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Fractal Antennas for Wearable Applications

Mohamed I. Ahmed and Mai F. Ahmed

Abstract

This chapter focuses on the design and fabrication of different types of flexible and inflexible wearable fractal for modern wireless applications with body-area-networks (BANs). A wearable antenna is intended to be a part of clothing used for modern wireless communication purposes. Fractal technology allowed us to design compact antennas and integrate multiple communication services into one device. The proposed antennas were simulated and measured by CST simulator version 2017 and Agilent N9918A VNA respectively. Furthermore, these antennas were fabricated using folded copper. The measured results agree well with the simulated results.

Keywords: fractal, wearable antenna, metamaterial, SAR, Sierpinski carpet, crown rectangular, textile antenna

1. Introduction

Conventional antenna designs which include planar dipoles, monopoles, planar inverted-Fs (PIFAs), and microstrip patches were used in recent research for wearable antennas design [1]. Wearable microstrip antennas are planar. This made them a practical antenna type due to their low cost, low profile, light weight, small size and eases for fabrication to be worn or carried on human body [2]. A wearable antenna is a body-worn antenna which designed from textile materials as antenna substrates to form the “smart clothes” or in the other mean, is an antenna which designed and meant to be a part of clothing or integrated into a personal accessory (such as shoes, glasses, buttons, and helmets) [3]. The wearable antennas are divided into two main categories: flexible and inflexible wearable antennas [4].

Nowadays, the compact antenna with a better performance and multi-bands working frequencies is one of the main trends in modern wireless communications systems [5]. One of the most important techniques used to reduce the antenna's dimensions is the fractal geometries. A fractal is a fragmented or split geometric shape that can be subdivided into parts; each of this is a reduced-size copy of the whole. Fractal antennas have more benefits such as; high radiation efficiency, high gain, wide bandwidth and reduced size etc. Generally, fractals are self-similar and independent of scale. There are many shapes of fractals such as Sierpinski's gasket; Cantor's comb, Von Koch's snowflake, the Mandelbrot set, and the Lorenz attractor see **Figure 1** [6].



Figure 1.
The different geometries of fractals in natural [6].

1.1 Wearable antennas design steps

1.1.1 Material selection

The fabrication process of flexible and wearable antennas depends mainly on the materials involved in the designed structure. Properties of conductive and dielectric materials used in flexible and wearable antennas, are surveyed in this section [7].

1.1.2 Dielectric materials

Dielectric materials that are used as substrates for antennas, these materials may be inflexible such as conventional soft PCB or flexible such as textile material in clothing. The textile materials must be it is flexible, easy to design, water resistant and light in weight to make the wearable antenna more suitable [8].

1.1.3 Conductive materials

Conductive materials may be pure metallic materials or electro-textile materials. The pure metallic material is pasted on the dielectric substrate which is made out of different materials such as: copper, gold and etc. The electro-textile materials are conductive fabrics [9].

1.2 Antenna design

In general, to design any rectangular wearable microstrip patch antenna should be considered the following parameters such as dielectric constant (ϵ_r), resonant frequency (f_o), and height of the substrate (h) for calculating the length and the width of the patch [10].

1.3 Antenna simulation

There are several technologies and simulators for analysis and simulation the wearable antennas. CST MICROWAVE STUDIO is a computer system technology and is a numerical simulator which uses the finite integration technique (FIT) [11].

1.4 Performance near human

Generally, wearable antenna or body-worn antenna radiates the electromagnetic waves (EMWs) which are absorbed by tissues of the human body. The

absorption of these waves will cause damage and burn human tissues [12]. So that it is necessary to decrease the electromagnetic energy interaction towards the human body tissue from the wearable antennas when in use [13]. The absorption of the electromagnetic waves (EMWs) from the human tissue is measured by the specific absorption rate (SAR) [14]. Therefore, the SAR value plays a vital role in any design of wearable antenna. There are some parameters which will effect on the SAR value such as: size, shape, location, radiated power and type of antenna used and etc. in [15, 16].

1.4.1 The SAR safety limitation

The SAR safety limit is based on the standardization committee and is various in different regions in over the world. In the US is regulated by the Federal Communications Commission (FCC) where the acceptable maximum SAR value 1.6 W/kg, averaged over 1 gram of tissue [17]. But in Europe, the acceptable maximum SAR value is 2.0 W/kg averaged over 10 grams of tissue which is regulated by the International Commission on Non-Ionizing Radiation Protection (ICNIPR) [17]. If the SAR value exceeds the safety limit, the antenna must be changed and replaced by antenna with a lower back radiation [18].

1.5 Applications of wearable microstrip antenna

The development of antenna technology for human and machine interface has made qualitative leaps in the use of textiles as antenna substrates [19]. In future, this will permit freedom to design antenna systems worn by the body and integrated into it so; these are called “smart clothes” [20]. They will emerge in various as shown in **Figure 2** [21]:

- 1. Emergency workers outfits.
- 2. Medical applications.
- 3. Space applications.
- 4. Military applications.
- 5. Sports outfits and so forth.



Figure 2.
The various applications of the wearable antenna [21].

2. Fractal wearable antenna on metamaterial cell

2.1 Fractal wearable antenna design

The simulated geometry of the proposed fractal wearable antenna is illustrated in **Figure 3**. The patch and the ground planes are squares with length = 46 mm, and 70 mm respectively. The substrate is made from FR4 material with thickness $h = 1.6$ mm, relative permittivity $\epsilon_r = 4.4$ and $\tan(\delta) = 0.02$.

The inset fed line of the proposed antenna is consisted of two sections: 50 Ω stripline and tapered line for achieving the 50 Ω impedance matching as shown in **Figure 4**. The port dimensions are tabulated in **Table 1**.

The proposed third iteration fractal antenna is designed based on an iteration length, L_m . It is calculated as follows [22]:

$$L^m = 2L^{m+1} + W1^{m+1} + 2W2^{m+1} \quad (14).$$

Where: m is the order of iteration, $W1^{m+1} = c_1L^m$; is the width of the middle segment, and $W2^{m+1} = c_2L^m$; is the indentation width.

Furthermore, Parameters c_1 and c_2 , are very important parameters for the efficiency of the size reduction [22]. Now, in the presented fractal wearable antenna c_1 and c_2 are chosen as 0.1 and 0.4 respectively. This antenna is designed to be suitable for operating in GPS, WiFi like Bluetooth, and WiMax frequencies at the time as shown in **Figure 5**.

In addition to, a metamaterial spiral cell is meandered in the ground plane of the presented 3rd iteration fractal wearable antenna for enhancement the SAR results (as shown in **Figure 6**). By using this spiral cell, the permeability and the permittivity will be negative, and then the reflection coefficient will be also negative, so that the SAR value is minimized.

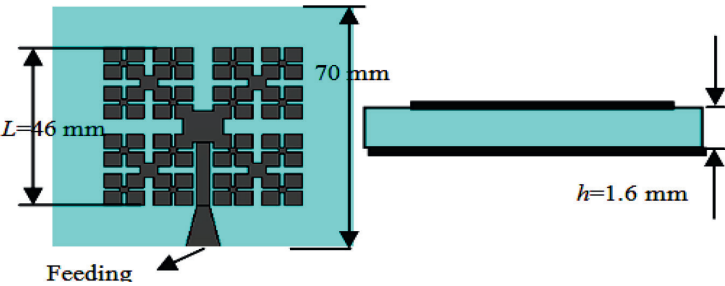


Figure 3.
The geometry of proposed antenna.

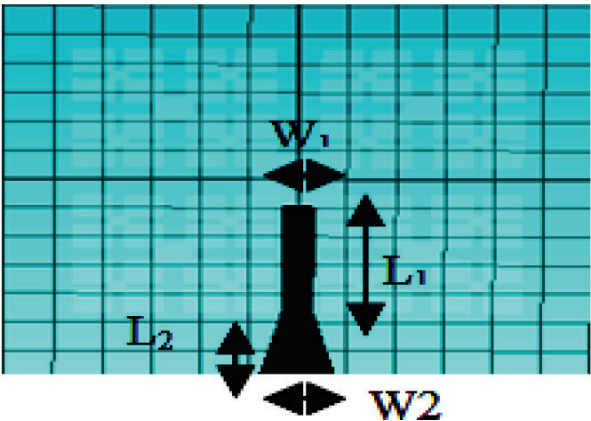


Figure 4.
The port geometry.

| Parameter | W1 | L1 | W2 | L2 |
|------------|----|------|----|----|
| Value (mm) | 3 | 18.4 | 8 | 12 |

Table 1.
Strip-Line Dimensions.

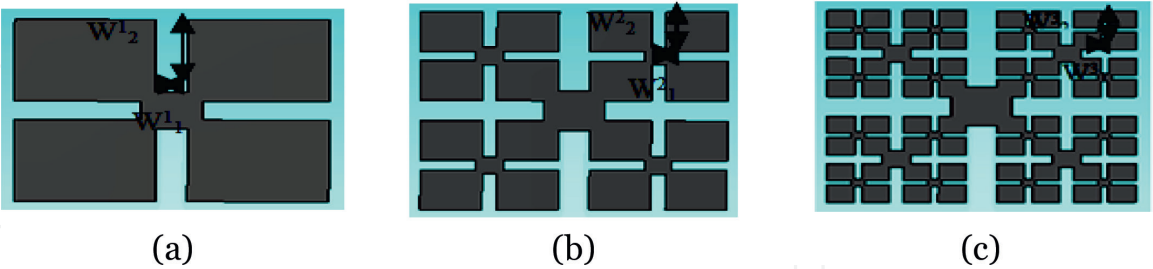


Figure 5.
The proposed fractal antenna with different iteration structures.

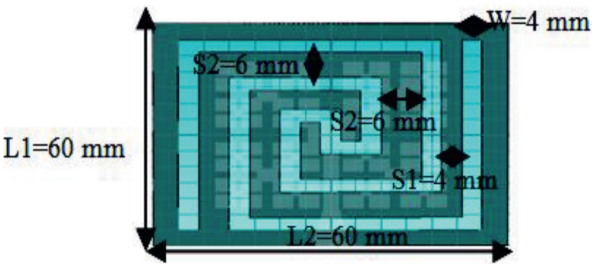


Figure 6.
The geometry of spiral cell.

2.2 Simulation results

Simulation analysis of the proposed antennas is performed through the commercial software simulator called CST 2016. The simulated S_{11} for the conventional patch, 1st iteration, 2nd iteration, and the 3rd iteration of the Fractal Wearable Antenna are shown in **Figure 7**. Also, the antenna radiation patterns with/without spiral cell in E-plane and H-plane are plotted in **Figures 8** and **9**.

For the four resonance frequency bands, the gain and efficiency are improved by using metamaterial spiral cell. The first band with return loss -23 dB from 1.54 to 1.62 GHz, this band is suitable for GPS application. In this band, the gain and efficiency are 2.152 dB and 44.7% and improved with MTM spiral cell to 4.41 dB and 79.1%. The second band with return loss -20.78 dB from 2.67 to 2.87 GHz, this band

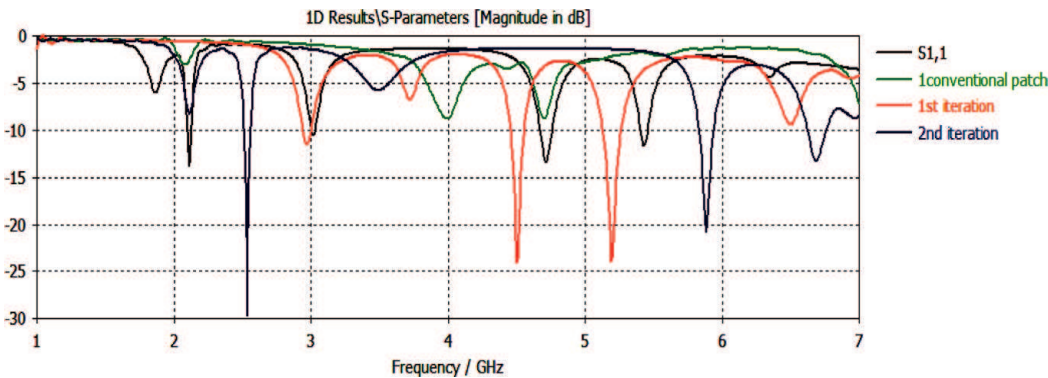


Figure 7.
The S_{11} against frequency for three different iterations.

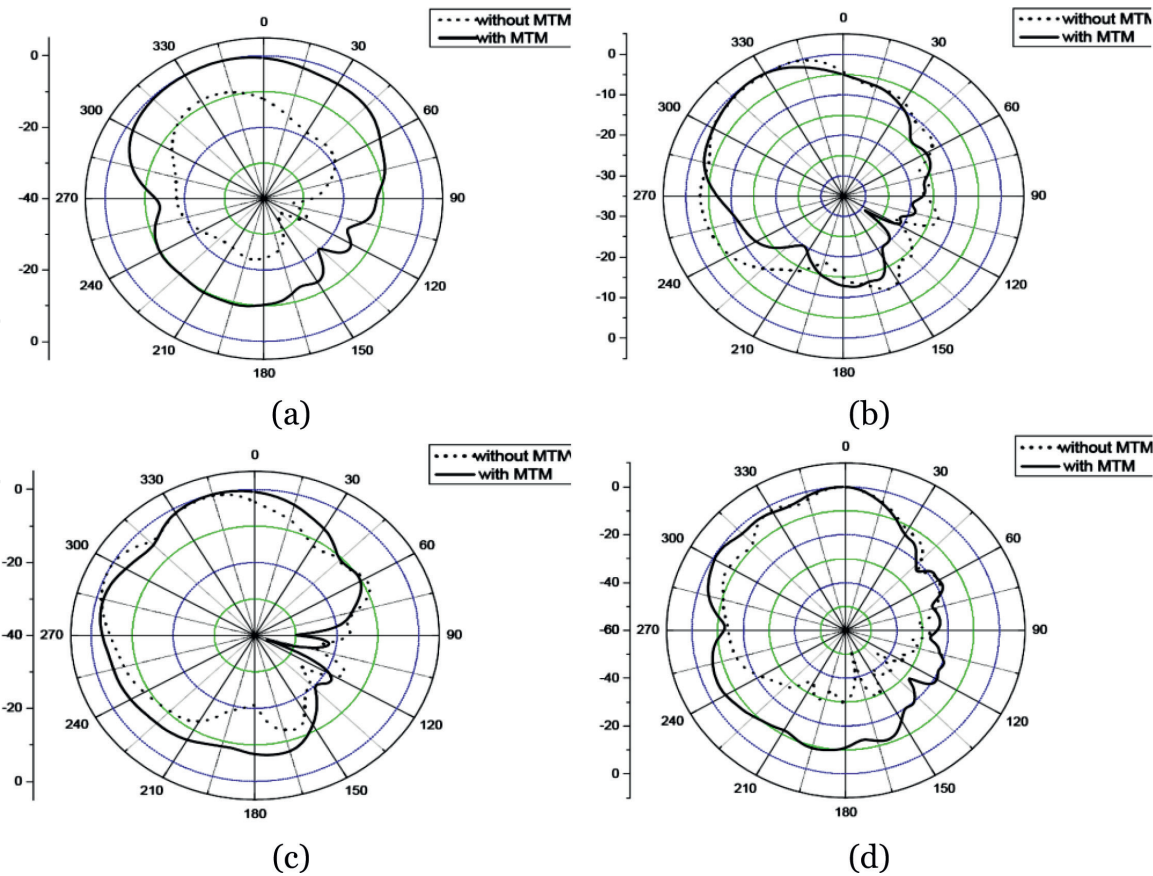


Figure 8.
Radiation pattern in E-plane at (a) 1.57, (b) 2.7, (c) 3.4 (d) 5.3 GHz.

is suitable for WiMax application. In this band, the gain and efficiency are 1.19 dB and 47.2% and improved to 3.56 dB and 55.54%. The third band with return loss -9.67 dB from 3.33 to 3.46 GHz, this band is suitable also for WiMax application. In this band, the gain and efficiency are 1.112 dB and 56.6% and improved to 2.89 dB

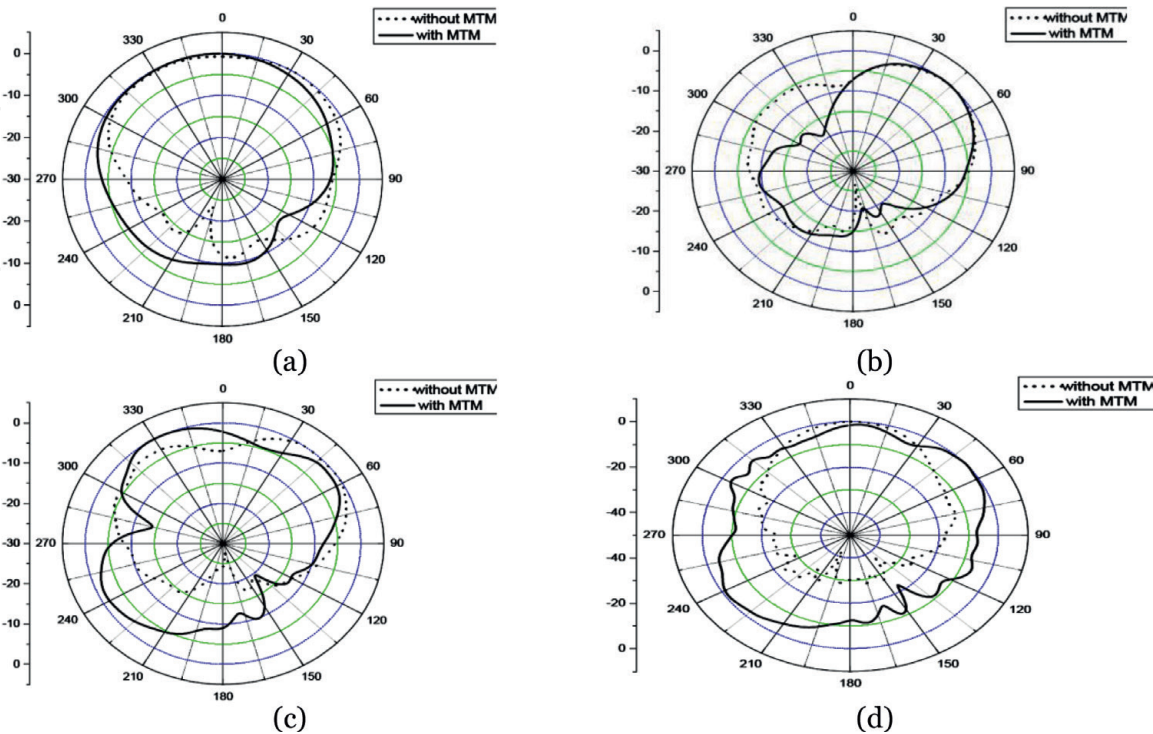


Figure 9.
Radiation pattern in H-plane at (a) 1.57, (b) 2.7, (c) 3.4 and (d) 5.3 GHz.

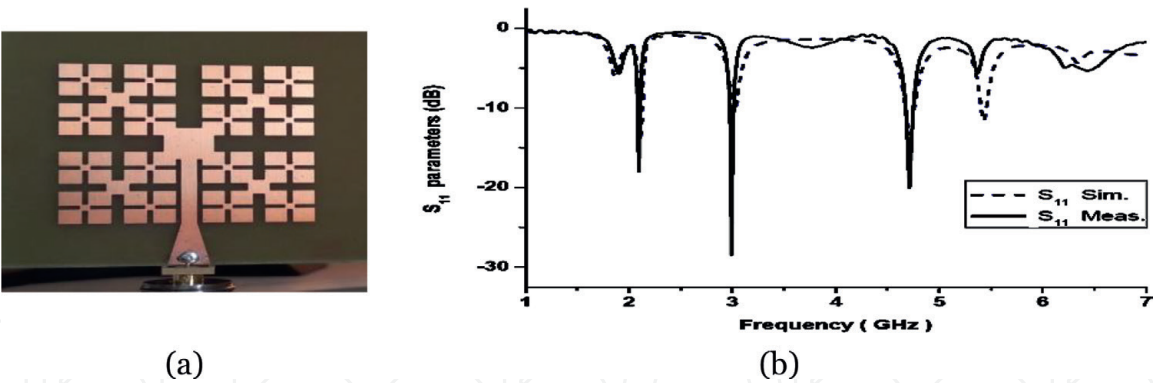


Figure 10.
The fabricated proposed antenna without MTM cell: (a) fabricated geometry, and (b) the measured and simulated return loss S_{11} with the frequency.

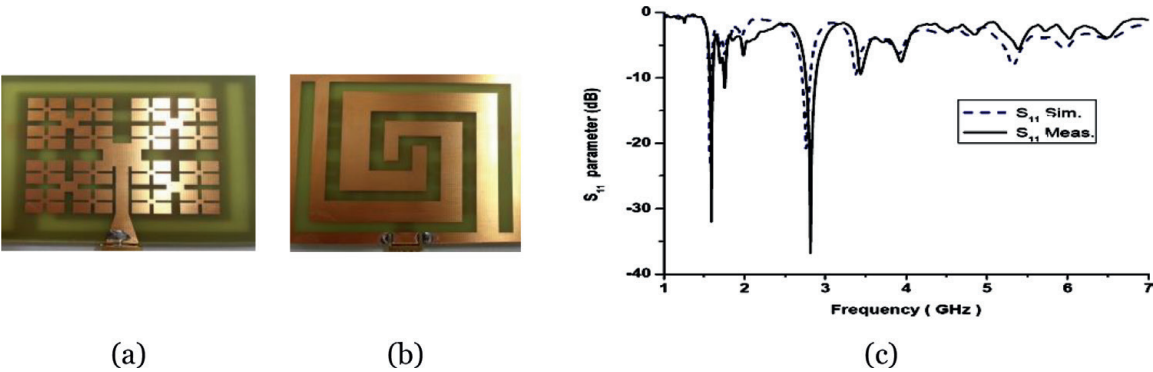


Figure 11.
Fabricated proposed antenna with MTM cell: (a) top and (b) bottom view and (c) the measured and simulated return loss S_{11} with the frequency.

and 67.45%. The forth band with return loss -8.56 dB from 5.24 to 5.42 GHz, this band is suitable for WiFi application. In this band, the gain and efficiency are 2.29 dB and 58.5% and improved to 3.38 dB and 68.1% .

2.3 Experimental results and discussion

The prototypes of the proposed fractal antenna without and with spiral cell and the measured S_{11} for those are shown in **Figures 10** and **11**.

2.4 SAR calculations

Figure 12 shows that the SAR simulation results for the proposed antenna with spiral MTM cell. These results are shown in **Figure 13** and mentioned in **Table 2**. From **Figure 13** and **Table 2**, the intended four bands have a very low SAR value and do not exceed unity. Also, can be notes as the distance between the proposed antenna and the human is maximized, the SAR value is minimized.

2.5 Proposed antenna integrated on life jacket as application

In this section, the presented 3rd iteration fractal wearable antenna with MTM spiral cell is used for integration on a floating life jacket. This smart life jacket can be used to help humans get away in the event of an accident [23]. Also, there is another benefit for using that life jacket; it can be used as an isolation cover to prevent the

water reaching the proposed antenna. The simulated life jacket with voxel model is shown in **Figure 14**, and the dimensions with some electrical characteristics of that simulated life jacket are tabulated in **Table 3**.

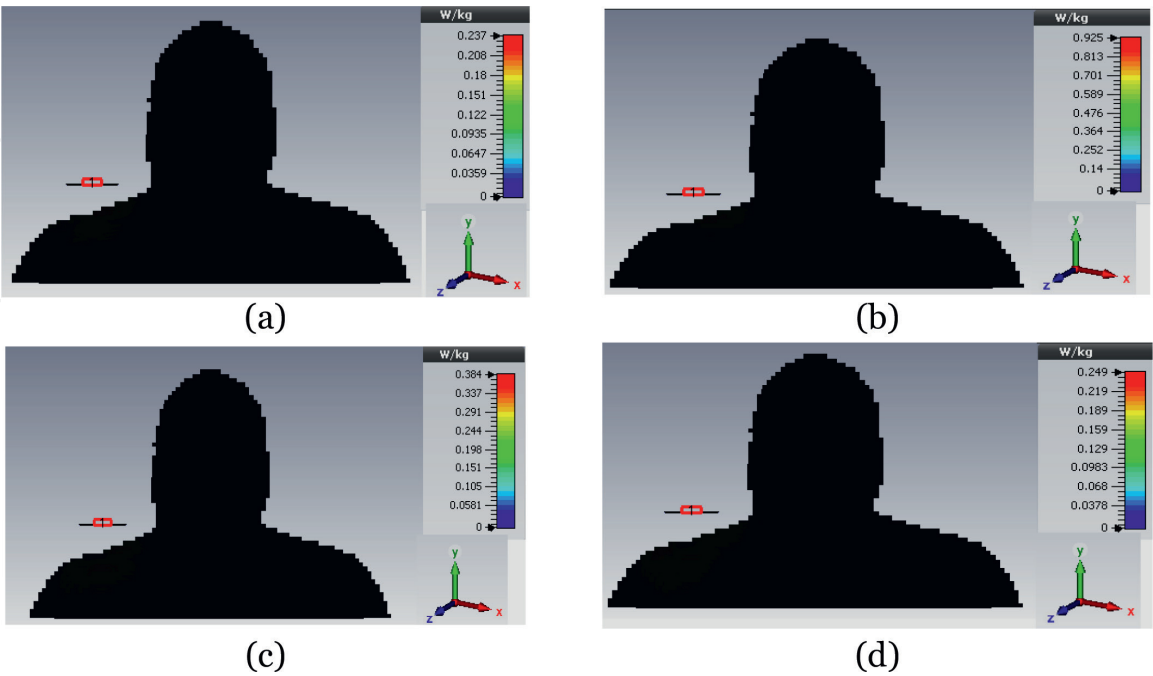


Figure 12.
SAR distribution at (a) 1.57, (b) 2.7, (c) 3.4 and (d) 5.3 GHz.

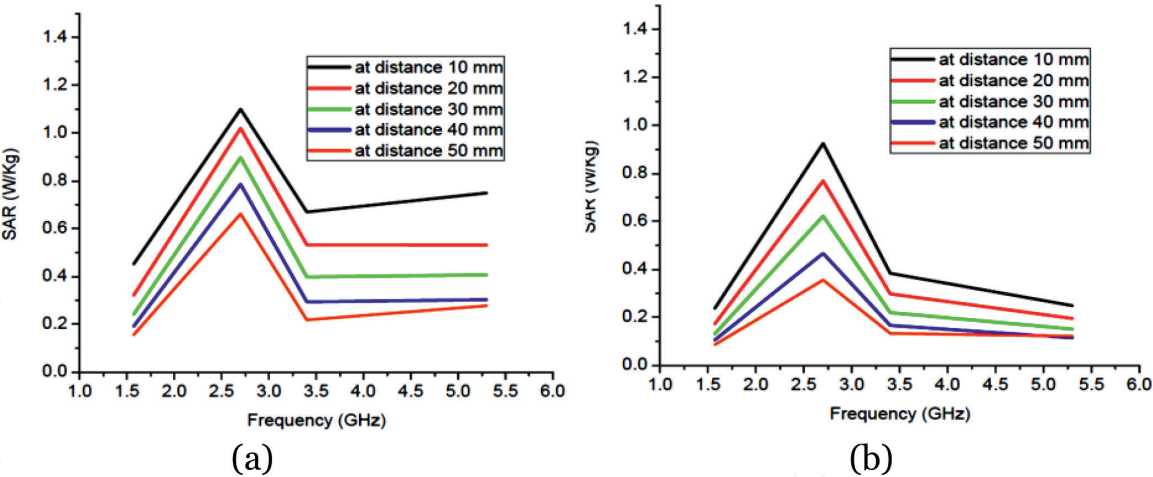


Figure 13.
Maximum SAR values by two standard: (a) FCC, and (b) ICNIRP.

| Resonance frequency (GHz) | SAR (W/kg) | |
|---------------------------|------------|-------|
| | 1 g | 10 g |
| 1.57 | 0.452 | 0.237 |
| 2.7 | 1.02 | 0.925 |
| 3.4 | 0.67 | 0.384 |
| 5.3 | 0.75 | 0.249 |

Table 2.
Max. SAR values for the proposed antenna with spiral cell.

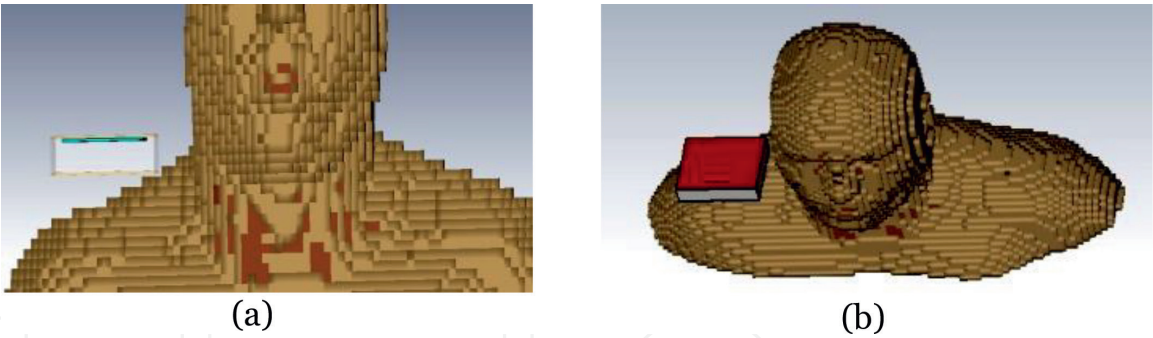


Figure 14.
The simulated life jacket attached to the proposed antenna with voxel model: (a) front and (b) top views.

| Layer type | Rubber | Air |
|--------------------------------------|--------|-------|
| Layer thickness (mm) | 1.9 | 20 |
| Dielectric constant (ϵ_r) | 3 | 1 |
| Tangent loss (σ) | 0.0025 | 0.002 |

Table 3.
Dimensions of simulated life jacket with some electrical characteristics.

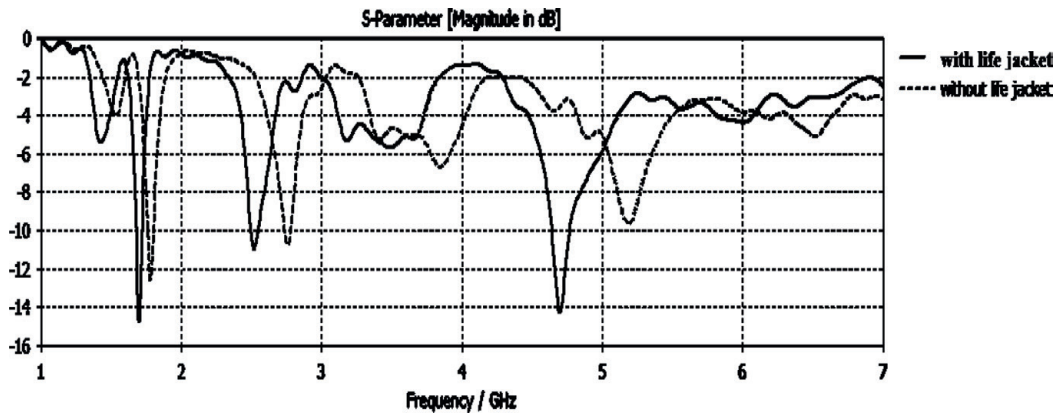


Figure 15.
Simulated S_{11} for the presented antenna with/without life jacket.

| Resonance frequency (GHz) | Gain (dB) | Efficiency (%) |
|---------------------------|-----------|----------------|
| 1.57 | 1.11 | 67.3 |
| 2.7 | 2.89 | 51.2 |
| 3.4 | 1.65 | 62.3 |
| 5.3 | 2.42 | 63.4 |

Table 4.
The simulation results of the proposed antenna with life jacket.

The simulated S_{11} for the presented wearable fractal antenna with and without the floating life jacket are shown in **Figure 15**. Furthermore, the simulated performance results for the intended antenna with the simulated floating life jacket are shown in **Table 4**.

By using the floating life jacket is as an isolation cover for the presented antenna, the SAR value is also improved as shown in **Figure 16**. The SAR simulation results are shown in **Table 5**.

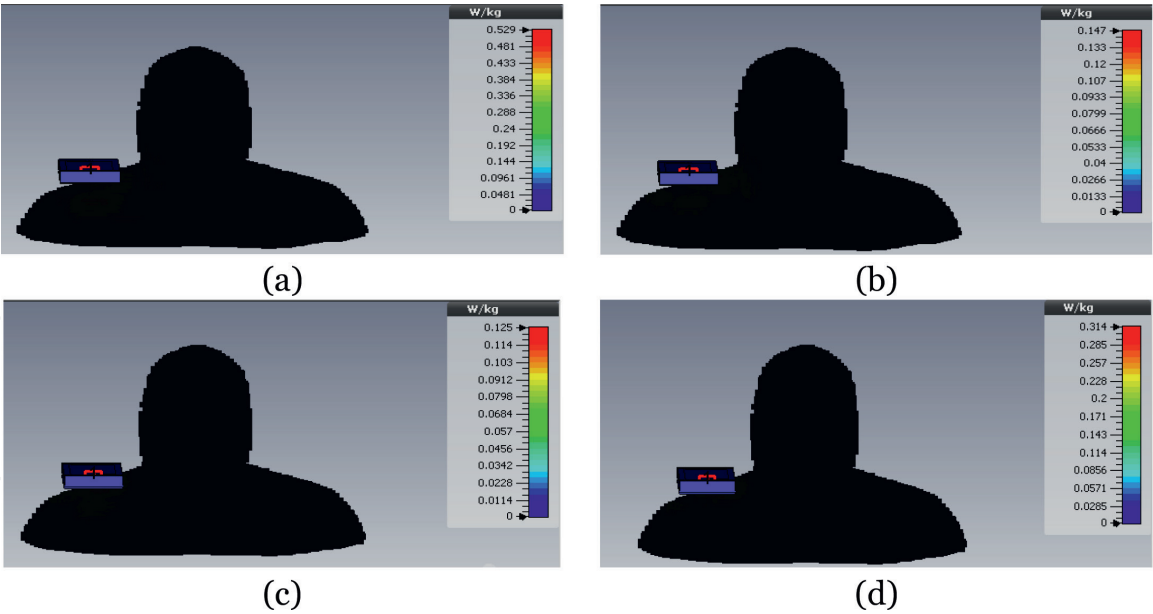


Figure 16.
SAR with life jacket at (a) 1.57, (b) 2.7, (c) 3.4, (d) 5.3 GHz.

| Resonance frequency (GHz) | SAR (W/kg) | |
|---------------------------|------------|-------|
| | 1 g | 10 g |
| 1.57 | 0.232 | 0.125 |
| 2.7 | 0.607 | 0.314 |
| 3.4 | 0.632 | 0.529 |
| 5.3 | 0.347 | 0.147 |

Table 5.
Max. SAR values for the proposed antenna with the life jacket.

3. Sierpinski carpet wearable fractal antenna

The construction of Sierpinski carpet fractal antenna is more simple and easy to design. The zeroth iteration, the base shape is a square. In the base shape, the central square is removed to obtain the first iteration. In first iteration geometry, eight squares are left to design the second iteration. This procedure is repeated to obtain next iterations [24]. Furthermore, this antenna is a wearable or body-worn antenna which used Jeans textile as a substrate. Two methods for measuring the dielectric constant (ϵ_r) and loss tangent ($\tan\delta$) of the Jeans material were presented in this chapter: a microstrip ring resonator method [25, 26] as shown in **Figure 17** and DAK (Dielectric Assessment Kit) method [27]. The results for the two methods are tabulated in **Table 6**. Therefore, use the second method to confirm the results that were selected by using the first one. Also, the thickness of the jeans textile is 0.6 mm which measured by using screw gauge.

3.1 Fractal wearable antenna design

Figure 18 represents the geometries of the initial, first and second iterations of the Sierpinski carpet fractal wearable microstrip antenna. The optimized dimensions of the presented three antennas are indicated in **Table 7**.

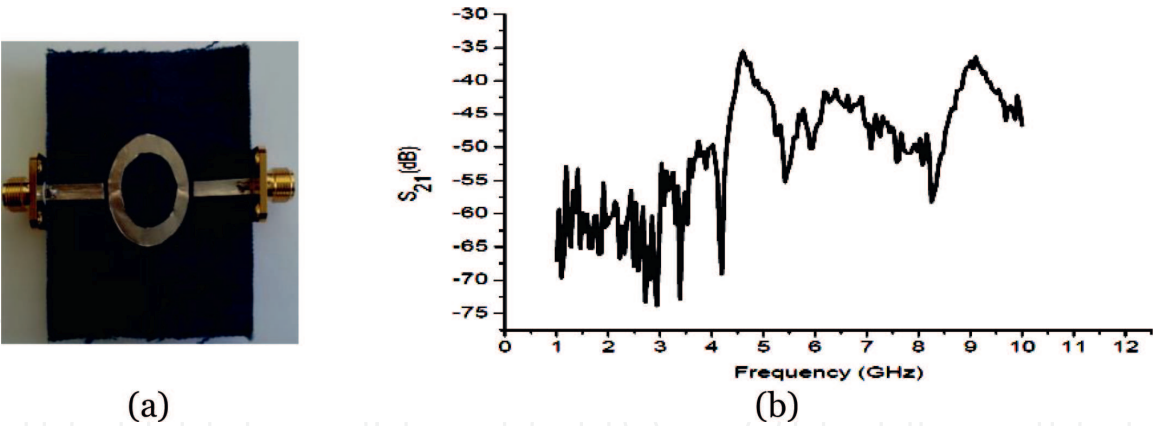


Figure 17.
(a) The fabricated ring resonator model, and (b) measured S_{21} .

| Material | The microstrip ring resonator method | | | | |
|--|--------------------------------------|---------------------------|---------------|--------------------------------------|-------------------------------|
| Dry jeans | Mode | Resonance frequency (GHz) | S_{21} (dB) | Dielectric constant (ϵ_r) | Loss tangent ($\tan\delta$) |
| | n = 1 | 4.26 | -35.5 | 1.73 | 0.077 |
| | n = 2 | 8.89 | -36.9 | 1.69 | 0.073 |
| Dielectric assessment kit method (DAK) | | | | | |
| Dielectric constant (ϵ_r) | | | | Loss tangent ($\tan\delta$) | |
| 1.78 | | | | 0.085 | |

Table 6.
Results of the two methods for characterization of jeans textile.

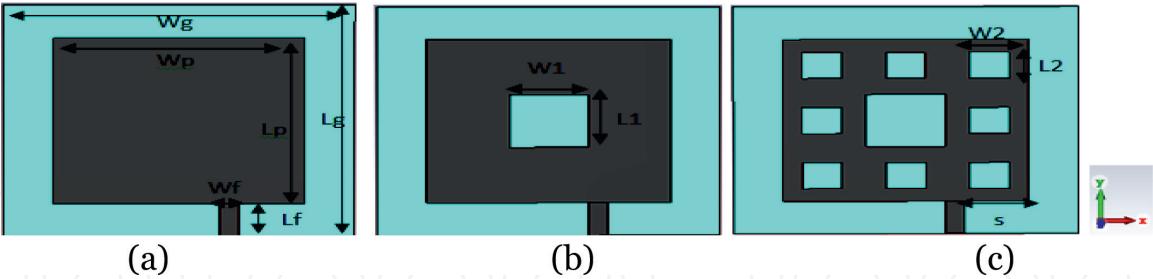


Figure 18.
Fractal antenna structures: (a) initial, (b) 1st, (c) 2nd iterations.

The fabricated geometry of the 2nd iterations Sierpinski carpet fractal wearable microstrip antenna is shown in **Figure 19a**. The simulated and measured S_{11} for the three iterations antennas are shown in **Figure 19b**. Furthermore, the radiation patterns of the proposed fractal antenna in E-plane ($\Phi = 0^\circ$) and H-plane ($\Phi = 90^\circ$) are simulated and plotted in **Figure 20**. From **Figure 19**, Consistent results are

| | Wg | Lg | Wp | Lp | Wf | Lf | L1 | W1 | L2 | W2 | s |
|------------|----|----|----|----|----|----|----|----|----|----|----|
| Value (mm) | 70 | 70 | 50 | 50 | 4 | 10 | 16 | 16 | 8 | 8 | 13 |

Table 7.
The optimized dimensions of three iterations antenna.

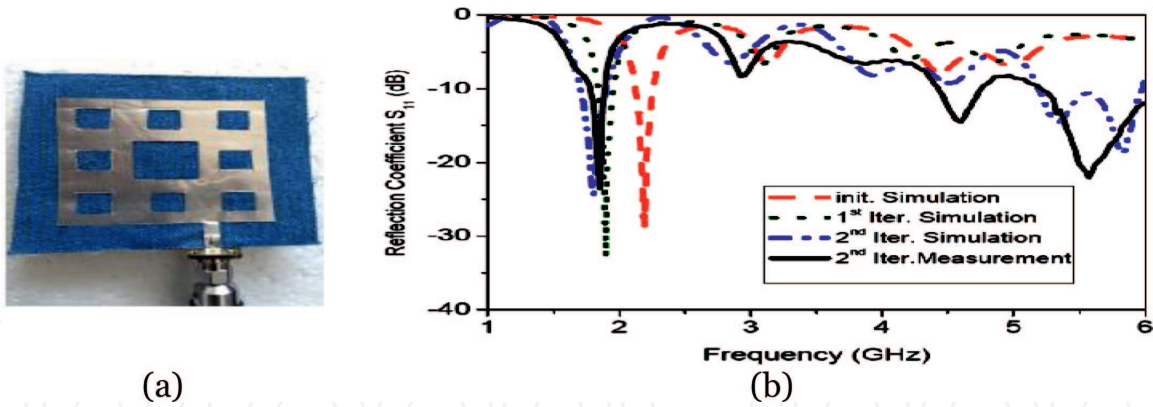


Figure 19. Proposed fractal antenna structures: initial, 1st, and 2nd iterations.

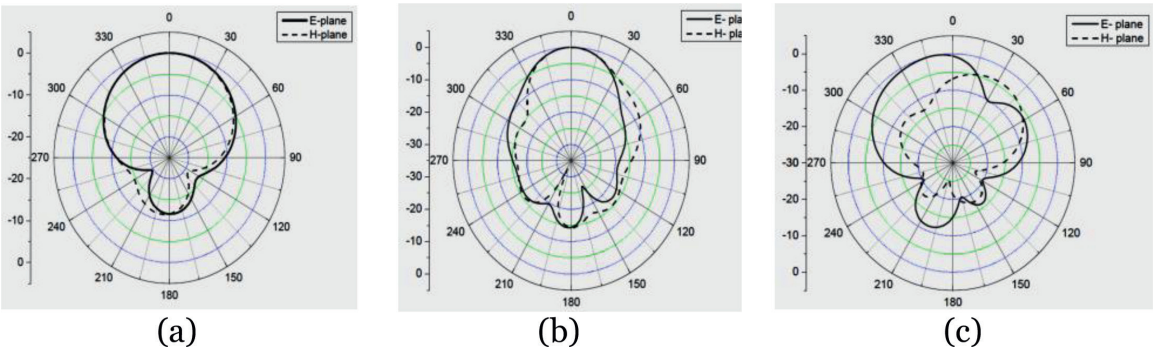


Figure 20. Radiation pattern in E-plane, H-plane at: (a) 1.7, (b) 5.3, (c) 5.8 GHz.

| Resonant Frequency (GHz) | S11 (dB) | Gain (dB) | Efficiency % |
|--------------------------|----------|-----------|--------------|
| 1.7 | -24.719 | 4.5 | 72.6 |
| 5.3 | -14.778 | 1.78 | 52.3 |
| 5.8 | -19.937 | 4.4 | 67.4 |

Table 8. Performance simulated results of proposed fractal antenna.

measured with simulation results. Further, the proposed 2nd iteration Sierpinski carpet fractal wearable microstrip antenna can be used as a multiband antenna. This antenna is operated at three frequency bands in the same time for modern wireless applications as GPS, WiMax and WiFi. The simulation performance results are tabulated in **Table 8**.

4. Crown rectangular wearable fractal (CRWF) antenna

The third wearable fractal antenna designed in this chapter is based on the rectangular shape and is called CRWF antenna. The base geometry construction as, zeroth iteration is a rectangle. The first iteration geometry is obtained by cutting an ellipse from the base shape and then inserting a rectangle such that the corners of the inserted rectangle touch the boundary of elliptical slot. The same procedure is repeated for the inner rectangle of first iteration geometry to obtain the second iteration geometry. The further iterations can be obtained [28].

4.1 Fractal wearable antenna design

Figure 21 represents the geometries of the initial, 1st and 2nd iterations of the crown rectangular fractal wearable microstrip antenna. The optimized dimensions of the presented three antennas are indicated in **Table 9**. This antenna is also pasted on Jeans material as a substrate. Also, the simulated S11 for the three iterations antennas are shown in **Figure 22**. In addition, the radiation patterns of the proposed antenna in E-plane ($\Phi = 0^\circ$) and H-plane ($\Phi = 90^\circ$) are simulated and plotted in **Figure 22**.

From **Figure 22**, the proposed 2nd iteration crown rectangular fractal wearable microstrip antenna can be used as a multiband antenna. This antenna is operated at three frequency bands in the same time with different application as WiMax, WiFi for modern wireless applications and the third frequency band may be used for fixed satellite (earth-space) applications. Also, note the great affinity between the first and second iterations (**Figure 23**). The simulation performance results are mentioned in **Table 10**.

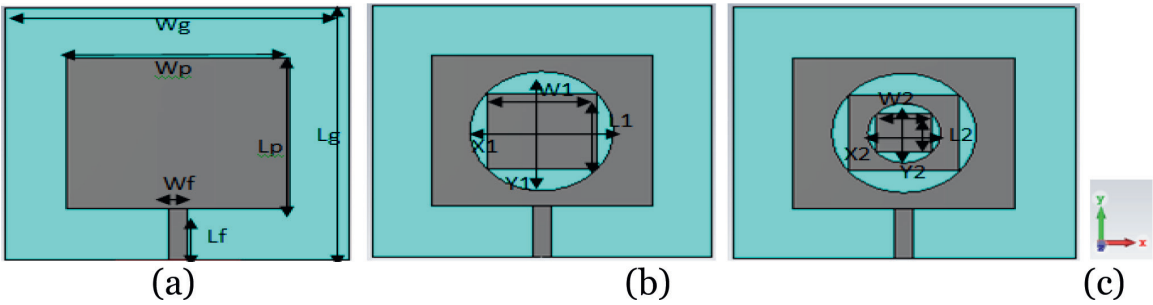


Figure 21.
Proposed fractal antenna structures: initial, 1st, and 2nd iterations.

| Wg | Lg | Wp | Lp | Wf | Lf | L1 | W1 | L2 | W2 | X1 | Y1 | X2 | Y2 |
|----|----|----|----|----|----|----|------|-----|------|----|-------|----|-----|
| 57 | 50 | 37 | 30 | 3 | 10 | 15 | 18.5 | 7.5 | 9.25 | 12 | 11.85 | 6 | 5.9 |

Table 9.
The optimized dimensions of three iterations antenna.

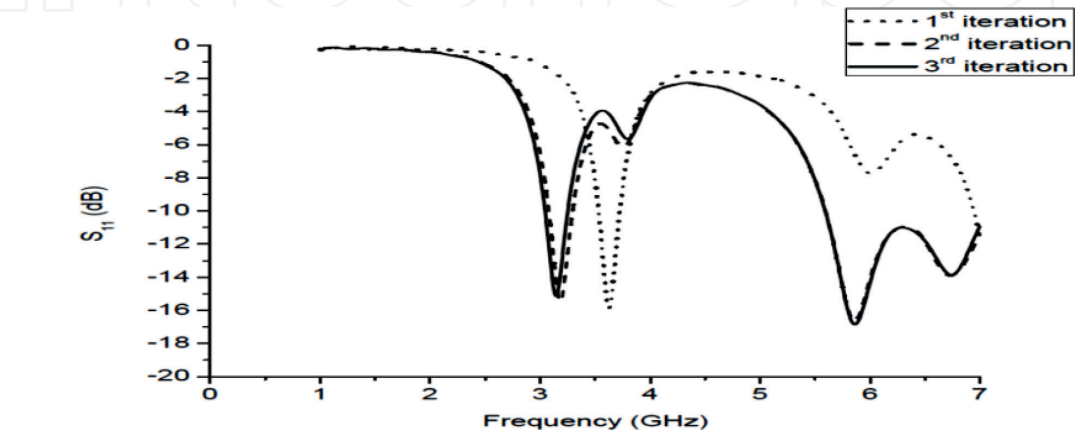


Figure 22.
The S11 for the three antennas: initial, 1st, and 2nd iterations.

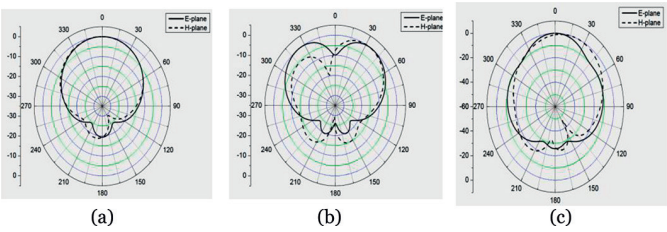


Figure 23.
Radiation pattern in E-plane, H-plane at: (a) 3.3, (b) 5.8, and (c) 6.7 GHz.

| Resonant Frequency (GHz) | S11 (dB) | Gain (dB) | Efficiency % | Applications |
|--------------------------|----------|-----------|--------------|--------------|
| 3.3 | -15.19 | 3.4 | 64.7 | WiMax |
| 5.8 | -16.797 | 3.5 | 65.2 | WiFi |
| 6.7 | -13.85 | 3.44 | 64.9 | Satellite |

Table 10.
The simulated performance results of the proposed fractal antenna.

5. Conclusion

This chapter focuses on the design and fabrication of different three types wear-able fractal for modern wireless applications with body-area-networks.

A 3rd iteration fractal wearable antenna is designed and fabricated. This antenna is designed to be suitable for GPS, WiMax and WiFi (Bluetooth) applications at the same time. The presented antenna is a body-worn antenna to be attached with the human body. Therefore, the specific absorption ratio (SAR) plays a vital role in the design of this body-worn antenna. So that, the SAR value should be calculated and also improved. Another design is presented and also fabricated to improve the SAR value. The intended fractal antenna is attached with a spiral MTM cell etched in the ground plane. This spiral is used to minimize the SAR value by reducing the energy absorbed by the human body tissue. Finally, this design is integrated onto a floating life jacket. This smart jacket can be used for finding the human body if an accident happens.

A 2nd iteration Sierpinski carpet wearable antenna was designed and fabricated. This antenna was pasted on Jeans textile material as substrate. Two methods for measuring the dielectric constant (ϵ_r) and loss tangent ($\tan\delta$) of the Jeans material were presented in this chapter: a microstrip ring resonator method and DAK method. This antenna was operated at three resonance frequencies which were suitable for GPS, WiFi, and WiMax application.

A crown rectangular wearable fractal antenna was designed and fabricated. The proposed antenna was a 2nd iteration fractal antenna to operate at three resonance frequencies which were suitable for WiFi and WiMax applications over BAN-network and also might be used for satellite applications.

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Author details

Mohamed I. Ahmed^{1*} and Mai F. Ahmed²

1 Microstrip Department, Electronics Research Institute, Giza, Egypt

2 Department of Electrical and Electronics Engineering, Faculty of Engineering,
Zagazig University, Zagazig, Egypt

*Address all correspondence to: miahmed@eri.sci.eg

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References

- [1] Dumanli S, Sayer L, Mellios E, Fafoutis X, Hilton G, Craddock I. Off-body antenna wireless performance evaluation in a residential environment. *IEEE Transactions on Antennas and Propagation*. 2017
- [2] Salonen P, Jaehoon K, Rahmat-Samii Y. Dual-band E-shaped patch wearable textile antenna. In: *Proceedings of the IEEE International Symposium on the Antennas and Propagation Society*; 2005
- [3] Salonen P. Dual-band wearable textile antenna. *International Symposium on the IEEE Antennas and Propagation Society*. 2004;1:463-466
- [4] Tanaka M, Jang JH. Wearable microstrip antenna. *International Symposium on the IEEE Antennas and Propagation Society*; Columbus, OH. 2003;2:704-707
- [5] Crownver RM. *Introduction to Fractals and Chaos*. London, England: Jones and Bartlett Publishers; 1995
- [6] Gianvittorio JP, Rahmat-Samii Y. Fractal antennas: A novel antenna miniaturization technique, and applications. *IEEE Antennas and Propagation Magazine*. January 2002;44(1):20-36
- [7] Famolari D, Agrawal P. Architecture and performance of an embedded IP bluetooth personal area network. In: *IEEE International Conference on Personal Wireless Communications*. 2000. pp. 75-79
- [8] Vallozzi L, Torre PV, Hertleer C, Rogier H. A textile antenna for off-body communication integrated into protective clothing for fire fighters. *IEEE Transactions on Antennas and Propagation*. April 2009;57(4):919-925
- [9] Koski K, Vena A, Sydanheimo L, Ukkonen L, Rahmat-Samii Y. Design and implementation of electro-textile ground planes for wearable UHF RFID patch tag antennas. *IEEE Antennas and Wireless Propagation Letters*. 2013;964-967
- [10] Arya S, Khan S, Shan CK, Lehana P. Design of a microstrip patch antenna for mobile wireless communication systems. *Journal of Computational Intelligence and Electronic Systems*. 2013;1(2):1-5
- [11] Milligan TA. *Modern Antenna Design*. 2nd ed. John Wiley & Sons, Inc.; 2005
- [12] Zainud-Deen SH, Malhat H, Awadalla KH. *Radio frequency identification antennas: Design and applications [PhD dissertation]*. Department of Electronics and Electrical Communications Engineering; 2011
- [13] Sunohara T, Laakso I, Hirata A, Onishi T. Induced field and SAR in human body model due to wireless power transfer system with induction coupling. *IEEE Electromagnetic Compatibility*. 2014;5:40-48
- [14] Hirata A, Fujiwara O, Nagaoka T, Watanabe S. Estimation of whole-body average SAR in human models due to plane-wave exposure at resonance frequency. *IEEE Transactions on Electromagnetic Compatibility*. 2010;52:41-48
- [15] Zhao K, Zhang S, Ying Z, Bolin T, He S. SAR study of different MIMO antenna designs for LTE application in smart mobile handsets. *IEEE Transactions on Antennas and Propagation*. June 2013;61(6):3270-3279

- [16] Tateno A, Tanaka K, Nagaoka T, Watanabe S, Saito K, Takahashi M, et al. Comparison of SAR in human body radiated from mobile phone and tablet computer. In: International Symposium on Electromagnetic Compatibility, vol. 6; Tokyo. 2014. pp. 55-59
- [17] Nagaoka T, Watanabe S. Large-scale calculation of the specific absorption rate in a human body exposed to RF-EMFs by GPU cluster system. In: International Symposium on Electromagnetic Compatibility, vol. 3. 2013. pp. 110-116
- [18] Kivekäs O, Ollikainen J, Lehtiniemi T, Vainikainen P. Bandwidth, SAR, and efficiency of internal mobile phone antennas. *IEEE Transactions on Electromagnetic Compatibility*. February 2004;**46**(1)
- [19] Hadjem A, Conil E, Gati A, Wong MF, Wiart J. Analysis of power absorbed by children's head as a result of new usages of mobile phone. *IEEE Transactions on Electromagnetic Compatibility*. Nov. 2011;**52**(4):812-819
- [20] Tanaka M, Jang JH. Wearable microstrip antenna. In: IEEE APS International Symposium and URSI North American Radio Science Meeting; Columbus, OH, USA; vol. 5. June 2003. pp. 41-48
- [21] "<http://www.antenna-theory.com/antennas/wearable-antennas.php>"
- [22] Ismail M, Elsadek H, Abdallah EA, Ammar AA. New configurations of planar fractal microstrip antenna. In: IEEE International Symposium on Antennas and Propagation; San Diego, California. July 2008
- [23] Serra AA, Nepa P, Manara G. A wearable two-antenna system on a life jacket for Cospas-Sarsat personal locator beacons. *IEEE Transactions on Antennas and Propagation*. February 2012;**60**(2):1035-1042
- [24] Yadav AN, Chawhan R, Singhal DPK, Tiwari KA. Simulation of Sierpinski carpet fractal antenna. *Telecommunications*. May 2011;**8**
- [25] Hopkins R, Free C. Equivalent circuit for the microstrip ring resonator suitable for broadband materials characterisation. *IET Microwaves, Antennas & Propagation*. February 2008;**2**(1):66-73
- [26] Rashidian A, Aligodarz MT, Klymyshyn DM. Dielectric characterization of materials using a modified microstrip ring resonator technique. *IEEE Transactions on Dielectrics and Electrical Insulation*. Aug. 2012;**19**(4)
- [27] www.speag.com/products/dak/dielectric-measurements/
- [28] Mehak S, Rana SB, Bhomia Y. Design of a combined crown and Sierpinski fractal antenna. *International Journal of Electronics & Communication Technology*. Sept 2016;**7**