

Design of a Computationally Efficient High Accuracy Ray-Tracing Engine

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Ray-tracing engines have been a cornerstone of deterministic radio propagation prediction since the 1990s and continue to be widely employed, particularly due to advancements in computational technologies such as high-performance computing, GPUs, and artificial intelligence. These engines are extensively applied across various domains within the electromagnetic community, including wireless propagation, optical antenna design, and radar cross-section estimation. Their computational efficiency in electrically large environments positions them as a favourable alternative to both extensive measurement campaigns and other deterministic simulation methods, such as FDTD, MoM, and FEM. Nevertheless, achieving the dual objectives of high accuracy and low computational load remains a significant challenge, particularly in scenarios involving complex electromagnetic phenomena, including diffraction, transmission, and scattering (Schweins *et al.*, IEEE Open J. Antennas Propag., **5**(2), 2024, Azpilicueta *et al.*, IEEE Trans. Antennas Propag., **7**(10), 2023, Seretis *et al.*, IEEE Trans. Antennas Propag., **70**(6), 2022.).

To reduce the computational burden, commercial and research ray-tracing engines often adopt assumptions about these phenomena and interaction orders, which can significantly degrade accuracy, particularly in deep shadow regions. This study validates the proposed model by implementing its enhanced 2D version and comparing its predictions against measurement data in five cities. The model achieves a high level of agreement with measurement data, with discrepancies of only 0.41 dB in LOS regions and 1.68 dB in reflected ray-dominated NLOS regions for these outdoor environments. This demonstrates our model's capability to provide accurate results while maintaining significantly reduced computational complexity. In specific outdoor environments, the performance is comparable to that of advanced 3D ray-tracing engines. Furthermore, the developed engine is versatile and can be effectively extended to 3D. These findings highlight our engine's capability to deliver accurate and efficient propagation predictions, contributing to the development of advanced ray-tracing tools for next-generation networks.

This study also proposes a novel approach that incorporates up to second-order diffraction using improved coefficients (Nechayev and Constantinou, IEE P-MICROW ANTEN P, **153**(2), 2006.) and/or slope diffraction with efficiently reduced intersection tests. This approach aims to mitigate discrepancies in deep shadow regions, a common issue even in advanced 3D engines. The proposed engine achieves computational feasibility without relying on hardware- or machine-learning-assisted acceleration by transforming the computational complexity of diffraction—typically exhibiting exponential growth with interaction order—into a linear relationship. Specifically, the simulation completes in 0.83 s for reflection-only cases. Using our algorithm, this increases to 7.92 s for first-order diffraction and 91 s for second-order diffraction. In contrast, a naive algorithm takes 57.44 s and >48 hours, respectively. This demonstrates that our method significantly improves both computational and memory efficiency without compromising accuracy. This significant advancement provides a scalable solution for scenarios that require high-order diffraction modeling, as well as for applications in dense urban environments with numerous diffraction candidates. On the other hand, the study extends its scope to the critical challenge of outdoor-to-indoor propagation, a key area in propagation research. It focuses on transmission effects through glass panes rather than accounting for the entire structure. This approach not only reduces computational complexity but also ensures enhanced simulation capabilities.