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Chapter

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 ease 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].
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 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 ($\varepsilon_r$), resonant frequency ($f_0$), 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 $\varepsilon_r = 4.4$ and $\tan(\delta) = 0.02$.

The inset fed line of the proposed antenna is consisted of two sections: 50 $\Omega$ stripline and tapered line for achieving the 50 $\Omega$ 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]:

$$L_m^m = 2L_{m+1}^m + W_{1m+1}^m + 2W_{2m+1}^m$$

(14).

Where: $m$ is the order of iteration, $W_{1m+1}^m = c_1L_m^m$; is the width of the middle segment, and $W_{2m+1}^m = c_2L_m^m$; 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.
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

**Table 1. Strip-Line Dimensions.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>W1</th>
<th>L1</th>
<th>W2</th>
<th>L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (mm)</td>
<td>3</td>
<td>18.4</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>

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

Figure 6. The geometry of spiral cell.

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

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 \(-9.67 \, \text{dB}\) 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 8. 
Radiation pattern in E-plane at (a) 1.57, (b) 2.7, (c) 3.4 (d) 5.3 GHz.

Figure 9. 
Radiation pattern in H-plane at (a) 1.57, (b) 2.7, (c) 3.4 and (d) 5.3 GHz.
and 67.45%. The forth band with return loss $-8.56 \, \text{dB}$ 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.](image)

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

<table>
<thead>
<tr>
<th>Resonance frequency (GHz)</th>
<th>SAR (W/kg) 1 g</th>
<th>SAR (W/kg) 10 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.57</td>
<td>0.452</td>
<td>0.237</td>
</tr>
<tr>
<td>2.7</td>
<td>1.02</td>
<td>0.925</td>
</tr>
<tr>
<td>3.4</td>
<td>0.67</td>
<td>0.384</td>
</tr>
<tr>
<td>5.3</td>
<td>0.75</td>
<td>0.249</td>
</tr>
</tbody>
</table>

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

---

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

<table>
<thead>
<tr>
<th>Layer type</th>
<th>Rubber</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer thickness (mm)</td>
<td>1.9</td>
<td>20</td>
</tr>
<tr>
<td>Dielectric constant ($\varepsilon$)</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Tangent loss ($\sigma$)</td>
<td>0.0025</td>
<td>0.002</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Resonance frequency (GHz)</th>
<th>Gain (dB)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.57</td>
<td>1.11</td>
<td>67.3</td>
</tr>
<tr>
<td>2.7</td>
<td>2.89</td>
<td>51.2</td>
</tr>
<tr>
<td>3.4</td>
<td>1.65</td>
<td>62.3</td>
</tr>
<tr>
<td>5.3</td>
<td>2.42</td>
<td>63.4</td>
</tr>
</tbody>
</table>
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 ($\varepsilon_r$) and loss tangent (tanδ) 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.
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

<table>
<thead>
<tr>
<th>Material</th>
<th>The microstrip ring resonator method</th>
<th>Resonance frequency (GHz)</th>
<th>$S_{21}$ (dB)</th>
<th>Dielectric constant ($\varepsilon_r$)</th>
<th>Loss tangent (tan$\delta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry jeans</td>
<td>Mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n = 1</td>
<td></td>
<td>4.26</td>
<td>−35.5</td>
<td>1.73</td>
<td>0.077</td>
</tr>
<tr>
<td>n = 2</td>
<td></td>
<td>8.89</td>
<td>−36.9</td>
<td>1.69</td>
<td>0.073</td>
</tr>
<tr>
<td>Dielectric assessment kit method (DAK)</td>
<td>Dielectric constant ($\varepsilon_r$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loss tangent (tan$\delta$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.78</td>
<td></td>
<td></td>
<td></td>
<td>0.085</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Wg</th>
<th>Lg</th>
<th>Wp</th>
<th>Lp</th>
<th>Wf</th>
<th>Lf</th>
<th>L1</th>
<th>W1</th>
<th>L2</th>
<th>W2</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>70</td>
<td>50</td>
<td>50</td>
<td>4</td>
<td>10</td>
<td>16</td>
<td>16</td>
<td>8</td>
<td>8</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 7.
The optimized dimensions of three iterations antenna.
Fractal Analysis

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.

<table>
<thead>
<tr>
<th>Resonant Frequency (GHz)</th>
<th>S11 (dB)</th>
<th>Gain (dB)</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>−24.719</td>
<td>4.5</td>
<td>72.6</td>
</tr>
<tr>
<td>5.3</td>
<td>−14.778</td>
<td>1.78</td>
<td>52.3</td>
</tr>
<tr>
<td>5.8</td>
<td>−19.937</td>
<td>4.4</td>
<td>67.4</td>
</tr>
</tbody>
</table>

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].
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4.1 Fractal wearable antenna design

Figure 21 represents the geometries of the initial, 1\textsuperscript{st} and 2\textsuperscript{nd} 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 2\textsuperscript{nd} 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, 1\textsuperscript{st}, and 2\textsuperscript{nd} iterations.

<table>
<thead>
<tr>
<th>(W_g)</th>
<th>(L_g)</th>
<th>(W_p)</th>
<th>(L_p)</th>
<th>(W_f)</th>
<th>(L_f)</th>
<th>(L_1)</th>
<th>(W_1)</th>
<th>(L_2)</th>
<th>(W_2)</th>
<th>(X_1)</th>
<th>(Y_1)</th>
<th>(X_2)</th>
<th>(Y_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>50</td>
<td>37</td>
<td>30</td>
<td>3</td>
<td>10</td>
<td>15</td>
<td>18.5</td>
<td>75</td>
<td>9.25</td>
<td>12</td>
<td>11.85</td>
<td>6</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Table 9. The optimized dimensions of three iterations antenna.

Figure 22. The S11 for the three antennas: initial, 1\textsuperscript{st}, and 2\textsuperscript{nd} iterations.
This chapter focuses on the design and fabrication of different three types wearable fractals 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 ($\varepsilon_r$) 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.

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

<table>
<thead>
<tr>
<th>Resonant Frequency (GHz)</th>
<th>S11 (dB)</th>
<th>Gain (dB)</th>
<th>Efficiency %</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>-15.19</td>
<td>3.4</td>
<td>64.7</td>
<td>WiMax</td>
</tr>
<tr>
<td>5.8</td>
<td>-16.797</td>
<td>3.5</td>
<td>65.2</td>
<td>WiFi</td>
</tr>
<tr>
<td>6.7</td>
<td>-13.85</td>
<td>3.44</td>
<td>64.9</td>
<td>Satellite</td>
</tr>
</tbody>
</table>

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


