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Analytical Modeling of Antenna Near-Field Characteristics and Their Application in the Uniform Theory of Diffraction

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Abstract
Accurate prediction of electromagnetic fields in the vicinity of radiating antennas is a fundamental requirement in modern communication, radar, and sensing systems. The near- field region of an antenna is characterized by strong reactive fields, rapid spatial variations, and complex coupling mechanisms that cannot be accurately described using far-field approximations. Analytical modeling of antenna near-field characteristics therefore plays a crucial role in understanding electromagnetic behavior in complex environments, especially when obstacles and diffracting structures are present. The Uniform Theory of Diffraction (UTD) provides a powerful high-frequency asymptotic framework for modeling wave propagation and diffraction around objects with edges, wedges, and curved surfaces. However, conventional UTD formulations primarily rely on far-field assumptions of the incident wave. Integrating accurate antenna near-field models into the UTD framework significantly enhances prediction accuracy in realistic scenarios such as urban propagation, antenna placement near structures, and electromagnetic compatibility analysis. This study presents an analytical study of antenna near-field characteristics and their application within the UTD framework. The formulation of near-field electromagnetic components is discussed, followed by their coupling with UTD diffraction mechanisms. The study highlights the advantages of near-field-based UTD modeling for precise field prediction in complex electromagnetic environments.
Keywords: *Antenna near-field analysis; Uniform Theory of Diffraction (UTD); Electromagnetic field modeling; High-frequency wave propagation*

I. Introduction

Antennas act as transducers that convert guided electromagnetic energy into radiated waves and vice versa. Depending on the distance from the antenna, the surrounding space is divided into the reactive near-field, radiating near-field (Fresnel region), and far-field (Fraunhofer region). In the near-field region, electromagnetic fields exhibit strong spatial dependence, non-uniform phase distribution, and significant electric–magnetic field coupling.

Traditional antenna analysis often emphasizes far-field radiation patterns due to their simplicity and relevance in long-range communication. However, many practical applications—such as antenna placement on platforms, near-field measurements, electromagnetic interference (EMI), and wireless channel modeling—require accurate near- field predictions. Analytical modeling of near-field behavior becomes essential for these applications.

The Uniform Theory of Diffraction extends geometrical optics by incorporating diffraction effects from edges and discontinuities. UTD is widely used for high-frequency electromagnetic analysis in complex environments. When antennas are located close to diffracting objects, the incident field on these objects lies within the near-field region rather than the far-field. In such cases, classical UTD formulations lead to inaccuracies unless near- field characteristics are properly included.

Basic Radiated Field Expression

The time-harmonic electric field radiated by an antenna element can be expressed as:

$$\mathbf{E}(\mathbf{r}) = \frac{j\omega\mu}{4\pi}\int_V \mathbf{J}(\mathbf{r}')\frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|}\,dV'$$

Where

$\mathbf{J}$ = current density distribution,

k = wave number,

ω = angular frequency.

This formulation forms the basis for near-field analytical modeling.

II. Analytical Description of Antenna Near-Field Region

The near-field region is dominated by reactive energy storage rather than radiation. The field components decay rapidly with distance and show non-propagating characteristics.

Near-Field Distance Criterion

$$R < \frac{2D^2}{\lambda}$$

where

R = distance from antenna,

D = maximum antenna dimension,

λ = wavelength.

In this region, the electric and magnetic fields are not orthogonal, and their magnitudes do not follow the inverse distance law.

Near-Field Electric and Magnetic Fields

$$|\mathbf{E}_{NF}| \propto \frac{1}{R^3}, \quad |\mathbf{H}_{NF}| \propto \frac{1}{R^2}$$

These higher-order terms dominate near the antenna and must be retained in analytical modeling.

III.Uniform Theory of Diffraction: Analytical Framework

The Uniform Theory of Diffraction provides a uniform solution to field discontinuities at shadow boundaries by introducing diffraction coefficients.

UTD Diffracted Field Expression

$$\mathbf{E}_d = \mathbf{E}_i \cdot D(\phi_i, \phi_d) \frac{e^{-jkL}}{\sqrt{L}}$$

where

$\mathbf{E}_i$ = incident field,

D = diffraction coefficient,

L = distance from diffraction point.

Classical UTD assumes that Ei\mathbf{E}_iEi is a plane wave or spherical far-field wave, which limits accuracy when antennas are close to diffracting objects.

IV.Integration of Near-Field Antenna Models with UTD

To overcome far-field limitations, near-field expressions of antenna radiation are incorporated into the UTD incident field formulation.

Near-Field Incident Wave Representation

$$\mathbf{E}_i^{NF}(\mathbf{r}) = \mathbf{E}_0 \left(\frac{1}{R} + \frac{1}{jkR^2} - \frac{1}{k^2 R^3} \right) e^{-jkR}$$

This modifiedincident field captures reactive and radiative components simultaneously, enabling accurate diffraction prediction in close-proximity scenarios.

V.Advantages of Near-Field-Based UTD Modeling

Incorporating near-field characteristics into UTD analysis provides several advantages:

a. Improved accuracy in antenna–structure interaction problems
b. Reliable field prediction in cluttered and confined environments
c. Enhanced modeling of electromagnetic compatibility and interference
d. Better agreement with experimental near-field measurements

Field Transition Relation

$$\mathbf{E}_{total} = \mathbf{E}_{direct}^{NF} + \mathbf{E}_{diffracted}^{UTD}$$

This superposition ensures continuity from near-field to diffracted regions.

VI.Representative Figures

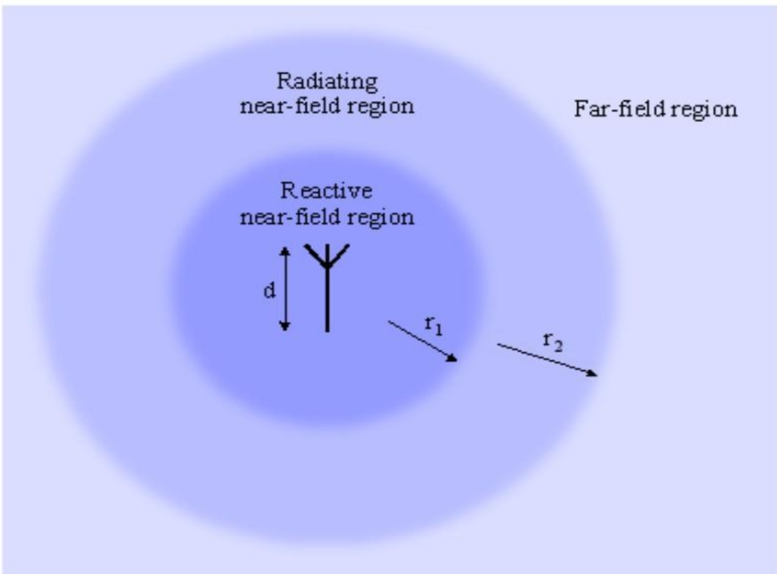

Figure 1: *Antenna near-field and far-field regions*

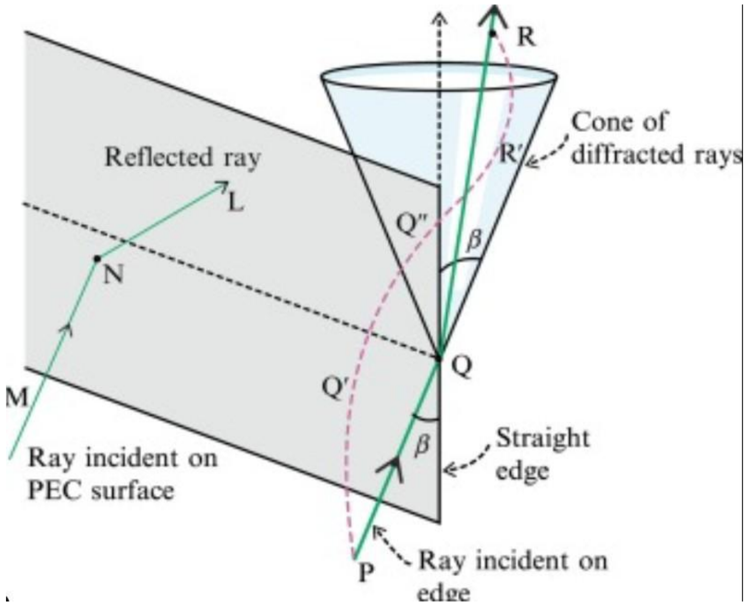

Figure 2: *Geometry of diffraction in UTD*

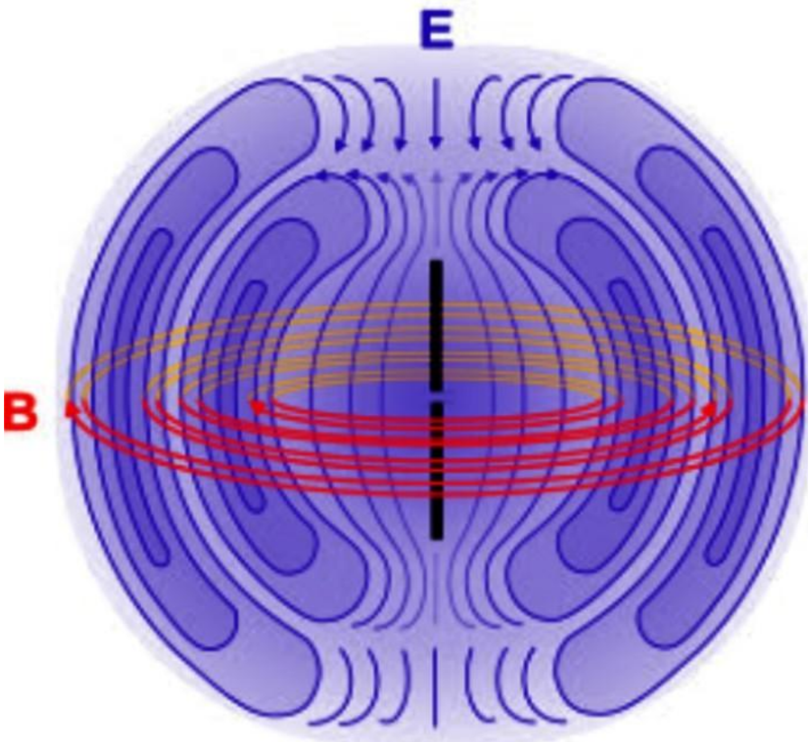

Figure 3: *Interaction of antenna near-field with diffracting edge*

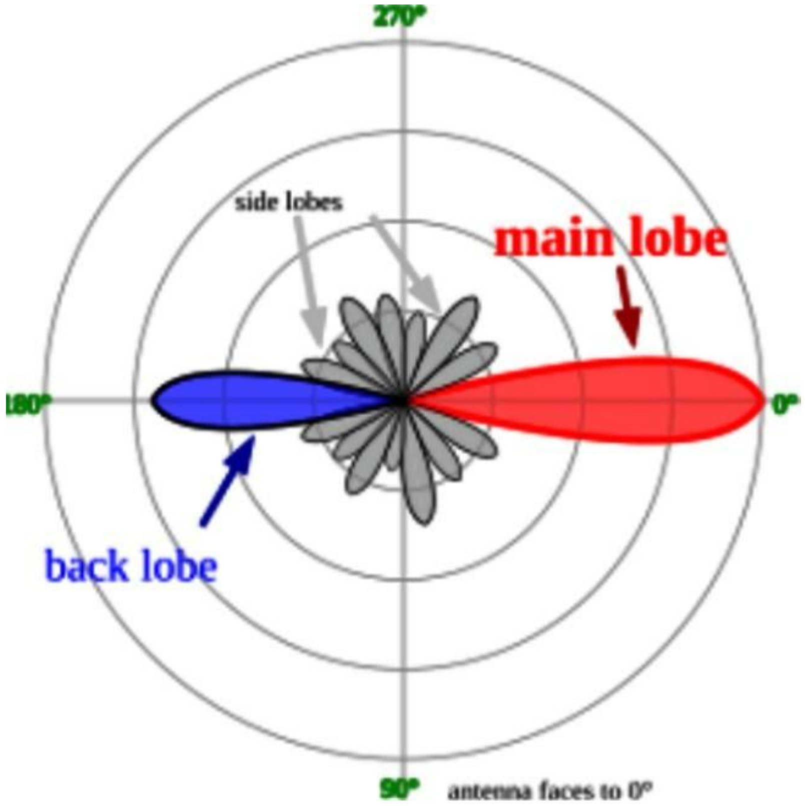

Figure 4: *Combined near-field antenna radiation and UTD-based diffracted field model for accurate electromagnetic field prediction in complex environments.*

VII. Conclusion

This analytical study demonstrates the importance of accurately modeling antenna near-field characteristics for reliable electromagnetic field prediction in complex environments. Near-field regions exhibit strong reactive behavior and spatial non-uniformity, which cannot be neglected when antennas operate in close proximity to diffracting objects. The Uniform Theory of Diffraction, while highly effective for high-frequency wave propagation, requires modification when applied to near-field excitation conditions.

By integrating analytical near-field antenna models into the UTD framework, the accuracy of diffraction-based predictions is significantly enhanced. This approach bridges the gap between rigorous electromagnetic theory and practical engineering applications, making it valuable for antenna design, electromagnetic compatibility studies, and advanced wireless propagation modeling. The methodology provides a robust foundation for future developments in hybrid analytical–asymptotic electromagnetic techniques.

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