wearable medical applications, 3.1 to 10.6GHz frequency band is used for ultra wide band (UWB), Medical Micropower Networks (MNNs) assign 413-457 frequency band that is used for implantable medical device applications, in medical body area network (MBANs) assign 2.36 to 2.4 GHz frequency band, for Bluetooth, Wifi and Zigbee assign the frequency band 2.4 to 2.4833GHz, 902 to 908MHz and 5.725 to 5.85GHz respectively, in Wireless Medical Telemetry Services (WMTS) used the frequency band 608–614, 1395–1400, and 1427–1429 MHz [8].

According to the RF spectrum allocations in the Europe, 9 to 315GHz is used for active medical implant device in a range of ultra-lower power, for the blood pressure measurement gadgets 30–37.5 MHz frequency band is used, for implanted medical devices and patient monitoring gadgets

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in indoor communication 2.4835–2.5GHz frequency band is allocated, 430-440MHz frequency band is allocated for the application of wearable Ultra-Low Power Wireless Medical Capsule Endoscopy [8]

II. IMPLANTABLE ANTENNA

The biomedical implantable devices are available from more than last six decades. The first biomedical implantable device is design and developed by Erl Bakken for cardiac pacemaker in 1957 [9]. For support and improve the quality of lives a huge number of peoples are worldwide depend on implantable medical gadgets. RF connected implantable medical gadgets are now being used for a wide assortment of utilizations [10]. The evolution of implantable antennas represents a pivotal technological breakthrough in the field of biomedical applications. These antennas play a vital role in enabling wireless communication within the human body, especially in the domain of medical devices. The incorporation of implantable antennas has substantially propelled advancements in healthcare technologies, fostering creative solutions for various applications, including biomedical monitoring and implantable medical devices. This introductory overview establishes the foundation for delving into the intricacies of designing, understanding the functionalities, and examining the applications of implantable antennas designed to meet the distinctive requirements of biomedical contexts. In the fig 2 shown the classification of the implantable antennas or implantable electronics devices that help to replicate the human organ function [11-12].

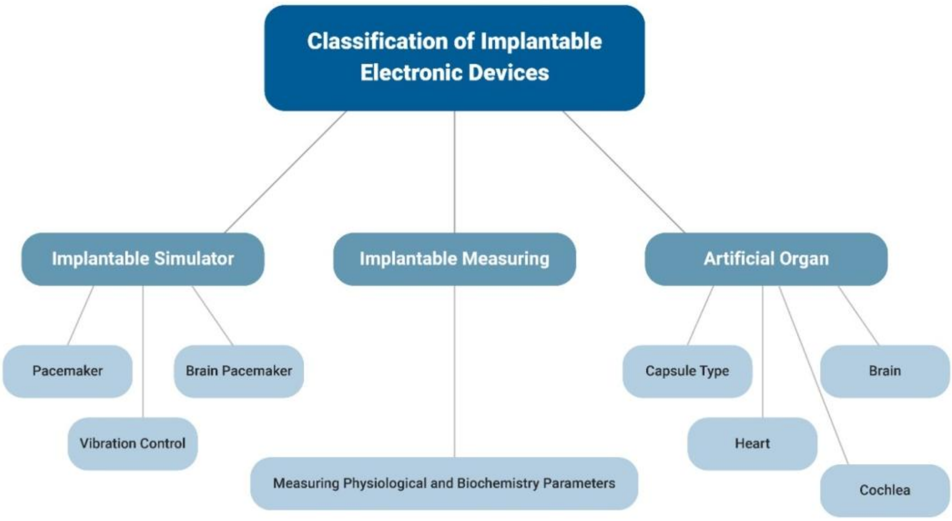

Fig 2. Classification of implantable electronics devices

The implantable antennas are used in numerous ways such as pacemaker, artificial organs, temperature monitors, Functional Electrical Stimulators (FES), blood-glucose sensors, cochlea, retinal implant and more to improve the human life.

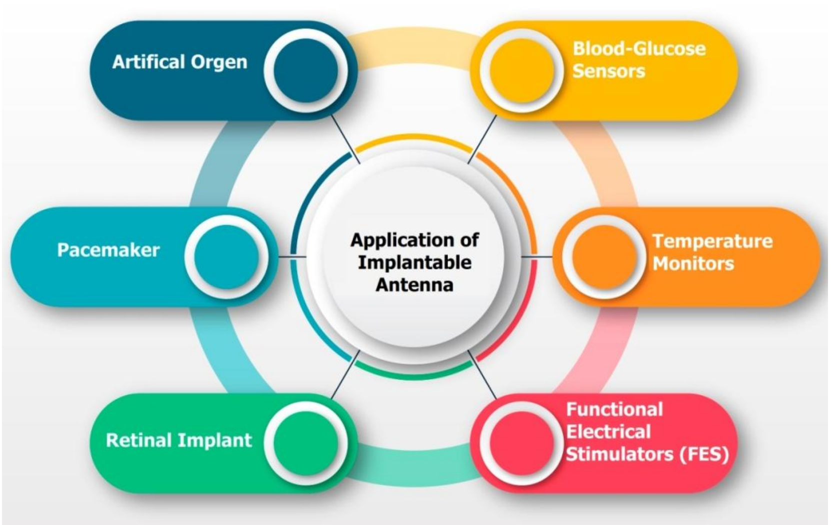

Fig 3. Application of implantable antenna

The mainly challenges in the biomedical implants are comfort and safety of the patient [13]. At the forefront of progress in biomedical technologies is the exploration of techniques for managing power in implantable antennas. Implantable antennas are instrumental in wireless communication within the human body, serving diverse applications in the medical field. Ensuring the longevity and reliability of these implantable devices necessitates effective power management. This study extensively investigates strategies and techniques aimed at optimizing power utilization in implantable antennas, taking into account the distinctive challenges and constraints presented by biomedical environments. By addressing these facets of power management, this research actively contributes to the continuous improvement of implantable antenna systems, fostering both innovation and reliability in the dynamic field of biomedical communication. So, for the power management purpose different types of the power management approaches are used that are shown in the fig 4.

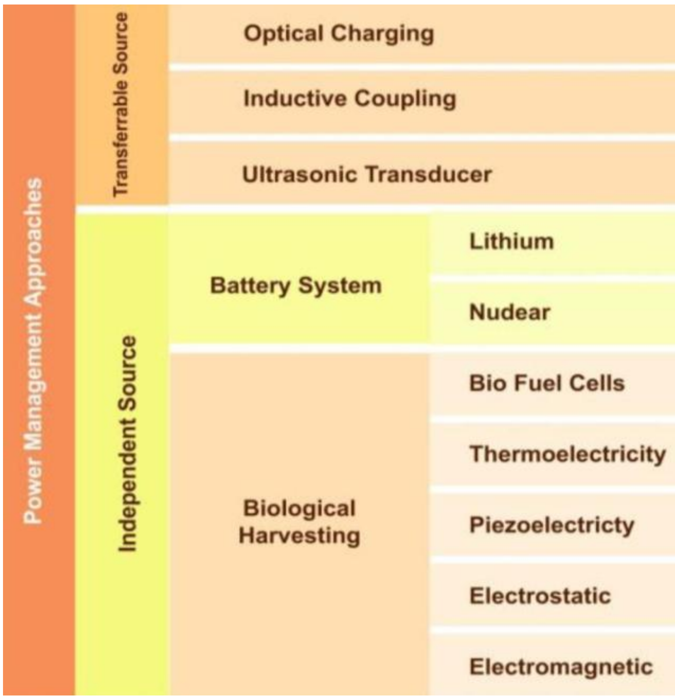

Fig 4. Classification of implantable antenna power management techniques [8]

III. Related Work

Lamkaddem et al. designed a small dual-band implantable antenna (6 × 6 × 0.25 mm) for 915 MHz and 2.4 GHz ISM applications. It provides bandwidths of 120 MHz and 310 MHz, with gains of -21.8 dBi and -19.2 dBi. The design has a full ground plane and independent frequency bands, making it suitable for biomedical use. Tests in minced pork showed it can communicate over 20 meters at both frequencies [14]. Alshammari et al. designed a small dual-band implantable antenna (8.2 × 8.2 × 0.635 mm) for wireless capsule endoscopy. It works at 1.4 GHz (WMTS) and 2.45 GHz (ISM) and uses special slots and pins to make it compact. Tests in minced pork showed gains of -29.4 dBi at 1.4 GHz and -30.4 dBi at 2.45 GHz, with bandwidths of 7.2% and 4.2%. The antenna enables reliable wireless communication over 10 meters, with safe SAR values of 4.77 and 6.07 W/kg [15]. Shah et al. developed a tiny implantable antenna (0.7 mm^3) for compact IMDs in IIoMT applications. It operates on quad-band frequencies, including ISM (915 MHz, 2450 MHz) for biotelemetry and control, and midfield (1450 MHz, 1900 MHz) for wireless power. Tests in saline and phantom models confirmed reliable performance, safety, and effective communication, making it ideal for advanced IMDs [16]. Jing et al. introduced a small circularly polarized (CP) implantable antenna with improved performance in the ISM band. It offers an impedance bandwidth (IBW) of 30% and an axial ratio bandwidth (ARBW) of 28.7%. The design uses stacked layers, a modified square ring, and cross-shaped slots to enhance CP properties while keeping the antenna compact. A slotless ground makes the antenna more durable, which was tested with dummy electronics in tissue models. Tests in minced pork confirmed the performance matched simulations. This compact and reliable antenna is ideal for biomedical wireless systems [17]. Hussein et al. developed a compact dual-band rectenna for implantable medical devices, operating at 1.5 GHz (WMTS) and 5.8 GHz (ISM). The L-shaped antenna has bandwidths of 227 MHz and 540 MHz, with S11 values of -22.6 dB and -23.1 dB, and gains of -36.9 dBi and -24.3 dBi. It is small (2.84 mm^3) and provides an omnidirectional radiation pattern. A QW InGaAs ASPAT diode, designed using SILVACO, is used in a voltage doubler rectifier to convert RF power to DC for charging devices, with higher output in a double-stage setup [18]. Abbas et al. created a small dual-band implantable antenna (7 × 7 × 0.2 mm) for BMI devices. It switches between sleep and wake modes to save power and can communicate up to 10 meters at 100 kbps. Tests showed it works well, with good signal strength and low radiation, making it ideal for future high-speed BMI devices [19]. Yang et. al. presents a compact and miniaturized implantable antenna designed for wireless cardiac pacemakers was introduced. The presented antenna is design using the Rogers 3010 substrate and works on 2.45GHz frequency. The size of the presented antenna 3×3×0.5 mm^3, peak gain is -24.9dBi and the SAR (1g) and SAR (10g) values are 32.3W/Kg and 10.8Kg respectively [20]. Ahmad et. al. presented bear shaped implantable antenna for in body wireless communication. This antenna is designed using roger duroid RT5880 substrate with size of antenna is 7×7×0.254 mm^3. Operating frequency of the antenna is 915MHz, gain is -22dBi and SAR (1g) is 8.22 W/Kg [21]. Narmadhaa et. al. presented circular patch implantable antenna for ISM band. The presented antenna is designed in Roger 3010 substrate and operates at 2.45GHz frequency. The gain of the presented antenna is -14.7dBi, SAR (1g) value is 1.8mW/Kg and SAR (10g) value is 0.3mW/Kg. The presented antenna geometry and fabricated antenna is shown in fig 5 [22]. Zada et. al. presented implantable antenna for leadless cardiac pacemaker system (LCPs). This antenna is operating on 2.4GHz frequency ISM band and design using Rogers RT/duroid 6010 substrate. Maximum gain is -25.95dBi, size of antenna is 3×4×0.5mm^3, human phantom size is 120×80× 60mm^3, |S11| with system is 25dB and without system is 31dB [23]. Yousaf et. al. presented ultra-wideband characteristics antenna for ISM band. The presented antenna designed using Rogers ULTRALAM substrate for biomedical application at 2.45GHz frequency and the size of antenna is 7×7×0.2 mm^3.The maximum gain (dBi) of presented antenna is on head, on leg, on arm and measured -26.6, -28.4, -25.4 and -22 respectively. SAR 1(g) value for head, leg and arm is 289.76W/Kg, 350.81W/Kg and 282.63W/Kg respectively [24].

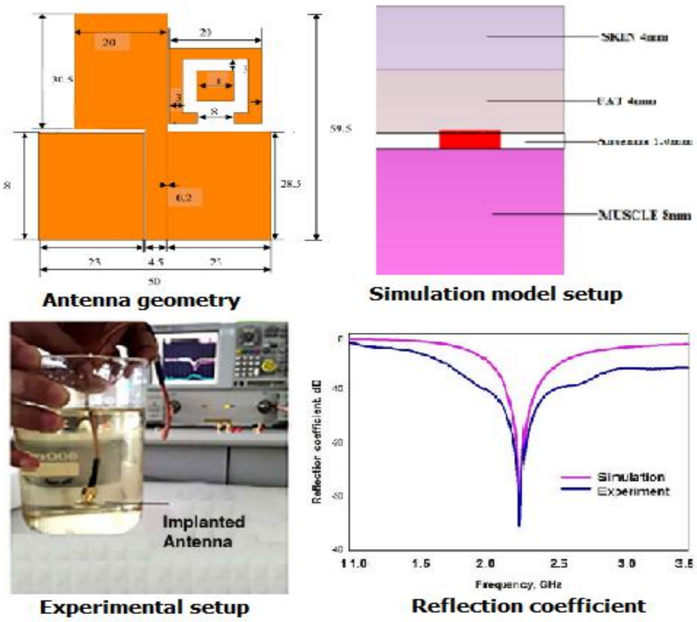

Fig 5. Presented antenna geometry, experimental setup, simulated and experimental reflection coefficient [22]

Hayat et. al. presented an antenna for wireless capsule endoscopic system operating at ISM band 0.915 and 2.45GHz. The presented antenna is designed using ULTRALAM 3850HT substrate and the size of antenna is 6.5×6.5×0.05mm^3. The SAR (1g) and SAR(10g) is 420.3 and 45.0 for 0.915GHz frequency and 232.2 and 27.7 for 2.45Ghz frequency [25]. Zada et. al. presented the metamaterial antenna design for ISM band with operating frequency 0.915GHz and 2.45GHz for biomedical application. This presented antenna is designed using Roger 6010 substrate with size of antenna is 7×6×0.254mm^3. The SAR (1g) and SAR (10g) is 576.1W/Kg and 54.5W/kg for 0.915 GHz frequency and 524.3W/Kg and 50.2W/Kg for 2.45GHz frequency respectively [26].

Ganeshwaran et al. developed a compact dual-band circular implantable antenna (797.96 mm³) for biomedical use, operating in the MICS (402–405 MHz) and ISM (2.4–2.4835 GHz) bands. The design uses via holes, slots, and a superstrate for miniaturization. Tests in tissue models showed gains of -33.1 dBi at 400 MHz and -14.55 dBi at 2.45 GHz, with bandwidths of 38.1% and 17.6%. The antenna meets SAR safety standards and works well in biomedical settings [27].

Ketavath et. al. introduces a CPW-fed implantable patch antenna designed specifically for biomedical applications. This antenna is design using the polyimide substrate and size of antenna is 24×22×0.07mm^3. The |S11| is 25.34 and 19.43 in free space simulated and measured respectively and 22.2 and 34.68 with muscle simulated and measured respectively. The maximum SAR (1g) is 0.914W/Kg [28]. Luo et al. designed a small circular PIFA for biomedical use, working in the MedRadio (401–406 MHz) and ISM (2.4–2.4835 GHz) bands. The antenna has a U-shaped patch, a circular ground, and a shorting pin. Open-end slots help it work in two bands, providing 41% bandwidth (345–510 MHz) in MedRadio and 27.8% bandwidth (1.92–2.60 GHz) in ISM.

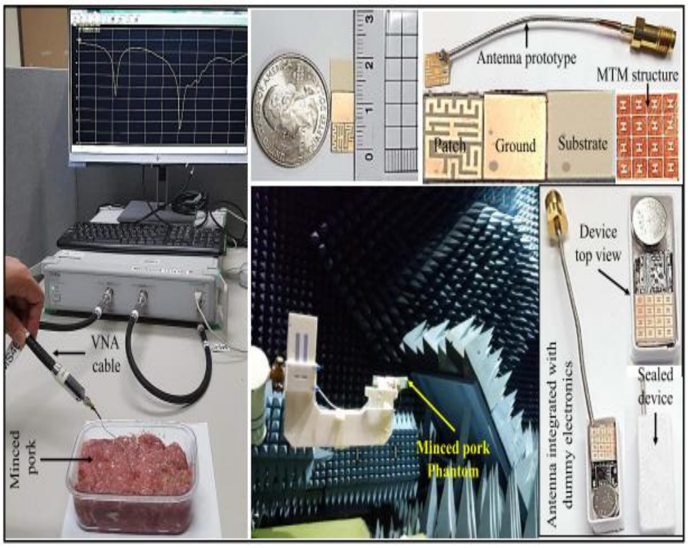

Fig 6. Fabricated MTM antenna with experiment setup for results measurements [26].

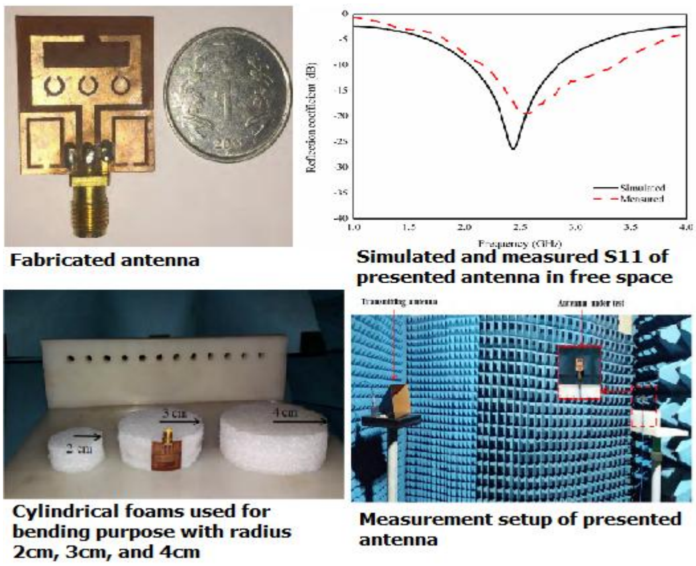

Fig 7. Fabricated antenna with experiment setup and obtained return loss results [28].

TABLE I
COMPARATIVE INVESTIGATION ON DIFFERENT IMPLANTABLE DESIGN

Ref No., Year	Antenna Type	substrate	Freq. (GHz)	|S11| (dB)	Gain (dBi)	-10dB BW (%)	Application	Size of Antenna (mm^3)
[14], 2024	Slot with loop shaped structure	Rogers RO3010	0.915 2.4	-29.5 -14	-21 -19	12.6 12.8	ISM Band	6×6×0.25
[15], 2024	Circular Patch Antenna	Rogers RO3010	1.4 2.45	-20.6 -23.2	-29.4 -30.4	7.2 4.2	Wireless Capsule Endoscopy	8.2×8.2×0.635
[16], 2024	Ultra-miniaturized implantable antenna	Polyimide	0.915 1.45 1.9 2.45	-15 -27.5 -16.3 -25.5	-27.4 -22.5 -21.7 -21.2	16.3 8.7 5.0 5.4	Pacemaker Capsule	4×3.5×0.5
[17], 2023	Circularly Polarized	Rogers RO6010	2.4	-30	-24.7	28.7	ISM Band Biomedical Application	9.8×9.8×0.889
[18], 2023	L-Shaped FDA antenna	Gallium Arsenide	1.5 5.8	-22.6 -23.1	-36.9 -24.3	15.13 9.31	WMTS Band ISM Band	4.5×1×0.63
[19], 2023	L-shaped and an inverted L-shaped slot	Polyimide	0.915 2.45	-20 -31.5	-28.3 -18.5	—	BMI Device	7×7×0.2
[20], 2022	Flat	Rogers 3010	2.45	22	-29.49	22	Cardiac Pacemaker	3×3×0.5
[21], 2022	circular	Roger duroid RT5880	0.915	20	-22	25.13	In body communication	7×7×0.254
[22], 2022	circular	Rogers 3010	2.45	36	-14.7	—	ISM band application	50×59.5×0.6
[23], 2021	Flat	Roger RT/duriod 6010	2.4	25 (with system) 31(without system)	-25.9	21.8	Leadless Cardiac Pacemaker	3×4×0.5
[24], 2021	Flat	Rogers ULTRALAM	2.45	28 (on arm) 31 (on head and on leg) 30.5 (measured)	-26.6 (on head), -28.4 (on arm), -25.4 (on leg) -22 (measured)	—	ISM band	7×7×0.2
[25], 2021	Circular	ULTRALAM 3850HT	0.915 2.45	35 20	-28.2 -24.5	13.63 6.28	Capsule Endoscopic	6.5×6.5×0.05
[26], 2020	Flat	Roger RT/duriod 6010	0.915 2.45	28 22	-17.1 -9.8	17.8 35.8	Bio telemetric	7×6×0.254
[27], 2020	Circular	Rogers 6010	0.402 2.45	30 28	-34.08 -15.2	38.1 17.6	MICS & ISM band	3.14 × 100 × 2.54
[28], 2019	Flat	polyiide	2.48	25.34	-19.7	24.9	ISM Band	24×22×0.07
[29], 2019	Circular	Rogers 3010	0.402 2.45	15 23	-41 -21.3	41 27.8	MICS & ISM band	π×5.35×5.35×1.34

IV. CONCLUSION

The realm of biomedical communication has experienced notable progress with the introduction of implantable antennas. This research investigates the design and categorization of these antennas, emphasizing their vital function in enabling wireless communication within the human body. In the evolving landscape of healthcare technology, a profound comprehension of implantable antennas is imperative for the development of inventive solutions in biomedical communication. This inquiry establishes a foundation for a thorough analysis of design principles and classifications, meticulously tailored to address the distinct requirements of biomedical applications. In this paper introduced the implantable antenna, its characteristics and different applications in daily life that improve the human life. Implantable antenna's has mostly used for in body, on body and off body biomedical applications. Implantable antennas are designed using different substrate with shape according to their application and utilization. In the implantable antenna flexible and convocational both the types of material are used. The detailed comparative analysis of the implantable antenna are representing in the table I. In the implantable antenna mostly MICs and ISM frequency band are utilized. The MICs band frequency range is 0.402GHz to 0.405GHz and in ISM band frequency range is 902–928MHz, 2.4–2.4835GHz, and 5.725–5.825GHz.

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