Radiation Pattern Analysis of Dipole Antennas

Reem AL Zouhby

October 24, 2025

1 Introduction

This report presents a comprehensive analysis of radiation patterns for dipole antennas with different length-to-wavelength ratios. The study includes the Hertzian dipole (infinitesimally short dipole) and finite-length dipoles with varying l/λ ratios.

1.1 Objectives

The main objectives of this assignment are:

- Simulate and visualize radiation patterns for dipole antennas
- Analyze the effect of antenna length on radiation characteristics
- Calculate and plot directivity as a function of l/λ
- Determine half-power beamwidth for different antenna lengths

2 Theoretical Background

2.1 Hertzian Dipole

The Hertzian dipole is an idealized infinitesimally short current element. Its normalized electric field pattern is given by:

$$E(\theta) = \sin(\theta) \tag{1}$$

The radiation pattern is omnidirectional in the azimuthal plane (ϕ) and has a figure-eight pattern in the elevation plane (θ).

2.2 Finite-Length Dipole

For a finite-length dipole antenna of length l, the electric field pattern is:

$$E(\theta) = \frac{\cos(\beta l \cos\theta) - \cos(\beta l)}{\sin\theta(1 - \cos\beta l)} \tag{2}$$

where $\beta = 2\pi/\lambda$ is the phase constant and λ is the wavelength.

2.3 Directivity

Directivity is defined as the ratio of maximum radiation intensity to the average radiation intensity:

$$D = \frac{4\pi U_{max}}{P_{rad}} \tag{3}$$

where U_{max} is the maximum radiation intensity and P_{rad} is the total radiated power.

For a dipole antenna:

$$D = \frac{2}{\int_0^\pi |E(\theta)|^2 \sin\theta \, d\theta} \tag{4}$$

3 Methodology

3.1 Simulation Parameters

The following parameters were used in the simulations:

- Angular resolution: 1000 points for θ and 1000 points for ϕ
- l/λ ratios analyzed: 0.1, 0.25, 0.5, 0.625, 0.75, 0.999
- Directivity calculation range: 0 to 1 with step 0.001

3.2 MATLAB Implementation

The radiation patterns were computed using MATLAB. The key steps include:

1. Calculate the electric field pattern using the dipole equation
2. Normalize the field patterns
3. Generate 2D polar plots for E vs θ and E vs ϕ
4. Create 3D surface plots of the radiation pattern
5. Compute directivity through numerical integration

4 Results

4.1 Hertzian Dipole Pattern

4.1.1 2D Radiation Patterns

The Hertzian dipole exhibits the classic figure-eight pattern in the E-plane (θ variation) and an omnidirectional pattern in the H-plane (ϕ variation).

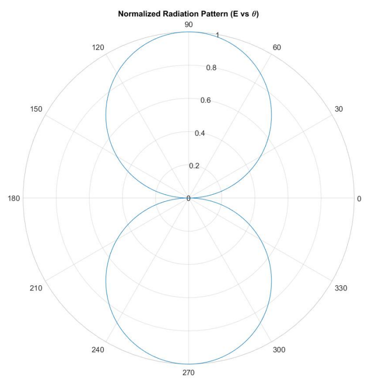

Figure 1: Normalized radiation pattern E vs θ for Hertzian dipole

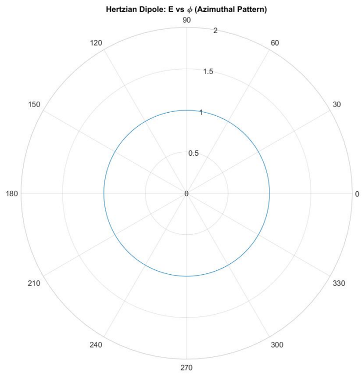

Figure 2: Normalized radiation pattern E vs ϕ for Hertzian dipole

4.1.2 3D Radiation Pattern

The 3D pattern resembles a toroid (donut shape) with maximum radiation perpendicular to the dipole axis.

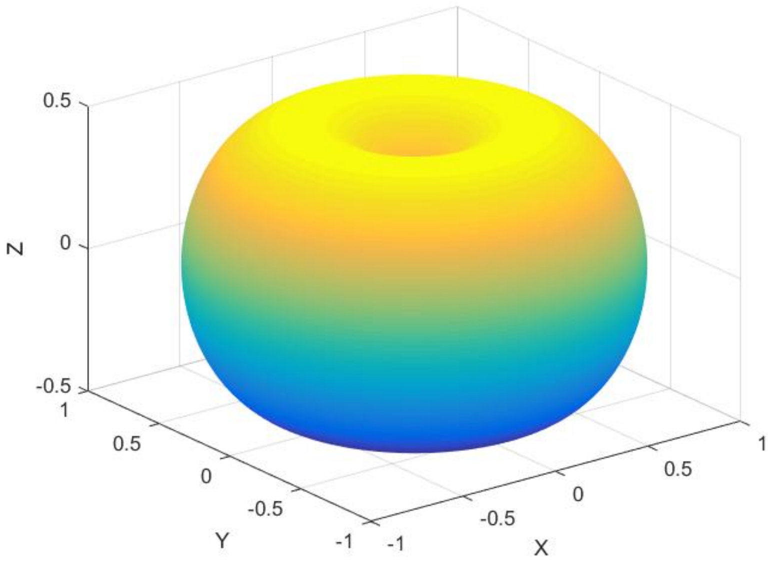

Figure 3: 3D radiation pattern of Hertzian dipole

4.2 Finite-Length Dipole Patterns

4.2.1 E vs θ Patterns

As the antenna length increases, the radiation pattern becomes more directional with narrower beamwidth.

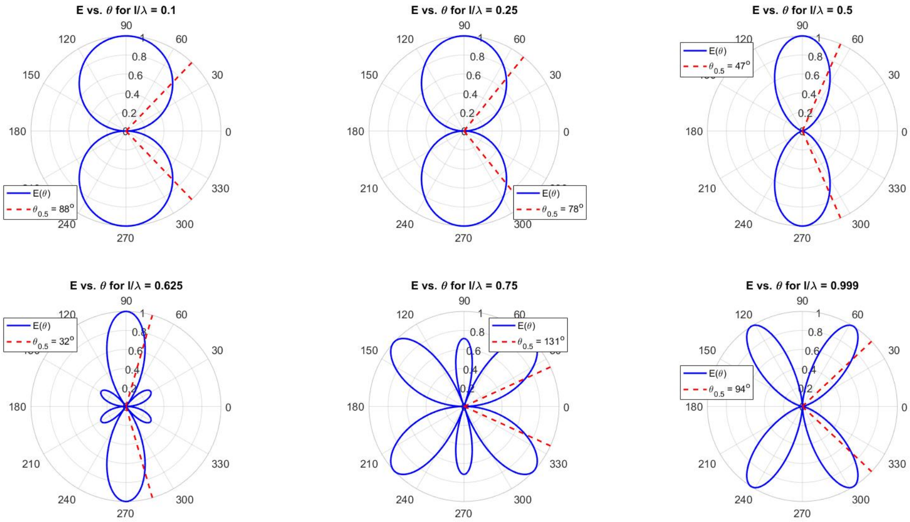

Figure 4: Normalized E vs θ for different l/λ ratios

Observations:

- For $l/\lambda = 0.1$: Nearly omnidirectional (similar to Hertzian dipole)
- For $l/\lambda = 0.5$ (half-wave dipole): Classic figure-eight with moderate directivity
- For $l/\lambda = 1.0$ (full-wave dipole): Multiple lobes appear

4.2.2 E vs ϕ Patterns

All dipole antennas show omnidirectional patterns in the azimuthal plane, confirming cylindrical symmetry.

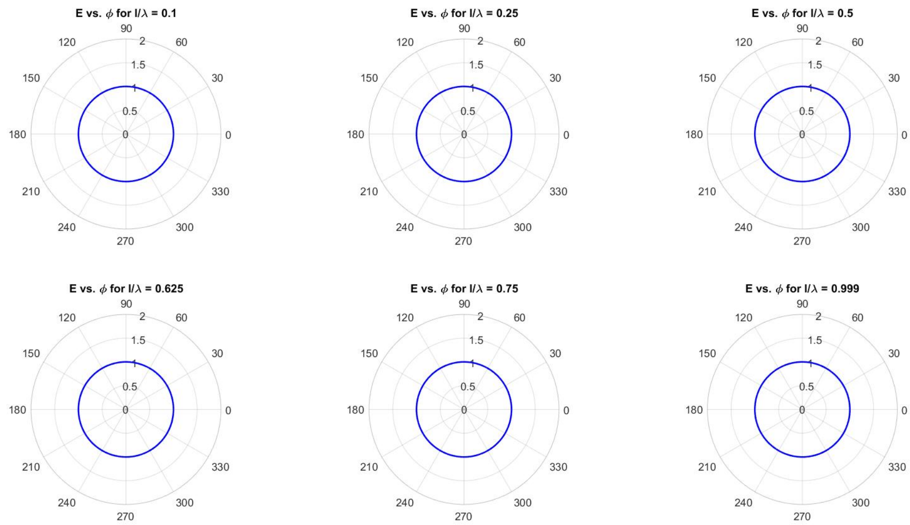

Figure 5: Normalized E vs ϕ for different l/λ ratios

4.2.3 3D Radiation Patterns

The 3D visualization shows how the radiation pattern evolves from a toroid to more complex shapes as antenna length increases.

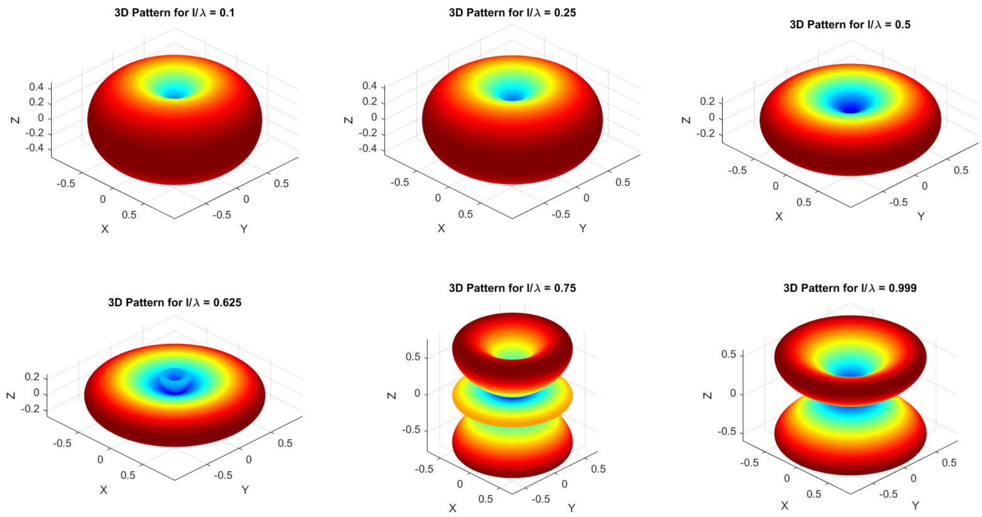

Figure 6: 3D radiation patterns for different l/λ ratios

4.3 Directivity Analysis

The directivity was calculated for l/λ ranging from 0 to 1. Key values are highlighted for specific ratios.

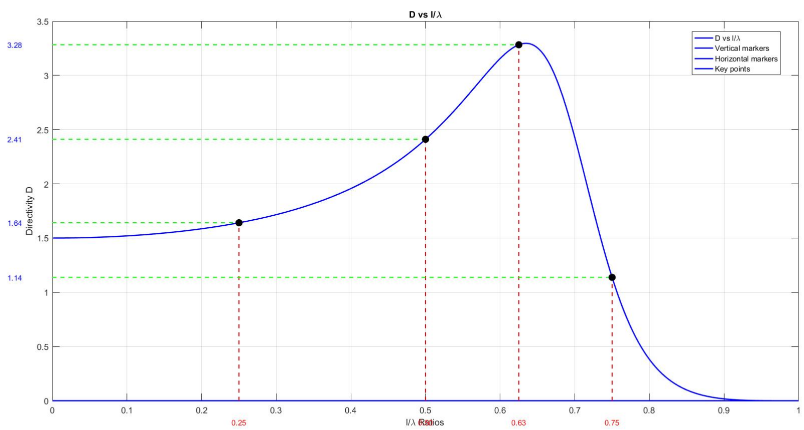

Figure 7: Directivity D vs l/λ ratio

5 Discussion

5.1 Effect of Antenna Length

The antenna length significantly affects the radiation characteristics:

- **Short dipoles ($l/\lambda < 0.25$):** Nearly omnidirectional with low directivity
- **Half-wave dipole ($l/\lambda \approx 0.5$):** Optimal balance between directivity and pattern simplicity
- **Long dipoles ($l/\lambda > 0.5$):** low directivity

5.2 Half-Power Beamwidth

The half-power beamwidth ($\theta_{0.5}$) decreases as the antenna length increases, indicating more focused radiation. This is desirable for point-to-point communication applications.

5.3 Practical Implications

- Half-wave dipoles are widely used due to their good directivity and simple feed
- Short dipoles are suitable for applications requiring wide coverage
- Longer dipoles can be used when higher directivity is needed

6 Conclusion

This study successfully analyzed the radiation patterns of dipole antennas with varying length-to-wavelength ratios. The simulations demonstrate:

1. The evolution of radiation patterns from omnidirectional to directive as length increases
2. The relationship between antenna length and directivity
3. The optimal performance of half-wave dipole antennas

The MATLAB simulations provide visual and quantitative insights into antenna behavior, which are essential for antenna design and selection in practical applications.

A MATLAB Code

A.1 Hertzian Dipole Simulation

```
%simulate the radiation pattern ( normalized) for different values l/lamda
%+ directivity  Hertezian dipole
% first define the theta and fille
clc; clear; close all;
theta = linspace(0, 2*pi,1000);
phi =linspace(0, 2*pi,1000);
%E pattern
E= abs(sin(theta));
E_norma=E/max(E);
%plot E vs theta
figure('Name', 'E␣vs␣theta','NumberTitle','off');
%plot in polar coordinates
polarplot(theta, E_norma);
title('Normalized␣Radiation␣Pattern␣(E␣vs␣\theta)');
%E vs phi should be a circle
E_phi=ones(size(phi));
E_phi_norm=E_phi/max(E_phi);
figure('Name','E␣vs␣phi','NumberTitle','off');
polarplot(phi,E_phi_norm);
title('Hertzian␣Dipole:␣E␣vs␣\phi␣(Azimuthal␣Pattern)');
%3d plot : should be like a donut
[theta,phi]=meshgrid(theta,phi);
%sph2cart use the spherical coordinate
%   =   /2 (equator)     elevation = 0     MATLAB sees it in x y  plane
[X,Y,Z]=sph2cart(phi,pi/2 - theta,sin(theta));
figure('Name','3D␣Radiation␣Pattern␣of␣Hertzian␣Dipole','NumberTitle','off');
surf(X,Y,Z);

xlabel('X'); ylabel('Y'); zlabel('Z');
shading interp;
```

Listing 1: Hertzian dipole radiation pattern

A.2 Finite-Length Dipole Simulation

```
clc; clear; close all;
theta = linspace(0, 2*pi,1000);
phi = linspace(0, 2*pi, 1000);
[Theta, Phi] = meshgrid(theta, phi);

region = [0.1, 0.25, 0.5, 0.625,0.75,0.999];

figure_theta = figure('Name', 'E␣vs␣Theta', 'NumberTitle', 'off')
;
```

```matlab
figure_phi = figure('Name', 'E␣vs␣Phi', 'NumberTitle', 'off');
figure_3D = figure('Name', '3D␣Radiation␣Pattern', 'NumberTitle', 'off');

for i = 1:length(region)
    ratio = region(i);
    beta_l = 2 * pi * ratio;

    % Calculate the E-field pattern
    E_theta = abs((cos(beta_l .* cos(theta)) - cos(beta_l)) ./ sin(theta).* (1 - cos(beta_l)));
    E_3D = abs((cos(beta_l .* cos(Theta)) - cos(beta_l)) ./ sin(Theta));

    % Normalize
    E_theta_norm = E_theta / max(E_theta);
    E_3D_norm = E_3D / max(E_3D(:));

    % Calculate theta_0.5 (half-power beamwidth)
    E_max = max(E_theta_norm);
    idx_half = find(E_theta_norm >= E_max / sqrt(2), 1, 'first');
    if ~isempty(idx_half)
        theta_0_5 = theta(idx_half);
    else
        theta_0_5 = 0;
    end

    % Plot E vs. theta - Full 360 degree pattern
    figure(figure_theta);
    subplot(2, 3, i, polaraxes);

    % Create full circle pattern
    theta_full = [theta, pi + fliplr(pi - theta)];
    E_full = [E_theta_norm, fliplr(E_theta_norm)];

    polarplot(theta_full, E_full, 'b', 'LineWidth', 1.5);
    hold on;
    if theta_0_5 > 0
        polarplot([theta_0_5 theta_0_5], [0 E_max], 'r--', 'LineWidth', 1.5);
        polarplot([2*pi-theta_0_5 2*pi-theta_0_5], [0 E_max], 'r--', 'LineWidth', 1.5);
    end
    hold off;
    title(['E␣vs.␣\theta␣for␣l/\lambda␣=␣' num2str(ratio)]);
    if theta_0_5 > 0
        beamwidth = 2 * rad2deg(pi/2 - theta_0_5);
        legend('E(\theta)', ['\theta_{0.5}␣=␣' num2str(abs(round(beamwidth))) '^o'], 'Location', 'best');
    end

```

```
    % Plot E vs. phi for constant theta (pi/2)
    figure(figure_phi);
    subplot(2, 3, i, polaraxes);
    E_phi = ones(size(phi));
    polarplot(phi, E_phi, 'b', 'LineWidth', 1.5);
    title(['E␣vs.␣\phi␣for␣l/\lambda␣=␣' num2str(ratio)]);

    % Plot the 3D radiation pattern
    figure(figure_3D);
    subplot(2, 3, i);
    [X, Y, Z] = sph2cart(Phi, pi/2 - Theta, E_3D_norm);
    surf(X, Y, Z, E_3D_norm);
    title(['3D␣Pattern␣for␣l/\lambda␣=␣' num2str(ratio)]);
    xlabel('X'); ylabel('Y'); zlabel('Z');
    shading interp;
    axis equal;
    grid on;
    colormap jet;
    view(45, 30);
end
```

Listing 2: Finite-length dipole patterns

A.3 Directivity Calculation

```
clc; clear; close all;

range = 0:0.001:1;
beta_l = 2 .* pi .* range;
 % Calculate the E-field pattern
 D = zeros(length(beta_l));
 for i=1:length(beta_l)
 den = @(theta) ((cos(beta_l(i) .* cos(theta)) - cos(beta_l(i)))
    ./ (sin(theta) .* (1 - cos(beta_l(i))))).^2 .* sin(theta);
 D(i) = 2 ./ (integral(den, 0, pi));
 end

% Plot D vs l/lambda
figure('Name', 'Directivity␣vs␣l/lambda', 'NumberTitle', 'off');
plot(range, D, 'b-', 'LineWidth', 1.5);
hold on;

xlabel('l/\lambda␣Ratios');
ylabel('Directivity␣D');
title('D␣vs␣l/\lambda');
grid on;
% Specific l/lambda
specific_ratios = [0.25, 0.5, 0.625, 0.75];
% Find the corresponding values of D for these ratios
specific_D = zeros(size(specific_ratios));

```

```matlab
for j = 1:length(specific_ratios)
    % Find index for the specific ratio
    [~, idx] = min(abs(range - specific_ratios(j)));
    specific_D(j) = D(idx); % Get corresponding D value

    % Plot vertical line
    plot([specific_ratios(j), specific_ratios(j)], [0, specific_D(j)], 'r--', 'LineWidth', 1.2);

    % Plot horizontal line
    plot([0, specific_ratios(j)], [specific_D(j), specific_D(j)], 'g--', 'LineWidth', 1.2);

    % Add text labels
    text(specific_ratios(j), -0.2, sprintf('%.2f', specific_ratios(j)), ...
        'HorizontalAlignment', 'center', 'Color', 'r', 'FontSize', 9);
    text(-0.04, specific_D(j), sprintf('%.2f', specific_D(j)), ...
        'HorizontalAlignment', 'right', 'Color', 'b', 'FontSize', 9);
end

% Add markers at the intersection points
plot(specific_ratios, specific_D, 'ko', 'MarkerSize', 8, 'MarkerFaceColor', 'k');

% Add a legend
legend('D vs l/\lambda', 'Vertical markers', 'Horizontal markers', 'Key points', 'Location', 'best');
hold off;
```

Listing 3: Directivity vs l/λ