Design of a Novel Split-Bowtie Slotted Multi-Resonant Antenna

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Abstract—This article demonstrates a novel design of a split-bowtie slotted multi-resonant antenna. The design process was inspired from previous research of integrating a slot of a similar profile to the outer boundary of a rectangular patch antenna. The followed approach presents steps of proposed antenna evolution, which starts with a bowtie-shape slotted antenna and a coaxial feed to a final design with a split-bowtie-shaped slot, and a double transmission line feed. Polar dimensions of the outer boundary (radii and angle) and slot profiles together with the dimensions of the feed, whether coaxial or transmission line, were considered as parameters for optimization. Four antennas were accordingly studied, which led to the final split-bowtie-shaped antenna IV. These designs were performed utilizing a special simulation package called “CST Microwave Suite” that included the optimizer “Genetic Algorithm”. The final design offers 4 simultaneous bands from a single split-bowtie-shaped slot; a big advantage of unnecessary integration of a set of complicated slots on front and ground planes. Further, the antenna finds applications in mobile GSM and LTE bands 900/1800 MHz and 2.1 GHz, together with the satellite communications band 1.25 GHz. It is therefore simple, non-reconfigurable, easy to fabricate, designed on a single copper layer, with a low cost FR4 substrate and a plane copper ground.

Index Terms—Split-bowtie-shaped slot, multi-resonant, double-slotted, GSM 900/1800, LTE 2.1, GPS 1.25

I. INTRODUCTION

Multi resonant antennas have received much interest from researchers and users of various wireless applications with benefits of size compactness and reduced cost. While microstrip antennas can be etched in different shapes and sizes, bowtie antennas can be designed to serve narrow and ultra-band frequency ranges. Bowtie antennas have been extensively applied in radar [1]–[3] and mobile base-stations [4]. Some researchers [5] studied its robust characteristics over the frequency range (3 GHz to 11 GHz). Others [6] studied the effect of changing the angle on the return loss and the radiation patterns. They concluded that “doubling the angle to 80° had no effect on return loss but on a narrower half power beam-width (HPBW) in the radiation pattern.” Rounding [7] the side edges of the bowtie antenna, on the other hand, “improved the return loss, the input impedance and the stability of radiation patterns.”

On a different front, “changing the position of certain slit configurations on various parts of the antenna arms” was studied [8] and was found to “produce resonances at around 3 GHz, 5 GHz and 7 GHz frequencies.” Inserting “circular and polygon shaped slots on the bowtie arms” were introduced [9] in a new antenna with “multi-resonant bands” that could be utilized for many wireless applications. By “etching slots of different lengths in a bowtie patch,” the authors in [10] were able to introduce “bent monopoles that produced various operating frequencies.” As the lengths of the introduced multiple bent monopoles met the quarter wavelength resonance condition, they successfully produced a slotted bowtie antenna with three bands; “300 MHz within the 2GHz to 3 GHz range, 300 MHz within the 3 GHz to 4 GHz range, and 600 MHz within the 5 GHz to 6 GHz range.”

More recently, the authors in [11] proposed a novel triple-band dipole antenna, where slots were etched on the bowtie patch. Accordingly, “three bent dipoles with different lengths that corresponded to different operating frequencies were formed.” The proposed antenna produced three bandwidths; “270 MHz in the 2.3 GHz to 2.7 GHz range, 910 MHz in the 3.1GHz to 4.1 GHz range and 1.25 GHz in the 4.5 GHz to 6.00 GHz range, with a satisfactory reflection coefficient of less than -10 dB.” The authors in [12] presented a multiband reconfigurable bowtie slot antenna using switchable pairs of slots. The proposed approach is based on “the integration of two pairs of slots on the two sides of the antenna to create new bands.” The properties of the bowtie antenna have been used to design a “reconfigurable frequency antenna with a high realized gain, operating in the WiFi, WiMAX, and WLAN with four operating modes, one in single band, two in dual band and one in triple band.”

Kavith [13] investigated the design and performance of “Sierpinski Fractal Bowtie antenna to obtain multiband behavior.” The evaluation of “Sierpinski fractal antenna was made up to two iterations.” The overall dimension of Sierpinski fractal antenna was 110x70 mm². The final design was able to operate at frequencies “1.4 GHz, 3.5 GHz, 4.6 GHz and 7.4 GHz with gains of 6.4 dB, 9.2 dB, 6.7 dB and 9.1 dB respectively.” Kumar et al. [14] investigated a “bowtie antenna on FR4 substrate (40 mm × 58 mm × 1.5 mm) with a modified symmetric split ring resonator (SRR) that was implemented beneath the substrate, as meta-material loading, which consisted of two circles and three circles.” Each circle was broken into four quarter circles by four rods. The effect of “the modified symmetric SRR locations and consequent geometry” was analyzed. In both configurations, 4 bands...
between 3.3 GHz and 7.1 GHz were produced. With the two proposed circles, a fifth band at 1.6 GHz was claimed with a return loss just below the -10 dB margin.

Idris et al. [15] investigated a multiband and wideband frequency reconfigurable. A “stripline, in the middle of a slotted bowtie antenna was achieved for wideband configuration, whereas two additional slotted arms were integrated for multiband configuration.” As a result, the antenna operated, through switches, at multiband mode (1.7 GHz and 2.6 GHz) and wideband mode (3.5 GHz to 9.0 GHz) simultaneously. Ghaffar et al. [16] presented a “frequency reconfigurable triangular (half bowtie) antenna with compact size to cover sub 6 GHz.” Two slots were included in the design to get multiband response while “two pin diodes were added to get dual-band and tri-band mode.” By “changing the states of pin diode, resonance in the sub 6 GHz band (2.5 GHz, 3.5 GHz, and 3.7-4.2 GHz) was achieved.” When both diodes were on, it resonated at “2.18-2.36 GHz, 2.68-3.32GHz, and 3.75 GHz to 4.50 GHz.” When both diodes were off, the resonance frequency was “2.25 GHz to 2.58 GHz, and 3.5 GHz to 4.46 GHz.”

Dhanaraj et al. [17] proposed a Bowtie antenna that was integrated with a “metamaterial reflector array.” “Electrically coupled split-ring resonator (ECSRR) unit cells were accordingly designed and analyzed of different geometrical shapes with negative permeability and negative permittivity.” The 5 to 6 periodical ECSRR unit cell embedded with modified Bowtie antenna were fabricated on FR4 epoxy substrate (1.6 mm). The “metamaterial embedded bowtie antenna” achieved a maximum gain of 11.08 dBi and a 50% broadband resonance at 5.5 GHz. Two more narrow bands at 4.2 GHz and 6.6 GHz were achieved. Roy et al. [18] proposed an antenna that consisted of a “self-complementary vacant cross dipole on a circular patch” where the “front and back side dipole, together made a bow-tie configuration.” There were “two equilateral triangle shapes with an internal circle inside the vacant dipole”, one in front side and the other on the back side. A coaxial feed was constructed in the back side. The antenna was printed on 1.6 mm thick FR4 substrate with a relative permittivity of 4.4 and the total square shaped region measured 154 mm x 160 mm. The antenna resonated at “0.89 GHz, 1.83 GHz, 2.18 GHz and 2.45 GHz.”

Ramalakshmi et al. [19] presented a new approach to design a “miniaturized, multiband bowtie fractal antenna by employing a rectangular slotted Sierpinski fractal geometry corresponding to many wireless communication applications.” The antenna was evaluated for 2 iterations and the final proposed antenna gave a “frequency coverage of (0.1 GHz to 0.2 GHz), (3.4 GHz to 3.45 GHz), (5.6 GHz to 5.85 GHz), (8.4 GHz to 9.0 GHz), (10.67 GHz to 11.1 GHz), (11.2 GHz to 12.00 GHz) bands for L, S, C, and X band applications with appropriate return loss and VSWR values.” The gain was calculated as “0.529 d at 0.2 GHz and 5.074 dB at 3.5 GHz.” Dayo et al. [20] investigated a “new compact high gain and multiband bowtie slot antenna with miniaturized triangular shaped metallic ground plane.” The antenna was realized on the low-cost FR4 epoxy thick substrate. High gain of “6.3 dBi, 5.72 dBi, 3.64 dBi, 2.89 dBi and 2.58 dBi are achieved at 17.5 GHz, 15.5 GHz, 2.86 GHz, 6.72 GHz and 10.66 GHz resonances.” The antenna was proposed as a favorable candidate for the advanced heterogeneous wireless communication applications.

Other structures than bowtie antennas were reported that utilized metamaterial technology to excite multiband frequencies. These consist of “Split Ring Resonators” (SRRs) [21] to produce “negative permeability which help to improve performance parameters such as bandwidth and miniaturization of microwave antennas.” Selvi et al. [22] reported a “CPW-fed SRR metamaterial-inspired antenna” for multiband operation. The five circular rings contributed to resonance at “2.20 GHz, 2.88 GHz, 3.54 GHz, 4.27 GHz, 5.51 GHz and 6.55 GHz” respectively. Al-Tumah et al. [23] proposed a “novel double annular-ring microstrip antenna”, split into six sectors to achieve multiband operation with high gain and impedance bandwidth. The gaps on the “driven and parasitic patches” excited resonant frequencies that were located in the “Ku-, K-, and Ka-bands, centered at 13.10 GHz, 20.72 GHz, 25.00 GHz, and 28.85 GHz,” respectively, thus making the antenna capable of these multiband applications. Christydas et al. [24] proposed a structure that achieved multiband operation by “engraving 2 Complementary Split Ring Resonators (CSRRs) and a C-Shaped slot”. In addition, “2 Split Ring Resonators (SRRs) were printed on the adjacent sides of the radiating element.” The proposed structure operated at “2.25 GHz, 3.86 GHz, 4.60 GHz, 5.64 GHz, 5.86 GHz, 6.94 GHz, 7.48 GHz, and 9.47 GHz.”

In the present work, a baseline bowtie antenna, with no slots, and three more antennas, with a “bowtie-shaped” slot and a “split-bowtie-shaped slot etched on the bowtie patch”, are designed and analyzed. Three of the designs are tested with a coaxial transmission line, fed into one of the arms. The final antenna is fed with a transmission line network that, in turn feeds the two arms. The remainder of the paper is organized as follows: Section two reviews design equations and considerations of bowtie antennas. Section three describes the antenna designs and their optimization. Section four presents the results of return loss and radiation patterns. Section five is a conclusion.

II. BOWTIE ANTENNA DESIGN CONSIDERATIONS

The conventional way to design a microstrip bowtie antenna, as shown schematically in Fig. 1, is to identify its geometrical parameters using an approximate mathematical equation [25]. Equation (1) shows that the resonant frequency, $f$, depends on $W$, $W_c$, $L$, and $S$, as shown in Fig. 1, which determine the dimensions and shape of the antenna.

![Fig. 1. Schematic diagram showing the layout of a microstrip bowtie antenna.](image-url)
The final double-slotted antenna was designed with a transmission feed line as in [6], but with a thin gap introduced in the middle which is inset into the patch, reaching opposite to the slot mouths. This allows simultaneous excitation of the two arms of the antenna. The dimensions of the double feed line were optimized to match a 50 ohm feed. A “1.6 mm FR4 dielectric of $\varepsilon_r = 4.4$” layer, measuring 100 mm × 100 mm was chosen for the design.

The resonant frequencies are described as in [28]:

$$f_r = \frac{ck_{mn}}{2\pi \sqrt{\varepsilon_r}} = \frac{2c\sqrt{m^2 + mn + n^2}}{3a\sqrt{\varepsilon_r}}$$  \hspace{1cm} (4)

where $f_r$ is the resonant frequency, $k_{mn}$ is the missing mode, $m$ and $n$ are the number of modes, $c$ is the velocity of light in free space, and $a= L/2$ is the side length of the bowtie antenna.

Equation (4) assumes that the antenna is enclosed by a “perfect magnetic wall.” A number of modifications were suggested in [28] for the more realistic case where the antenna was not enclosed by such a “perfect magnetic wall.” An expression for $a_{eff}$ has been arrived for the resonant frequency of the dominant TM$_{10}$ mode. This is shown in (5) to (7):

$$f_{r_{th}} = \frac{2c}{3a\sqrt{\varepsilon_r}}$$  \hspace{1cm} (5)

The side length is accordingly expressed as

$$a = \frac{2c}{3f_r \sqrt{\varepsilon_r}}$$  \hspace{1cm} (6)

The effective value of the side length is expressed as

$$a_{eff} = a + \frac{h}{\sqrt{\varepsilon_r}}$$  \hspace{1cm} (7)

The effective dielectric constant is expressed as

$$\varepsilon_{eff} = \left(\frac{\varepsilon_r + 1}{2}\right) + \left(\frac{\varepsilon_r - 1}{4\sqrt{1 + (12h/a)}}\right)$$  \hspace{1cm} (8)

Hence the antenna wavelength is calculated as

$$\lambda_y = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}$$  \hspace{1cm} (9)

III. ANTENNA DESIGNS AND OPTIMIZATION

This section describes the progressive approach used in the design of the bowtie antennas studied. Multiband bowtie antennas were investigated with and without “bowtie-shaped” slots on both arms of the antenna. Several designs, as shown in Fig. 3 to Fig. 6, were studied before reaching the final design. An FR4 substrate ($\varepsilon_r = 4.4$) of 110 mm × 50 mm × 1.6 mm was initially considered for the designs. Antenna I, shown in Fig. 3, was a baseline bowtie antenna, without slots and with a coaxial feed, located on the antenna’s horizontal axis.

![Figure 2. Schematic diagram of a “slotted bowtie antenna”](image)
Antenna II, shown in Fig. 4, was a slotted version of the baseline antenna. Antenna III, shown in Fig. 5, was modified to have a “split-bowtie-shaped” slot. Antenna IV, shown in Fig. 6, was designed with a “split-bowtie-shaped” slot and a double transmission line feed.

Possible design approaches for obtaining the four resonance bands were either to change the feed to a double transmission line feed, and affect simultaneous excitation of the two antenna arms, or to build another “split-bowtie-shaped” slot inside the original slot, re-optimize all associated dimensions and test for a fourth resonant band. It was decided to follow the first approach, as it looked less complicated and more promising. The extra parameters required for the transmission-line feed were the sizes of the lower transmission line, \( W_L \) and \( L_m \), and the width of the upper transmission line, \( W_t \). The width of the transmission line feed was kept constant at 1 mm. The input impedance at all feeding ports was optimized to 50 Ω.

The parameters \( (r_1, r_2, r_3 \) and \( θ) \), shown in Fig. 2, \( (D_1, D_2, X_0 \) and \( Y_0) \) of the coaxial feed, and \( (W_0, L_0 \) and \( L_1) \) of the transmission line feed were subjected to the optimization process. Tables I and II show the design range for each parameter and the obtained optimized value. The optimization was simultaneously conducted on all parameters in each antenna. In regard to the antenna coaxial feed, only \( X_0 \) of the feed coordinates \( (X_0, Y_0) \) on the bowtie right arm of Fig. 5 was optimized, while \( Y_0 \) was kept constant at zero value. The split gap width of the transmission feed in Fig. 6, on the other hand, was kept constant at 1 mm. The goals were set at producing four resonance frequency bands, centered at 900 MHz, 1800 MHz, 2.15 GHz and 2.1 GHz, with a return loss that is clearly lower than –10 dB.

### TABLE I: DESIGN AND OPTIMIZED PARAMETERS OF ANTENNA III (\( X_0, Y_0, \) ARE THE FEED COORDINATES, \( D_1, D_2, \) ARE THE INNER AND OUTER DIMENSIONS OF THE COAXIAL FEED, RESPECTIVELY)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value (mm)</th>
<th>Min (mm)</th>
<th>Max (mm)</th>
<th>Optimized (mm)</th>
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</thead>
<tbody>
<tr>
<td>( r_1 )</td>
<td>20</td>
<td>18</td>
<td>22</td>
<td>20.22</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>21</td>
<td>18</td>
<td>24</td>
<td>23.14</td>
</tr>
<tr>
<td>( r_3 )</td>
<td>55</td>
<td>54</td>
<td>58</td>
<td>57.53</td>
</tr>
<tr>
<td>( θ )</td>
<td>15°</td>
<td>10°</td>
<td>20°</td>
<td>13.95°</td>
</tr>
<tr>
<td>( d_1 )</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
<td>0.95</td>
</tr>
<tr>
<td>( d_2 )</td>
<td>5</td>
<td>4</td>
<td>6</td>
<td>5.82</td>
</tr>
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<td>( x_0 )</td>
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<td>0</td>
<td>20</td>
<td>16.03</td>
</tr>
<tr>
<td>( y_0 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### TABLE II: DESIGN AND OPTIMIZED PARAMETERS OF ANTENNA IV (\( W_1, L_1 \) AND \( W_2 \) ARE THE LOWER AND UPPER PARAMETERS OF THE TRANSMISSION LINE FEED DIMENSIONS)

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Min (mm)</th>
<th>Max (mm)</th>
<th>Optimized (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_1 )</td>
<td>20</td>
<td>18</td>
<td>23</td>
<td>22.53</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>25</td>
<td>23</td>
<td>27</td>
<td>25.64</td>
</tr>
<tr>
<td>( r_3 )</td>
<td>50</td>
<td>48</td>
<td>53</td>
<td>52.91</td>
</tr>
<tr>
<td>( θ )</td>
<td>25°</td>
<td>20°</td>
<td>30°</td>
<td>25.26°</td>
</tr>
<tr>
<td>( W_1 )</td>
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<td>8</td>
<td>12</td>
<td>9.98</td>
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<tr>
<td>( L_1 )</td>
<td>10</td>
<td>8</td>
<td>13</td>
<td>12.68</td>
</tr>
<tr>
<td>( w_i )</td>
<td>2</td>
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<td>3</td>
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### IV. RESULTS

This section contains results obtained for the return loss and radiation patterns of antenna designs I-IV when using the optimized parameters obtained from the CST Studio software.

#### A. Return Loss

Fig. 7 to Fig. 10 show the return loss versus frequency for optimized Antenna I to Antenna IV, respectively.
Antenna I produced two resonances at “700 MHz and 2.1 GHz,” as shown in Fig. 7. Fig. 8 shows the effect of introducing a “bowtie-shaped” slot, in Antenna II, by down-shifting the higher frequency to 1.8 GHz. Several attempts were made to produce more than two resonant frequencies utilizing the 4 optimization parameters: r1, r2, r3 and θ, as demonstrated in Fig. 2. Fig. 9 shows the effect of introducing a “split-bowtie-shaped” slot on producing three resonance frequencies. The third resonance frequency emerged, “at 1.4 GHz with a -8 dB return loss level, while the higher frequency shifted up from 1.8 GHz to 2.1 GHz.” A transmission line feed, whose width and length were optimized, except for the fixed middle-gap, was introduced in Antenna IV to divide the signal power between the “split-bowtie-shaped” slot, as shown in Fig. 6. Fig. 10 resulted in four resonance frequencies: “1 GHz, 1.25 GHz, 1.8 GHz and 2.1 GHz, which were below the -10 dB return loss level”.

**B. Radiation Patterns**

Fig. 11 to Fig. 14 show the E-plane and H-plane radiation pattern of the four optimized Antenna I to Antenna IV, at their dominant resonant frequency bands.
In general, for a patch in the \( xy \) plane, where the \( E \) vector points in the \( y \) direction of the \( xyz \) Cartesian coordinate system, then as angle \( \phi \) is varied while angle \( \theta \) is kept constant at \( 0^\circ \), the \( E \)-plane (i.e. the \( yz \)-plane) radiation pattern can be produced. On the other hand, as \( \theta \) is varied while \( \phi \) is kept constant at \( 0^\circ \), the \( H \)-plane (i.e. \( xz \)-plane) radiation pattern can be produced. The \( E \)-plane and \( H \)-plane radiation patterns for Antenna I to Antenna IV were obtained at the center resonance frequencies; 700 MHz, 1.8 GHz, 2.1 GHz and 1.8 GHz, respectively.

![Table III: Comparative Analysis of Various Multiband Slotted Bowtie Antennas](image)

Table III compares seven different multiband slotted bowtie antennas. Our antenna offers a simple, low cost, low profile design, on a single copper layer and merits over the rest that it has 4 bands, instead of 3 bands, with a relatively high gain at relatively lower bands; GSM 1800 and LTE 2.1. In addition, the combination of GSM, LTE and GPS bands in a single antenna makes it a versatile one for mobile and satellite radio applications. It has relatively most compact patch dimensions, after the fractal and meta-material embedded antennas, considering the low frequencies of its quad bands.

![Fig. 11 and Fig. 12](image)

Fig. 11 and Fig. 12 show fairly similar radiation pattern trends, at 700 MHz and 1.8 GHz frequencies. Most notably, Fig. 13 and Fig. 14 had fairly similar radiation patterns at 2.1 GHz and 1.8 GHz frequencies, respectively. However, the radiation pattern of Antenna IV in Fig. 14, appeared to be more directional with a BW= 90° in the \( E \)-plane pattern, compared to antenna III with a BW= 120°. The \( H \)-plane patterns in Fig. 13 and Fig. 14 had comparatively a similar directivity with a BW= 60°.

V. COMPARATIVE ANALYSIS

Table III compares seven different multiband slotted bowtie antennas. Our antenna offers a simple, low cost, low profile design, on a single copper layer and merits over the rest that it has 4 bands, instead of 3 bands, with a relatively high gain at relatively lower bands; GSM 1800 and LTE 2.1. In addition, the combination of GSM, LTE and GPS bands in a single antenna makes it a versatile one for mobile and satellite radio applications. It has relatively most compact patch dimensions, after the fractal and meta-material embedded antennas, considering the low frequencies of its quad bands.

VI. CONCLUSION

A novel split-bowtie slotted multi-resonant antenna was designed and tested. The design is simple, low-cost and low-profile. Towards the final design, four antennas with different bowtie slot patterns and feeds were accordingly designed and developed. Antenna IV with a “split- bowtie-shaped” slot and double-line feed had the best performance, resulting in four resonant frequencies at 0.9 GHz, 1.25 GHz, 1.8 GHz, and 2.1 GHz. As far as radiation patterns, antenna IV had relatively the highest directivity with a half power bandwidth of 90° in the \( E \)-plane and 60° in the \( H \)-plane. It merits over the compared
Effect of round corners on bowtie antennas in the published literature, as the simplest self-profile slotted quad band antenna design. With a single split-bowtie-shaped slot, having a similar profile to the antenna outer boundary that is simple, non-configurable, easy to fabricate and does not involve further designs or deformations on the ground plane, while suitable to GSM 900/1800, LTE 2.1 and GPS 1.25 band applications, the novel antenna has a potential for extra bands if a second or more split-bowtie-shaped slots are carefully added and optimized inside the original slot.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
O.W. Ata conducted the research, analyzed the data and wrote the paper. M.I. Jawadah executed the simulation of the antennas on CST Microwave Suite. Both authors had reviewed and approved the final version.

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