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DIFFERENTIABLE RAY TRACING-BASED ANALYSIS OF TRANSMITTER DEPLOYMENT STRATEGIES IN SITE-SPECIFIC SCENARIOS

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Abstract: Accurate modeling of wireless signal propagation in complex environments is essential for the efficient planning of next-generation communication networks. This study investigates the impact of transmitter placement and elevation on signal coverage and interference levels within a structured campus environment. Using Sionna ray tracing, a differentiable and GPU-accelerated ray tracing framework, realistic 3D models of the Aydin Adnan Menderes University main campus were constructed and simulated. Three transmitter deployment scenarios—distributed, centralized, and optimized—were evaluated in terms of path gain, Received Signal Strength (RSS), and Signal-to-Interference-plus-Noise Ratio (SINR). The simulation results reveal how different spatial configurations influence signal propagation, coverage uniformity, and interference. The findings provide valuable insights into strategic transmitter placement for enhanced network performance in real-world deployments.

Keywords: Ray tracing, Wireless propagation, Path gain, SINR, RSS, Sionna

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1. Introduction

Large-scale environments including campuses, cities, and industrial complexes depend on dependable and efficient wireless communication. Optimizing coverage and controlling interference grow more difficult as wireless technologies move toward 5G and 6G. Accurate modeling of wireless propagation in realistic environments is indispensable to build networks fulfilling these needs.

Offering a degree of spatial consistency and environmental specificity that traditional models cannot match, ray tracing (RT) has become a powerful tool for simulating the intricate interactions of radio waves with their surrounds (Yun and Iskander, 2015; Egea-Lopez et al., 2021). By means of GPU-accelerated, flexible, and differentiable simulation tools, advanced frameworks such as NVIDIA's Sionna (Hoydis et al., 2023b) improve the capacity of RT even further. These developments enable high fidelity real-world wireless performance, so supporting more informed decisions in network planning and optimization.

Especially in relation to next-generation wireless systems, major efforts have been made recently to improve wireless channel modeling and network simulation by using the features of Sionna RT. Creating reasonable large-scale digital twins of metropolitan settings to enable accurate ray tracing simulations has become a main priority. In this sense, the BostonTwin project (Testolina et al., 2024) produced a comprehensive 3D model of Boston by combining actual cellular base station placements to support city-scale propagation investigations. Complementing this, the extension of RayMobtime with Sionna RT (Bastos et al., 2023) introduced dynamic scene modeling, including not only stationary buildings but also mobile objects such vehicles and pedestrians, so enabling the generation of realistic and mobility-aware wireless channel datasets.

Beyond broad environmental modeling, efforts have also focused on producing high-fidelity, site-specific digital twins for more localized but extremely detailed propagation analysis. Combining 3D mesh modeling with SUMO-based mobility traces and Sionna RT simulations, the study in (Noh and Choi, 2024) produces subcarrier-level MIMO-OFDM channel data appropriate for fine-grained system evaluations.

Parallel with advances in scene modeling, there is increasing interest in including physically consistent wireless channels into system-level network simulations. A major step in this direction is the development of (Zubow et al., 2024), which enables spatially and temporally coherent ray tracing-based channels inside the ns-3 network simulator. Particularly for indoor Wi-Fi and cellular systems, this integration lets evaluations of network performance under reasonable propagation conditions be more accurate.

Studies of comparative benchmarks have strengthened Sionna RT even more. Particularly in complex multi-link and scattering situations, in (Zhu et al., 2024a) methodically compared several ray tracing solutions to show that Sionna RT provides high computational efficiency while preserving modeling accuracy. Likewise, for particular tasks such urban path loss prediction, the study in (Xia et al., 2024) showed that using accurate 3D propagation scene models with Sionna RT greatly increases prediction accuracy, especially in environments including dense vegetation and small-scale structures.

Deeper methodologically, the development of differentiable ray tracing capabilities inside Sionna RT (Hoydis et al., 2023a) has created fresh avenues for learning and direct environmental parameter optimization straight from data. Sionna RT promotes gradient-based optimization for applications including environment calibration and transmitter placement tuning by letting gradients be computed regarding material properties, antenna configurations, and node positions. Complementary to this, performance evaluations presented in (Zhu et al., 2024b) confirmed that Sionna RT, especially with GPU acceleration, achieves significant computational speed-ups, so enabling real-time large-scale wireless digital twin implementations. These developments together prove Sionna RT as a flexible and strong platform for both basic research and pragmatic design in next-generation wireless communication systems.

Although practical deployment strategies such as transmitter location and elevation greatly affect network performance due to architectural geometry, signal reflections, and LOS coverage, ray tracing precisely models wireless channel locations. This study contributes to the literature by examining the effect of transmitter placement and height on wireless communication performance in a real campus environment with detailed simulations based on ray tracing. In addition to scenarios created with real base station locations, centralized placement based on user density and optimization-oriented strategic placement alternatives were comparatively evaluated. It was shown that more homogeneous and fair coverage can be provided with fewer transmitters, and it was revealed that it is possible to balance infrastructure efficiency and service quality.

This paper is arranged mainly as follows: First, we examine closely the deployment scenarios and how they affect path gain. Subsequently, for every scenario, SINR and RSS distributions over campus are fully assessed. Finally, a comparative study emphasizes the performance trade-offs and advantages of strategic transmitter location, so offering information for best network design in challenging settings.

2. Materials and Methods

2.1. Sionna Ray Tracing

Using Sionna RT, an expansion of the open-source radio propagation simulation system Sionna, ray tracing simulations were conducted. Constructed atop Mitsuba 3 (Jakob et al., 2022) and TensorFlow (Martín et al., 2015), Sionna RT offers a GPU-accelerated, flexible, differentiable platform for high-fidelity radio propagation modeling. Operating natively in Python, the framework is completely compatible with Jupyter notebooks, so enabling reproducible and easily modifiable simulations.

Sionna RT lets the user create comprehensive simulation settings regarding the carrier frequency, bandwidth, antenna array geometries, material properties including relative permittivity, permeability, and conductivity. This information computes multipath components by following the propagation of electromagnetic waves across reflections, diffractions, and scattering events inside the 3D scene. Sionna RT generates complete channel information for every transmitter-receiver pair including path gains, propagation delays, angles of departure and arrival.

Using the open-source 3D modeling tool Blender (Blender Foundation, 2023), together with the Mitsuba-Blender plugin (Anonymous, 2023), scene models fit for Sionna RT are produced. The Blender-OSM add-on (Prochitecture, 2023) was used for realistic environmental modeling since it lets one import comprehensive geospatial data from OpenStreetMap (OpenStreetMap Foundation, 2023). This arrangement allows the quick creation of accurate and site-specific propagation simulations' realistic large-scale scenes.

2.2. Scene Setup

The central campus of Aydin Adnan Menderes University formed the basis for the simulation scene. Using the Blender-OSM plugin, OpenStreetMap's building layouts, road data, and vegetation information were imported into a thorough 3D model of the university. Blender helped the imported map data to be polished and corrected so that it faithfully portrayed important environmental elements including open spaces, surface materials, and building heights.

Common construction materials determined material properties for ground surfaces and buildings; relative permittivity and conductivity matched concrete, brick, metal, and ground. Exported in Mitsuba 3-compatible format, the built 3D scene was used in Sionna RT for the ray tracing simulations (Figure 1). Using this scene setup, multiple transmitter and receiver configurations were simulated to investigate the effects of transmitter placement and elevation on signal propagation across the campus environment (Figure 2).

Following the construction of the campus scene, three different transmitter deployment scenarios were designed to systematically analyze the effects of placement strategies on wireless signal propagation and network performance. These scenarios differ in terms of the number of transmitters, their spatial distribution across the campus, and their deployment heights. A summary of the scenarios considered is provided in Table 1, and the simulation parameters are shown in Table 2.

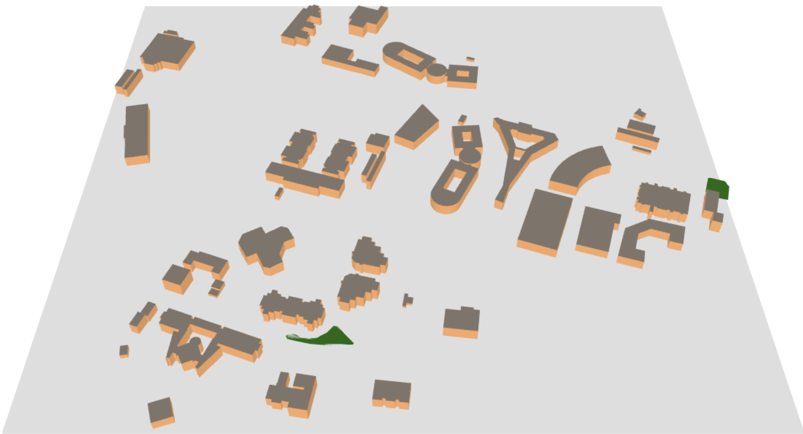


Figure 1. 3D scene of the campus in Sionna.

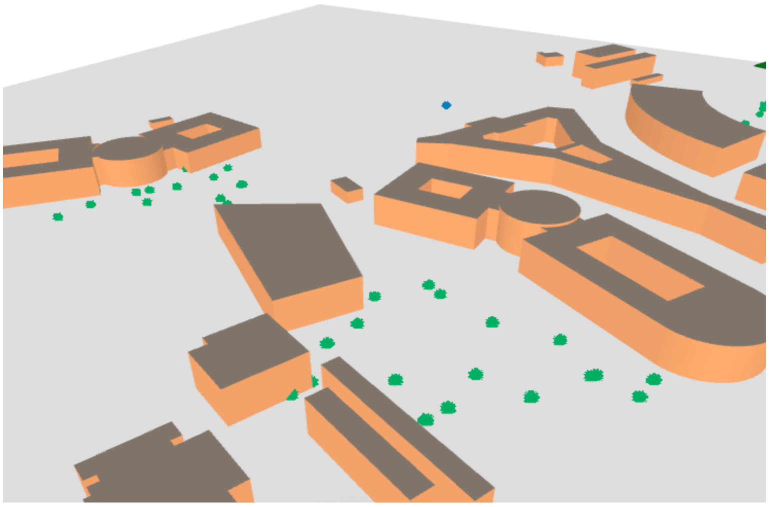


Figure 2. A transmitter (blue dot) and a receiver (green dot) representation in Sionna.

Table 1. Overview of transmitter deployment scenarios

Scenario	Number of Transmitters (TXs)	Transmitter Heights (m)	Deployment Type	Description
Scenario 1	4	1 TX: 40 m, 3 TXs: 30 m	Distributed	Real-world locations based on existing base stations within the campus
Scenario 2	3	All at 30 m	Centralized	Transmitters clustered in the central area of the campus
Scenario 3	3	All at 30 m	Optimized	Transmitters strategically placed for optimal campus-wide coverage

Table 2. Simulation parameters

Parameter	Value
Bandwidth	20 MHz
Number of users	60
Number of transmitters	Varies by scenario (see Table 1)
Transmitter array type	Planar array
Transmitter array pattern	TR 38.901 standard
Receiver array type	Planar array
Receiver array pattern	Dipole

The impact of transmitter placement and elevation on communication performance is evaluated by using ray tracing techniques. Table 2 indicates that Scenario 1 was designed by taking the real locations of the base stations located within the campus, while in Scenario 2, the transmitters were positioned in the center of the campus where the user density is high. In addition, the optimum placement scenario, Scenario 3, was determined through multiple simulation experiments to maximize the communication performance across the campus. The transmitter locations were optimized based on the signal strength and interference balance evaluated through RSS and SINR distributions. The selected configuration provides more homogeneous coverage and lower performance variance with fewer transmitters, thus increasing both efficiency and service fairness. For the simulation environment described, the methodology used to calculate key performance metrics such as path gain, SINR and RSS are described in detail.

To generate a coverage map for a given transmitter, path gain is calculated for each cell $C_{i,j}$ (equation 1). This represents the average signal strength across the cell.

$$g_{i,j} = \frac{1}{|C|}\int_{C_{i,j}} |h(s)|^2 ds \tag{1}$$

where $h(s)$ is the channel coefficients at position s(x,y), $C_{i,j}$ represents the specific cell in the map. This formula calculates the average path gain over the cell area by integrating the channel coefficients.

Path gain is converted to RSS by using equation 2. This represents the signal strength at the receiver for a specific cell.

$$RSS_{i,j} = P_{tx} g_{i,j} \tag{2}$$

where P_{tx} is the transmitter power (in dBm or Watts). RSS reflects the total signal power received at the receiver's location, which is critical for analyzing network coverage.

SINR (equation 3) is computed for every transmitter present in the scene to measure how much interference and noise influence the intended signal.

$$SINR_{i,j}^{k} = \frac{RSS_{i,j}^{k}}{N_0 + \sum_{k' \neq k} RSS_{i,j}^{k'}} \tag{3}$$

This formula shows that SINR treats signals from all other transmitters as interference while concentrating on the signal from the target transmitter. Thermal noise power N_0 (W) is computed using bandwidth, temperature, and Boltzmann's constant as in equation 4.

$$N_0 = B \times T \times k \tag{4}$$

where B is bandwidth (Hz), T is temperature (Kelvin) and k is Boltzmann constant 1.380649×10^{-23} J/K.

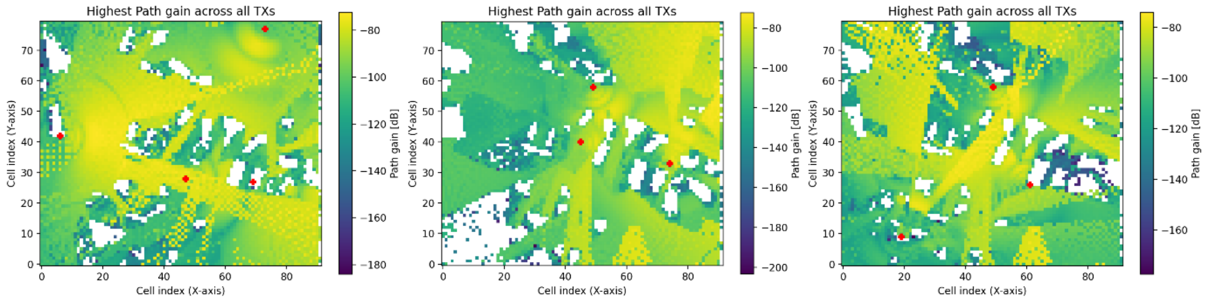
With the simulation setup and performance metrics defined, the following section provides a detailed analysis of the results, highlighting how transmitter placement and elevation influence wireless communication performance across the campus environment.

3. Results

This study analyzes the performance of path gain, SINR, and RSS in different transmitter deployments within Aydin Adnan Menderes University central campus environment. Three different scenarios (Table 1) are examined to investigate the impact of transmitter positions and heights on communication quality.

The effect of various placement techniques on coverage is clearly shown in Figure 3, which shows the placements of the transmitters (red dots), and their path gain distribution. In the first scenario (Figure 3a), the location of the transmitters in outer regions guarantees broad coverage but causes degraded signals in the inner sections of the campus. In the second scenario (Figure 3b), signal strength decreases toward the campus borders while the central placement of transmitters produces high path gain values in interior areas. In the third scenario (Figure 3c), strategic deployment results in a more homogeneous coverage distribution with less coverage gaps.

The cumulative distribution of path gain over the assessed scenarios (Figure 4) provides significant insights into signal quality and deployment efficiency. The distributed placement scenario (scenario 1), comprising four transmitters with one elevated to 40 meters, attains the maximum median path gain, surpassing the 50% cumulative probability at around -90 dB. Nonetheless, this incurs increased infrastructure complexity and expenditure. This arrangement demonstrates a considerable path gain range, spanning from -183 dB to -83 dB, signifying substantial spatial variation in signal strength throughout the area. The broad dynamic range indicates that although many users receive robust signal levels, others suffer from significantly impaired connectivity, compromising overall service consistency. The central placement (scenario 2) covers a broader range, from -200 dB to -82 dB, yielding the lowest median path gain, indicating suboptimal performance, particularly at the cell boundaries. Conversely, the ideal placement scenario (scenario 3), utilizing merely three transmitters positioned at a height of 30 meters, attains a median path gain of -100 dB with a more restricted range (-182 dB to -83 dB). This indicates a more uniform quality of coverage with diminished extreme weak areas. Despite its median being somewhat lower than that of scenario 1, the ideal configuration provides a superior equilibrium among deployment cost, simplicity, and fairness in user experience. Consequently, when evaluating both signal efficiency and implementation feasibility, the ideal placement emerges as the best balanced and efficient solution.



(a) (b) (c)

Figure 3. Highest path gain across all TXs for (a) scenario 1 (b) scenario 2 and (c) scenario 3.

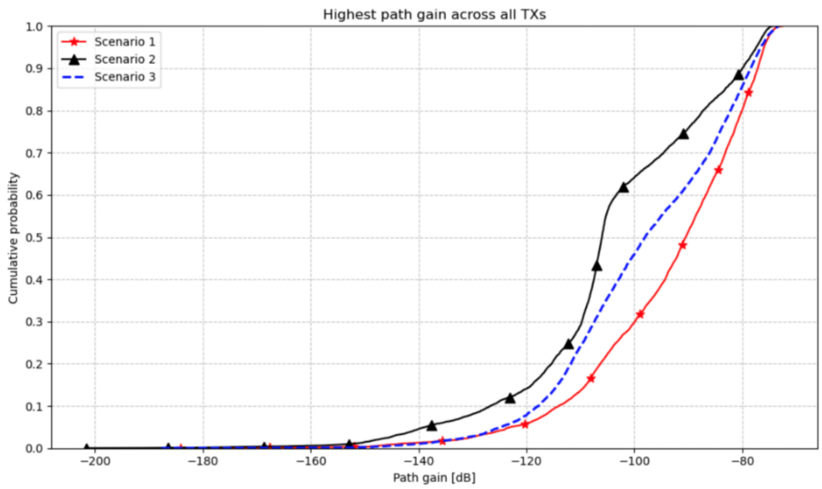
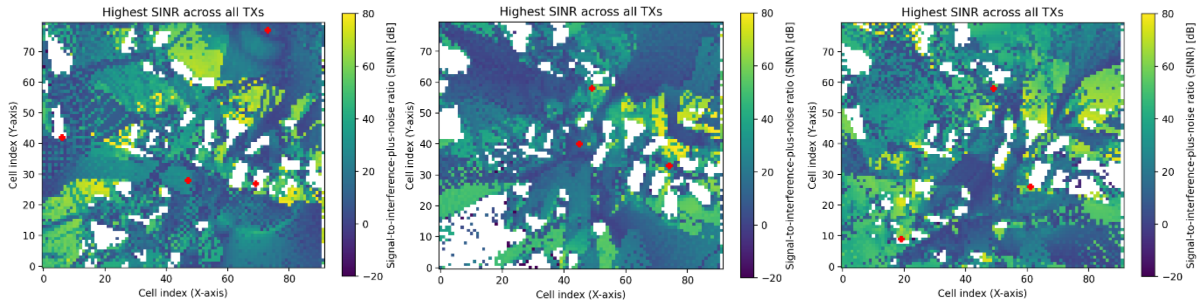


Figure 4. Cumulative probability distribution of highest path gain across all TXs for all scenarios.

The spatial distribution of SINR among the three deployment scenarios indicates significant disparities in interference management and coverage uniformity. In scenario 1 (Figure 5a), results in localized zones of higher SINR—surpassing 60 dB in certain areas—while also demonstrating considerable spatial variation, with many places, especially near the lower boundary, registering below 0 dB. This signifies variable service quality and inadequate interference dispersion despite elevated peak performance. Scenario 2 (Figure 5b), including centrally located transmitters, yields robust SINR in the central region but struggles to sustain satisfactory performance at the peripheries, where extensive areas of diminished SINR (often below -10 dB) arise due to restricted signal propagation and cumulative interference. Conversely, scenario 3 (Figure 5c), with an optimally distributed configuration with three transmitters at a consistent elevation, attains a well-balanced SINR distribution throughout the campus. The SINR values predominantly reside within the 20-70 dB range, with few regions exhibiting critically low levels. This suggests that the strategic positioning in scenario 3 provides more reliable and uniform signal quality, rendering it the most effective option regarding interference management and user experience consistency.

The cumulative distribution analysis of SINR values (Figure 6) demonstrates major differences in interference patterns and signal quality across the assessed transmitter setups. Scenario 2 demonstrates the poorest SINR performance, with values starting at -42 dB and a median SINR of roughly 13 dB. The significant increase in the lower SINR region suggests that a considerable number of users encounter severe signal degradation, especially at the cell edges, possibly attributable to concentrated interference and restricted spatial diversity. Scenario 1 provides modest enhancement with a median SINR of around 20 dB, due to the inclusion of an additional transmitter and expanded geographical coverage; yet, this results in elevated deployment costs and diminished SINR uniformity. Conversely, Scenario 3 attains superior SINR consistency throughout the network, exhibiting a median approximately at 27 dB and a more gradual increase in cumulative probability. This signifies enhanced overall signal quality and a more equal user experience, reducing the percentage of users exposed to low SINR circumstances. The results indicate that strategically planned transmitter positioning can surpass more resource-demanding options by enhancing SINR while maintaining deployment simplicity and cost-effectiveness.



(a) (b) (c)

Figure 5. Highest SINR across all TXs for (a) scenario 1 (b) scenario 2 and (c) scenario 3.

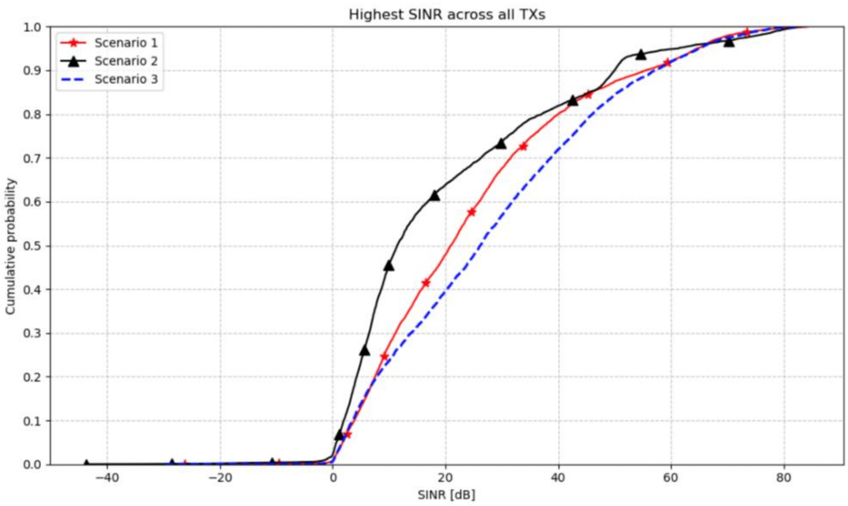
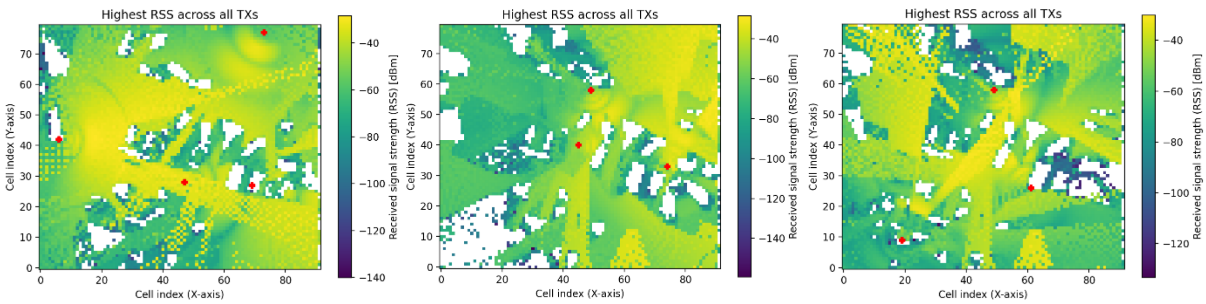


Figure 6. Cumulative probability distribution of highest SINR across all TXs for all scenarios.

The comparative examination of RSS distributions among the three deployment scenarios demonstrates significant variations in signal coverage and geographic homogeneity. Scenario 1 (Figure 7a) offers wide signal coverage with significant regions surpassing -60 dBm. Nonetheless, isolated areas with values below -100 dBm signify inconsistent transmission and fluctuation in coverage. Scenario 2 (Figure 7b) has robust RSS near the core but experiences rapid signal attenuation toward the periphery, resulting in notable coverage gaps. Conversely, scenario 3 (Figure 7c) attains a more uniform RSS distribution throughout the entire region. The diminished occurrence of weak-signal areas and the uniform coverage pattern indicate that strategic positioning not only elevates average signal strength but also augments equity in user experience throughout the network.



(a) (b) (c)

Figure 7. Highest RSS across all TXs for (a) scenario 1 (b) scenario 2 and (c) scenario 3.

The cumulative RSS distribution supports spatial RSS map findings (Figure 8). The highest median RSS performance is scenario 1 intersecting the 50% probability threshold near -47 dBm. However, the curve's wider spread suggests greater signal fluctuation over coverage. Scenario 2 has the lowest median RSS value at -62 dBm and a steeper slope, indicating rapid signal loss outside center locations. Scenario 3 balances strength and consistency with a median RSS of roughly -55 dBm and a gentler slope. This improves signal homogeneity and coverage equity. Scenario 1 performs best in ideal locations, whereas scenario 3 has fewer weak-signal zones and better service quality, proving its efficiency and reliability.

An integrated evaluation of RSS and SINR outcomes indicates that elevated signal strength does not ensure communication quality without adequate interference management. Although scenario 1 provides superior RSS values, it experiences SINR inconsistency as a result of heightened interference. Scenario 3, though exhibiting marginally reduced RSS, attains the most uniform SINR distribution, signifying that deliberate transmitter positioning guarantees both effective coverage and dependable signal quality with diminished resources.

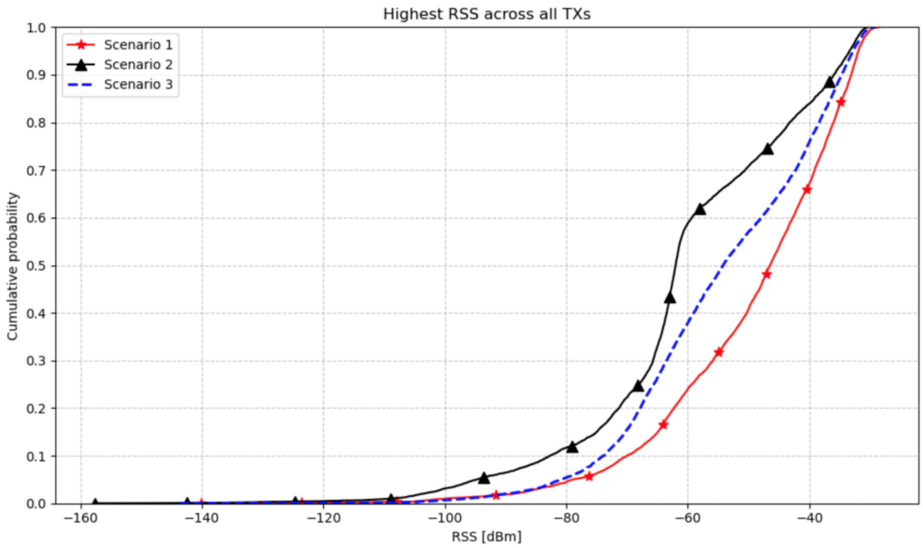


Figure 8. Cumulative probability distribution of highest RSS across all TXs for all scenarios.

4. Discussion

This work verifies that signal strength, interference distribution, and general network performance are much influenced by the location of the transmitter. Unlike many previous works that give coverage maximizing through more infrastructure top priority, our results show that a well-optimized deployment with less transmitters can produce more consistent and dependable signal quality. Especially, balanced SINR and RSS distributions found in the optimal scenario draw attention to the importance of strategic orientation above designs with only resource-intensive character. These results underline the need of including performance as well as deployment economy into network design. Moreover, the results provide a road for future integration of AI-based optimization models in which real-time system feedback and environmental data can be used to automate and improve placement decisions depending on machine learning.

5. Conclusion

The study shows that performance of wireless communication depends on the location of the transmitter, so influencing signal strength, interference management, and spatial coverage uniformity. It implies that a balance between power and interference avoidance is required since maximizing signal intensity by itself does not ensure dependable connectivity. While designs that evenly distribute RSS and SINR offer dependable and fair user experiences, excessive path gain and RSS variability can cause coverage discrepancies. Appropriate location can minimize infrastructure resources, so stressing the need of strategic and economical planning in the design of wireless networks.

Author Contributions

The percentages of the author's contributions are presented below. The author reviewed and approved the final version of the manuscript.

	O.Y.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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References

Anonymous. 2023. Mitsuba Blender Add-on. URL: https://github.com/mitsuba-renderer/mitsuba-blender (accessed date: February 4, 2025).

Bastos S, Oliveira A, Suzuki, D, Gonçalves L, Sousa I, Klautau A. 2023. Generation of 5G/6G Wireless Channels Using Raymobtime with Sionna's Ray-Tracing. XLI Simpósio Brasileiro de Telecomunicações e Processamento de Sinais.

Blender Foundation. 2023. Blender. URL: https://www.blender.org (accessed date: February 3, 2025).

Egea-Lopez E, Molina-Garcia-Pardo JM, Lienard M, Degauque P. 2021. Opal: An open source ray-tracing propagation simulator for electromagnetic characterization. Plos one, 16(11): e0260060.

Hoydis J, Aoudia FA, Cammerer S, Nimier-David M, Binder N, Marcus G, Keller A. 2023a. Sionna RT: Differentiable ray tracing for radio propagation modeling. 2023 IEEE Globecom Workshops (GC Wkshps), pp: 317–321.

Hoydis J, Cammerer S, Aoudia FA, Vem A, Binder N, Marcus G, Keller A. 2023b. Sionna: An Open-Source Library for Next-Generation Physical Layer Research, pp:45.

Jakob W, Speierer S, Roussel N, Vicini D. 2022. DR.JIT: A just-in-time compiler for differentiable rendering. ACM Transactions on Graphics, 41(4): 1–19.

Martín A, Ashish A, Paul B, Eugene B, Zhifeng C, Craig C, Greg SC, Andy D, Jeffrey D, Matthieu D. 2015. TensorFlow: Large-scale machine learning on heterogeneous systems,Mountain View, CA, USA, pp:1-19

Noh YJ, Choi KW. 2024. High-Precision Digital Twin Platform Based on Ray Tracing Simulation. 2024 15th International Conference on Information and Communication Technology Convergence (ICTC), pp: 1464–1465.

OpenStreetMap Foundation. 2023. OpenStreetMap. URL: https://www.openstreetmap.org (accessed date: February 1, 2025).

Prochitecture. 2023. Blender-OSM: OpenStreetMap and Terrain for Blender. URL: https://prochitecture.gumroad.com/l/blender-osm (accessed date: February 2, 2025).

Testolina P, Polese M, Johari P, Melodia T. 2024. Boston Twin: The Boston Digital Twin for Ray-Tracing in 6G Networks. Proceedings of the ACM Multimedia Systems Conference 2024 on ZZZ, pp: 441–447.

Xia G, Zhou C, Zhang F, Cui Z, Liu C, Ji H, Zhang X, Zhao Z, Xiao Y. 2024. Path Loss Prediction in Urban Environments with Sionna-RT Based on Accurate Propagation Scene Models At 2.8 GHz. IEEE Transactions on Antennas and Propagation.

Yun Z, Iskander MF. 2015. Ray tracing for radio propagation modeling: Principles and applications. IEEE Access, 3: 1089–1100.

Zhu M, Cazzella L, Linsalata F, Magarini M, Matteucci M, Spagnolini U. 2024a. On the Digitization of the EM Environment: A Comparison of Ray Launching Solutions. 2024 IEEE International Mediterranean Conference on Communications and Networking (MeditCom), pp: 85–90.

Zhu M, Cazzella L, Linsalata F, Magarini M, Matteucci M, Spagnolini U. 2024b. Toward Real-Time Digital Twins of EM Environments: Computational Benchmark for Ray Launching Software. IEEE Open J Commun Soc, pp: 54.

Zubow A, Pilz Y, Rösler S, Dressler F. 2024. Ns3 meets Sionna: Using Realistic Channels in Network Simulation, pp: 41.