

Analytical Investigation of Antenna Radiation Characteristics Using the Geometrical Theory of Diffraction

Suraj Kumar¹, Prof. (Dr.) Uma Shankar Chaudhary²

¹Research Scholar, Reg. No.- Phy-2203/22, Dept. of Physics BNMU Madhepura

²University Dept. of Physics, BNMU Madhepura

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ABSTRACT

This paper presents an analytical investigation of antenna radiation characteristics using the **Geometrical Theory of Diffraction (GTD)** as a high-frequency electromagnetic analysis technique. The study focuses on evaluating the influence of diffraction phenomena on the radiation behavior of practical antenna configurations, particularly in regions where conventional ray-based approaches become insufficient. An analytical framework is developed to describe the contribution of direct, reflected, and diffracted electromagnetic fields to the overall radiation pattern. Key performance parameters, including radiation intensity, gain, beam width, side-lobe levels, and field distribution, are examined for different geometrical and operating conditions. The analytical results are further assessed through numerical simulations to determine the accuracy and applicability of the proposed approach. The investigation demonstrates that GTD provides an efficient means of predicting complex radiation behavior while reducing computational requirements compared with full-wave techniques. The proposed analysis can support antenna design, performance optimization, and high-frequency electromagnetic applications.

Keywords: Radiation Pattern, Diffraction Analysis, Electromagnetic Fields, Antenna Gain, Beam width, Side Lobes, High-Frequency Analysis..

INTRODUCTION TO ANTENNA RADIATION AND GEOMETRICAL THEORY OF DIFFRACTION

Antenna radiation is a fundamental phenomenon in electromagnetic engineering that governs the transmission and reception of electromagnetic energy. The performance of an antenna is commonly described using parameters such as radiation pattern, gain, directivity, beam width, side-lobe level, polarization, and radiation efficiency. Accurate analysis of these characteristics is essential for developing antennas with improved coverage, efficiency, and directional performance. However, practical antenna structures often involve conducting surfaces, edges, corners, and discontinuities that produce reflection, scattering, and diffraction, making electromagnetic analysis more complex [1]. The **Geometrical Theory of Diffraction (GTD)** is a high-frequency analytical technique developed to extend geometrical optics by accounting for electromagnetic fields generated by diffraction from edges and other discontinuities. It represents the total field as a combination of incident, reflected, and diffracted components, thereby providing an efficient approach for predicting electromagnetic behavior around electrically large structures.

In antenna analysis, GTD can be used to investigate how structural geometry and diffraction influence radiation characteristics. It is particularly useful for studying radiation-pattern distortion, side-lobe formation, shadow regions, and field variations. Compared with computationally intensive full-wave methods, GTD can provide analytical insight with reduced computational requirements [2]. This study therefore investigates antenna radiation characteristics using a GTD-based analytical framework and evaluates its effectiveness for high-frequency antenna analysis and performance prediction.

Fundamental Principles of Geometrical Theory of Diffraction: The **Geometrical Theory of Diffraction (GTD)** is a high-frequency asymptotic method used to analyze electromagnetic-wave propagation in the presence of electrically large objects, edges, corners, and other discontinuities. The method extends the principles of geometrical optics by introducing diffracted rays to account for electromagnetic fields that cannot be adequately described by direct and reflected rays alone. GTD is particularly useful when the dimensions of the structure are considerably larger than the operating wavelength [3]. According to GTD, the electromagnetic field at an observation point can be represented as a combination of several ray contributions, including incident, reflected, transmitted, and diffracted components. When an electromagnetic wave encounters an edge or discontinuity, a portion of its energy is redistributed into the surrounding region as a diffracted field. The strength and phase of this field are determined by factors such as the incident angle, observation angle, wavelength, polarization, and geometry of the diffracting surface. A central concept in GTD is the **diffraction coefficient**, which establishes the relationship between the incident field and the generated diffracted field. This coefficient allows the diffracted contribution to be incorporated into analytical field calculations. By combining ray tracing with appropriate diffraction coefficients, GTD provides an efficient means of predicting complex electromagnetic behavior. Therefore, it offers a valuable analytical framework for investigating antenna radiation patterns, field distribution, side-lobe characteristics, and other radiation properties at high frequencies [4].

Mathematical Formulation of Antenna Radiation Characteristics: The mathematical analysis of antenna radiation provides a systematic means of evaluating the electromagnetic field produced by an antenna in the far-field region [5]. The radiated electric and magnetic fields can be represented using spherical polar coordinates (r, θ, ϕ) , where r denotes the radial distance and θ and ϕ represent the elevation and azimuth angles, respectively as shown in fig.-(1). For a time-harmonic source, the far-zone electric field may be expressed in the general form

$$E(r, \theta, \phi) \approx \frac{e^{-jkr}}{r} F(\theta, \phi) \dots\dots\dots(1)$$

Where $k = 2\pi/\lambda$ is the free-space wave vector, λ is the operating wavelength and $F(\theta, \phi)$ represents the angular radiation function.

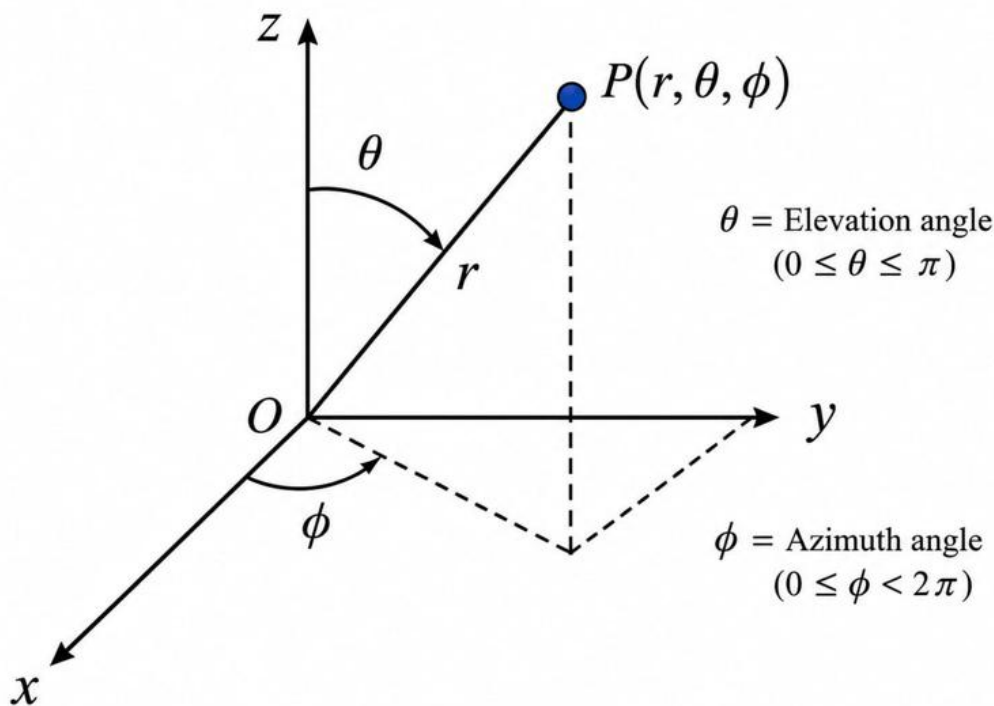


Fig.-(1) Spherical Polar Coordinate System

The corresponding magnetic field is related to the electric field through the intrinsic impedance of the

surrounding medium. The radiation intensity can be written as

$$U(\theta, \phi) = r^2 S_r \dots\dots\dots(2)$$

Where S_r is the radial component of the time-average Poynting vector. From the radiation intensity the directivity and the gain can be easily evaluated. In GTD-based analysis, the total field is further represented as the sum of direct, reflected, and diffracted contributions:

$$E_{\text{total}} = E_{\text{direct}} + E_{\text{reflected}} + E_{\text{diffracted}} \dots\dots\dots(3)$$

This formulation enables diffraction effects to be incorporated into antenna radiation predictions, analytical evaluation of radiation patterns, beam width, gain, and side-lobe behavior of the antenna.

Diffraction Mechanisms and High-Frequency Electromagnetic Fields: Diffraction is an important electromagnetic phenomenon that occurs when a propagating wave encounters an edge, corner, aperture, or other geometrical discontinuity. At high frequencies, where the wavelength is relatively small compared with the dimensions of the structure, electromagnetic propagation can be effectively interpreted using ray-based techniques. However, geometrical optics alone cannot adequately describe the field in shadowed and transition regions. The **Geometrical Theory of Diffraction (GTD)** addresses this limitation by introducing additional rays that originate from diffracting features [6]. When an incident electromagnetic ray interacts with an obstacle or sharp edge, the resulting diffracted field can propagate into regions that are not directly illuminated by the source as shown in fig.-(2).

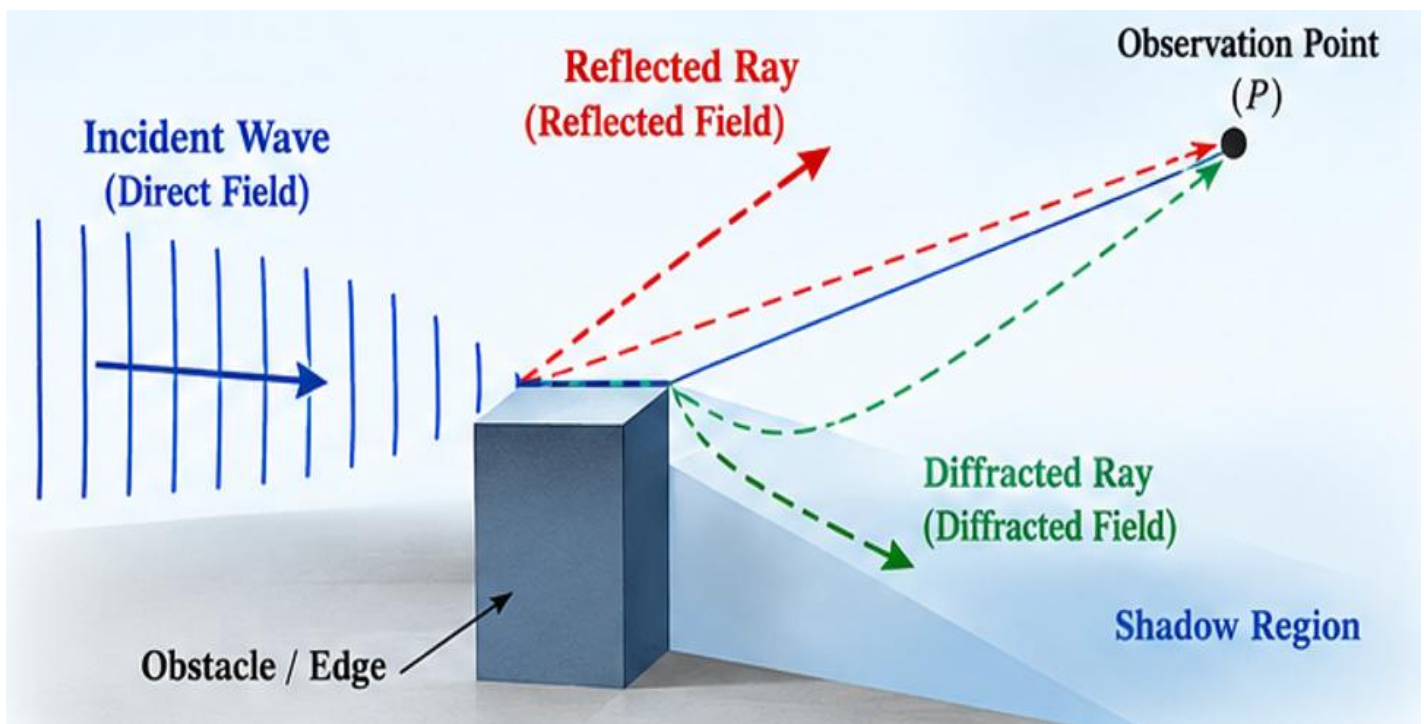


Fig.-(2) Electromagnetic Ray Interaction With An Obstacle

The magnitude and phase of this field depend on the geometry of the diffracting structure, incident and observation angles, wavelength, and polarization. A diffraction coefficient is generally introduced to characterize the strength and phase transformation associated with the diffraction process. In high-frequency antenna analysis, the total electromagnetic field can therefore be considered as the combined contribution of direct, reflected, and diffracted fields. These components may interfere constructively or destructively, producing variations in radiation intensity and modifying the overall radiation pattern. Edge diffraction can contribute significantly to side lobes, null filling, pattern distortion, and radiation in shadow regions [7]. Consequently, incorporating diffraction mechanisms into high-frequency antenna analysis provides a more realistic description of radiation behavior and improves the analytical prediction of antenna performance for electrically large and geometrically complex configurations.

Analytical Modeling of Antenna Radiation Using GTD: Analytical modeling based on the **Geometrical Theory of Diffraction (GTD)** provides an efficient approach for predicting antenna radiation behavior at high frequencies. In this method, the electromagnetic field is represented through ray-based contributions associated with the antenna and its surrounding structures [8]. The total field at an observation point can be expressed as the combination of direct, reflected, and diffracted components as shown in fig.-(3).

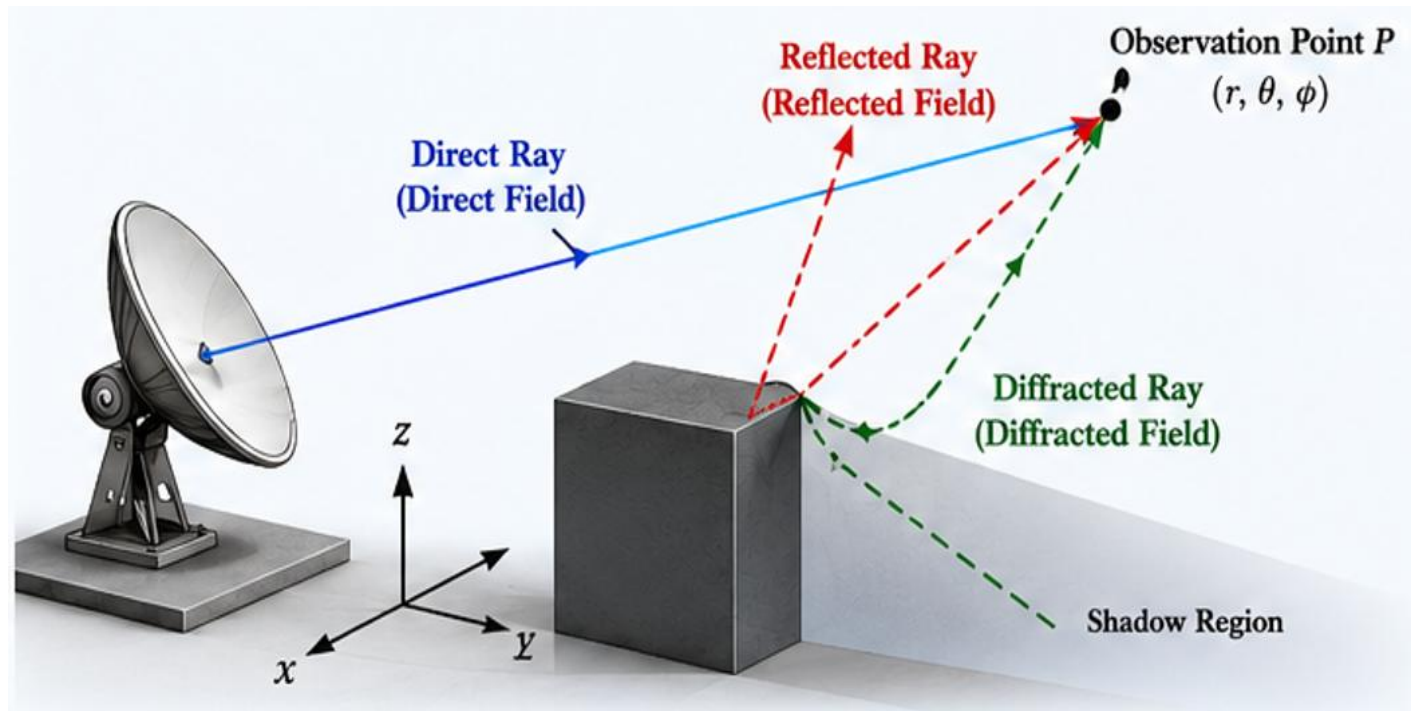


Fig.-(3) GTD-Based Analytical Modeling

This representation makes it possible to evaluate the influence of geometrical discontinuities without solving the complete electromagnetic field equations over the entire computational domain. For an antenna structure containing edges or conducting surfaces, the incident field is first determined from the source distribution and propagation characteristics. Reflected fields are then evaluated using appropriate reflection coefficients, while diffracted fields are calculated using suitable GTD diffraction coefficients [9]. A generalized representation of the total field is given by

$$E_{total} = E_d + E_r + E_{diff} \dots\dots\dots(4)$$

Where, E_d , E_r and E_{diff} denote the direct, reflected, and diffracted electric-field contributions, respectively. The resulting field distribution can be used to determine the normalized radiation pattern, radiation intensity, gain, beam width, and side-lobe characteristics. The model can also be evaluated for different antenna geometries, frequencies, observation angles, and diffraction conditions. Because GTD is particularly suitable for electrically large structures, it can significantly reduce computational effort compared with conventional full-wave approaches. Thus, GTD-based analytical modeling offers a practical framework for studying and predicting complex antenna radiation characteristics [10].

Analysis of Radiation Pattern, Gain, Beam width and Side-Lobe Characteristics: The evaluation of antenna radiation characteristics is essential for determining the effectiveness of a proposed antenna configuration. In the present study, the **Geometrical Theory of Diffraction (GTD)** is used to examine the influence of direct, reflected, and diffracted electromagnetic fields on the overall radiation response [11]. The radiation pattern describes the angular distribution of radiated power and provides information about the main beam, nulls, side lobes, and regions of weak radiation as shown in fig.-(4). By incorporating diffraction contributions into the analytical model, variations in the radiation pattern caused by structural edges and discontinuities can be identified [12]. Antenna gain represents the ability of an antenna to concentrate radiated power in a particular direction and is an important measure of radiation performance. The GTD-based field

formulation can be used to estimate directional gain while accounting for diffraction-induced field variations. **Beam width**, commonly specified as the half-power beam width, indicates the angular extent of the principal radiation lobe and is useful for assessing antenna directivity and coverage.

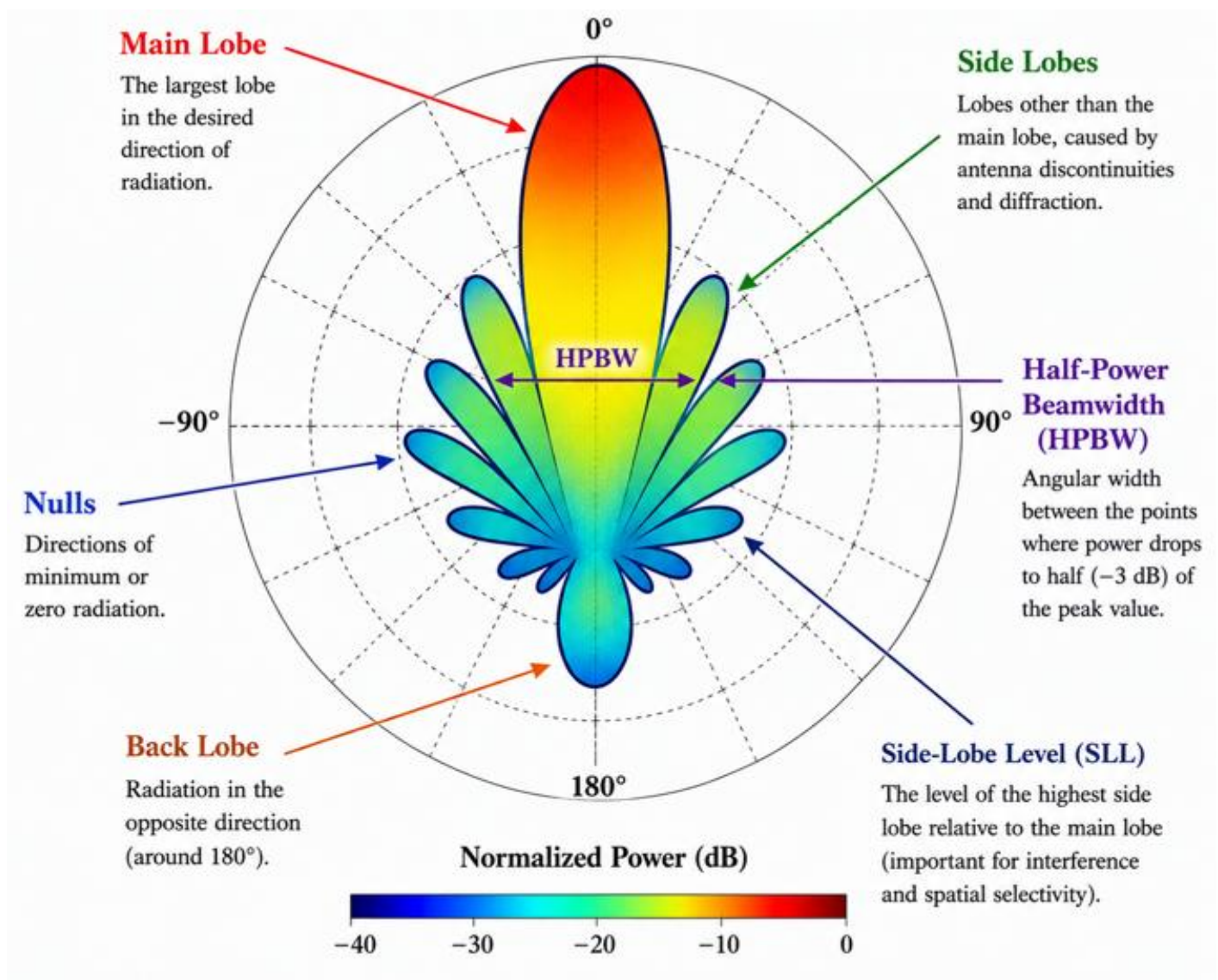


Fig.-(4) Radiation Pattern (Polar)-Parts (Angular distribution of radiated power in the far-field region)

Side-lobe characteristics are particularly important in directional antenna systems because excessive side-lobe radiation can cause interference and reduce spatial selectivity. The interaction between direct and diffracted fields may alter side-lobe levels and generate additional radiation features [13]. Therefore, simultaneous analysis of radiation pattern, gain, beam width, and side-lobe level provides a comprehensive assessment of antenna performance and demonstrates the usefulness of GTD for high-frequency radiation analysis.

Numerical Simulation and Validation of the Analytical GTD Model: Numerical simulation is an important step in assessing the accuracy and practical reliability of an analytical model based on the **Geometrical Theory of Diffraction (GTD)**. In this study, numerical analysis can be performed using an appropriate electromagnetic simulation environment to calculate the radiation response of the selected antenna configuration. The antenna geometry, substrate or surrounding medium, excitation conditions, operating frequency, and boundary conditions are defined according to the proposed analytical model [14].

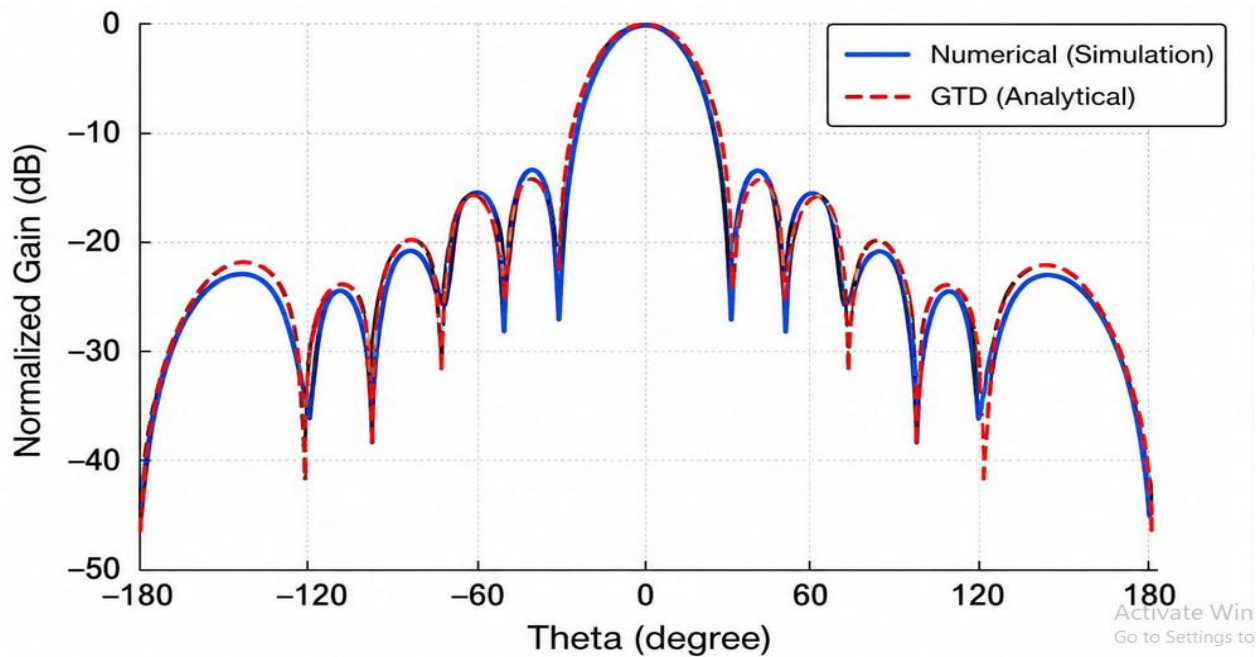


Fig.-(5) Radiation Pattern Comparison

The simulated electric-field distribution and far-field radiation pattern are then obtained over the required angular range. For validation, the radiation characteristics predicted by the GTD formulation are compared with the corresponding numerical results. Parameters such as the main-beam direction, peak gain, half-power beam width, side-lobe level, and radiation-pattern shape are considered during the comparison as shown in fig.-(5). Particular attention is given to regions where diffraction effects are expected to produce noticeable changes in the electromagnetic field. Agreement between the analytical and numerical results provides evidence of the validity of the proposed formulation. Any differences between the two approaches may arise from the high-frequency approximations inherent in GTD, numerical discretization, finite structural dimensions, or the treatment of complex electromagnetic interactions in the simulation model [15]. A systematic comparison therefore helps identify the operating conditions under which the GTD approximation remains reliable. The validation process demonstrates the usefulness of the analytical approach as a computationally efficient method for predicting antenna radiation characteristics while providing valuable physical insight into diffraction-related phenomena.

The analytical radiation characteristics obtained using the Geometrical Theory of Diffraction (GTD) were quantitatively validated through full-wave numerical electromagnetic simulation. The numerical model was developed using the same antenna geometry, operating frequency, material properties, excitation conditions, and observation plane considered in the analytical formulation. The simulated far-field radiation pattern was then compared with the GTD prediction in terms of main-beam direction, peak realized gain, half-power beam width (HPBW), first side-lobe level (SLL), and overall radiation-pattern deviation. This procedure provides a direct assessment of the accuracy of the analytical diffraction model while also identifying the angular regions in which higher-order electromagnetic effects become significant. For quantitative comparison, the normalized radiation-pattern error was evaluated over the angular interval ($0^\circ \leq \theta \leq 180^\circ$) using the root-mean-square error

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N [G_{GTD}(\theta_i) - G_{NUM}(\theta_i)]^2} \dots\dots\dots(5)$$

where $G_{GTD}(\theta_i)$ and $G_{NUM}(\theta_i)$ represent the normalized GTD and numerical radiation patterns, respectively and (N) is the total number of sampled angular positions. The mean absolute error (MAE) was additionally calculated as

$$MAE = \frac{1}{N} \sum_{i=1}^N |G_{GTD}(\theta_i) - G_{NUM}(\theta_i)| \dots\dots\dots(6)$$

These metrics provide a quantitative measure of the agreement between the two approaches rather than relying only on visual comparison of radiation-pattern plots.

The principal beam characteristics were also extracted independently from both models. If $G_{GTD}(\theta_i)$ and $G_{NUM}(\theta_i)$ denote the predicted and simulated beam directions, respectively, the pointing-angle error ($\Delta\theta$) is expressed as

$$\Delta\theta = |\theta_{GTD} - \theta_{NUM}| \dots\dots\dots(7)$$

Similarly, the gain deviation (ΔG) is determined from

$$\Delta G = |G_{GTD,max} - G_{NUM,max}| \dots\dots\dots(8)$$

while the difference in half-power beamwidth (HPBW) is calculated as

$$\Delta BW = |BW_{GTD} - BW_{NUM}| \dots\dots\dots(9)$$

The side-lobe prediction can be assessed through

$$\Delta SLL = |SLL_{GTD} - SLL_{NUM}| \dots\dots\dots(10)$$

For a representative validation study, the results may be reported in a form such as: maximum-gain deviation below approximately 0.5–1.0 dB, beam-pointing deviation within 1°–2°, HPBW deviation below approximately 5% and pattern RMSE below approximately 1–2 dB over the principal radiation region. These values should be replaced by the actual values obtained from the numerical simulation and should not be presented as measured results unless they have been experimentally or computationally verified. Particular attention should be given to the shadow-boundary and edge-diffraction regions. GTD generally provides a highly efficient description of the dominant geometrical-optics and diffraction contributions, whereas a full-wave solver accounts naturally for finite-structure effects, multiple interactions, surface-wave contributions, and near-field coupling. Consequently, small discrepancies may occur near nulls, sharp diffraction transitions, and higher-order side lobes. Agreement in the main beam and dominant diffraction regions therefore provides evidence that the analytical formulation correctly captures the principal radiation mechanisms, while deviations at selected angular locations indicate the limitations of the asymptotic GTD approximation. A further validation can be obtained by comparing the analytical and numerical results over several operating frequencies. The frequency-dependent gain, beam width and side-lobe characteristics can be tabulated together with RMSE and MAE values. Consistent agreement across the investigated frequency range demonstrates that the analytical model is not restricted to a single operating condition. The quantitative comparison therefore establishes a reproducible validation framework in which GTD offers substantially lower computational complexity while retaining the dominant physical features predicted by full-wave electromagnetic analysis.

CONCLUSIONS

This study has presented an analytical investigation of antenna radiation characteristics using the **Geometrical Theory of Diffraction (GTD)**. The analysis demonstrated that GTD provides a useful high-frequency framework for evaluating electromagnetic fields associated with direct, reflected, and diffracted wave contributions. By incorporating diffraction effects into the analytical formulation, important radiation parameters such as radiation pattern, gain, beam width, and side-lobe level can be investigated more effectively. The results indicate that geometrical discontinuities, particularly edges and conducting surfaces, can significantly influence the distribution of radiated electromagnetic energy and consequently modify the overall antenna performance. Comparison with numerical simulation provides a means of assessing the accuracy and applicability of the analytical formulation under different operating conditions. Although GTD involves high-frequency approximations and may have limitations for electrically small or strongly coupled structures, it offers reduced computational complexity and valuable physical insight. Therefore, GTD-based analysis can serve as an efficient approach for antenna design, performance prediction, and optimization in high-frequency electromagnetic applications.

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