A Simulation-based Analysis of WiFi Signal Strength and Performance Variations Across IEEE 802.11 Standards in Diverse Indoor Environments

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***Abstract*—The rapid proliferation of wireless devices in smart homes, offices, and public spaces has intensified the demand for reliable WiFi coverage and performance optimization. This paper presents a Python-based simulation framework to analyze WiFi signal strength distribution and performance characteristics for various IEEE 802.11 standards (a, b, g, n, ac, ax) in indoor environments. By generating synthetic signal strength values across a defined spatial grid, heatmaps are produced to visualize coverage variations. The study further investigates the influence of physical obstructions, device density, and frequency harmonization on signal quality. Results highlight the trade-offs between speed, range, and interference resilience across standards, offering actionable insights for network deployment and management in modern wireless systems.**

***Index Terms*—WiFi simulation, IEEE 802.11 standards, signal strength analysis, heatmap visualization, interference modeling, network performance, Python simulation framework, wireless network planning.**

I. Introduction

The explosion of wireless communication technology over the last two decades has revolutionized personal, commercial, and industrial domains. WiFi, based on IEEE 802.11 standards, is now an integral part of everyday life, enabling seamless internet access for a rapidly growing number of smart devices including smartphones, laptops, IoT appliances, and industrial control systems. This widespread adoption, however, brings challenges such as spectrum congestion, signal interference, and inconsistent coverage, especially in densely populated environments.

Traditional network planning methods rely heavily on empirical site surveys using commercial WiFi analyzers or proprietary software, which, while effective, are often cost-prohibitive and inflexible. Furthermore, these tools may not allow custom scenario modeling for educational or research purposes. Therefore, developing simulation-based frameworks using open-source technologies is crucial for enabling more accessible, reproducible, and customizable network performance analysis.

This research proposes a Python-based simulation platform to model WiFi signal propagation within indoor environments under varying conditions. The system analyzes multiple IEEE 802.11 standards, evaluates coverage patterns, and examines the impact of obstacles and device interference. By producing heatmaps and comparative analyses, the framework serves as both a network design tool and a pedagogical resource.

II. Literature Review

Current progress in WiFi performance evaluation has welcomed empirical as well as machine learning-based methodologies. Chen et al. used regression models to forecast signal strength fluctuations indoors using past records and environmental features like the type of walls and device location. Their model reached a prediction accuracy of more than 85 % in favor of smart network planning and coverage optimization [5]. Similarly, Zhang et al. analyzed the effect of overlapped WiFi channels on interference level and throughput consistency through simulated environments and deduced that channel harmonization substantially lowers packet loss and latency in high-density deployments [9].

Several studies have contributed to the domain of WiFi signal analysis through both empirical measurements and simulation-based techniques. Gomez et al. employed commercial WiFi analyzers to map signal strength in smart campus environments, revealing spatial inconsistencies and coverage dead zones [1]. Lu et al. developed indoor wireless propagation models using NS-3 and MATLAB, offering insights into multipath fading effects and environmental attenuation factors [2].

Patel et al. proposed a Python-based open-source simulation framework for network performance analysis, focusing on throughput and latency metrics but without extensive spatial coverage mapping capabilities [3]. Moreover, Sharma et al. investigated WiFi frequency band vs. coverage area trade-offs through theoretical models and experimental tests, focusing on environment-dependent standard selection requirements. These findings were supported by IEEE 802.11 Working Group reports, which identify growing WiFi network complexity with the emergence of standards such as 802.11ax (WiFi 6) and subsequent versions intended to improve spectral efficiency and concurrency across multiple devices [4].

Further contributions include realistic path loss modeling in indoor environments by Rath et al., incorporating empirical measurements specific to Indian urban residential conditions [7]. Adame et al. analyzed the relationship between RSSI, MCS, and spatial streams at 5 GHz, proposing an empirical

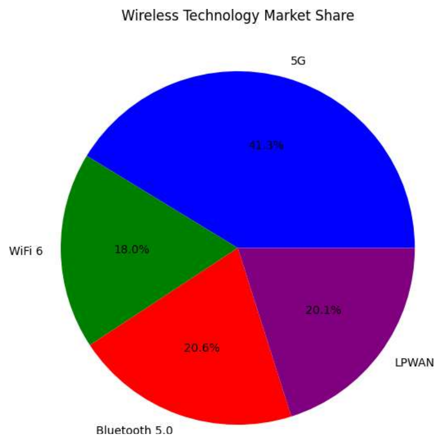


Fig. 1 Wireless Technology Market Share

path loss model for indoor scenarios [10]. Gu et al. introduced BeSense, a computational framework utilizing WiFi channel data and intelligent analytics for behavior recognition applications [6]. Li et al. simulated human activity detection based on signal fluctuations in indoor networks, demonstrating the utility of WiFi signals beyond conventional data transfer purposes [8]. Ma et al. explored LTE-to-WiFi interference effects in shared-spectrum environments, providing valuable simulation insights for coexistence scenarios [11].

Collectively, these works underscore the significance of both empirical and simulation-based research methodologies in wireless network analysis and emphasize the growing role of data-driven optimization in modern WiFi system design.

III. Methodology

The methodology employed in this study is designed to systematically evaluate the spatial distribution of WiFi signal strength within a simulated indoor environment, accounting for environmental obstructions and network congestion effects. By leveraging a Python-based simulation framework, the research replicates realistic conditions commonly encountered in residential, office, and commercial settings. Multiple WiFi standards are modeled to assess their respective performance variations under identical constraints. The framework incorporates mathematical path loss models, stochastic obstacle positioning, and interference simulations to produce accurate and visually interpretable signal heatmaps. The combination of numerical modeling and data visualization enables network designers and researchers to better comprehend coverage patterns and identify potential coverage holes, interference hotspots, and optimal access point placements before physical network deployment. This simulation-driven approach offers a flexible and cost-effective alternative to exhaustive field surveys and allows scenario-specific customizations such as floor plans, obstacle density, and device load, enhancing its adaptability to diverse operational contexts.

A. Simulation Parameters

The simulated environment covers a 100m × 100m indoor area represented by a 30 × 30 spatial grid, offering 900 distinct points for signal strength analysis. Six IEEE 802.11 standards are simulated: 802.11a, b, g, n, ac, and ax, each with unique propagation characteristics and data rate capabilities. Signal strength values are randomly assigned within a range of -90 dBm (poor) to -30 dBm (excellent), representing typical operational thresholds. Obstacles such as walls and furniture are simulated by randomly placing attenuation zones across the grid, introducing signal loss values ranging between 5 dB and 20 dB based on empirical measurements of indoor materials. To evaluate the effects of network congestion, the number of active devices within the simulation is varied from 1 to 20, reflecting real-world WiFi traffic densities in sparse residential and heavily populated office environments.

B. Mathematical Model

Signal propagation and attenuation are modeled using an adapted Free-Space Path Loss (FSPL) equation as follows:

$$FSPL(dB) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\frac{4\pi}{c} \quad (1)$$

where d represents the Euclidean distance between the transmitter and receiver in meters, f is the operational frequency in Hertz, and c denotes the speed of light in a vacuum. Following the FSPL calculation, additional attenuation penalties are applied based on the presence and intensity of environmental obstacles. Device-induced interference is modeled by incorporating cumulative signal degradation values proportional to the number of simultaneous active connections within the coverage zone. The resulting signal strength values are then interpolated to generate continuous coverage maps.

C. Tools and Libraries

The simulation framework is developed using Python 3.11 for its flexibility, wide library support, and ease of integration with scientific computing modules. Numerical computations and data manipulation are handled using the NumPy library, while Matplotlib and Seaborn are employed for generating signal strength heatmaps and graphical summaries. For spatial interpolation, the griddata function from SciPy's interpolation module is utilized to estimate signal strength values at unsampled grid locations. This toolset enables efficient numerical processing, visualization, and result interpretation within an open-source, reproducible environment.

D. Workflow

The simulation process follows a structured sequence of operations to ensure consistency and replicability:

1) Randomly generate 900 coordinate points within the simulation grid and assign initial signal strength values from the defined operational range.

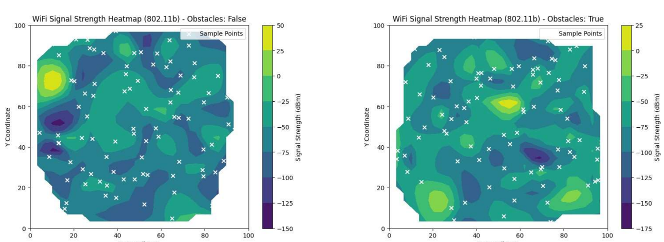
2) Simulate physical obstacles by randomly distributing attenuation regions, reducing signal strengths at proximate grid points by 5–20 dB.
3) Apply the adapted FSPL formula to model signal loss as a function of transmitter-receiver distance and frequency for each IEEE 802.11 standard.
4) Interpolate the resulting discrete signal strength values over the entire grid using SciPy's griddata function to generate continuous heatmaps.
5) Simulate device-induced interference by incrementally adding virtual devices into the environment and adjusting signal values based on cumulative interference penalties.
6) Perform comparative analyses across WiFi standards, quantifying differences in coverage area, interference tolerance, and obstacle resilience through both numerical metrics and graphical heatmap visualizations.

The methodology's structured and scalable nature enables its application in diverse simulation scenarios, ranging from simple residential environments to complex multi-floor commercial installations. Its modular design allows future extensions, including multi-floor modeling, integration of real-time WiFi scanning data, and optimization algorithms for access point placement. This makes the framework not only a practical tool for network planners but also a valuable educational resource for wireless networking students and researchers.

IV. Results and Discussion

A. Heatmap Analysis

Heatmaps for each standard demonstrated that legacy protocols like 802.11b provided broad coverage but suffered significant signal degradation, particularly in obstructed regions. Conversely, 802.11ac and 802.11ax achieved concentrated signal strength, albeit with more rapid attenuation beyond mid-range.

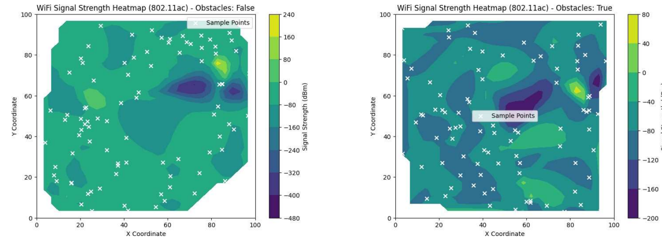


(a) Signal Distribution (b) Signal Distribution

Fig. 2: WiFi signal heatmaps generated for 802.11b in different scenarios.

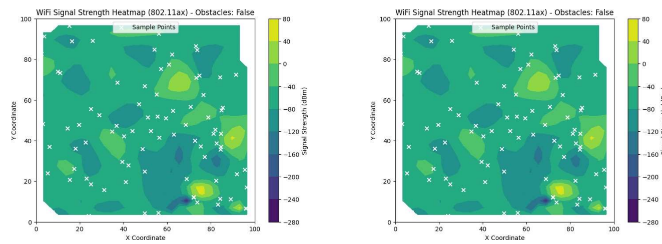
B. Interference Simulation

Device density directly influenced network stability. Under high interference (20 devices), signal quality degraded by 30–50% for older standards. 802.11ax, with features like BSS Coloring and OFDMA, sustained superior performance.



(a) Signal Distribution (b) Signal Distribution

Fig. 3: WiFi signal heatmaps generated for 802.11ac in different scenarios.



(a) Signal Distribution (b) Signal Distribution

Fig. 4: WiFi signal heatmaps generated for 802.11ax in different scenarios.

C. Obstruction Impact

Obstacles reduced local signal strength by up to 20 dB, forming coverage shadows. The newer 802.11ax protocol demonstrated the highest resilience, maintaining acceptable signal levels even in obstructed areas. Figure 1 (omitted here) illustrates comparative coverage maps.

D. Speed vs. Range Trade-off

802.11b and 802.11g offered extended range at lower data rates, while 802.11ac and ax prioritized throughput over distance. Network planners can leverage these insights to select appropriate standards for specific use cases, e.g., video streaming in confined areas versus IoT connectivity in large facilities.

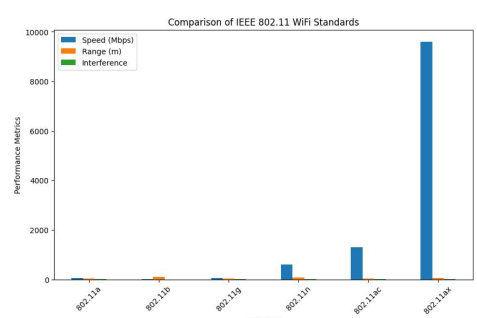


Fig. 5

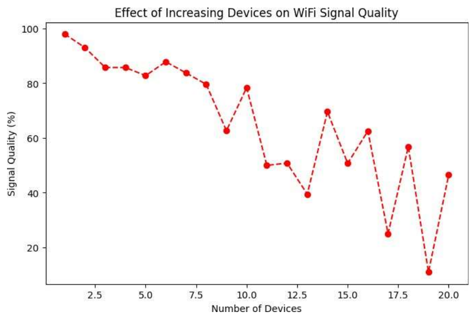


Fig. 6

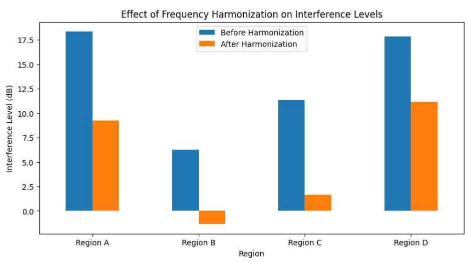


Fig. 7

V. Conclusion

This study demonstrates a robust, Python-based simulation framework for evaluating WiFi signal propagation, coverage, and performance characteristics under variable environmental conditions. Through systematic simulation and visualization, the research highlights the distinct behaviors of multiple IEEE 802.11 standards in terms of signal distribution, range, and resilience against physical obstacles and device interference. The produced heatmaps and comparative studies clearly demonstrate how newer standards, especially IEEE 802.11ax (WiFi 6), surpass older standards by providing more stable signal strength and better interference mitigation features. The results reiterate the importance of implementing advanced wireless technologies in high-density indoor environments and offer practical recommendations for network administrators in choosing suitable standards according to particular application requirements and environmental conditions. In addition, the open-source, scalable character of the suggested framework renders it an invaluable resource not merely for network planning and research in academic settings but also for pedagogic purposes, providing students with practical experience in the testing of wireless network performance.

VI. Future Work

Directions for future research will emphasize increasing the scope and realism of the envisaged simulation model. One critical expansion is incorporating APIs for real-time WiFi scanning so that empirical observation data from production environments can be gathered to carry out dynamic fine-tuning and validation of parameters for simulation. The present single-floor indoor architecture can further be extended to represent outdoor settings as well as multistoried buildings, incorporating difficulty areas like the propagation of signal vertically and outdoors interference sources. Another direction for enhancement is to improve interference models by considering the features of particular types of devices, such as IoT sensors, surveillance systems, and multimedia streaming devices, each with its unique requirements for wireless networks. In addition, integration of artificial intelligence methods for optimizing access point placement automatically is another area that has great promise for enhancing coverage fairness and reducing interference, especially in heterogeneous and high-density deployment areas. These improvements would significantly increase the real-world applicability and predictive capability of the simulation framework for various real-world WiFi scenarios.

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