ISBN: 978-628-95207-8-1. ISSN: 2414-6390. Digital Object Identifier: 10.18687/LACCEI2024.1.1.156

Urban Signal Propagation Study Using Ray Tracing Methods in Tegucigalpa, Honduras

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Abstract*— Ray tracing function plays a crucial role in urban signaling, expanding its application from multipath propagation to the detailed analysis of different signal paths in urban environments. This study focuses on the comprehensive exploration of coverage analysis and the adaptation of building structures in the mountainous region of Central America, specifically in Tegucigalpa, Honduras. The goal is to improve accuracy in predicting radio frequency coverage and signal quality in the region. The electromagnetic analysis is considered, contributing to loss calculations using the Fresnel equation, the Uniform Diffraction Theory, geometric angle, and the permittivity of building materials. A key innovation in this research is the integration of ray tracing algorithm with Shooting and Bouncing Ray (SBR) and the Image Method. Emitting rays in various directions enables a holistic understanding of signal propagation across multiple paths within urban environments. The model titled 'Urban Link and Coverage Analysis Using Ray Tracing' provides the fundamental framework for this analysis, showing significant potential to streamline the estimated time required to design communication networks in urban areas. Furthermore, the use of multiple signal paths in urban environments offers a crucial advantage to enhance signal robustness and reliability.

***Keywords*—Ray tracing, signal, reflection, diffraction, shooting and bouncing ray (SBR), transmitter (Tx), receiver (Rx).**

I. INTRODUCTION

The trajectory of computer graphics evolution has been consistently oriented towards achieving heightened realism in image rendering. In this pursuit, researchers in this domain have meticulously observed the real world, employing cutting-edge technology to replicate lifelike images [1]. This relentless endeavor to enhance computer-generated images involves the integration of realistic elements, encompassing faithful representation of occlusion, refinement of details in well-lit objects, and precise depiction of surface textures. These advancements have paved the way for techniques that significantly elevate the quality of computer-generated images [2]. One particularly noteworthy approach in this quest is ray tracing (RT), a technique that assumes a pivotal role in predicting various characteristics of radio signal propagation. These characteristics span factors such as signal loss, temporal changes, and angular dispersion. The primary function of RT is to identify the main paths traversed by rays between a transmitting antenna and a receiving antenna, with these ray paths intricately tied to the geometry of the surrounding environment [3]. A comprehensive ray tracing simulator takes into consideration fundamental aspects such as reflection, penetration, diffraction, and scattering, utilizing geographical data for modeling. This positions ray tracing models as the acknowledged standard for precision in predicting signal behavior across diverse environments [4]. Ray tracing methods, integral to both computer graphics and electromagnetic wave propagation analysis, include two commonly employed techniques: the Image Method and the Shooting and Bouncing Ray (SBR) method [5]. The Image Method, frequently utilized for tracing reflected ray paths from flat surfaces, relies on identifying intersection points determined by transmitter (Tx) and receiver (Rx) positions, as depicted in Fig. 1 [6].

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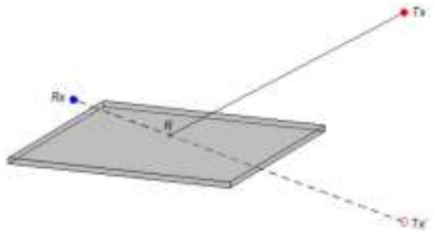

Fig. 1. Image method

In contrast, the SBR method amalgamates principles from both Physical Optics (PO) and Geometrical Optics (GO) with ray tracing algorithms, as illustrated in Fig. 2. Its notable advantage lies in the capability to model reflections of multiple orders, surpassing traditional constraints [7].

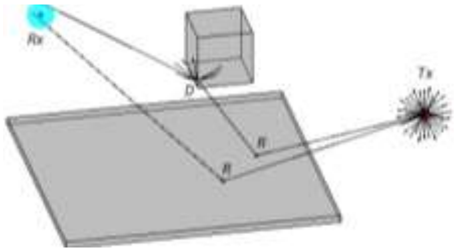

Fig. 2. SBR method

The synergy of the SBR and Image Theory as a hybrid approach offers a balanced solution. SBR efficiently traces rays through complex scenes but may overlook interactions with smaller objects and accumulate errors. On the other hand, Image Theory is precise but computationally intensive. Together, they synergistically overcome these limitations [8]. These techniques contribute to the representation of the Fresnel zone and consequently enhance the precision of signal propagation in urban environments. The first Fresnel zone describes an ellipsoidal region around the line of direct sight between the transmitter and receiver. When objects obstruct this zone, the free space assumption is no longer valid, and the simulator will not generate any ray traces [9]. Implementing a hybrid method in signal propagation analysis yields substantial benefits by calculating the electromagnetic field of each ray and examining the first Fresnel zone to account for losses due to partial blockage. Although this approach may increase computational time due to considering more reflections and diffractions, it reveals additional signal propagation areas [10]. Greater precision becomes imperative when evaluating communication links and coverage areas in complex urban environments. By systematically considering additional reflections and diffractions, the hybrid method provides a comprehensive insight into signal propagation within these demanding landscapes. This level of precision is indispensable for the effective execution of Urban Signal Transmission Analysis [11].

II. MODEL DESCRIPTION

Urban Link and Coverage Analysis Model using Ray Tracing is a powerful tool designed for analyzing communication links and coverage areas in urban environments. Its primary objective is to determine optimal locations for transmission and reception sites, considering the effects of coverage, signal propagation, the Fresnel zone, line of sight, and surrounding materials. To maintain signal quality and reduce signal loss from obstructions, having a clear line of sight and minimizing obstacles in the area is crucial. By integrating considerations of topography and building height, a comprehensive understanding of radio signal behavior in urban areas can be obtained, aiding in the planning and optimization of wireless communication networks.

A. Import and Visualize Buildings Data

Here, the Siteviewer function is introduced, providing a three-dimensional view of the Earth using OpenStreetMap (OSM), a community-driven mapping service created as an alternative to authoritative sources. OSM has gained widespread adoption in various geoscience applications, demonstrating its value as a versatile resource. For further exploration, you can visit the OpenStreetMap website at https://www.openstreetmap.org/ [12].

In this case, an .osm file for the Tegucigalpa, Honduras region will be imported. Figure 3 illustrates the three-dimensional representation generated by the Siteviewer function for this specific location, offering a detailed and contextual visualization of the geographic environment.

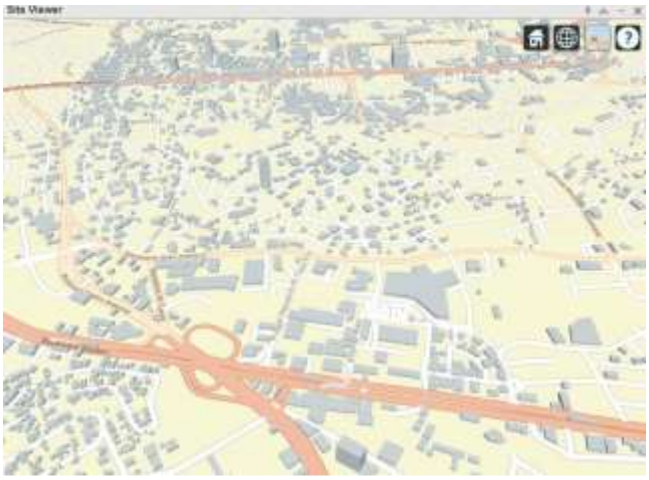

Fig. 3. Building Data in Tegucigalpa, Honduras.

B. Defining Transmitter and Receiver Sites Based on Antennas

In this section, our research delves into a thorough analysis of different propagation scenarios, aiming to understand the dynamics of signal transmission across varied terrains and urban landscapes. To facilitate this investigation, we utilize a simulator capable of accurately positioning both the transmitting and receiving stations based on provided coordinates, irrespective of line-of-sight conditions. Additionally, we factor in the antenna height to comprehensively study line-of-sight considerations. As part of our methodology, we solicit specific parameters from users to enhance the precision of our analysis. These parameters include latitude and longitude of the transmitting station, antenna height, transmitter power, transmitter frequency, atmospheric temperature, atmospheric pressure, and water vapor density. By meticulously analyzing connection quality in scenarios both with and without obstacles, we aim to offer deeper insights into communication efficiency under diverse environmental conditions. This approach not only enriches our understanding of propagation phenomena but also aids in the development of robust communication systems adaptable to real-world complexities. [13].

C. Coverage Map for Propagation

The choice of propagation algorithm varies depending on the presence of reflections in the signal path. For one or two reflections, image techniques are employed as a precise tool to determine the propagation path. However, in cases with multiple reflections, complexity increases, limiting the effectiveness of the algorithm, and the Shooting and Bouncing Rays (SBR) method is used. This method combines the principles of physical and geometrical optics with ray tracing. When generating coverage maps, the generated power is shown in each sector, highlighting small buildings that provide greater accuracy in the reflected signal.

D. Plot Propagation Path using Ray Tracing

In the analysis of radio wave propagation, the term "reflected" or "transmitted" ray is employed when a ray undergoes multiple reflections or transmissions before reaching the field point. This phenomenon involves the reflection or transmission of electromagnetic waves at interfaces between different mediums, with the propagation direction determined by the laws of reflection and refraction. The magnitude of the reflected or transmitted field is governed by Fresnel's equations for various polarizations.Within the ray tracing model, this function visualizes signal propagation in a specific environment by adjusting the model to include single-reflection paths. The graphical representation of these paths illustrates how the signal propagates along them, allowing users to explore features such as received power and arrival angles.The theory of Fresnel is crucial for understanding propagation conditions, especially concerning free-space loss. It is essential that the direct path between antennas is free from obstructions, as nearby obstacles can affect reflection, influencing signal reception. In scenarios with obstacles in proximity, the path loss may exceed free-space loss, even without a direct line-of-sight blockage. The quantitative measurement of the required space is obtained through Fresnel zone ellipsoids, defining the first zone.

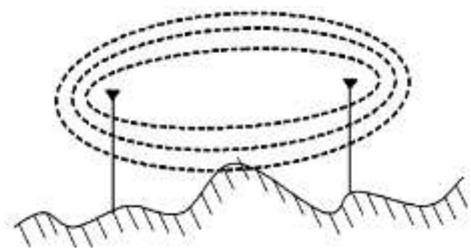

Fig. 4. Limits of the Fresnel zones

The figure 4 demonstrates how waves traversing circles in the vertical plane between antennas cover longer distances than the direct line, and the ellipsoid family quantifies this phenomenon.

The formula for the Fresnel zone

$$h = r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}} \quad (1)$$

In the presented model, when the direct path is obstructed, a link is not established between different locations. However, if the direct path is unobstructed but the first Fresnel zone is partially obstructed, additional loss is considered [14].

E. *Analyze Signal Strength and Effect of Materials*

Signal strength analysis is a key component of the model. In real-world environments, a link between a radio transmitter and a receiver depends on various factors, as depicted in Figure 5. This graphical representation illustrates terms used in the transmission loss concept, such as losses in antennas or transmission lines, attenuation, losses due to faulty impedance matching, or polarization. Recognizing the importance of incorporating these losses into the simulation is essential to achieve accurate and detailed results [15].

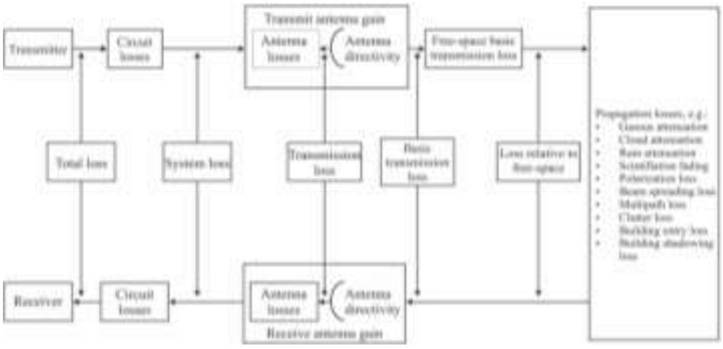

Fig. 5 Graphical depiction of terms used in the transmission loss concept.

Free Space Loss: These losses measure the attenuation of the radio link in an unobstructed space between the transmitting and receiving antennas [16]. Using the expression

$$FSPL\ (dB) = 20 * log10(d) + 20 * log10(f) + 32.44 \quad (2)$$

The free space loss can be divided into losses of different types, and in this research, it will be divided into the following:

Absorption Loss (atmospheric gases, clouds, rain) : the atmosphere produces an absorption effect on electromagnetic energy due to the presence of water vapor molecules, oxygen molecules, rainwater, snow, etc [17].

Specific attenuation of oxygen (dry air)

$$f \leq 57GHz$$

$$\gamma_o = \left[\frac{7,27}{f^2+0,35\, r^2pr^2t} + \frac{7,5}{(f-57)^2+2,44\, r^2pr^5t}\right] f^2\, r^2p\, r^2tx10^{-3} \quad (3)$$

Rain Attenuation

$$\gamma_R = kR^{\alpha} \quad (4)$$

Specific Attenuation of Water Vapor

$$f \leq 180\ GHz$$

$$\gamma_w = \left[3,27x10^{-2} + 1,67x10^{-3}\rho + 7,7x10^{-4}f^{0,5} + \frac{3,79}{(f-22,23)^2+9,81} + \frac{11.73}{(f-183.31)^2+11.85} + \frac{4.01}{(f-325.153)^2+10.44}\right] f^2\rho x10^{-4} \quad (5)$$

Reflection and Diffraction Loss The influence of the link profile is mainly due to reflection and diffraction. These are categorized as losses due to the location of the link and the path the wave takes between the antennas.

Diffraction Loss over Irregular Terrain

$$V_n = h\sqrt{2d_{ab}/\lambda d_{an}d_{nb}} \quad (6)$$

Loss due to material effects: The integration of realistic materials into the model is crucial, as it significantly influences both the calculated signal loss and received power. Assigning materials to buildings not only considers conductivity but also the losses they introduce.

Relative Permittivity

$$\eta' = af^b \quad (7)$$

Conductivity

$$\sigma = cf^d \quad (8)$$

Please refer to Table 1 for a detailed list of various building materials.

TABLE I. VARIOUS BUILDING MATERIALS

Material	Relative permittivity	Conductivity (S/m)	Frequency (GHz)
Vacuum (≈ air)	1	0	0.001-100
Concrete	5.24	0.0462	0.7822
Brick	3.91	0.0238	0.16
Plasterboard	2.73	0.0085	0.9395
Wood	1.99	0.0047	1.0718
Glass	6.31	0.0036	1.3394
Glass	5.79	0.0004	1.658
Ceiling board	1.48	0.0011	1.0750
Ceiling board	1.52	0.0029	1.029
Chipboard	2.58	0.0217	0.7800
Plywood	2.71	0.33	0
Marble	7.074	0.0055	0.9262
Floorboard	3.66	0.0044	1.3515
Metal	1	0	107
Very dry ground	3	0.00015	2.52
Medium dry ground	15	-0.1	0.035
Wet ground	30	-0.4	0.15

As evidenced in Table I, the repetition of materials is observed based on the frequency range to be utilized. This repeating pattern underscores the importance of considering the electromagnetic properties of construction materials across a broad spectrum of frequencies. The variability in these properties emphasizes the need for a detailed and frequency-specific analysis when designing wireless communication systems and assessing the signal propagation quality through built structures.

Taking into account each of these aspects, the received power is calculated based on the calculated losses and the gain of the antenna to be used.

$$[dBW] = EIRP[dBW] - Ls[dB] + Gr[dBi] \quad (9)$$

III. Mapping Urban Signal Pathways

This study is based on the application of the "Urban Link and Coverage Analysis Using Ray Tracing" model, an advanced tool that prioritizes the precise definition of locations for transmitters and receivers in urban scenarios. This approach involves the detailed representation of base stations providing services to surrounding areas, enabling a comprehensive analysis of each potential route generated by multiple propagations and ray tracing.

The methodology adopted in this study is hybrid, comparing the characteristics of each route to select the most suitable method, whether it be the image method or Shooting and Bouncing Ray (SBR). This strategic approach ensures the flexibility and adaptability of the model to various conditions and specific needs of the urban environment under study.

Emphasizing the importance of a robust "link budget," the model underscores the need for the first Fresnel zone to be clear to carry out accurate simulations, considering the specific conditions of urban zones. Additionally, the study addresses commonly observed losses affecting link efficiency, such as attenuation due to atmospheric gases, fog, clouds, rain, reflection, and diffraction, as well as losses associated with the conductivity and permittivity properties of materials present.

After completing this essential process in establishing a radio link, the model consolidates techniques to steer the transmitter's antenna and achieve optimal link quality. This ability to optimize the beam direction significantly contributes to improving received power and, consequently, link quality in challenging urban environments.

IV. SIMULATION

This section begins by collecting essential data to tailor the 'Urban Link and Coverage Analysis Using Ray Tracing' model in Matlab for research conducted within the Honduran territory. Various critical parameters that impact the propagation of electromagnetic waves in the area under study are necessary. As illustrated in Figure 6, the Studied Area, precise geographical coordinates of the transmission site are entered to establish the simulation's exact location in Tegucigalpa. These data play a crucial role in defining the specific terrain geography and ensuring an accurate depiction of the urban environment. Subsequently, details regarding the antenna height of the transmitting station, transmitter power, and operating frequency are requested. These parameters are essential for modeling the emission of signals from the transmission station and understanding how they will propagate throughout the city.

Fig. 6 Studied area - Tegucigalpa M.D.C. Honduras

In addition, atmospheric data such as ambient temperature, atmospheric pressure, and water vapor density are collected. These atmospheric factors have a significant impact on the propagation of electromagnetic waves and are essential for accurate simulation. With the information of the transmitting station defined, the location of the receiving station in Tegucigalpa is then addressed, as depicted in Fig. 7. The corresponding data regarding the geographical location and height of the receiving antenna are entered to complete the configuration of the communication scenario.

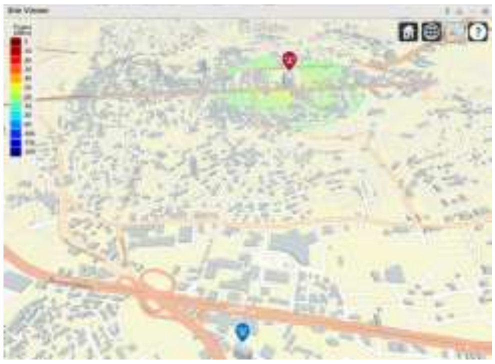

Fig. 7 Transmitter and receiver placement

Once all these parameters are set, the ray tracing adapted to the topography and specific characteristics of Tegucigalpa is initiated, as illustrated in Fig. 8. This process simulates how electromagnetic waves will propagate in the urban environment, considering elements such as buildings, terrain, and atmospheric conditions. The figure visually represents the intricate paths of these waves, reflecting the complex interplay of signals with the urban landscape.

Fig. 8 Ray-tracing

After defining the parameters, attenuation curves due to atmospheric gases, rain, and vapor are plotted. Subsequently, the simulator displays a results box with various scenarios to assess the quality of the wireless communication link, as shown in Fig. 9. The results encompass received power under ideal conditions (perfect reflection), account for weather losses, analyze the impact of multiple reflections, and evaluate the influence of diffraction.

Fig. 9 Signal intensity

Finally, additional data, including azimuth angles, elevation angles, maximum sidelobe attenuation (in dB), and antenna tilt angle (in degrees), are requested for the selected antenna. The objective is to optimize received power. The antenna is dynamically adjusted to direct the beam in the optimal direction, thereby maximizing link quality, as illustrated in Fig. 10. This process facilitates a detailed and adaptive simulation to evaluate and improve the efficiency of wireless communication in the urban environment of Tegucigalpa.

Fig. 10 Directional antenna

V. RESULTS

The utilization of the "Urban Link and Coverage Analysis Using Ray Tracing" model has yielded valuable insights into signal propagation, providing detailed information about potential routes through ray tracing. The deployment of this link involved assigning coordinates.

14.100395, -87.182697, and 14.083535, -87.185358

to the transmitter and receiver sites, respectively. Four distinct routes were identified, each possessing unique characteristics:

TABLE II. CHARACTERISTICS OF PROPAGATION PATHS

Distance (m)	Received Power (dBm)	Diffraction	Reflection
2723.11	-117.5	1	1
1894.74	-118.7	1	1
1890.1	-101.7	1	0
1887.73	-78.9	0	0

The selection of the optimal route was grounded in received power, signaling superior signal quality in comparison to alternative routes. This strategic decision aimed at minimizing distance to alleviate any potential signal attenuation. While Route 4's elevation profile, depicted in Figure 11, was crafted to ensure a clear Fresnel zone, a limited line of sight was noted, necessitating resolution through adjustments in antenna height at each site.

Fig. 11 Elevation profile

To visually depict the attenuation levels due to rain and atmospheric gases, specific graphs have been crafted and are presented in Figure 12. Notably, there is observed gas attenuation of 0.04 dB/km at 10 GHz and a rainfall-induced attenuation of 1.5 dB.

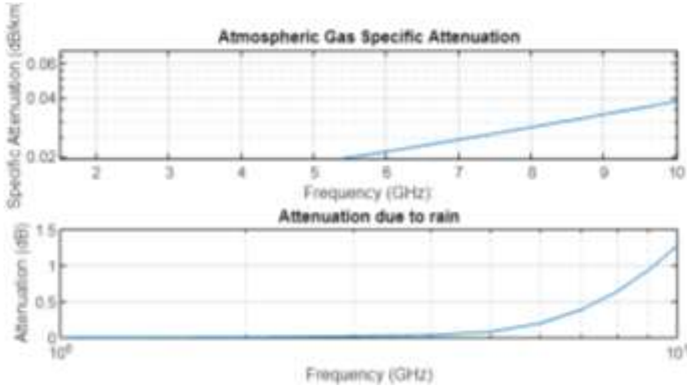

Fig. 12 Attenuation levels

It is crucial to acknowledge that, despite the positive outcomes, further optimization of the link is feasible through advanced antenna pointing techniques. In this context, azimuth consideration entails complete coverage around a central point, while elevation spans from the lowest to the highest point. The direction assignment is contingent upon the relative position of the transmitting station with respect to the receiving station, indicated, for example, by -90, signifying the direction from the transmitter towards the south. In Figure 13, Route 4 is clearly visualized as the optimal choice for the system.

Fig. 13 Route 4

These findings underscore the importance of continuous optimization and adaptability of antenna configurations to achieve efficient wireless communication in the complex urban environment of Tegucigalpa. The precise adjustment of antenna pointing, considering both azimuth and elevation, proves essential in maximizing the link's quality and efficiency, particularly in adverse atmospheric conditions.

This comprehensive analysis underscores the critical importance of considering environmental factors in the planning of wireless communications, offering valuable insights for optimizing communication networks in urban environments.

VI. Conclusions

The analysis of radio links using the "Urban Link and Coverage Analysis Using Ray Tracing" model has proven to be a powerful and versatile tool for the planning and optimization of wireless communication networks in urban environments. By integrating advanced ray-tracing methods, such as Fresnel zone calculations, the model provides a detailed representation of electromagnetic wave propagation, considering key factors such as terrain topography, building height, and surrounding material composition.The model's ability to identify and select optimal propagation paths based on criteria such as received power and minimizing signal attenuation underscores its utility in decision-making for the strategic placement of transmission and reception sites. Special attention to the influence of rain and atmospheric gases on signal attenuation provides a more comprehensive understanding of potential challenges in adverse weather conditions.Furthermore, the integration of additional parameters, such as antenna height and dynamic beam optimization, demonstrates the model's adaptability to changing environmental conditions. This is crucial to ensuring reliable and high-quality connectivity in wireless communication systems. The "Urban Link and Coverage Analysis Using Ray Tracing" model emerges as an essential tool for network engineers and planners, providing detailed and accurate information for informed decision-making in the deployment of communication infrastructures in challenging urban environments. Its comprehensive approach and ability to consider a wide range of variables position it as a valuable resource in the design and improvement of wireless networks in the dynamic context of current communication technologies.

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