Performance Optimization of a Microstrip Patch Antenna using Characteristic Mode and D/Q Analysis

Bidisha Barman\textsuperscript{1}, Kalyan C. Durbhakula\textsuperscript{1,3}, Benjamin Bissen\textsuperscript{2,3}, Deb Chatterjee\textsuperscript{1,3} and Anthony N. Caruso\textsuperscript{1,2,3}

\textsuperscript{1}Department of Computer Science and Electrical Engineering
\textsuperscript{2}Department of Physics and Astronomy
\textsuperscript{3}Missouri Institute for Defense & Energy

\textsuperscript{FR-UB.2A.7} Distribution A
OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
Microstrip patch antennas have found wide acceptance in the antenna community.

Advantages: Light weight, Small size, Simple design, Tractable performance.

Major disadvantage: Low VSWR bandwidth.

Conventional Designs [1]: Coaxial probe is placed at an offset distance from patch center – Antenna I.

The antenna dimensions are calculated using the equations in [2].


Coaxial probe is strategically placed along the patch diagonal, at 2/3rd distance from the patch center.

All other antenna dimensions are unchanged.

> 30% 2:1 VSWR bandwidth could be obtained using this technique.
OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
OVERVIEW OF ELECTRICALLY SMALL ANTENNAS (ESAs)

Electrically Small Antenna (ESA)

Antennas that satisfy the condition \( ka < 1 \)

where

\[ k = \frac{2\pi}{\lambda} \]

is the wavenumber

\( a \) = minimum radius of the circumscribing sphere of antenna (Chu’s Sphere)

OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- **Performance Comparison of Conventional and Proposed Design**
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
**Performance Comparison of Antenna I and Antenna II**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Optimized Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_r$</td>
<td>9.8</td>
</tr>
<tr>
<td>$\tan \delta$</td>
<td>0.002</td>
</tr>
<tr>
<td>$h$ (mm)</td>
<td>6.35</td>
</tr>
<tr>
<td>$L$ (mm)</td>
<td>9.61</td>
</tr>
<tr>
<td>$W$ (mm)</td>
<td>14.42</td>
</tr>
<tr>
<td>$r_p$ (mm)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antenna</th>
<th>$(x_p, y_p)$ (mm, mm)</th>
<th>$f_L$ (GHz)</th>
<th>$f_c$ (GHz)</th>
<th>$f_U$ (GHz)</th>
<th>% BW</th>
<th>Max. Gain (dB)</th>
<th>$ka$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANTENNA I</td>
<td>(3.5, 0)</td>
<td>3.315</td>
<td>3.5975</td>
<td>3.88</td>
<td>15.70</td>
<td>1.86</td>
<td><strong>0.6533</strong></td>
</tr>
<tr>
<td>ANTENNA II</td>
<td>(3.2, 4.8)</td>
<td>2.867</td>
<td>3.6</td>
<td>4.333</td>
<td>40.72</td>
<td>2.85</td>
<td><strong>0.6536</strong></td>
</tr>
</tbody>
</table>

*Full-wave simulations have been performed using FEKO on an infinite ground plane.*
This design methodology is applicable at all frequency ranges and for various substrate parameters.

To prove this, we chose two other substrates (with different permittivity values):

- $\varepsilon_r = 3.27$
- $\varepsilon_r = 12.85$

### Optimized Dimensions of the Antennas

<table>
<thead>
<tr>
<th>$f_r$ (GHz)</th>
<th>$\varepsilon_r$</th>
<th>$\tan \delta$</th>
<th>$h$ (mm)</th>
<th>$h\sqrt{\varepsilon_r}/\lambda$</th>
<th>$L$ (mm)</th>
<th>$W$ (mm)</th>
<th>$r_p$ (mm)</th>
<th>$(x_p, y_p)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.27</td>
<td>0.0020</td>
<td>5.080</td>
<td>0.1532</td>
<td>11.4986</td>
<td>17.2478</td>
<td>0.9</td>
<td>(3.3, 5.7493)</td>
</tr>
<tr>
<td>2.5</td>
<td>12.85</td>
<td>0.0019</td>
<td>7.620</td>
<td>0.2278</td>
<td>9.1063</td>
<td>13.6594</td>
<td>0.6</td>
<td>(3.04, 4.55)</td>
</tr>
</tbody>
</table>
Conclusion: This design methodology yields > 30% 2:1 VSWR bandwidth irrespective of the frequency range and substrate parameters.

*Full-wave simulations have been performed using FEKO on an infinite ground plane.
OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
The 2:1 VSWR bandwidth of the antenna has been found to be maximum when the probe is placed at 2/3\textsuperscript{rd} distance along the patch diagonal.

This may be attributed to the excitation of higher order modes.

To identify contributing modes, CMA is performed for the antenna for the two probe locations.

- Modal behaviors of the antennas are illustrated via modal significance (MS\textsubscript{n}) curves.
- MS\textsubscript{n} shows the n\textsuperscript{th} eigen current mode:
  \[ MS_n = \frac{1}{|1 + j\lambda_n|} \]
  where, \( \lambda_n \) = eigenvalue for the n\textsuperscript{th} eigen current.
- n\textsuperscript{-th} eigen current is considered dominant if its corresponding \( \lambda_n = 0 \) or \( MS_n \rightarrow 1 \) [4].

---

\( \text{MS}_n \) and VSWR of the Antenna for Different Probe Locations

Major contributing modes:
- Position #1: Mode J3
- Position #2: Modes J1 and J3

The bandwidth enhancement for #2 occurs due to excitation of multiple modes.
OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
Experimental characterization of an antenna requires finite size PEC-backed substrate.

To validate the design methodology, we chose the antenna design at 3.75 GHz on a TMM-10i substrate ($\varepsilon_r = 9.8$, $\tan \delta = 0.0020$).

Effect of finite ground plane on antenna parameters studied - Full-wave simulations performed via FEKO.

Two different finite ground plane shapes are considered:

- Square
- Circular

### SIMULATED RESULTS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Optimized Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_r )</td>
<td>9.8</td>
</tr>
<tr>
<td>( \tan \delta )</td>
<td>0.0020</td>
</tr>
<tr>
<td>( h ) (mm)</td>
<td>6.35</td>
</tr>
<tr>
<td>( L ) (mm)</td>
<td>9.61</td>
</tr>
<tr>
<td>( W ) (mm)</td>
<td>14.42</td>
</tr>
<tr>
<td>( r_p ) (mm)</td>
<td>0.6</td>
</tr>
<tr>
<td>( (x_p, y_p) ) (mm, mm)</td>
<td>(3.20, 4.80)</td>
</tr>
</tbody>
</table>

### Ground Plane Parameters

<table>
<thead>
<tr>
<th>Ground Plane</th>
<th>( f_L ) (GHz)</th>
<th>( f_c ) (GHz)</th>
<th>( f_U ) (GHz)</th>
<th>% BW</th>
<th>Max. Gain (dB)</th>
<th>( k_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infinite</td>
<td>2.867</td>
<td>3.6</td>
<td>4.333</td>
<td>40.72</td>
<td>2.85</td>
<td>0.6536</td>
</tr>
<tr>
<td>Finite Square (L_g = 41.64 mm)</td>
<td>2.773</td>
<td>3.491</td>
<td>4.209</td>
<td>41.13</td>
<td>unstable</td>
<td>0.6339</td>
</tr>
<tr>
<td>Finite Circular (r_g = 23.49 mm)</td>
<td>2.745</td>
<td>3.7475</td>
<td>4.75</td>
<td>53.50</td>
<td>5.65</td>
<td>0.6805</td>
</tr>
</tbody>
</table>
OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- **Experimental Validation**
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
EXPERIMENTAL VALIDATION OF THE ANTENNA DESIGN

Fabricated Prototype

<table>
<thead>
<tr>
<th></th>
<th>$f_L$ (GHz)</th>
<th>$f_c$ (GHz)</th>
<th>$f_U$ (GHz)</th>
<th>% BW</th>
<th>$k_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>2.745</td>
<td>3.7475</td>
<td>4.75</td>
<td>53.50</td>
<td>0.6805</td>
</tr>
<tr>
<td>Measured</td>
<td>2.72</td>
<td>3.69</td>
<td>4.66</td>
<td>52.57</td>
<td>0.6701</td>
</tr>
</tbody>
</table>
Radiation Pattern at Frequency = 2.745 GHz

E-plane ($\phi = 0^\circ$)

H-plane ($\phi = 90^\circ$)
Radiation Pattern at Frequency = 3.7475 GHz

E-plane ($\phi = 0^\circ$)

H-plane ($\phi = 90^\circ$)
Radiation Pattern at Frequency = 4.75 GHz

E-plane (φ = 0°)

H-plane (φ = 90°)
OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
One of the useful performance optimization technique is the D/Q ratio of the antennas [6].

- **D** = Directivity (Far Field parameter)
- **Q** = Quality Factor (Near Field Parameter)

Using this method it is possible to optimize the far field parameter and the near field parameter **simultaneously**.

- For our calculations, we exported the directivity from FEKO.
- Quality Factor of the antenna is calculated using two methods:
  1. Exact Quality Factor (using antenna input impedance)
  2. Approximate Quality Factors (applicable only for ESAs).

EXACT Q FROM ANTENNA INPUT IMPEDANCE [7]

\[ Q(\omega_0) \approx \frac{2\sqrt{\beta}}{\text{FBW}_v(\omega_0)} \]

Where,
Matched VSWR Fractional Bandwidth
\[ \text{FBW}_v(\omega_0) = \frac{\omega_- - \omega_+}{\omega_0} \]
And,
\[ 4\beta R_0(\omega_0) = \frac{X_0^2(\omega_\pm) + [R_0(\omega_\pm) - R_0(\omega_0)]^2}{R_0(\omega_\pm)} \]

To calculate the exact Quality Factor, we are exporting the input impedance of the antenna from FEKO.

APPROXIMATE QUALITY FACTORS

• They take into account only the electrical length of the antenna (i.e., $ka$)
• Where, $k$ = wavenumber and $a$ = radius of the minimum sphere (Chu’s sphere) that encloses the antenna.
• Since our designed antennas are electrically small, we consider these approximate expressions to check their validity for our design.

Harrington [8]:
\[
Q = \frac{1}{2} \left[ \frac{1}{(ka)} + \frac{1}{(ka)^3} \right]
\]

McLean [9]:
\[
Q = \frac{1}{2} \left[ \frac{2}{(ka)} + \frac{1}{(ka)^3} \right]
\]

Thal [10]:
\[
Q = \frac{1}{(ka)^3}
\]


For ESA, $ka < 1$
Comparison of Quality Factors

- Exact Q of the probe fed rectangular patch on finite circular ground is compared to the Approximate Quality Factors.
- For D/Q calculation, Directivity and Impedance exported from FEKO.
OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work
Presented a new method to obtain > 30% 2:1 VSWR bandwidth using a simple coaxial probe fed rectangular patch antenna – probe placed at 2/3rd distance along patch diagonal.

Design methodology is experimentally verified.

CMA shows increase in bandwidth is due to excitation of modes J1 and J3.

Antennas designed on Circular Ground Planes have improved performances in terms of VSWR and Gain compared to Square Ground Planes.

Optimization of antenna parameters using D/Q method has been explored.
FUTURE WORK

- Developing analytical model to characterize the designed microstrip patch antenna.
- Investigations into edge diffraction effects of finite ground planes.
- Investigations into the performance optimization of an antenna using the multi-parameter D/Q method.