УДК 537.87:502.11

ENHANCED METHODS FOR MEASURING ELECTROMAGNETIC WAVE PROPAGATION CHARACTERISTICS IN URBAN ENVIRONMENTS

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Аннотация. Данная работа представляет подробный анализ методологий измерения распространения электромагнитных волн (ЭМВ) в городских условиях, объединяя математические модели и эмпирические измерения для создания точного представления поведения сигнала. Распространение ЭМВ сильно зависит от городских построек, растительности и факторов окружающей среды, что создает значительные трудности для предсказания сигнала, его оптимизации и производительности сети в плотнозастроенных районах. Сочетая теоретические и эмпирические подходы, исследование анализирует и совершенствует модели потерь пути, затухания, дифракции и рассеяния, а также подтверждает полученные результаты данными из полевых измерений. Благодаря этой синтезированной работе авторы стремятся создать надежную базу для оценки характеристик ЭМВ, что особенно важно для беспроводных систем следующего поколения, таких как 5G и 6G.

Abstract. This paper provides an in-depth analysis of methodologies for measuring electromagnetic wave (EMW) propagation in urban environments, combining mathematical models and empirical measurements to create an accurate understanding of signal behavior. EMW propagation is heavily influenced by urban structures, vegetation, and environmental factors, leading to significant challenges in signal prediction, optimization, and network performance in densely built areas. By merging theoretical and empirical approaches, this work examines and refines path loss, attenuation, diffraction, and scattering models, and validates findings with data from measurement campaigns. Through this synthesis, we aim to establish a robust framework for assessing EMW characteristics, crucial for next-generation wireless systems like 5G and 6G.

Introduction

Urban environments, with their dense structures, varied vegetation, and complex infrastructure, create challenging conditions for electromagnetic wave (EMW) propagation. Wireless networks depend on accurate prediction and measurement of EMW behavior, especially as new technologies like 5G require high precision for data rate, reliability, and coverage. Traditional models, though informative, often lack accuracy in dense urban conditions. This paper synthesizes the latest methodologies, combining mathematical models and empirical measurements, to provide a refined understanding of EMW propagation characteristics and their practical applications in urban settings.

Theoretical Background and Key Influencing Factors

Electromagnetic wave behavior in urban environments is dictated by the principles in Maxwell's equations, where the general wave equation in a homogenous medium is given by:

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = 0$$

where E is the electric field and c is the speed of light. Wave propagation in urban areas is subject to multiple effects, including reflection, diffraction, and scattering, which can each degrade or alter signal quality.

Several environmental factors directly impact EM wave behavior:

- Reflection from buildings and infrastructure creates multipath interference.
- Diffraction occurs around obstacles, affecting signal continuity.
- Scattering from irregular surfaces leads to signal dispersion.
- Vegetation has a significant impact due to foliage density and moisture content, which attenuate signal strength, especially at higher frequencies.

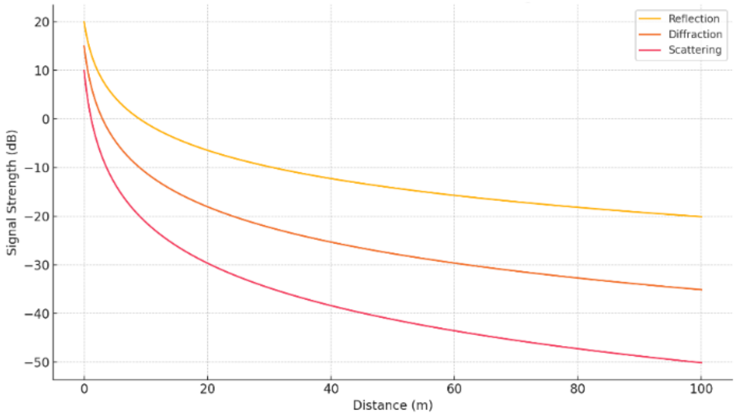

Fig 1. Effects of Reflection, Diffraction, and Scattering on EM Waves

Methods for Measuring EMW Propagation Characteristics

Empirical measurement remains essential for validating theoretical models in dynamic urban environments.

- Spectrum Analyzers measure frequency components, providing insight into channel characteristics.
- Field Strength Meters are used to assess signal strength at specific locations, capturing local propagation conditions.
- Car-Mounted Measurement Campaigns: Mobile measurement setups capture spatial variability in EMW exposure across urban landscapes, such as those used in studies in Beijing, where kriging interpolation techniques map exposure levels across cities.

Path loss models are critical in estimating signal attenuation across varying distances. The Free-Space Path Loss (FSPL) formula is fundamental for calculating basic signal degradation:

$$FSPL\ (dB) = 20log_{10}(d) + 20log_{10}(f) - 147.55$$

where d is the distance in meters, and f is the frequency in Hz.

The Hata-Okumura Model and COST-231 Walfisch-Ikegami models extend these predictions for urban settings:

$$PL_{urban} = 69.55 + 26.16log_{10}(h_{BS}) + (44.9 - 6.55log_{10}(h_{BS}))log_{10}(d)$$

where h_{BS} is the height of the base station and d the distance between the transmitter and receiver.

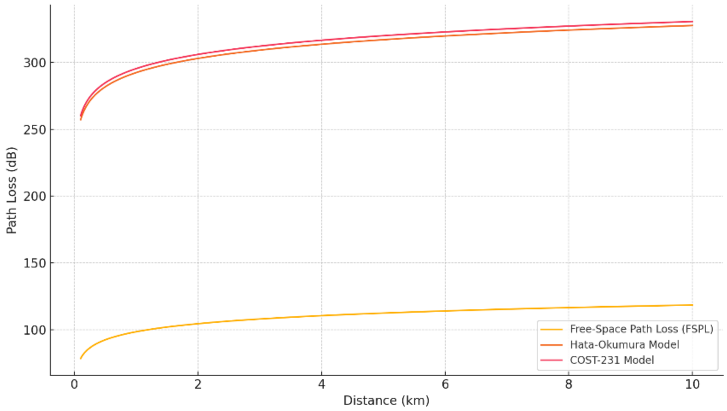

Fig 2. Path Loss Models Comparison

Large-Scale and Small-Scale Fading Models For capturing signal variability due to environmental factors, large-scale fading models account for average attenuation, while small-scale fading models handle rapid fluctuations.

- Rayleigh Fading Model: Suitable for environments without a direct line-of-sight (LOS), the Rayleigh distribution provides an accurate statistical description of signal variation.

- Nakagami-m Model: More versatile than Rayleigh, the Nakagami model better captures fading in dense urban environments by adjusting the shape parameter mmm to describe different multipath conditions.

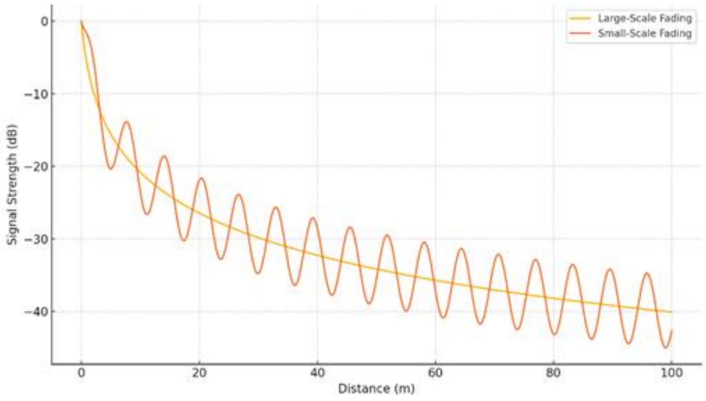

Fig. 3. Large-Scale and Small-Scale Fading

Advanced Propagation Analysis: Diffraction and Scattering

Knife-edge diffraction is crucial for predicting wave behavior around building edges. diffraction loss can be approximated by:

$$\Delta PL_{diffraction} = 20log_{10}\left(2 - 2\cos\left(\frac{\pi h_{obs}}{\sqrt{2\lambda d}}\right)\right)$$

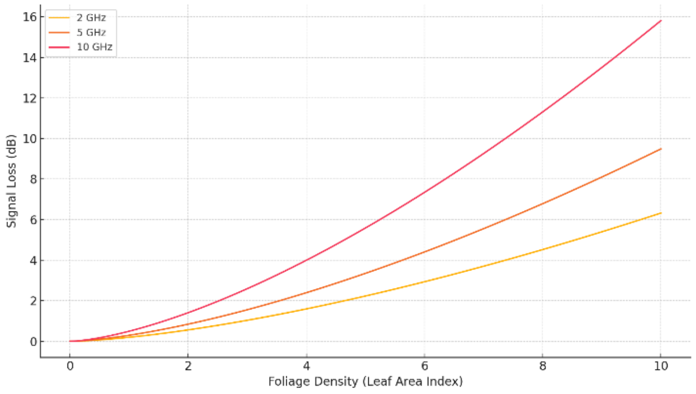

Fig. 4. Signal Attenuation vs. Foliage Density

where h_{obs} represents obstacle height, λ the wavelength, and d the distance to the observation point.

The Rayleigh scattering model captures the dispersion of waves when encountering irregular surfaces, especially critical at higher frequencies where scattering effects are pronounced. The scattered power can be estimated by:

$$P_{scattered} = P_{incident} \times \left(\frac{d^2}{\lambda^2}\right) sin^2(\theta)$$

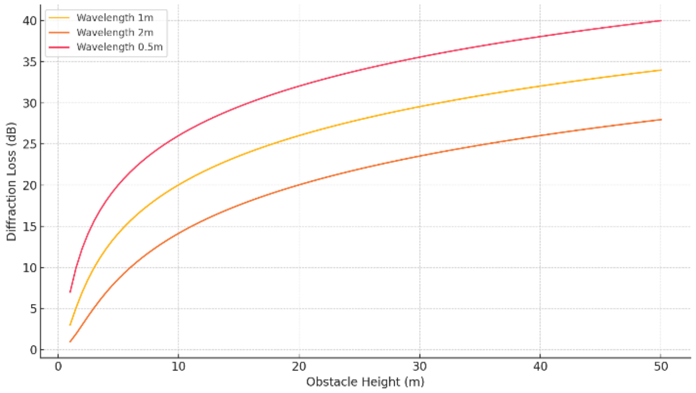

Fig. 5. Diffraction Loss vs. Obstacle Height and Wavelength where d represents obstacle diameter, and θ is the scattering angle.

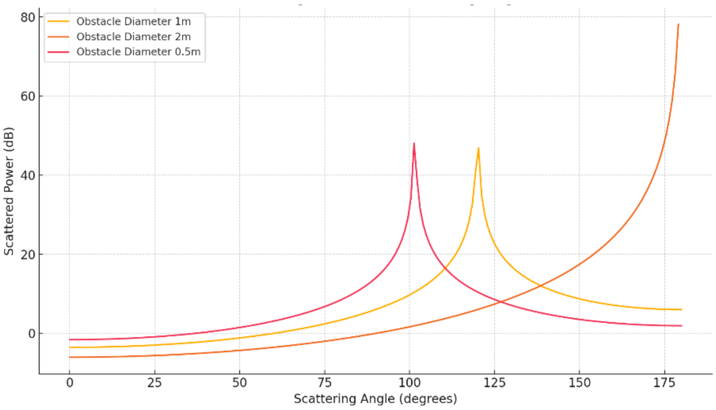

Fig. 6. Scattering Power vs. Scattering Angle

Case Studies and Validation

Measurement campaigns using mobile setups in cities like Beijing enable the mapping of EM wave exposure, utilizing kriging interpolation to depict exposure variability across city sections(test1). Studies confirm that street layouts and building densities heavily influence signal behavior.

Urban vegetation, which differs widely in density and composition, introduces signal attenuation based on leaf structure and moisture. Research confirms that denser foliage contributes to higher signal degradation, with models adjusted for vegetation density showing higher predictive accuracy.

Simulations examining building density reveal a strong correlation with increased path loss, underscoring the importance of high-resolution urban data in EMW propagation models. High-density areas exhibit significant signal degradation, which calls for adaptive modeling techniques tailored to urban features.

Conclusion

The integration of empirical measurement with mathematical modeling presents a comprehensive picture of EMW propagation in urban environments. Large-scale path loss models such as the Hata-Okumura and COST-231 provide reliable, general predictions, while deterministic models like Ray-Tracing and Geometric Theory of Diffraction (GTD) excel in high-density scenarios. The empirical data validated the superiority of these models in addressing urban complexity, such as variations in street canyons and high-rise clusters.

This study synthesized advanced methods for measuring and predicting electromagnetic wave propagation in urban environments, highlighting the effectiveness of combining empirical measurements with rigorous mathematical models. With increasing urban density and reliance on high-frequency communications, further development of adaptive models — potentially incorporating machine learning—is essential for accurate, real-time prediction and efficient network planning.

References

1. Rappaport T. S. “Wireless Communications: Principles and Practice”. Prentice Hall, 2001.
2. Fernández-García R., Gil I. "Measurement of the environmental broadband electromagnetic waves in a mid-size European city". Science of The Total Environment, 2017.
3. Tang C., Yang C., Cai R., et al. "Analysis of the relationship between electromagnetic radiation characteristics and urban functions in highly populated urban areas". Environmental Pollution, 2019.
4. Zhang C., Ma Z., Wang J., et al. "Measurement, data analysis and modeling of electromagnetic wave propagation gain in a typical vegetation environment". PLoS ONE, 2023.