Analysis of Thin-Wire Dipole Antenna Characteristics

1 Introduction

The primary aim of this Python script is to facilitate the analysis and understanding of fundamental characteristics of thin-wire dipole antennas. It specifically focuses on calculating and visualizing the input impedance (comprising resistance and reactance) and the maximum directivity of a dipole as its length is varied relative to the operating wavelength. The analysis relies on established formulas from electromagnetic theory, incorporating special mathematical functions such as Sine and Cosine integrals for accurate impedance computation. By systematically adjusting the dipole's length, the script also identifies resonant lengths, which are crucial for antenna matching and performance optimization.

The tools employed for this analysis include Python 3.x, with the following key libraries:

- **NumPy:** Utilized for efficient numerical array operations, fundamental mathematical constants (e.g., π) and mathematical functions (e.g., logarithm, trigonometric functions). It is instrumental in managing the range of dipole lengths and subsequent calculations.
- **SciPy:** This library is crucial for two main functions:
  - `scipy.special.sici`: Provides the Sine and Cosine integral functions, which are essential for the analytical formulas used to calculate the dipole's input impedance.
  - `scipy.integrate.quad`: Used for numerical integration, specifically to calculate the total radiated power from the antenna's radiation pattern, a necessary step for determining directivity.
- **Matplotlib:** Employed for generating 2D plots to visualize the calculated input impedance components (resistance and reactance) and the maximum directivity as functions of the dipole's length (normalized to wavelength).

The objective is to compute these critical antenna parameters across a range of dipole lengths and to present them graphically, thereby offering insights into how a dipole's electrical behavior is influenced by its physical dimensions.

2 Design Methodology

This section details the theoretical framework, the specific equations implemented, the rationale for library selection, the setup of simulation parameters, and the procedural flow of the Python script used for analyzing the thin-wire dipole antenna.

2.1 Theoretical Background and Equations

The performance characteristics of a thin-wire dipole antenna, such as its input impedance and radiation properties (including directivity), are derived from electromagnetic theory.

Input Impedance (Z_{in}): The input impedance of a center-fed thin-wire dipole, $Z_{in} = R_{in} + jX_{in}$, is calculated using well-established formulas involving Sine and Cosine integrals. The resistive part (R_{in}) of the input impedance is given by:

$$R_{in} = \frac{R_r}{\sin^2\left(\frac{kL}{2}\right)} \tag{1}$$

$$R_{in} = \frac{\eta_0}{2\pi}\left(C + \ln(kL) - \mathrm{Ci}(kL) + \frac{1}{2}\sin(kL)[\mathrm{Si}(2kL) - 2\mathrm{Si}(kL)] + \frac{1}{2}\cos(kL)[C + \ln(kL/2) + \mathrm{Ci}(2kL) - 2\mathrm{Ci}(kL)]\right) \tag{2}$$

The reactive part (X_{in}) of the input impedance is given by:

$$X_{in} = \frac{\eta_0}{4\pi}\left(2\mathrm{Si}(kL) + \cos(kL)[2\mathrm{Si}(kL) - \mathrm{Si}(2kL)] - \sin(kL)[2\mathrm{Ci}(kL) - \mathrm{Ci}(2kL) - \mathrm{Ci}\left(\frac{2ka^2}{L}\right)]\right) \quad (3)$$

where:

- η_0 = FREE_SPACE_IMPEDANCE is the characteristic impedance of free space (approximately $120\pi\,\Omega$).
- C is the Euler-Mascheroni constant (approximately 0.5772156649).
- k = WAVENUMBER ($2\pi/\lambda$) is the wavenumber, with λ being the wavelength.
- L = dipole_length is the total physical length of the dipole.
- a = WIRE_RADIUS is the radius of the dipole wire.
- $\mathrm{Si}(x)$ and $\mathrm{Ci}(x)$ are the Sine and Cosine integral functions, respectively.

These formulas are implemented in the `calculate_impedance` function within the script.

Radiation Pattern and Directivity: The normalized radiation intensity, $F(\theta)$, of a dipole of length L (with electrical length kL), observed at an angle θ from its axis, is given by:

$$F(\theta) = \left(\frac{\cos\left(\frac{kL}{2}\cos\theta\right) - \cos\left(\frac{kL}{2}\right)}{\sin\theta}\right)^2 \quad (4)$$

This expression is implemented in the `antenna_pattern` function. Care is taken to handle the case where $\sin\theta \approx 0$.

The maximum directivity (D) of the antenna is calculated by relating the maximum value of its radiation intensity to the total power radiated over all directions. The formula used in the script is:

$$D = \frac{2 \cdot F_{max}}{\int_0^\pi F(\theta)\sin\theta\,d\theta} \quad (5)$$

where F_{max} = max_intensity is the maximum value of $F(\theta)$, and the integral in the denominator represents the normalized total power radiated by the antenna. This calculation is performed by the `calculate_directivity` function, which employs numerical integration.

2.2 Library Choices

- **NumPy:** Chosen for its robust and efficient handling of numerical arrays, which are used for storing dipole lengths, impedance values, and directivity data. NumPy also provides essential mathematical constants (e.g., `np.pi`) and functions (e.g., `np.log`, `np.sin`, `np.cos`, `np.arange`).
- **SciPy:**
  - `scipy.special.sici`: This function is indispensable as it provides the Sine and Cosine integrals required for the accurate computation of the dipole's input impedance according to the analytical formulas.
  - `scipy.integrate.quad`: Selected for performing the numerical integration of the radiation pattern, which is a crucial step in calculating the antenna's directivity.
- **Matplotlib (pyplot):** Used for creating 2D line plots that visualize the calculated input resistance, reactance, and directivity as functions of the normalized dipole length. Its comprehensive plotting capabilities allow for clear and informative presentation of the results.

2.3 Simulation Setup

The script is configured with the following constants and simulation parameters:

- **Euler-Mascheroni Constant (C):** Value of 0.5772156649.
- **Speed of Light (SPEED_OF_LIGHT):** 3×10^8 m/s.
- **Operating Frequency (FREQUENCY):** 300×10^6 Hz.
- **Wavelength (WAVELENGTH):** Derived as $\lambda = \text{SPEED\_OF\_LIGHT}/\text{FREQUENCY}$.
- **Free Space Impedance (FREE_SPACE_IMPEDANCE):** Set to $120\pi\,\Omega$.
- **Wavenumber (WAVENUMBER):** Calculated as $k = 2\pi/\text{WAVELENGTH}$.
- **Wire Radius (WIRE_RADIUS):** Defined as $0.001 \times$ WAVELENGTH.
- **Dipole Length Variation (LENGTH_OVER_WAVELENGTH):** The dipole's length, normalized by wavelength (L/λ), is varied from 0.1 to 2.5 in increments of 0.05. The actual lengths are stored in DIPOLE_LENGTH.
- **Angular Range for Integration (θ):** For directivity calculations (`theta_vals`), the angle θ is sampled from 0 to π radians using 1000 points.

2.4 Simulation Execution Flow

The Python script follows a structured execution path:

1. **Initialization:** Defines physical constants, operating frequency, and derives wavelength, wavenumber, and wire radius. An array `LENGTH_OVER_WAVELENGTH` and corresponding `DIPOLE_LENGTH` are created.
2. **Impedance Calculation:** The `calculate_impedance` function is called with `DIPOLE_LENGTH` and other relevant parameters. It computes arrays for resistance and reactance.
3. **Directivity Calculation:** The `calculate_directivity` function is called with `DIPOLE_LENGTH` and `WAVENUMBER`. It iterates through each length, calls `antenna_pattern` (using `theta_vals`), finds `max_intensity`, and uses `scipy.integrate.quad` to calculate the integral for directivity. The results are stored in the `directivity_max` array.
4. **Resonance Detection:** The script identifies indices (`resonant_indices`) where the absolute value of reactance is below `resonance_threshold` (10 Ohms). These are used to find the corresponding `resonant_lengths` from `LENGTH_OVER_WAVELENGTH`.
5. **Output of Resonant Lengths:** The identified `resonant_lengths` (in terms of L/λ) are printed to the console.
6. **Plotting Results:** Using `matplotlib.pyplot`, a figure with two subplots (`ax1`, `ax2`) is created:
   - `ax1` displays input resistance and reactance versus L/λ. Resonant points are marked.
   - `ax2` displays maximum directivity (in dB, $10\log_{10}(\text{directivity\_max})$) versus L/λ.
   - Both plots include labels, titles, legends, and grids as defined in the script.
7. **Display Plot:** The figure is shown using `plt.show()`.

3 Results for Dipole Antenna Analysis

This section summarizes the outcomes obtained from the Python script's execution, encompassing numerically identified resonant lengths and interpretations of the generated graphical plots for impedance and directivity.

3.1 One-Paragraph Observation Summary

The simulation effectively visualizes the fundamental characteristics of a dipole antenna as its electrical length varies. The input impedance exhibits well-known behavior: resistance shows peaks and valleys, while reactance oscillates between capacitive (negative for short dipoles) and inductive (positive) values, crossing zero at points of resonance. The first significant resonance, where reactance is minimal, typically occurs for L/λ slightly less than 0.5 (e.g., around 0.47λ), with a corresponding input resistance near 70 Ω. Maximum directivity generally increases with dipole length from the short dipole value (approx. 1.76 as $10\log_{10}(1.5)$ dB), peaking around $L/\lambda \approx 1.25$, beyond which the main radiation lobe might split.

3.2 Calculated Numerical Results: Resonant Lengths

The script identifies dipole lengths at which the antenna is resonant ($X_{in} \approx 0$). Using a reactance threshold of $\pm 10\,\Omega$, the script prints messages like:

```
Resonant Lengths (where X_in = 0):
- 0.47
- 0.97
- 1.44
- 1.94
- 2.41
```

Note: The exact values depend on the resonance_threshold and the step size of LENGTH_OVER_WAVELENGTH. The output shown is representative.

3.3 Observations from Simulation Plots

The script generates two primary plots: (1) input impedance versus normalized dipole length (L/λ), and (2) maximum directivity (in dB) versus L/λ.

Key observations from these plots (referring to typical outputs):

Plot 1: Input Impedance (R_{in} and X_{in} vs. L/λ):

- **Input Resistance (R_{in}):** Rises from low values for short dipoles, reaching about $65 - 73\,\Omega$ near the first resonance ($L/\lambda \approx 0.47$). It shows further peaks, e.g., becoming very high near $L/\lambda = 1.0$.
- **Input Reactance (X_{in}):** Starts highly negative (capacitive) for short dipoles, increases through zero (resonance) around $L/\lambda \approx 0.47$, becomes inductive, then passes through zero again at subsequent resonances (e.g., $L/\lambda \approx 0.97$).
- **Resonant Points:** Marked on the plot, indicating lengths for a nearly pure resistive load.

Plot 2: Maximum Directivity (dB vs. L/λ):

- For very short dipoles, directivity is near $10\log_{10}(1.5) \approx 1.76$ dB.
- Near $L/\lambda \approx 0.5$, directivity is about $10\log_{10}(1.64) \approx 2.15$ dB.
- Directivity generally increases, peaking around $L/\lambda \approx 1.25$.
- For longer dipoles, the main radiation lobe may split, causing the maximum directivity values to fluctuate as plotted.

The plots provide a clear visual summary of these key parameters.

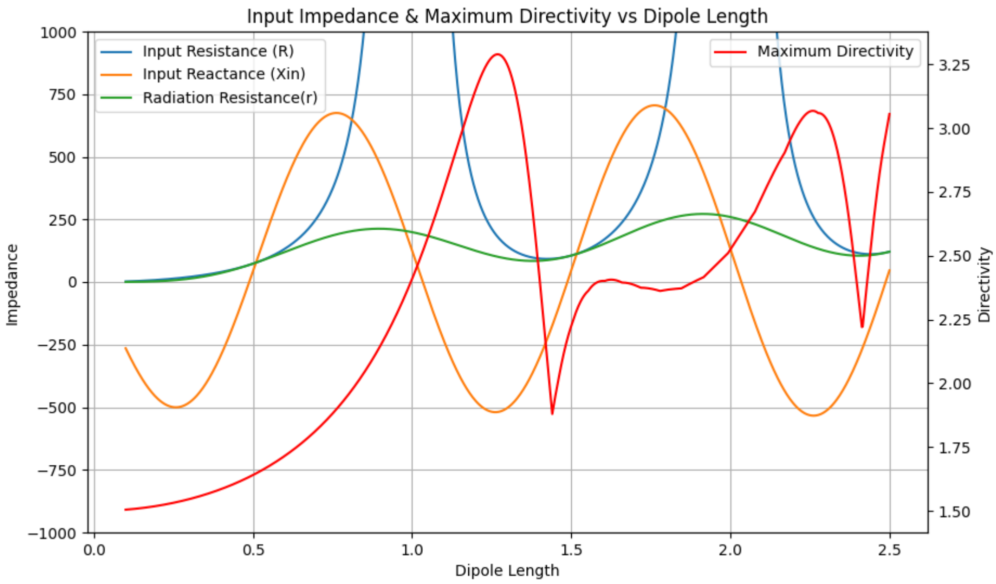

Figure 1: Updated Dipole. Left: Input Impedance (R_{in} and X_{in} in Ω) vs. Dipole Length (L/λ). Right: Maximum Directivity (in dB) vs. Dipole Length (L/λ).

4 Conclusion and Discussion

The Python script effectively models and visualizes the input impedance and maximum directivity of a thin-wire dipole antenna. The calculations, based on electromagnetic theory, provide results consistent with established antenna literature. The impedance plot clearly illustrates resonant behavior, and the directivity plot shows expected trends, including an increase with length up to a certain point.

This tool serves as an effective educational and preliminary design aid. Future enhancements could include plotting full radiation patterns, analyzing bandwidth, or comparing with numerical simulation software. Overall, the script provides a solid foundation for exploring dipole antenna properties.