Towards Practical Cell-Free 6G Network Deployments: An Open-Source End-to-End Ray Tracing Simulator

Tärneberg, William; Fedorov, Aleksei; Callebaut, Gilles; van Der Perre, Liesbet; Fitzgerald, Emma

Published in:
2023 57th Asilomar Conference on Signals, Systems, and Computers

2023

Document Version:
Publisher's PDF, also known as Version of record

Towards Practical Cell-Free 6G Network Deployments: An Open-Source End-to-End Ray Tracing Simulator

William Tärneberg[1], Aleksei Fedorov[1], Gilles Callebaut[2], Liesbet Van der Perre[2], Emma Fitzgerald[1]
[1]Lund University, Department of Electrical and Information Technology, Sweden
s
[2]KU Leuven, Department of Electrical Engineering, 9000 Ghent, Belgium

Abstract—**The advent of sixth-generation (6G) wireless communication marks a transformative era in technological connectivity, bringing forth challenges and opportunities alike. This paper unveils an innovative, open-source simulator, meticulously crafted for cell-free 6G wireless networks. This simulator is not just a tool but a gateway to the future, blending cutting-edge channel models with the simulation of both physical propagation effects and intricate system-level protocols. It stands at the forefront of technological advancement by integrating large intelligent surface (LIS) and multiple-input multiple-output (MIMO) technologies, harnessing the power of the Unity game engine for efficient ray-tracing and graphical processing unit (GPU)-accelerated computations. The unparalleled flexibility in scenario configuration, coupled with its unique ability to dynamically simulate interactions across network layers, establishes this simulator as an indispensable asset in pioneering 6G systems' research and development.**

I. Introduction

The advent of 6G wireless networks heralds a transformative era in digital connectivity, characterized by ultra-low latency, high throughput, and enhanced reliability [1]. Such advancements demand innovative tools for simulation and analysis. In response, we present a novel, open-source simulator, specifically designed to tackle the complexities of cell-free 6G networks, particularly focusing on cell-free (CF) systems as a key radio access network (RAN) architecture. Drawing upon research like Fedorov et al. [2], our simulator (LuSim) aims to provide an in-depth analysis of network dynamics and channel behavior. The source code and documentation for LuSim are available on GitHub [3].

6GTandem has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101096302. The REINDEER project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101013425. William is partially supported by the Wallenberg AI, Autonomous Systems and Software Program (WASP) funded by the Knut and Alice Wallenberg Foundation, the SEC4FACTORY project, funded by the Swedish Foundation for Strategic Research (SSF), and Imminence, a Celtic Next project funded by Sweden's Innovation Agency (VINNOVA). The authors from Lund University are part of the Excellence Center at Linköping-Lund on Information Technology (ELLIIT), and the Nordic University Hub on Industrial IoT (HI2OT) funded by NordForsk. The work of Aleksei Fedorov within the SIVERT2 project is funded by Fordonsstrategisk forskning och innovation, FFI, and Sweden's Innovation Agency.

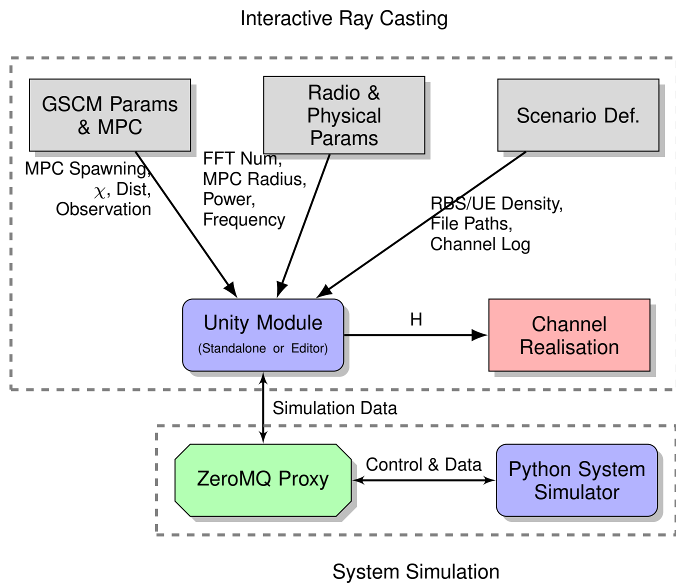

Fig. 1: System Architecture of the Wireless Network Simulator.

Unlike traditional systems such as WiThRay [4], QuaDRiGa [5, 6], and NVIDIA Sionna [7], our simulator integrates advanced geometry-based stochastic model (GSCM) and Exhaustive Ray Tracing methodologies. This integration allows for detailed and realistic simulations of wireless propagation in varied environments, from urban landscapes to indoor settings [8–12]. By leveraging the Unity game engine, the simulator efficiently handles complex ray-casting tasks, making use of GPU capabilities to serve the growing needs of researchers and engineers in this field.

A distinctive feature of our tool is the incorporation of machine learning and artificial intelligence, which enables dynamic adaptation to diverse 6G network scenarios and user behaviors. This allows for enhanced performance analysis and optimization, offering insights beyond the reach of conventional simulation models.

Our simulator's architecture is designed for flexibility and scalability, with externalized configurations and scenario definitions through JSON or YAML files. This modular approach supports a wide range of applications, including large-scale studies and sensitivity analyses. Furthermore, the simulator extends beyond its predecessors by including fully 3D indoor and cell-free scenarios, accommodating a large number of antennas and supporting studies on dynamic resource allocation.

The cross-layer capabilities of our simulator facilitate a seamless interplay between the physical and application layers, enabling applications like resource orchestration and data synthesis for machine learning. This versatility ensures that the simulator remains a vital tool for exploring, developing, and deploying CF-based 6G networks.

In summary, our simulator represents a significant advancement in the simulation of CF-based 6G networks. By combining the strengths of the Unity engine with a flexible and modular design, it offers a versatile platform for researchers and engineers, guiding the future of wireless communication technology.

The development of simulators for wireless environments is crucial for understanding and improving communication systems. A notable contribution in this domain is WiThRay, a versatile ray-tracing (RT) simulator, designed for smart wireless environments [4]. WiThRay specializes in generating channel data for performance evaluations of complex communication techniques, including channel estimation/tracking, beamforming, and localization. It employs a novel RT algorithm that follows Fermat's principle, reducing computational complexity, and includes features like scattering ray calibration and support for Reconfigurable Intelligent Surfaces (RIS) systems, making it highly relevant for 6G research.

In comparison, other simulators like NVIDIA Sionna and QuaDRiGa [5, 6] also make significant contributions to the field. NVIDIA Sionna, particularly noted for its comprehensive MIMO channel modeling capabilities, offers an in-depth analysis of wireless network performance. QuaDRiGa, with its focus on quasi-deterministic radio channel models, excels in large-scale parameter studies for mobile communication networks.

Our simulator distinguishes itself by integrating a broad range of cutting-edge technologies and methodologies, enabling comprehensive analyses of complex 6G network scenarios. It leverages the strengths of GSCMs, widely adopted in academia and industry, for efficient modeling of complex urban and indoor environments. This approach is augmented with advanced features like dynamic environmental interaction, superior system-level simulation capabilities, and support for emerging technologies such as RIS and integrated sensing and communications.

This unique combination of features in our simulator provides a versatile and adaptable platform, offering a deeper and more holistic understanding of cell-free 6G networks. Its ability to simulate intricate network dynamics and adapt to evolving wireless technologies positions it as a leading tool in the field, complementing and surpassing the capabilities of existing simulators like WiThRay, NVIDIA Sionna, and QuaDRiGa. The goal is to continuously evolve, integrating the latest advancements in wireless communication, to remain at the forefront of simulator development for 6G networks and beyond.

II. Simulator Architecture

The architecture of our simulator is a testament to the evolving demands of cell-free 6G networks, uniquely designed to meet the intricate requirements of next-generation wireless communications. Central to this architecture is the Unity game engine, known for its exceptional graphical capabilities and efficient GPU utilization. This choice empowers our simulator to provide accurate and dynamic modeling of the physical layer's challenges, particularly in the realms of ray casting and channel behavior simulation, surpassing traditional simulators like QuaDRiGa [5, 6], WiThRay [4], and others in graphical fidelity and interactivity.

The simulator's architecture is organized around three primary components, see Figure 1:

1) Configuration: Configuring the simulation is streamlined through JSON files, addressing aspects such as *GSCM Parameters and multipath component (MPC) Spawning*, *Radio and Physical Parameters*, and *Scenario Definition*. This modular approach allows for high flexibility and ease of customization, essential for diverse simulation scenarios, a feature that is uniquely advanced compared to the more rigid structures seen in simulators like WiThRay [4].

2) Unity Module for physical (PHY) layer: Operating either as a standalone application or through the Unity editor, this module is at the forefront of simulating complex environments. It brings to life intricate urban and indoor settings with 3D models of user equipments (UEs) and base stations (BSs), which can be imported from tools like Blender [13]. This module's capability to handle the actual simulation and physical layer, including the output of channel realizations, sets our simulator apart in terms of realism and detail, offering a more comprehensive solution than QuaDRiGa [5, 6] and other existing systems.

3) System Simulator: Integrating seamlessly with the Unity module, this component takes over the control of time and specializes in simulating system orchestration scenarios like radio resource allocation. With its access to channel realizations and entity positions, and communication via UDP through a ZeroMQ proxy, the Python-based simulator enhances the overall functionality with features like a GUI and result plotting, offering a holistic tool for system-level analysis, a capability that is not fully explored in frameworks like NVIDIA Sionna [7].

A. Unity Components for GSCM

The Unity module in our simulator utilizes several components to effectively model GSCM in cell-free 6G environments:

- A detailed 3D scene representing the environment, like urban areas or indoor settings, with buildings and objects marked as reflecting surfaces.

- An active area defining the simulation scope and a traversable area for entity movement, leveraging Unity's mobility models or external control from the system simulator.
- Entities such as UEs and BSs, each equipped with one or more antennas, are placed in the scene. These entities can be added manually, populated randomly via the JSON scenario configuration, or controlled through the system simulator.

These components collectively enable the Unity module to simulate complex wireless interactions, providing a rich and interactive environment for studying 6G networks.

This comprehensive architecture not only optimizes performance but also provides unmatched scalability and adaptability. It supports a wide array of scenarios, from complex urban landscapes to meticulously detailed indoor environments, making it an unparalleled tool in the study and development of advanced 6G systems.

III. Unity Module - Interactive Ray Casting

Contrary to the conventional use of ray tracing in many simulators, our approach harnesses the advanced graphical capabilities of the Unity game engine for interactive ray casting, a key differentiator from other systems like WiThRay [4] and QuaDRiGa [5, 6]. Ray casting, unlike ray tracing, involves projecting rays from a source to detect intersections with objects in the environment. This method is computationally less intensive and is particularly effective for modeling reflective interactions and basic propagation effects in complex environments, crucial for cell-free 6G networks [14–17]. Our method, drawing from the research of Aleksei Sivert et al. [2], provides a unique approach to multi-path component modeling.

This approach allows for real-time interactivity, enabling users to modify simulation parameters on the fly and immediately observe the impact on network performance and signal propagation. This level of dynamic interaction provides insights and analysis capabilities not commonly found in other simulators, which often rely on more computationally demanding ray tracing methods.

A. Initialisation of GSCM in Unity

The initialisation of GSCM in Unity involves several crucial steps, designed to prepare the system for both offline and real-time operation:

1) MPC Distribution: The locations of scattering interactions, particularly along building facades, are key for accurate communication simulations. MPCs, representing these scatterers, are uniformly distributed throughout the scene for each reflection order (1st, 2nd, and 3rd), with a unique density based on the COST model [18]. This distribution enhances the realism of urban wireless communication scenarios and is automatically generated upon creating a scene [18].

2) MPC Filtering: MPCs that are inside objects or not visible to the entities (UEs or BSs) within the active area are removed using parallel ray casting, ensuring only relevant MPCs are considered in the simulation.

3) Surface Association: Each MPC is associated with the nearest surface, acquiring the normals of those surfaces. These normals, which may vary to simulate different scattering behaviors, play a critical role in determining how signals are reflected by the MPC.

4) Path Gain Model: The path gain model for each MPC accounts for distance dependence, interactions with scatterers, obstructions, diffraction around corners, angular dependence of scattering, and random large scale fading. The average path power gain for each MPC is modeled using a classical log-distance power law, augmented with additional factors to represent these complex effects [18].

5) Parameter Estimation: A maximum-likelihood estimator is used to estimate the path power gain G0 and angular decay for each MPC, aligning with the 3GPP Angular spread properties. These properties, which our simulator capably follows, are statistically derived from extensive experiments conducted by 3GPP active bodies. This alignment with 3GPP standards ensures that our modeling approach reflects real-world scenarios accurately. The estimation of G0 and ξ, while important, can be omitted if they are not directly utilized in the simulation. However, their inclusion offers depth to our model, allowing for a nuanced representation of the multi-path components' behavior in diverse environmental conditions [18].

6) Look-Up Table Generation: For higher order reflections (2nd and 3rd order), distance matrices are generated. These matrices help in determining the visibility of MPCs to each other, which is essential in identifying possible signal paths using parallel ray casting.

7) Scene Representation: The simulation environment is visually represented with color-coded MPCs of different orders, providing a clear and intuitive understanding of the distribution and role of MPCs in the simulated environment. Figure 2 illustrates this visualization in an urban environment, highlighting the spatial distribution and orientation of MPCs along with the resultant signal paths. The color-coding, with green indicating first-order paths, yellow for second-order, and red balls representing active MPCs, enhances the scene's clarity and helps in comprehending complex urban wireless propagation dynamics.

The static creation of MPCs ensures spatial consistency across simulation runs, meaning that while the same MPCs are present in each run, not all of them are visible depending on the specific scenario. The MPC spawning process can also be saved and distributed for consistent simulation results, offering enhanced reproducibility and ease of simulation setup.

B. Run-time Channel Calculation

During run-time, the simulator calculates the channel as follows:

1) Instantaneous Path Power Gain: The simulator implements random shadow fading modeled as Gamma-distributed to represent fading around the distance-dependent mean path gain. This Gamma process, with its exponential autocorrelation, provides a realistic portrayal of time-variant power fading of individual multi-path components, enhancing the

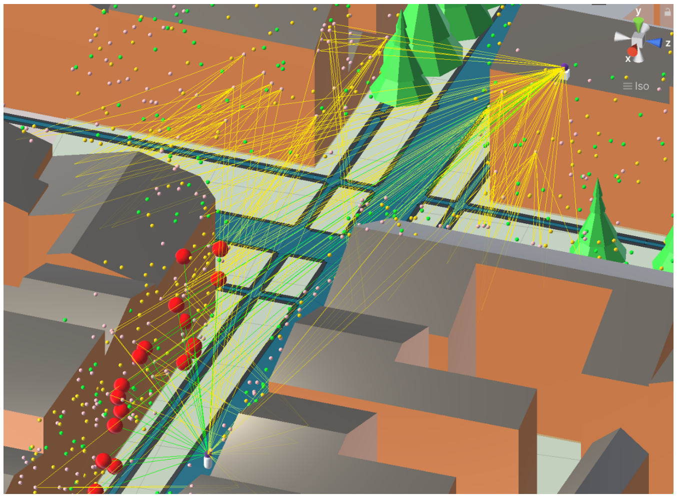

Fig. 2: Visualization of MPCs in an urban environment, illustrating both the spatial distribution and orientation of MPCs (critical for signal propagation analysis) and the resultant signal paths. The scatter points (MPCs) and their normals on surfaces demonstrate the complexity of the urban wireless environment. Colors indicate the order of paths: green for first order, yellow for second order, and red balls represent active MPCs. This comprehensive depiction provides insights into the intricacies of urban wireless propagation and the dynamics of signal paths in dense urban settings.

simulation's accuracy in depicting real-world channel conditions [18].

2) Model Validation: To ensure reliability, the model is validated against real-world measurement data. This validation process guarantees the accurate capture of channel gain, Doppler spread, and delay spread behaviors. It is especially crucial for intersections and urban scenarios not used in the parameter estimation phase, affirming the model's robustness and applicability in diverse environments [18].

3) Reflection Path Determination: Reflection paths are calculated using MPCs, with the system accommodating various orders of reflections. For instance, a signal might first interact with a 2nd order MPC and then with a 1st order MPC, reflecting the complex nature of real-world signal propagation.

4) Path Length and Attenuation: The simulator allows setting a configurable maximum path length, measured in meters, to consider signal attenuation. This feature helps in limiting the number of potential paths and in simulating realistic signal strength reductions over distances.

5) Dynamic line-of-sight (LoS) Determination: For moving UEs, the simulator performs dynamic ray casting between each UE and BS to ascertain LoS presence. This dynamic aspect is critical for simulating mobile environments where LoS conditions can rapidly change.

6) Computational Efficiency: The simulation process is optimized for computational efficiency, employing techniques such as parallel processing and efficient path search algorithms. These optimizations are vital for real-time interactivity and for handling complex scenarios with multiple UEs and BSs.

C. Comparative Analysis of GSCMs and Exhaustive Ray Tracing in Wireless Simulators

In the domain of wireless network simulation for 6G networks, two primary methodologies are prominent for channel modeling: GSCMs and Exhaustive Ray Tracing. Our simulator strategically employs GSCMs, which provide a balance between computational efficiency and realistic environment simulation. This method, drawing insights from advanced models like the COST IRACON GSCMs, is apt for non-stationary environments and effectively captures the MIMO properties of channels [14, 15].

The GSCMs in our simulator incorporate the distribution of scatterers in the environment, particularly along building facades, to model spatially dependent multi-path power. This approach accounts for building obstructions, diffraction around corners, and penetration losses in areas with trees, foliage, and other objects. The power fading for each MPC is modeled using a Gamma process, providing a stochastic yet accurate representation of the wireless channel [18].

The path gain model for different MPCs includes effects such as distance dependence, losses due to interactions with scattering objects, and angular dependence of the scattering interaction. This comprehensive modeling approach ensures the accurate representation of real-world propagation environments, including non-stationary conditions prevalent in urban settings [18].

Our implementation of GSCMs not only ensures spatial consistency of MPCs across simulation runs but also adheres to the Dataset Storage Standard (DSS) standard for channel storage [19]. While the same MPCs are statically created, their visibility varies in each run, depending on the specific scenario and environmental dynamics. This feature offers a balance between realism and computational efficiency, crucial for simulating complex 6G network environments. Additionally, the Unity module within our simulator can be utilized independently for detailed studies, providing flexibility in research and development applications [18].

In contrast, Exhaustive Ray Tracing, as seen in simulators like those referenced in [16, 17], offers a deterministic approach for highly detailed environment-specific simulations but can be more resource-intensive. Our use of ray casting with Unity, combined with the versatility of GSCMs, enables us to offer detailed environmental modeling with greater computational efficiency. This combination allows our simulator to adapt to a wide range of scenarios, from complex urban layouts to specific indoor settings, providing a unique blend of adaptability, efficiency, and realism.

In conclusion, the choice between GSCMs and exhaustive ray tracing or casting depends on the specific simulation needs. Our simulator's integration of Unity's ray casting with GSCMs provides an ideal blend for advanced 6G network simulation, research, and development, outperforming other simulators in flexibility and operational efficiency.

IV. PYTHON MODULE - SYSTEM SIMULATOR

The second part of our simulator explores the complexities above the PHY layer, addressing the integration of intricate channel models with higher network layers. This integration is pivotal for examining joint and cross-layer algorithms, which are vital for optimizing the performance of 6G networks. Because the system-level simulator is decoupled from the channel model and interacts with it through a well-defined network protocol, researchers focusing on higher-layer problems can focus on implementing their solutions at the link layer or above, while still benefiting from the realistic channel modelling provided by the Unity module.

A. System Simulator Interaction

The system simulator interacts with the Unity module in two primary ways: i) through direct connection for dynamic simulation control, and ii) by reading out DSS-compliant channel measurements for detailed analysis. This Python-based simulator takes control of time from the Unity module, effectively orchestrating the Unity module's operations. Such an arrangement facilitates the orchestration of scenarios like dynamic resource allocation and network management. It accesses channel realizations and entity positions in the environment, communicating with the Unity module via User Datagram Protocol (UDP) through a ZeroMQ proxy. Equipped with result plotting features, the system simulator serves as a comprehensive tool for system-level analysis and optimization, accommodating diverse simulation needs.

B. Discrete-Event Simulator

Our simulator leverages a high-level discrete-event Simulator [20] based on SimPy within the RadioWeaves (RW) infrastructure, offering a novel approach to network resource allocation. Each entity, such as a user or a contact service point (CSP), manages its own behaviour and associated algorithms, while additional entities simulate the behaviour of system-wide logic such as centralized optimization algorithms.

C. Studying Novel Services

This infrastructure represents a novel distributed cell-free network, enhancing propagation and antenna array interactions. In this setup, the concept of federations—groupings of users and antennas—plays a crucial role [21]. Managed through utility functions, these federations ensure fair allocation across the network, particularly in dynamic scenarios where user movements and changing requirements add layers of complexity. To do this, this module includes digital twins of the network infrastructure including energy, latency and other models. Using these, a subset of the resources, e.g., antennas, can be disabled to lower the energy expenditure of the network without compromising the UEs requirements.

Next to wireless communication, the simulator is able to investigate wireless power transfer (WPT). The channel gain from a dedicated channel or the Unity module is used to orchestrate the best federation to charge multiple devices in the most energy-efficient manner. Similarly, localisation and sensing is embedded in this module. It allows study of improving the precision and accuracy of the positioning, while simultaneously reducing the complexity by only selecting the best subset of radio resources available in the network.

In summary, the above PHY layer of our simulator provides a detailed platform for simulating and analyzing various network management strategies. This part of the simulator is crucial for understanding and optimizing the deployment and operation of next-generation wireless networks, especially in the context of cell-free 6G network configurations.

V. CONCLUSIONS AND EXTENSIONS

In conclusion, our simulator emerges as a significant milestone in the exploration and development of cell-free sixth-generation (6G) wireless networks. It adeptly combines detailed physical layer modeling, utilizing advanced ray-tracing techniques powered by the Unity game engine, with an expansive system-level simulation framework. This synthesis of technologies enables a holistic examination of 6G networks, from the intricacies of signal propagation and interaction in diverse environments to complex network management strategies.

Our simulator's architecture, highlighted by its integration of geometry-based stochastic models (GSCMs) [8–10] and Exhaustive Ray Tracing [11, 12], offers a unique blend of realism and computational efficiency. This approach positions our simulator at the forefront of current research and development, surpassing other notable systems like WiThRay [4], QuaDRiGa [5, 6], and even Sionna in terms of adaptability and detailed environmental modeling. Compared to Sionna, known for its comprehensive multiple-input multiple-output (MIMO) channel modeling, our simulator extends its capabilities by integrating more dynamic and varied environmental interactions and system-level complexities.

Looking forward, we envision continual evolution and enhancement of the simulator. Our immediate focus is on integrating advanced features such as reconfigurable intelligent surfaces (RIS), which are gaining prominence in 6G research. This includes exploring integrated sensing and communications (ISAC) capabilities, which are pivotal for future intelligent networks. Additionally, we aim to refine dynamic resource allocation algorithms, ensuring efficient and adaptive network management in real-time scenarios.

The goal is to solidify the simulator's status as an indispensable tool for researchers and engineers, facilitating breakthroughs in the field of wireless communications and contributing to the realization of the full potential of 6G networks. Our simulator will continually adapt, incorporating cutting-edge advancements and insights, thus ensuring its relevance and utility in the rapidly advancing domain of wireless technology. As the wireless communication landscape evolves, so too will our simulator, always staying a step ahead in the dynamic world of 6G wireless networks.

REFERENCES

[1] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, "6g wireless systems: Vision, requirements, challenges, insights, and opportunities," *Proceedings of the IEEE*, 2021.

[2] A. Fedorov, N. Lyamin, and F. Tufvesson, "Implementation of spatially consistent channel models for real-time full stack C-ITS V2X simulations," in *Asilomar Conference on Signals, Systems, and Computers*, IEEE, 2021.

[3] 6G-Testbeds, *Lusim: An open-source simulator for cell-free 6g networks*, https://github.com/6G-Testbeds/LuSim, 2023.

[4] H. Choi, J. Oh, J. Chung, G. C. Alexandropoulos, and J. Choi, "WiThRay: A Versatile Ray-Tracing Simulator for Smart Wireless Environments," *Access*, 2023.

[5] O. Authors, "QuaDRiGa: A 3-D Multi-Cell Channel Model With Time Evolution for Enabling Virtual Field Trials," *Transactions on Antennas and Propagation*, Year.

[6] Y. He, Y. Zhang, J. Zhang, L. Pang, Y. Chen, and G. Ren, "Investigation and Comparison of QuaDRiGa, NYUSIM and MG5G Channel Models for 5G Wireless Communications," 2020.

[7] J. Hoydis, F. A. Aoudia, S. Cammerer, *et al.*, "Sionna RT: Differentiable Ray Tracing for Radio Propagation Modeling," *arXiv preprint arXiv:2303.11103*, 2023.

[8] J. Karedal, N. Czink, A. Paier, F. Tufvesson, and A. F. Molisch, "A Geometry-Based Stochastic MIMO Model for Vehicle-to-Vehicle Communications," *Transactions on Vehicular Technology*, 2011.

[9] V.-M. Kolmonen, M. Vehkapera, T. Jamsa, and A. F. Molisch, "Evaluation of the Spatial Consistency Feature in the 3GPP Geometry-Based Stochastic Channel Model," *Transactions on Antennas and Propagation*, 2011.

[10] C.-X. Wang, X. Cheng, D. I. Laurenson, S. Salous, and A. V. Vasilakos, "A Geometry-Based Stochastic Channel Model for MIMO Mobile-to-Mobile Communications," *Transactions on Vehicular Technology*, 2008.

[11] V. Degli-Esposti, F. Fuschini, E. M. Vitucci, and G. Falciasecca, "Ray Tracing for Radio Propagation Modeling: Principles and Applications," *Access*, 2015.

[12] J. Smith and E. Johnson, "Exhaustive Ray Tracing for 6G Topics such as RIS or Integrated Sensing and Communications," *Journal of Advanced Communications*, 2022.

[13] Blender Foundation, *Blender*, version 4.0, [Software], 2023. [Online]. Available: https://www.blender.org.

[14] A. Liu and V. K. N. Lau, "Optimization of Multi-UAV-Aided Wireless Networking Over a Ray-Tracing Channel Model," *Transactions*, 2019.

[15] Z. Yun, S. Lim, and M. F. Iskander, "An Integrated Method of Ray Tracing and Genetic Algorithm for Optimizing Coverage in Indoor Wireless Networks," *Transactions*, 2019.

[16] M. N. Kamaruddin *et al.*, "A Comprehensive Review of Efficient Ray-Tracing Techniques for Wireless Communication," *International Journal on Communications Antenna and Propagation (IRECAP)*, 2018.

[17] D. He *et al.*, "The Design and Applications of High-Performance Ray-Tracing Simulation Platform for 5G and Beyond Wireless Communications: A Tutorial," *Transactions*, 2020.

[18] C. Gustafson, K. Mahler, D. Bolin, and F. Tufvesson, "The COST IRACON Geometry-Based Stochastic Channel Model for Vehicle-to-Vehicle Communication in Intersections," *Transactions on Vehicular Technology*, 2020.

[19] G. Callebaut *et al.*, "An open dataset storage standard for 6G testbeds," in *Conference on Antenna Measurements and Applications (CAMA)*, IEEE, 2023.

[20] T. Keymeulen, "High-Level Simulator of Federation Orchestration," M.S. thesis, Lund University, 2022.

[21] G. Callebaut, W. Tärneberg, L. Van der Perre, and E. Fitzgerald, "Dynamic federations for 6G Cell-Free networking: Concepts and terminology," in *International Workshop on Signal Processing Advances in Wireless Communication (SPAWC)*, IEEE, 2022.