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Recent Trends in Fractal Antenna Research for In-body Communications

[1]**Muhammad Miftahul Amri**, [2]**Ghafar Ramadhan Faqih***
Corresponding Author: *ghafar.rf@g.skku.edu
[1] Faculty of Industrial Technology, Universitas Ahmad Dahlan, Indonesia
[2] Department of Electrical and Computer Engineering, Sungkyunkwan University, South Korea

Abstract

Fractal structure is a unique geometry that can be seen in many objects in nature, such as clouds, coastlines, DNA, trees, and even pineapple. This structure has manifold geometries, self-similarities, and space-filling properties. Due to these properties, fractal geometries are preferred to miniaturize an antenna in wireless communications. There are many cases that require a small compact antenna, including in-body communications. In this article, we present a review of the recent trends and advancements in fractal antenna research, especially in the miniaturization of implantable antennas for in-body communications. The review is derived from articles that are gathered from online libraries such as IEEE, PubMed, Nature, MDPI, Elsevier, and Google Scholar. As a result, we have collected more than 60 articles related to fractal-implantable antenna and in-body communications. Indeed, many researchers have proposed an implantable compact antenna with fractal geometries in the last decades. Fractal geometry allows a longer electrical length to be routed in a smaller area of the antenna. However, several things remain challenging in designing a fractal antenna, including bandwidth, fabrication complexity, and intercell interference.

Keywords: *Fractal Geometry, Fractal Antenna, In-body Communications, Wireless Communications, Implantable Antenna*

Introduction

Nature and scientific development are two inseparable things. In many ways, nature always inspires human beings. While on the surface, the shape of the clouds, coastlines, DNA, trees, and even pineapple are totally different, in fact, there is a similarity in their geometrical property. This property is called 'fractal'. Perhaps, the most well-known definition of the term geometric fractal is "a rough or fragmented geometric shape that can be split into parts, each of which is (at least approximately) a reduced-size copy of the whole", introduced by Mandelbrot in 1983 [1]. Since then, many researchers took the inspiration from this fractal property to develop various technologies, such as antenna design [2], transistor development [3], digital imaging [4], computer graphics [5], enzymes research [6], and even arts [7].

In wireless communication, fractal plays an important role in antenna miniaturization. There are many ways to generate fractal structures, such as iterated function systems [8], strange attractors [9], escape-time fractals [10], random fractals [11], L-systems [12], and many more. Fig. 1 depicts various patterns of fractal geometry. Fractal geometry employs a recursive generating technique that yields contours with infinitely fine structures. Fractal structure enables a longer electrical length in a smaller area. Due to the manifold geometries, self-similarities, and space-filling properties that are often associated with the miniaturization technique, fractal geometries are preferred to minimize the antenna dimension.

In the last decade, research on human-tech integration and implant devices has gained massive popularity. However, one requires reliable in-body wireless communications to successfully realize such technologies. Indeed, since implanting a large-sized antenna is not feasible, antenna miniaturization is a must. In this article, we present a review of the recent trends and advancements in fractal antenna research, especially in the miniaturization of implantable antennas for in-body communications. The articles are gathered from online libraries such as IEEE, PubMed, Nature, MDPI, Elsevier, and Google Scholar. We have extensively searched for high-quality original research, meta-analyses, reviews, and surveys/tutorials, published in the last decade. We set 'English' as the only language of interest. As a result, we have gathered more than 60 articles related to fractal-implantable antenna and in-body communications.

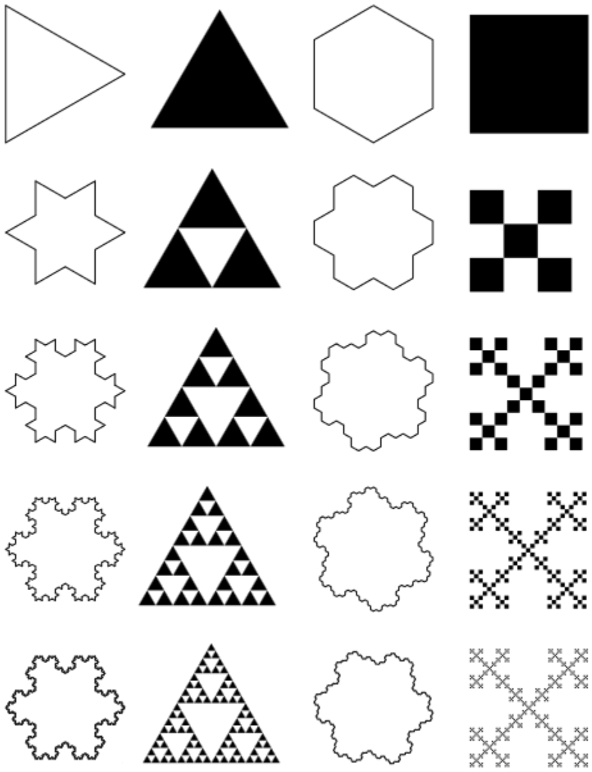

Fig. 1. Various patterns of fractal geometry

Fractal Technique and Challenges for Implantable Antenna Design

Compared to outside-body medical devices, implantable medical devices (IMDs) offer invaluable capabilities to detect human vital signs accurately. Because of this feature, IMDs have gained massive popularity in the therapeutics, diagnostics, and biomonitoring areas. Among the typical applications include implantable pacemakers, implantable drug pumps, cochlear implants, vagus nerve stimulators, and many more [13]. To fully exploit the usability of IMD, a wireless telemetry system for IMD is essential. A wireless telemetry system enables the communication between the IMD inside the host and the other devices outside. Previously, inductive coils have been used to accomplish this task

[14][15]. However, the inductive coils approach suffers from many limitations, such as a short communication range and a very low data rate. Therefore, implantable antenna rises as one of the promising solutions to solve the limitations of inductive coils approaches [16-18].

The implantable antenna is preferred to function at relatively lower frequency bands because electromagnetic (EM) waves propagate weaker through lossy human tissues as frequency increases. Federal Communications Commission (FCC) has authorized the frequency range between 402-405 MHz with channels of 300 kHz in each band for the Medical Implant Communication Services (MICS). Therefore, most implantable antennas are designed to work at these frequency bands [19]–[21]. However, due to the need for a higher data rate and a smaller antenna size, the FCC recently approved higher frequencies at ISM bands for IMDs usage. The frequency bands for which the implantable antennas are designed significantly affect the antenna design parameters. It is known that, generally, the antenna gain is proportional to the surface area. Therefore, a typical low-frequency band antenna usually has a relatively large dimension. However, the higher frequency bands have shorter wavelengths, allowing the antenna to be packed in a smaller area without sacrificing the antenna gain. Several parameters should be carefully considered to design an appropriate implantable antenna for the human body. These factors include the specific absorption rate (SAR) [22], power loss [23], stringent space limitation [24], biocompatibility [25], antenna gain [26], and antenna bandwidth [27].

First, let us discuss the SAR parameter. To ensure the safety of the human body from excessive electromagnetic (EM) wave exposure, IEEE has published an IEEE C95.1-2005 standard. The standard specifically stated that the maximum SAR averaged over 10 g of human tissue should be less than 2 W/kg [28]. Therefore, the maximum transmission power of the implantable antenna should be limited. In human tissue, SAR is mainly dominated by electric fields. Thus, the SAR can be obtained as [29]:

$$SAR = \int \frac{\sigma(r)|E(r)|^2}{\rho(r)} dr,$$

where $\sigma(r)$ denotes the tissue conductivity, $E(r)$ is the RMS electric field, and $\rho(r)$ denotes the tissue mass density. In [30], the authors proposed a differentially fed dual-band fractal antenna that is coated with a thin layer of a dielectric film that works on 402-405 MHz and 2.4-2.48 GHz. The authors validated the design through a Zubal phantom simulation (See Fig. 2). Through SAR simulation of the arm-implanted configuration (See Fig. 3), the authors validated that the average SAR distributions for the 10 g average peaked at 47.9 and 45.5 W/kg for MICS and 2.4 GHz ISM bands, respectively. With the differential input power of less than 41.8 mW, the proposed antenna design satisfies the requirement for human safety. Thanks to the fractal structure, the antenna is able to achieve a peak gain of -28.1 dBi for the MICS band and -31.3 dBi for the 2.4 GHz ISM band with only 9.5 x 9.5 x 0.635 mm^3 in size.

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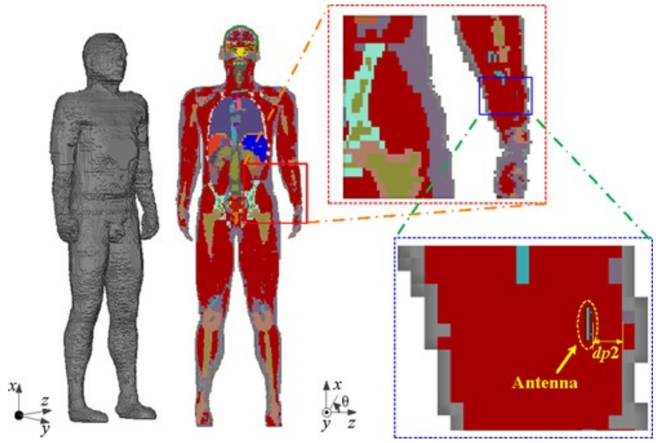

Fig. 2. Zubal phantom simulation environment in CST [30]

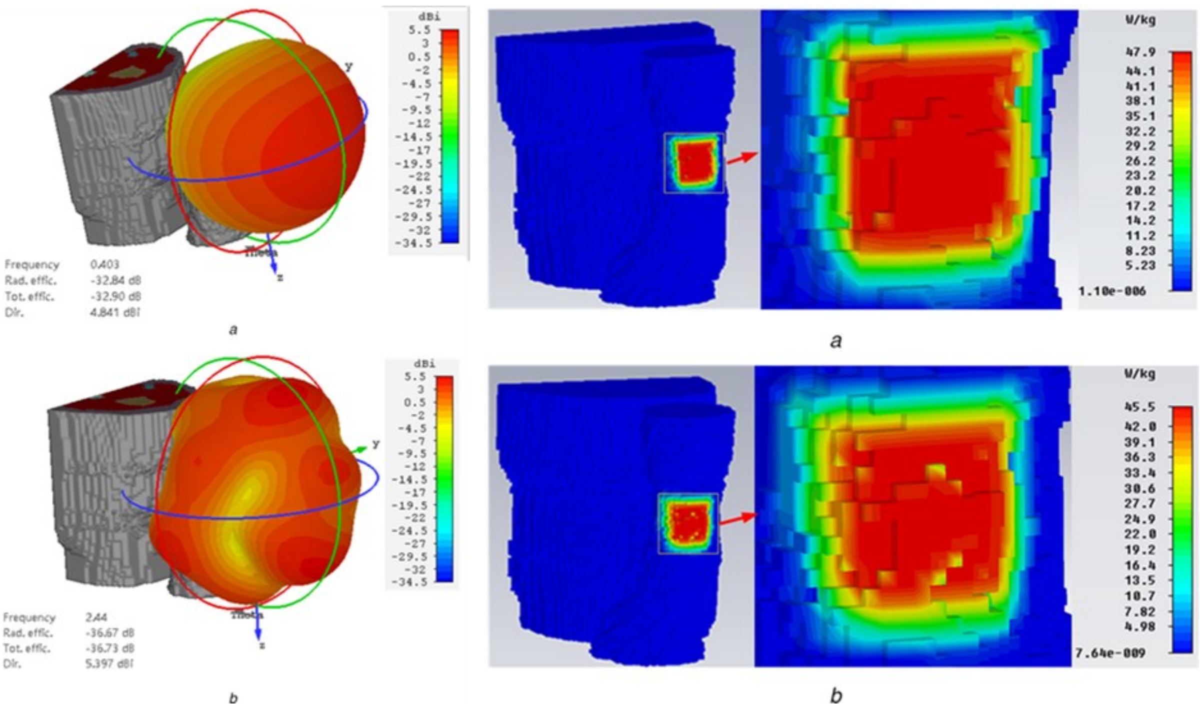

Fig. 3. 3D radiation patterns of the proposed antenna for the arm-implanted configuration (left) and 10-g average SAR distributions for the arm-implanted configuration (right) for (a) 403 MHz, (b) 2.44 GHz [30]

Ideally, an IMD should consume as less power as possible to reduce the frequency of battery replacement. Depending on the implant location, frequent battery replacement is not always feasible. While there are numerous ways to charge the battery through wireless power transfer, such as via inductive coupling [31], capacitive coils [32], and even radio frequency [33], it is always better to minimize the IMD's power consumption. An implantable antenna with low power loss is one of many ways to increase the battery life of IMDs. In [34][35], the authors proposed single-band implantable antennas that operated continuously in an uninterrupted system. This makes energy consumption relatively high. In [36], the authors proposed a dual-band implantable antenna that enables the IMDs to

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switch their state to sleep or standby mode through different bands. By doing so, a considerable amount of energy can be saved.

In [37], the authors proposed a dual bands small planar modified Minkowski fractal antenna with frequency ranges of 2.4 GHz and 5.8 GHz for passive deep brain stimulation (DBS) implants. The antennas can harvest the EM wave energy from the dual ISM bands to charge the DBS devices. With only 20 × 20 × 1.6 mm3 in dimension, the antennas managed to harvest 0.4 mW and 0.04 mW power from 2.4 GHz and 5.8 GHz frequency bands, respectively, at a 25 cm distance. The gain of the proposed antenna peaked at 3.2 dBi for the 2.4 GHz frequency band and 4.7dBi for the 5.8 GHz frequency band. As observed in Fig. 4, the return loss at both ISM bands is around 1–3 dB larger than the minimum value, implying a wide bandwidth for energy harvesting.

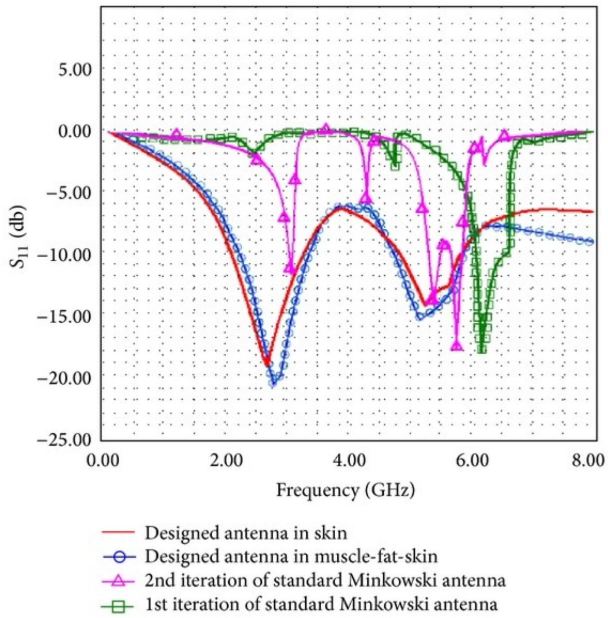

Fig. 4. The return losses (S_{11}) of the designed antenna in the human body and the 1st and 2nd iterations of standard Minkowski fractal antenna in the skin [37]

As aforementioned, the low-frequency band exhibits a lower RF loss in biological tissue than the higher one due to the higher magnetic field penetrability in the low-frequency band. However, because of the natural wavelength, a typical antenna for such low-frequency bands requires a larger dimension to maintain sufficient radiation efficiency. However, to satisfy the stringent space constraint of an IMD, an implantable antenna needs to have a compact size. Typically, an antenna's dimensions are closely associated with its performance [38–40]. The physical dimensions determine how the current distributes across the antennas, which in turn affects the antenna's input impedance, radiation pattern, losses, gain, and bandwidth. The antenna typically needs to be at resonance and has a size that is comparable to the wavelength or quarter wavelength to produce an appropriate current distribution with constructive radiation and sufficient gain. Hence, at the frequency of the MICS band (402-405 MHz), and even at the ISM bands (902-928 MHz, 2.4-2.4835 GHz, and 5.725-5.825 GHz), the dimension of the traditional antennas are relatively large. Therefore, it is crucial to develop an efficient way to downsize the antenna's dimensions without adversely compromising the antenna's performance metrics, such as radiation, gain, and bandwidth. In [41-46], numerous dimension-reduction techniques have been investigated, including the use of layered structures, shorting pins, meandering patches, and high-permittivity materials. However, such approaches caused an increase in the antenna design-fabrication cost and complexity. At this point, the fractal miniaturization approach promises an effective way to reduce the antenna dimension while keeping the length of the effective EM wave current's route due to its self-similarity and space-filling characteristics. Various works have investigated the fractal antenna design, including the Koch-modified antenna [47], the Minkowski fractal antenna [48], the Fern-fractal-shaped microstrip antenna [49], and the Peano-Gosper fractal antenna [50]. In Table 1, we have summarized several works on implantable fractal antennas. As depicted, the antenna dimensions are significantly smaller than the market-available antennas for the same frequency bands.

Table 1. Various works on implantable fractal antennas

Authors (Year)	**Antenna Dimension (l x w x t)**	**Antenna Bandwidth**	**Antenna Frequency**	**Application**
S. Chen and C. Yang (2010) [51]	8 x 11.5 x 2 + 3.5^2 mm^3 (Design I) and 8 x 8 x 2 mm^3 (Design II)	5 MHz	403.75 MHz	Dental Implant
S. Manafi and H. Deng (2014) [30]	520 x 400 x 20 mm	No Information	2.4 GHz and 5.8 GHz	Human Chest Implant
H. Liu, et al., (2015) [52]	9.4 x 9.4 x 0.635 mm^3	79 MHz and 220 MHz	364 MHz and 2.4 GHz	In-body Communications
H. Liu and X. Liu (2015) [26]	9.3 x 9.3 x 0.635 mm^3	77 MHz	405 MHz	Biomedical Applications
R. Patel, et al., (2016) [53]	0.675 x 0.2 x 0.2 mm^3	1205 MHz	730 MHz	Medical Implants
Y. Fan, et al., (2019) [15]	9.5 x 9.5 x 0.635 mm^3	92 MHz and 320 MHz	402 MHz and 2.4 GHz	Implantable Medical Devices
R. Kumar, et al., (2021) [54]	π x 5^2 x 0.762 mm^3	40.5 MHz	402 MHz	Muscle Tissue Implants

Another factor that needs to be considered in designing implantable antennas is bandwidth. The performance of an antenna is mainly affected by the impedance matching of the antenna. However, it is quite challenging to match the impedance of an implantable antenna. This is because human tissue has unique electromagnetic properties that may vary between individuals. Therefore, it is necessary to design an implantable antenna with wide bandwidth to combat this issue. In [21][55–57], the authors proposed various implantable antennas design. However, most of the antennas have less than 50 MHz bandwidth, which is a disadvantage for implant applications. In [58], the authors designed triple-band implantable antennas with a relatively wide bandwidth. The antenna design is targeted to operate at 400 MHz, 2.4 GHz, and 5.7 GHz. The authors proposed three antennas topology, namely fractal, meandered, and comb types. The designed antenna has an impedance bandwidth of 53 MHz to 120 MHz, 90 MHz to 320 MHz, and 300 MHz to 1200 MHz for the three frequency bands. Among those three, the fractal antenna has the smaller dimension of 1.4 × 10 × 10 mm3. However, in terms of bandwidth, the

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fractal antenna showed the narrowest bandwidth, followed by the meandered and comb types. For example, in the 2.4 GHz frequency band, the fractal antenna has only 90 MHz bandwidth, while the meandered and comb antennas have 237 and 320 MHz bandwidth, respectively. In terms of fabrication complexity, the fractal antenna has the most complex requirement, followed by the comb and the meandered types. Therefore, while a fractal antenna provides a smaller dimension, which is best for implantable antenna miniaturization, the bandwidth and the fabrication complexity are among many parameters in fractal antenna design that still need improvements.

Biocompatibility is another critical parameter that needs to be considered in designing implantable antennas. Biocompatibility is required to guarantee the host's safety (human body) and prevent implant rejection (e.g., allergy). To avoid implant rejection, an implantable antenna can be designed and fabricated on a biocompatible substrate [58]. Furthermore, an insulating material can be used to cover the implantable antenna's body (as well as the IMDs) to ensure the patient's safety from potential risks (e.g., electrocution by a short circuit or battery chemical leakage). Various bio-compatible coatings such as Parylene C [59], PEEK [60], and medical-grade silicone such as Silbione [61] can be used to encapsulate the implantable antenna. Moreover, by covering the antennas (and the IMDs), one can avoid the IMDs breakage caused by the human body (i.e., shorted circuit and corrosion from the human fluid). However, inappropriate substrates and improper insulating cover might deteriorate the antenna's performance [59]. In [52], the authors proposed a miniaturized differentially fed dual-band fractal antenna for IMD wireless communications. To ensure its biocompatibility, the authors have coated the antenna with a biocompatible coating material, Parylene C, with $\varepsilon_r = 2.95$ and $\tan\delta = 0.013$. Even with the Parylene C coating, the proposed antenna is still capable of achieving a peak gain of -32.8 dBi for 403MHz and -34.3 dBi for 2.44 GHz. Furthermore, by using the fractal structure, the antenna volume can be miniaturized to 56.11 mm3.

Among the primary considerations in designing an implantable antenna are the tissues in which the antenna will be implanted. Human skin, fat, bone, and muscle tissues have different dielectric parameters. Moreover, the dielectric constant parameters vary according to the frequency. In Table 2, we have presented the dielectric constant parameters of various human tissues in two frequency bands (403 MHz and 2.44 GHz) [52]. The value of these dielectric constant parameters was presented by Yale University [62] according to the Cole-Cole formulation [63] in the Zubal phantom. Furthermore, the dielectric parameters vary with the characteristic of every individual. For example, the dielectric parameters of normal people are different from the dielectric parameters of fat people. In [58], the authors simulated an implantable antenna with various implant locations for two different phantoms: normal phantom and fat phantom. As observed in Fig. 5, the performance of the implantable antenna (i.e., resonant frequency shift and bandwidth) varies with the implant placement and with the type of phantoms.

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Table 2. Dielectric parameters of human tissues [52]

Human Tissues	403 MHz		2.44 GHz	
	ε_r	σ (S/m)	ε_r	σ (S/m)
Skin	46.7	0.69	38.0	1.46
Muscle	57.1	0.79	52.7	1.73
Fat	11.6	0.08	10.8	0.27
Bone	22.4	0.24	18.6	0.80

Source: Zubal, et al., (Yale University) [62]

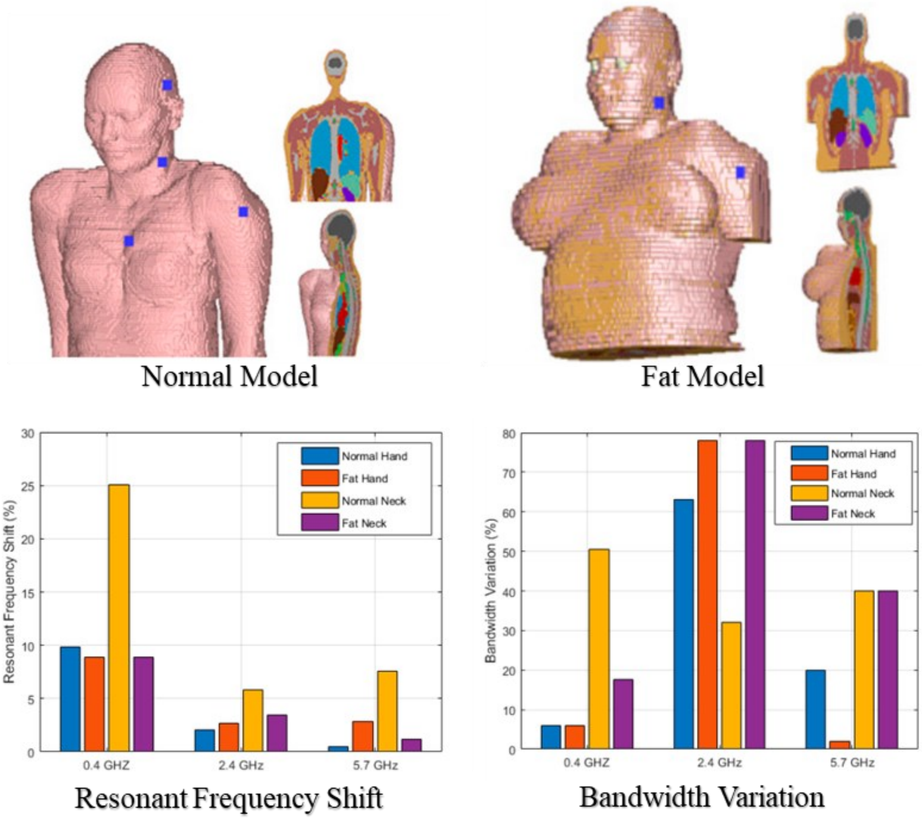

Fig. 5. Simulation of an implantable antenna with various implant locations for normal and fat phantoms [58]

With the rapid development of artificial intelligence, it is difficult to neglect artificial intelligence techniques to assist the antenna design process. In [64], the authors used artificial neural network (ANN) and particle swarm optimization (PSO) techniques to design a tree-shaped hybrid fractal antenna for biomedical applications. The authors combined the Koch-like structure with the Giuseppe Peano-like structure to realize a 24 × 20 × 1.6 mm3 fractal antenna (See Fig. 6). From the experiment, it is validated that in the 2.4 GHz frequency band, the measured -10 dB bandwidth is 1.44.

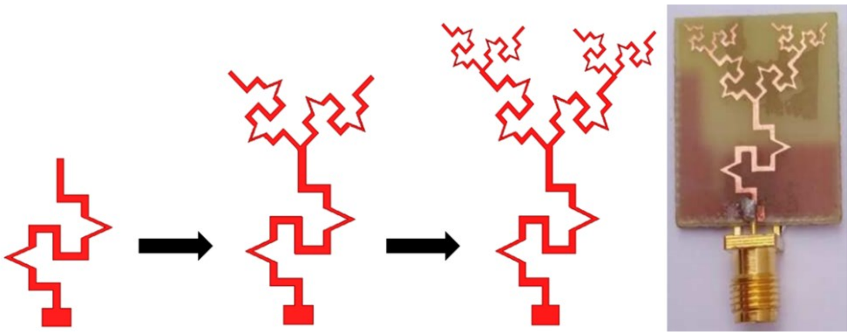

Fig. 6. Tree-shaped hybrid fractal antenna for biomedical applications [64]

Fractal Geometry in Wireless Communications Other Than Implantable Antenna

In this subsection, let us discuss two cases of fractal geometry in wireless communications areas other than the implantable antenna. First, in [65], the authors designed a tattoo-like fractal RFID to detect the cracks in implanted metal prostheses early. From the simulation and experiments, the authors have validated that the proposed device is able to identify surface cracks of the hip prosthesis as small as 0.6 mm and can be wirelessly interrogated from outside the body at up to 70 cm distance.

In [66], the authors proposed a fractal 1-bit reconfigurable intelligent surface (RIS) that works on 5.8 GHz (See Fig. 7). RIS is a new paradigm of realizing a smart radio environment through intelligent wireless control. RIS comprises a massive number of unit cells, each of which can be tuned to manipulate the incident EM waves. In [66], the authors designed a 5.8 GHz RIS with 256 fractal unit cells. Through simulations and experiments, the authors have demonstrated that the proposed RIS can steer and focus the impinging waves toward the desired direction and improve the wireless link. While the fractal structure enables the RIS to contain a larger number of unit cells within the smaller area, the lack of inter-cell distance causes considerable interference between one unit cell and another.

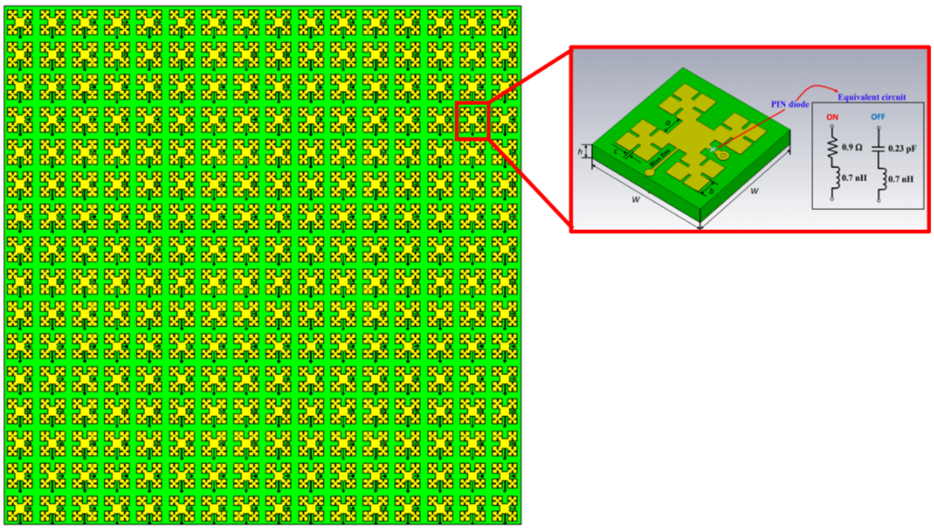

Fig. 7. 5.8 GHz reconfigurable intelligent surface (RIS) with fractal structure [66]

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Conclusion

The fractal structure is an impressive geometry that can be seen in many objects in nature, such as clouds, coastlines, DNA, trees, and even pineapple. This structure has manifold geometries, self-similarities, and space-filling properties. Due to these properties, fractal geometries are preferred to miniaturize an antenna in wireless communications. There are many cases that require a small compact antenna, including in-body communications. In this manuscript, we have presented recent trends in fractal antennas for implantable medical devices. Many researchers have recently proposed an implantable compact antenna with fractal geometries. Fractal geometry allows a longer electrical length to be routed in a smaller area of the antenna. However, several things remain challenging in designing a fractal antenna, including bandwidth, fabrication complexity, and intercell interference.

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Authors

Muhammad Miftahul Amri received his B.S. from the Department of Computer Science and Electronics, Universitas Gadjah Mada Indonesia in 2018, and an M.S. from the Department of Electrical and Computer Engineering, Sungkyunkwan University South Korea in 2021, where he is currently pursuing his Ph.D. In 2022, he received his M.M. and professional engineer degrees from Universitas Terbuka Indonesia and the Universitas Muhammadiyah Yogyakarta Indonesia, respectively. In 2021, he joined the faculty at Universitas Ahmad Dahlan Indonesia, where he is currently a lecturer in the Department of Electrical Engineering. His research interests include wireless communication and reconfigurable intelligent surface. He can be contacted by email: muhammad.amri@te.uad.ac.id.

Ghafar Ramadhan Faqih is a bachelor's graduate from the Department of Computer Science and Electronics, Universitas Gadjah Mada, Indonesia (2017). Between 2017 and 2019, he was with PT Bintang Komunikasi Utama as a system (hardware) engineer. He then joined Widya Analytic from 2020 to 2021 as a product owner. In February 2022, he joined the Department of Electrical and Computer Engineering, Sungkyunkwan University, South Korea as a master's degree student. His research interests are wireless communications, IoT, robotics, and brain-computer interfaces. (email: ghafar.rf@g.skku.edu).