Wunderlich Fractal-based Printed Dual-band Dipole Antenna for Wearable RFID Applications

Ghufran M Hatem, Technical College, Najaf, Iraq
Ali J. Salim, Department of Electrical Engineering, University of Technology, Iraq
Jawad K. Ali, Department of Electrical Engineering, University of Technology, Iraq
Hussam Alsaedi, Centre of Intelligent Antenna and Radio Systems Department of Electrical and Computer Engineering, University of Waterloo (UW), Waterloo, Ontario, Canada
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Ghufran M. Hatem(1), Ali J. Salim(1), Jawad K. Ali(1) and Hussam Al-Saedi(1,2)

(1) Microwave Research Group, Department of Electrical Engineering, University of Technology, Iraq
(2) Centre of Intelligent Antenna and Radio Systems Department of Electrical and Computer Engineering, University of Waterloo (UW), Waterloo, Canada

Abstract- Recent challenges, imposed on the wearable textiles antennas, have made the designers seeking for antenna structures that are multiband and with a compact size. In this report, a compact dual-band printed dipole antenna has been presented as a candidate for use in wearable radio frequency identification RFID applications. The structure of the proposed dipole antenna takes the shape of the second order Wunderlich fractal topology. This fractal topology provides suitable and attractive shape; for security applications, the resulting antenna can be hidden in the cloth. The CST Microwave Studio is used to model, simulate, and evaluate the performance of the proposed antenna. The resulting antenna offers a compact size and dual narrow band resonant behaviour. The proposed antenna is designed to operate at center frequencies of 0.952 GHz and 2.66 GHz; covering dual bands of 0.973–1.013 GHz and 2.68–2.70 GHz respectively. These bands make the antenna suitable for dual-band RFID applications. Apart from the compact size and the dual-band response, results also show that the antenna presents acceptable radiation characteristics with reasonable peak gains throughout the two bands.

1. INTRODUCTION
The design of antennas for wearable RFID has shown ever increasing applications in many fields such as military, medicine, sports, and tracking. Extensive research has been carried out to design antennas for these applications. Designers have encountered additional challenges in that the wearable antennas should be with compact size and with multiband or dual-band responses. In this respect, the unique properties of fractal geometries have made them popular in the design of compact dual-band and multiband printed and microstrip antenna design for the various aspects of communication applications [1-6]. Furthermore, the fractal shapes are characterized by attractive shapes that can be easily embedded in the clothes for security applications. In this context, Koch and Sierpinski curves and their variants represent the most fractal geometries adopted in the design of wearable RFID applications reported in the literature [7-10]. A triple-band dipole antenna based on the first iteration Koch geometry has been proposed to design a textile antenna for wearable ISM applications. The indentation angle of the proposed fractal structure is varied to three different values of 30, 45 and 60 degrees respectively [7,8]. Dipole and loop antennas based on the 3rd iteration Koch curves have been proposed in [9] to design compact size UHF RFID Tags. Sierpinski fractals and their variants have been reported in [9-11] to design compact dipole and loop antennas for wearable RFID applications. The design of a dual-band wearable fractal-based monopole patch antenna integrated with an electromagnetic band-gap (EBG) structure. The prototype covers the GSM-1800 MHz and ISM-2.45 GHz bands [12].
In this paper, the Wunderlich fractal geometry has been applied to the conventional dipole antenna to produce a dual-band antenna for wearable RFID applications. The 2nd iteration Wunderlich fractal geometry will constitute the two arms of the printed dipole antenna structures.

2. THE PROPOSED FILTER CONFIGURATION

The steps of growth of the Wunderlich fractal geometry, up to the third iteration, are shown in Figure 1.

![Figure 1: The steps of growth of the Wunderlich fractal geometry, up to the third iteration.](image)

The proposed wearable printed antenna is based on second iteration Wunderlich fractal geometry. Figure 2 depicts the layout of this antenna with respect to the coordinate system. The antenna is supposed to be printed on Roger RT/Duroid 5880 substrate with dimensions of $W_s \times L_s$ and a relative dielectric constant of 2.2 and a thickness of 3.175 mm. These dimensions have been used for all the consequent antennas presented with different substrate materials in this section. This type of a dielectric material is adopted for modeling purposes as it is not suitable for wearable antenna applications because it is solid and difficult to be attached to clothes. Modeling and performance evaluation of the proposed antenna have been carried out using the commercial Finite Integration Technique (FIT) based EM simulator, CST Microwave Studio (CST MWS) [13]. The modeled antenna is excited using a 50 Ohm probe feed. By an appropriate dimension scaling, it seems that the modeled antenna offers a multiband response. Table 1 summarizes the dimensions of the modeled antenna.

![Figure 2: The layout of the modeled 2nd iteration antenna with respect to the coordinate system.](image)

<p>| Table 1: Summary of the modeled antenna dimensions |</p>
<table>
<thead>
<tr>
<th>Antenna Components</th>
<th>Symbols and their values of the proposed antenna in (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>( w = 116.35, \ l = 55.46, \ h = 3.175 )</td>
</tr>
<tr>
<td>Radiator</td>
<td>( W_s = 102.76, \ L_s = 85.5 )</td>
</tr>
</tbody>
</table>

3. PERFORMANCE EVALUATION OF THE MODELED ANTENNA

The antenna, with the layout depicted in Figure 2, has been modeled with prescribed substrate. Simulation results reveal that the antenna offers a triple-band resonance within the sweep frequency of (0–3) GHz. The resonant frequencies are at about 1.312 GHz, 2.0 GHz, and 2.28 GHz as shown in Figure 3. This does not prevent the possibility of the existence of other resonances outside this range. Table 2 shows the bandwidth of the proposed antenna for triple bands.

![Graph.png](attachment:Graph.png)

Figure 3: Simulated input reflection coefficient response of the dipole antenna depicted in Figure 2.

<table>
<thead>
<tr>
<th>Resonant frequency (GHz)</th>
<th>Bandwidth range (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.321</td>
<td>(1.2986-1.3274)</td>
</tr>
<tr>
<td>2</td>
<td>(1.9806-2.0283)</td>
</tr>
<tr>
<td>2.278</td>
<td>(2.2671-2.2866)</td>
</tr>
</tbody>
</table>

It is clear that the modeled antenna does not satisfy frequency ranges for RFID applications as reported in [14]. An attempt has been carried out to fill the gaps in the previous design according to the current distribution path to make antenna match with RFID range.
Figure 4: Simulated current distributions on the surface of the resulting triple band antenna at (a) 1.321 GHz, (b) 2GHz, and (c) 2.278GHz.

The current distributions at the surface of the modeled antenna, at the three resonant frequencies, have been shown in Figure 4. Furthermore, the proper selection of the feed location to matching with IC and the value of the chip impedance will result in the required antenna performance. Carrying out these steps, the proposed Wunderlich dipole antenna will be as shown in Figure 5.

Figure 5: The layout of the modified fractal-based antenna with matching IC.

The antenna with the layout depicted in Figure 5 has been modeled. A parametric study of the effect of the capacitor value of IC on the antenna input reflection coefficient response is shown in Figure 6, corresponding to a capacitor value variation from 0.1–0.9 pF in steps of 0.2 pF. The results imply that the antenna satisfies the
requirement of RFID applications when \( C = 0.9 \) pF. The antenna offers a dual-band response with resonances at 0.952 GHz and 2.5 GHz.

Figure 6: Simulated input reflection coefficient response of the resulting 2nd iteration Wunderlich curve antenna with different capacitor values.

A parametric study of the effect of the different values of substrate thickness on the antenna performance is shown in Figure 7. The results show that when the substrate thickness increased, the antenna offered a slight effect on the position of the lower resonant band while the position of the upper resonant band is shifted down as the responses in Figure 7 imply.

Figure 7: Simulated input reflection coefficient response of the resulting 2nd iteration Wunderlich antenna with different substrate thickness.

To get more insight into the EM characteristics of the proposed antenna, the current distributions generated at the surface of the modeled antenna have been simulated at 0.952 GHz and 2.5 GHz, as shown in Figure 8. The results of Figure 8 (a) implies that the resonance at 0.952 GHz is attributed to the longer surface current path as
compared with that at 2.5 GHz, as shown in Figure 8(b).

Figure 8: Simulated current distributions on the surface of the resulting dual-band antenna at (a) 0.952 GHz, (b) 2.5 GHz.

Figure 9 shows the simulated antenna far-field radiation patterns for the total electric field in the XY-plane, the XZ-plane, and the YZ-plane at the center frequencies of the two resonant bands.

Figure 9(a) depicts the radiation patterns at 0.952 GHz, in the XY-plane ($\theta=90^\circ$). The main lobe magnitude is 14.8 dB V/m; the main lobe direction is $90^\circ$, the angular width (3 dB) is $95.7^\circ$. In the XZ-plane ($\Phi=0^\circ$) the main
lobes magnitude is (14.8) dB V/m, and the main lobe direction is 90°. Whereas in the YZ- plane (Φ=90°), the main lobe magnitude is 14.2 dB V/m, the main lobe direction is 180°, and the angular width (3 dB) is 89.8°. On the other hand, Figure 9(b) demonstrates the radiation patterns at 2.5 GHz. In the XY- plane (θ=90°), the main lobe magnitude is 16.5 dB V/m, the main lobe direction is 213°, and the angular width (3 dB) is 155.8°. In the XZ- plane (Φ=0°), the main lobe magnitude is 15 dB V/m, the main lobe direction is 110°, and the angular width (3 dB) is 126.1°.

As far as the radiation properties are concerned, Figure 10 shows the simulated three-dimensional directivity radiation patterns of the resulting antenna. The directivity at 0.952 GHz, the center frequency of lower band, is of about 2.202 dBi as shown in Figure 10(a), whereas the directivity at 2.5 GHz, the center frequency of upper band, is of about 2.113 dBi as shown in Figure 10(b).

![Figure 10: Simulated 3D directivity of the modeled antenna at (a) 0.952 GHz, and (b) 2.5 GHz.](image)

The peak gain values in the two bands have been evaluated, as shown in Figure 11. In the lower frequency band, the peak gain as shown in Figure 11(a) is as large as 1.274 dBi while for the upper band, Figure 11(b), the maximum gain is found to be of about 2.448 dBi.

![Figure 11: Simulated peak gain of the resulting dual-band antenna at (a) 0.952 GHz, and (b) 2.5GHz.](image)

4. WUNDERLICH DIPOLE TAG ANTENNA DESIGN WITH A TEXTILE SUBSTRATE
In the previous section, the design of the 2nd iteration Wunderlich fractal based antenna has been printed on a solid conventional substrate. For wearable applications, the antenna has to be printed on a textile substrate. The antenna geometry is shown in Figure 12, where Figure 12(a) shows the front view of the structure, and Figure 12(b) shows the layout of the antenna with respect to the coordinate system. The proposed antenna is to be printed on material in the form of textile as a substrate with a relative dielectric constant of 1.8 and with thread radius $r = 0.8$ mm.

![Antenna Layout](image)

Figure 12: The layout of the modeled 2nd iteration Wunderlich based textile antenna with coordinate system (a) the front view (b) Perspective view

5. PERFORMANCE EVALUATION OF THE MODELED TEXTILE ANTENNA

The proposed antenna, depicted in Figure 12, has been modeled with prescribed substrate and its performance has been evaluated within frequency sweep range (0-3) GHz. Simulation results reveal that the antenna offers a dual resonant behavior at about 0.952 GHz and 2.7GHz, as shown in Figure 13.
5.1 PARAMETRIC STUDY
A parametric study has been conducted to explore the effect of many elements, such as the capacitor value of IC, the textile thread density, the number of layers, etc... on the simulated antenna responses. In the following subsections, the effects of these parameters will be demonstrated in terms of the simulated input reflection coefficient responses of the modeled antenna.

5.1.1 THE EFFECT OF THE MACHING CAPACITOR
The simulated antenna input reflection coefficient responses for different values of the capacitor value of IC as a parameter, have been presented in Figure 14, within the swept frequency range of 0–3 GHz. The presented responses correspond to capacitor values varied in the range of 0.1–0.9 pF in steps of 0.2 pF. The results imply that the antenna satisfies the requirement of RFID applications when $C=0.9$ pF; the antenna offers a dual-band response at RFID operating frequencies of 0.952 GHz and 2.7 GHz.

5.1.2 THE EFFECT OF THE THREAD DENSITY
The effect of thread density on the performance of the proposed antenna is investigated by sweep thread radius (r) mm variation from (0.5-0.9) mm. The density of the threads within the substrate antenna area decreased as the thread radius was decreased. The antenna with r=0.9 mm has the highest density, and the antenna with r=0.5 has the lowest density. When the radius decreases, the frequency shifted to upper frequency, as shown in Figure 15.

![Figure 15: Simulated input reflection coefficient response for different values of the thread radius.](image)

The suitable result has occurred when the value of radius is high. If the gap between threads has been increased, this causes the reduction in the tag antenna performance. This is because the added air in the textile substrate will modify its permittivity then detuning the antenna and resulting in antenna mismatch.

### 5.1.3 THE EFFECT OF THE OVERLAYS

Figure 16 shows the effect of adding a textile layer on the performance of the proposed antenna. In this study, the number of added layers has been varied from 1–3 layers. The results show that when the number of layers is increased, the lower resonant band will be slightly shifted to the right while at upper resonant band will be shifted down. Table 3 describes the number of layers with antenna resonant frequency.

<table>
<thead>
<tr>
<th>No. of layer</th>
<th>Resonant frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_1$</td>
</tr>
<tr>
<td>1</td>
<td>0.973</td>
</tr>
<tr>
<td>2</td>
<td>0.931</td>
</tr>
<tr>
<td>3</td>
<td>0.945</td>
</tr>
</tbody>
</table>
5.1.4 THE EFFECT OF THE TEXTILE MATERIALS

Figure 17 shows the simulated input reflection coefficient responses of the modeled antenna for various textile material. The results indicate that the lower resonant band positions have been slightly changed as compared with those of the upper resonant bands which are considerably improved according to the textile material types. Table 4 shows the dielectric constants of the examined materials together with the corresponding dual-band resonant frequencies.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \varepsilon_r )</th>
<th>( f_{11} ) (GHz)</th>
<th>( f_{22} ) (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyamide Spacer</td>
<td>1.1</td>
<td>1.029</td>
<td>2.926</td>
</tr>
<tr>
<td>Fleece</td>
<td>1.2</td>
<td>1.022</td>
<td>2.891</td>
</tr>
<tr>
<td>Polycot</td>
<td>1.3</td>
<td>1.015</td>
<td>2.863</td>
</tr>
<tr>
<td>Woolen Cotton</td>
<td>1.45</td>
<td>1.008</td>
<td>2.835</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.54</td>
<td>1</td>
<td>2.807</td>
</tr>
<tr>
<td>Jeans Cotton</td>
<td>1.6</td>
<td>0.994</td>
<td>2.779</td>
</tr>
<tr>
<td>Cotton Twill</td>
<td>1.707</td>
<td>0.987</td>
<td>2.758</td>
</tr>
<tr>
<td>Denim</td>
<td>1.8</td>
<td>0.980</td>
<td>2.73</td>
</tr>
<tr>
<td>Polyester</td>
<td>1.9</td>
<td>0.980</td>
<td>2.709</td>
</tr>
<tr>
<td>PET</td>
<td>2</td>
<td>0.973</td>
<td>2.689</td>
</tr>
</tbody>
</table>
To get more insight into the EM characteristics of the proposed antenna, the current distributions on the surface of the modeled antenna have been simulated at 0.952 and 2.7 GHz, as shown in Figure 18. As the results of Figure 18(a) implies, the resonance at 0.952 GHz is attributed to the longer surface current path as compared with that at 2.7 GHz, as shown in Figure 18(b).

Figure 19 shows the simulated far-field radiation patterns for the total electric field in the XY-plane, the XZ-plane, and the YZ-plane at the center frequencies of the two resonant bands of this antenna. Figure 19(a) demonstrates the radiation patterns at 0.952 GHz. In the XY-plane (θ=90), the main lobe magnitude is 15.5 dB V/m, the main lobe direction is 90, and the angular width (3 dB) is 95.6. In the XZ-plane (Φ=0) the main lobe magnitude is 15.2 dB V/m, the main lobe direction is 180 and the angular width (3 dB) is 90.8. Whereas in the YZ-plane (Φ=90 the main lobe magnitude is (15.5) dB V/m, the main lobe direction is 90, and the angular width (3 dB) is 90.12. Figure 19(b) depicts the radiation patterns at 2.7 GHz. In the XY-plane (θ=90), the main lobe magnitude is 17.5 dB V/m, the main lobe direction is 218, and the angular width (3 dB) is 60.3. In the XZ-plane (Φ=0), the main lobe magnitude is 15.5 dB V/m; the main lobe direction is 122, and the angular width (3 dB) is 121.8. Whereas in the YZ-plane (Φ=90 the main lobe magnitude is 17.1 dB V/m, the main lobe direction is 90, and the angular width (3 dB) is 121.5.
Figure 19: Simulated far-field radiation pattern of the modeled antenna for the total electric field at (a) 0.952 GHz, and (b) 2.7 GHz.

As far as the radiation properties are concerned, Figure 20 shows the simulated three-dimensional directivity radiation patterns of the resulting antenna. The directivity at 0.952 GHz the center frequency of lower band is 2.020 dBi as shown in Figure 20(a), whereas the directivity at 2.5 GHz the center frequency of upper band is 2.888 dBi as shown in Figure 20(b).
The 3D gain values in the two bands have been evaluated, as shown in Figure 21. In the lower frequency band, the peak gain pattern plotted in Figure 21(a) is as large as (1.214) dBi, for the upper band, is plotted in Figure 21(b), where the maximum gain is found to be of about (2.704) dBi.

### 5.2. ANTENNA READ RANGE

The maximum theoretical read range of the proposed RFID tag antenna $r_{\text{max}}$ is calculated using Friis free-space formula. The estimated read ranges of the antenna printed on a conventional and textile substrate are summarized in Table 5. The reader’s output power is set to 4.0 W EIRP) and threshold power required to turn on the NXP chip (-17.5dBm).

<table>
<thead>
<tr>
<th>Substrate Type</th>
<th>Gain (dB)</th>
<th>Operating Frequency (GHz)</th>
<th>Read Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>1.274</td>
<td>0.952</td>
<td>12.78</td>
</tr>
<tr>
<td></td>
<td>2.448</td>
<td>2.5</td>
<td>5.217</td>
</tr>
<tr>
<td>Textile</td>
<td>1.214</td>
<td>0.952</td>
<td>12.76</td>
</tr>
<tr>
<td></td>
<td>2.704</td>
<td>2.7</td>
<td>4.9</td>
</tr>
</tbody>
</table>
6. CONCLUSIONS
In this report, the design of Wunderlich fractal based dual-band dipole antenna has been presented as a candidate for use in wearable RFID applications. Besides the compact size the proposed antenna offers, there are also other interesting features. For security purposed which take into account the camouflage of the antenna within the cloth, the proposed antenna shape might represent a suitable choice. The conducted parametric study, of the effects of the different antenna elements, reveals the possibility of tuning of both of the resonant bands besides the bandwidth enhancement and the coupling degree of each of the resonant bands.

REFERENCES