A Survey of the Application of Ray-Tracing-Based Channel Modeling for Digital Twin Environments

Sehyun Ryu, Hyun Jong Yang*

POSTECH, *Seoul National Univ.

sh.ryu@postech.ac.kr, *hjyang@snu.ac.kr

디지털 트윈 환경에서의 레이 트레이싱 기반 채널 모델링 활용에 대한 동향 조사

류세현, 양현종*

포항공과대학교, *서울대학교

Abstract

This paper surveys the role and importance of ray-tracing-based channel modeling in emerging digital twin environments, with particular emphasis on recent developments led by NVIDIA, and discusses how such techniques are utilized in existing research as well as how they can be extended to guide future research directions.

Ⅰ. Introduction

Conventional research and standardization in wireless communications have predominantly relied on statistical channel models. Representative examples include Rayleigh fading for rich scattering environments without a dominant line-of-sight (LoS) component, Rician fading for scenarios with a strong LoS path, Nakagami fading as a flexible model encompassing a wide range of fading conditions, and Jakes' model for characterizing Doppler-induced temporal channel variations. Owing to their analytical tractability and simplicity, these models have been widely adopted in both theoretical analysis and system-level evaluation.

However, statistical channel models describe channel behavior in an averaged or probabilistic manner, limiting their ability to capture geometry-dependent variations caused by dynamic spatial and temporal changes, such as abrupt LoS blockage. While they can characterize attenuation and fading distributions, they do not explicitly model physical propagation mechanisms. To address these limitations, recent studies have increasingly explored ray-tracing (RT)-based channel modeling within digital twin environments, enabling deterministic characterization of time-varying wireless channels that accounts for the surrounding environment.

Recent progress in this research area has been supported by platforms developed by NVIDIA, including Sionna [1] and the Aerial Omniverse Digital Twin (AODT) [2], which have enabled systematic investigation of wireless systems in realistic environments. This paper reviews research trends leveraging Sionna and discusses their prospective applications.

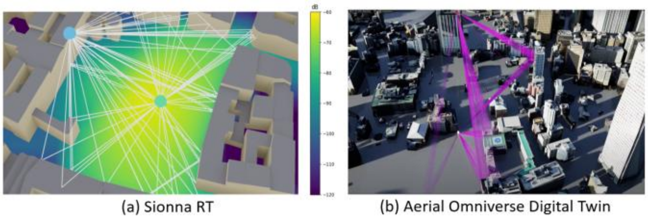

Fig 1. Illustration of RT-based channel extraction using NVIDIA Sionna and AODT.

Ⅱ. Research on Sionna-Based Ray-Tracing Channel Modeling

The authors of [3] exploited the capability of RT-based channel modeling to capture channel correlations arising from the shared physical environment between uplink and downlink channels. Based on this observation, they conducted a channel prediction study using Sionna-based simulations, in which downlink channel characteristics are inferred from uplink channel information. To this end, the authors proposed a Channel Prediction-based Reference Signal allocation (CPRS) framework that implicitly performs channel estimation and predicts an optimal demodulation reference signal (DM-RS) allocation from the uplink channel. The proposed framework is compliant with the 3GPP NR standard and aims to maximize downlink throughput through optimized DM-RS placement.

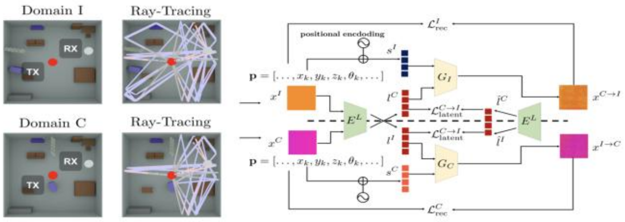

Fig 2. RT-based data augmentation pipeline and network architecture employed in RT-AugGAN.

In the RT-AugGAN [4], the authors addressed the inherent difficulty of acquiring comprehensive measured channel data that account for all possible physical environment variations in indoor scenarios. To mitigate this limitation, they proposed augmenting real-world measurement data with RT-based channel extraction performed in digital twin environments. Furthermore, as discussed in [5], the authors employed generative models to synthesize channel data corresponding to unseen physical environments that are not explicitly represented even within the digital twin, and validated the effectiveness of the generated data.

Ⅲ. Prospective Application Directions

In studies on channel state information (CSI) compression, such as [6], RT-based channel data are expected to provide more realistic performance evaluation, as they better reflect the underlying physical characteristics of real wireless channels compared to purely statistical models. Similarly, in weighted sum-rate (WSR) optimization studies for millimeter-wave (mmWave) reconfigurable intelligent surface (RIS) systems, such as [7], channel behavior is highly dependent on environmental geometry. In this context, leveraging RT-based channel modeling can enable more realistic and geometry-aware channel evaluation, thereby improving the fidelity of performance assessment.

Furthermore, in integrated sensing and communications (ISAC) research following the line of work in [8], RT-based channel data can be leveraged to enable the development and validation of algorithms tailored to realistic channel characteristics prior to costly real-world data collection, potentially reducing development cost and effort. In such scenarios, to protect sensitive user information embedded in channel data, privacy-preserving techniques—such as algorithmic approaches in [9] or reinforcement learning-based methods as in [10]—can be employed to ensure differential privacy guarantees.

Ⅳ. Conclusion

This paper surveyed recent research trends in RT-based channel modeling and discussed its potential applications. By capturing channel correlations arising from spatial and temporal variations, RT-based modeling provides a foundation for realistic and environment-aware wireless system research, and this survey aims to facilitate further studies that effectively leverage these characteristics.

ACKNOWLEDGMENT

This work was supported by the Institute of Information & Communications Technology Planning & Evaluation (IITP), funded by the Korean government (MSIT), under the 6G·Cloud Research and Education Open Hub (IITP-2025-RS-2024-00428780) and the Development of a 5G-Advanced vRAN Research Platform (RS-2024-00404972).

REFERENCES

[1] Hoydis, J., Cammerer, S., Aoudia, F.A., Vem, A., Binder, N., Marcus, G., and Keller, A, 2022. Sionna: An open-source library for next-generation physical layer research. arXiv.

[2] Cohen-Arazi, K., Roe, M., Hu, Z., Chavan, R., Ptasznik, A., Lin, J., Morais, J., Boccuzzi, J., Balercia, T, 2025. NVIDIA AI Aerial: AI-Native Wireless Communications. arXiv.

[3] Ryu, S. and Yang., H.J., 2025. Standards-Compliant DM-RS Allocation via Temporal Channel Prediction for Massive MIMO Systems, arXiv.

[4] Choi, J., Ryu, S., Choi, S. and Yang, H.J., 2025. RT-AUGGAN: Robust Fingerprint Positioning under Environmental Variations via Ray Tracing-Assisted GAN Augmentation. IEEE/IEIE International Conference on Consumer Electronics-Asia (ICCE-Asia), 2025.

[5] 류세현, 양현종, 2024. 무선 통신을 위한 생성형 모델 활용에 대한 동향. 한국통신학회지(정보와통신), 2024.

[6] Choi, S. Joo, H., Ryu, S., Melodia, T., and Yang, H.J., 2025. Performance-Guaranteed CSI Feedback via Model-Agnostic Incremental Residual Compression Framework. IEEE Wireless Communications Letters, 2025.

[7] Ryu, S., and Yang H.J., 2025. Blockage-Aware Multi-RIS WSR Maximization via Per-RIS Indexed Synchronization Sequences and Closed-Form Riemannian Updates. arXiv.

[8] Ouyang, C., Liu, Y., Yang, H., and Al-Dhahir, N., 2023. Integrated Sensing and Communications: A Mutual Information-Based Framework. IEEE Communications Magazine, 2023.

[9] Ryu, S., Jang, J., and Yang, H.J., 2024. Noise Variance Optimization in Differential Privacy: A Game-Theoretic Approach Through Per-Instance Differential Privacy. IEEE Access, 2024.

[10] Ryu, S., Joo, H., Jang, J., and Yang, H. J., 2024. Instance-Wise Laplace Mechanism via Deep Reinforcement Learning (Student Abstract). Proceedings of the AAAI Conference on Artificial Intelligence, 2024.