A Primer on Ray-Tracing: Shooting and Bouncing Ray Method

Yasir Ahmed [1] and Jeffrey Reed [2]

[1]Raymaps
[2]Affiliation not available

December 7, 2023

Abstract

Ray-tracing is a promising alternative for Radio Frequency Planning particularly in urban areas. There are two fundamental techniques used for ray-tracing namely Shooting and Bouncing Rays and Method of Images. In this paper, we focus on the former and present simulation results for an urban scenario in the city of Helsinki. We also give an insight into how the Shooting and Bouncing Ray method can be implemented using basic linear algebra techniques. We show that ray-tracing can be used to evaluate the performance improvement attained through electromagnetic reflectors. Finally, we close the discussion by outlining the existing challenges and the way forward.

A Primer on Ray-Tracing: Shooting and Bouncing Ray Method

Yasir Ahmed and Jeffrey H. Reed

Virginia Tech, Blacksburg, VA 24061

www.raymaps.com

***Abstract* – Ray-tracing is a promising alternative for Radio Frequency Planning particularly in urban areas. There are two fundamental techniques used for ray-tracing namely Shooting and Bouncing Rays and Method of Images. In this paper we focus on the former and present simulation results for an urban scenario in the city of Helsinki. We also give an insight into how Shooting and Bouncing Ray method can be implemented using basic linear algebra techniques. We show that ray-tracing can be used to evaluate the performance improvement attained through electromagnetic reflectors. Finally, we close the discussion by outlining the existing challenges and the way forward.**

1. Introduction

Ray-tracing has been used extensively for solving problems in Electromagnetics and Signal Propagation. It was originally used for calculating the path of high frequency (HF) radio waves within the ionosphere [1]-[4] and troposphere [5]-[9]. Later on, it was modified for calculating the path loss and delay spread for cellular networks [10]-[14], wireless LANs [15]-[18] and broadcast networks [19]. Most of the recent research has been focused on extending the 2D ray-tracing models to 3D, finding efficient techniques for simulating complex geometries and on applying these techniques to multi-input multi-output (MIMO) and ultra-wideband (UWB) systems.

2. Ray-Tracing Techniques

Most of the existing ray-tracing techniques are either derived from the Shooting and Bouncing Ray (SBR) method or Images Method (IM). The SBR method was originally proposed as a technique for calculating the radar cross section (RCS) of an arbitrarily shaped cavity [20]. It involves sending a dense cluster of rays into a cavity and then calculating the scattered field by integrating the rays over the aperture. This concept was then extended for calculating the path loss in indoor and outdoor wireless environments. A technique that is usually applied to find the total E-field strength within a region is to define a small reception sphere and combine all the rays that pass through the sphere [21]. The size of the sphere is defined by the angular separation of the rays. It is quite obvious that this is an approximate technique that would yield more accurate results as the angular separation is reduced.

The Images Method is more efficient since it only finds the paths that terminate at the receiver. It is also more accurate since the E-field strength is calculated at a point in space and no reception sphere is used. This is obvious from Fig 1 where the Images Method finds the exact path whereas SBR fails to do so. This method is especially useful in an indoor environment where multiple reflections occur between the walls, ground and the ceiling. It is somewhat less practical in a scenario where there are multiple reflections and refractions.

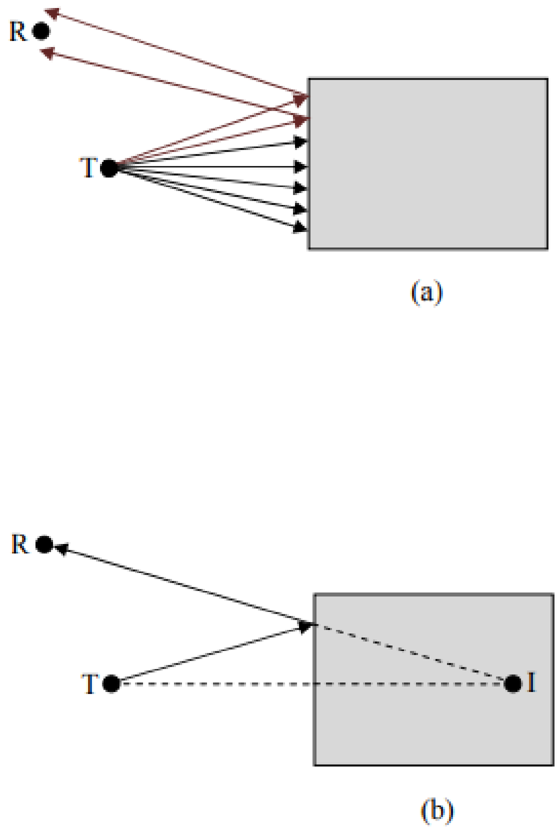

Fig 1. Single reflection between the transmitter (T) and receiver (R)

(a) Shooting and Bouncing Rays (b) Method of Images

3. Ray-Tracing Fundamentals

Finding the point of intersection of two lines has many important applications such as in ray-tracing using SBR method. Two lines always intersect at some point unless they are absolutely parallel, like the rails of a railway track. We start with writing the equations of the two lines in slope-intercept form.

$$y_1 = b_1 + m_1x_1$$

$$y_2 = b_2 + m_2x_2$$

Here m_1 and m_2 are the slopes of the two lines and b_1 and b_2 are their y-intercepts. At the point of intersection $y_1 = y_2$, so we have.

$$b_1 + m_1x_1 = b_2 + m_2x_2$$

But at the point of intersection $x_1 = x_2$ as well, so replacing x_1 and x_2 with x we have.

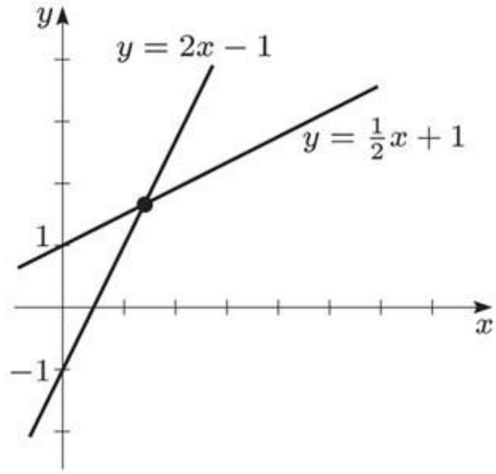

Fig 2. Finding the intersection of two straight lines

$$b_1 + m_1 x = b_2 + m_2 x$$

$$b_1 - b_2 = m_2 x - m_1 x$$

$$b_1 - b_2 = -x(m_1 - m_2)$$

$$x = -\frac{b_1 - b_2}{m_1 - m_2}$$

Once the x-component of the point of intersection is found we can easily find the y-component by substituting x in any of the line equations above.

$$y = b_1 + m_1 x$$

Once the point of intersection is found, Snell's law is used to find the angle of reflection and refraction for further propagation of the ray. Reflection and transmission coefficients are found based upon the material properties and the angles involved. A rectangular grid is used for summation of received E-field vectors.

4. Eclipse: A Ray-Tracing Engine

Radio frequency planning is an essential component of network planning, roll-out, up-gradation, expansion etc. Several methods can be adopted for this from something as simple as free space models, empirical path loss models to the significantly more complicated, time consuming and expensive drive testing. Drive testing gives very accurate results but these results can be rendered useless by changing the position of an antenna or the tilt of an antenna requiring another run in the field. Changing weather conditions can also have an impact on the coverage map. One solution to this problem is ray-tracing which is very accurate but is usually considered to be very computationally expensive and of little practical value. But recent advances in computational power of machines coupled with efficient techniques have made this technique to be much more practical.

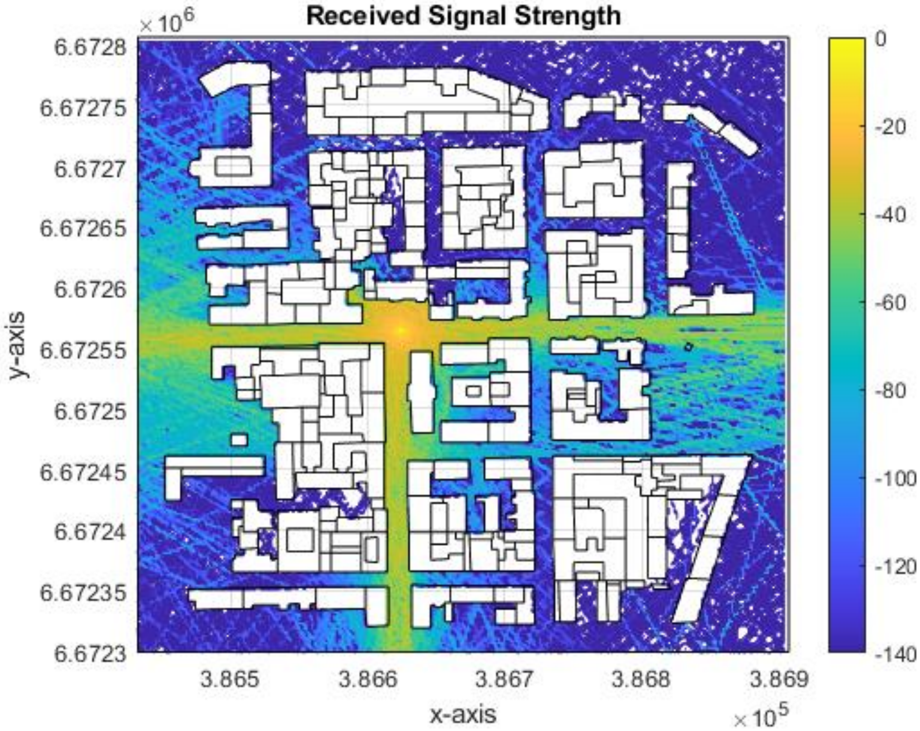

Fig 3. Ray-tracing simulation using calculated reflection coefficient

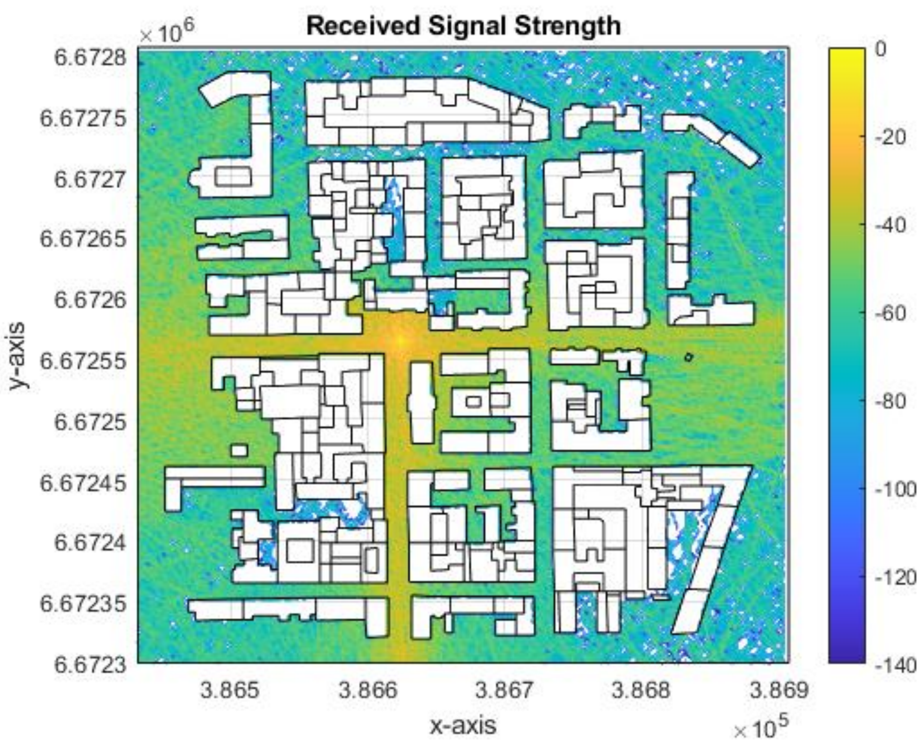

Fig 4. Ray-tracing simulation using almost perfect reflection coefficient ($R = 0.9$)

Eclipse is a near real-time simulation software for prediction of signal strength in urban areas. The software uses Shooting and Bouncing Ray (SBR) method of ray-tracing with 1-degree ray separation, 1 m step size and 50 interactions per ray path. The simulation parameters can be varied according to the resolution required. The code is highly optimized to give results in shortest possible time. It is especially useful for network planning of ultra-dense wireless networks where a dense network of antennas is placed on lamp posts instead of telecom towers. Various frequency bands can be simulated, along with different antenna radiation patterns and MIMO configurations.

A 2D simulation of a scenario with one transmit antenna located in downtown Helsinki is shown above. We compared the signal strength using exact calculation of reflection coefficient with the signal strength using reflection coefficient of 0.9. This is done to understand the benefits that can be achieved by using electromagnetic reflecting surfaces placed strategically in the coverage area. It is seen that even without perfectly aligning the phases at the receiver there is a significant increase in the received signal strength in the shadowed regions. It is expected that when using Reconfigurable Intelligent Surfaces (RIS) the increase in signal strength would be even more. The number and size of reflecting surfaces required is still an open question.

It must be noted that for calculating exact reflection coefficient we have assumed building relative permittivity to be 7.5 and relative permeability to be 0.95. All simulations are carried out at a frequency of 1GHz. As the frequency of operation changes the properties of the building material also change and with it the reflection coefficient. One thing we discovered during our simulations was that if the exact reflection coefficient cannot be calculated at each and every point of interaction, a value of $R = 0.5$ gives a ballpark estimate. Ground reflected component can also be included in our simulations in future to make the results even more realistic.

5. Ray-Tracing Challenges and Way Forward

It's very easy to get lost in the jargon when selecting a simulation tool for planning your wireless network. You will be faced with complex terminology which would not make much sense. At one end of the spectrum are solutions based on simple empirical models while at the other end are solutions based on ray-tracing techniques. Empirical models are based on measurement data and are your best bet if you want a quick and cheap solution whereas ray-tracing techniques are based on laws of physics and promise more accurate results. In principle ray-tracing techniques are quite simple: just transmit a bunch of rays in all directions and see how they behave. However, when the number of rays and their interactions becomes large the simulation time may become prohibitively expensive. The simulation time for complex geometries may vary from a few hours to several days. Following are some of the factors that you must consider when selecting a ray-tracing simulator.

a. Upper limit on the number of interactions

Ray-tracing simulators essentially generate a bunch of rays (image-based techniques are an exception) and then follow them around as they reflect, refract, diffract and scatter. Each interaction decreases the strength of the rays. The strength of the rays also decays with distance. As a result, the simulator needs to decide when to terminate a ray path. This is usually done based upon the number of interactions that a ray undergoes (typically 8-10 interactions are considered) or based upon its strength (once the strength of a ray falls below -110 dBm there is no point following it any further). Higher the number of interactions considered, greater the accuracy of the simulation but higher the computational complexity.

b. Granularity in field calculations

Field calculations cannot be performed at each and every point within the simulation space. The usual approach is to divide the region under study into a grid such that locations closer to a transmitter are covered more finely and the regions further away are covered in lesser detail. The rays are then combined within each block of the grid to get the resultant field strength. The level of granularity determines the computation load. It would be prohibitively expensive to have a very high level of granularity for a large coverage area.

c. Accuracy in modeling the various propagation phenomenon

As mentioned previously an accurate modeling of all propagation phenomena is required including reflection, refraction, diffraction and scattering. Some ray-tracing simulators might model reflection and refraction only while ignoring the other phenomenon such as diffraction. Furthermore, some ray-tracing simulators might consider all reflections to be specular (no scattering). This is a good approximation for large smooth surfaces but is not such a good assumption for irregular terrain.

d. Granularity of the terrain database

Most state-of-the-art ray-tracing tools use some sort of terrain database to perform their calculations. These terrain databases are required for determining the paths of the rays as they travel in dense urban environments. These databases may contain simple elevation data or actual 3D building data and may have accuracy of 10m or 30m or maybe more. The accuracy of the simulation is highly dependent on the granularity of the terrain database.

e. Accuracy in representation of building materials

The wireless signal propagation within cities is governed by complex phenomena such as reflection, refraction, diffraction and scattering. Let’s take the example of the phenomenon of reflection. The percentage of signal reflected back at a particular interface is dependent on permittivity and permeability of the object. Based on these properties only 10% of the signal maybe reflected or 50% of the signal may be reflected. So, for accurate simulation not only should we have a high level of granularity of the 3D building data, we also need an accurate description of the building materials.

f. Dynamic Channel Behavior

A wireless channel is continuously changing i.e. the channel is dynamic (as opposed to being static). However, the ray-tracing techniques available in the literature do not capture this dynamic behavior. The dynamic behavior of the channel is mainly due to the motion of the transmitter or receiver as well as motion of the surroundings. While the position of the transmitter and receiver can be varied in the ray-tracing simulation the surroundings are always stationary. Hence a ray-tracing simulator is unable to capture the time-varying behavior of the channel.

Conclusion

The accuracy of ray-tracing simulators is bound to increase as the computational power of computers increases and as accurate 3D building databases become available throughout the world. Until that time, we would have to fall back to approximate methods or maybe measurement results. It is also expected that in future, Reconfigurable Intelligent Surfaces would have an important part to play in Wireless Communications, increasing the coverage and capacity of 6G networks and beyond.

Note: A somewhat surprising observation from the ray-tracing simulations was that the most computationally intensive task was not the generation of the building structures or generation and intersection of rays with the building structures or calculating the reflection coefficients. The most computationally intensive task was the integration of E-fields for all the elements of the rectangular grid to generate the required plot.

References

[1] A.H. De Voogt, "The Calculation of the Path of a Radio-Ray in a Given Ionosphere," Proceedings of the IRE, vol. 41, no. 9, pp. 1183 – 1186, Sep. 1953.

[2] D. Muldrew, "An ionospheric ray-tracing technique and its application to a problem in a long-distance radio propagation," IEEE Transactions on Antennas and Propagation, vol. 7, no. 4, pp. 393 – 396, Oct. 1959.

[3] L. Myung, J. Nisbet, "Propagation predictions and studies using a ray-tracing program combined with a theoretical ionospheric model," IEEE Transactions on Antennas and Propagation, vol. 23, no. 1, pp. 132 – 136, Jan. 1975.

[4] A. Vastberg, B. Lundborg, "Ray-tracing studies of multipath fading in the ionospheric HF channel," Seventh International Conference on HF Radio Systems and Techniques no. 441, pp. 30 – 34, July 1997.

[5] M. Schulkin, "Average Radio-Ray Refraction in the Lower Atmosphere," Proceedings of the IRE vol. 40, no. 5, pp. 554 – 561, May 1952.

[6] L. Vogler, "An approximate height formula for tropospheric ray-tracing," IEEE Transactions on Antennas and Propagation, vol. 19, no. 6, pp. 794 – 796, Nov. 1971.

[7] A. R. Webster, "Ray Path Parameters in Tropospheric Multipath Propagation," IEEE Transactions on Antennas and Propagation, vol. AP-30, no. 4, pp. 796-800, July 1982.

[8] D. Rao, M. Murthy, S. Sarkar, P. Pasricha, H. Dutta, B. Reddy, "Hilly terrain LOS fadeouts and Fresnel zone considerations from ray-tracing techniques," IEEE Transactions on Antennas and Propagation, vol. 35, no. 11, pp. 1330 – 1333, Nov 1987.

[9] H. N. Kheirallah, H. M. Rashwan, A. K. Aboul-Saoud, "Refractive multipath ray-tracing model," IEE Proceedings on Microwaves, Antennas and Propagation, vol. 136, no. 2, pp. 175 – 178, Apr 1989.

[10] A. J. Rustako, N. Amitay, G. J. Owens, R. S. Roman, "Radio propagation at microwave frequencies for line-of-sight microcellular mobile and personal communications," IEEE Transactions on Vehicular Technology, vol. 40, issue 1, part 2, pp. 203 – 210, Feb. 1991.

[11] P.G Brown, C.C. Constantinou, "Prediction of radio wave propagation in urban microcell environments using ray-tracing methods," Ninth International Conference on Antennas and Propagation, ICAP '95, no. 407, vol. 2, pp. 373 – 376, April 1995.

[12] A.R. Nix, J.P. McGeehan, G.E. Athanasiadou, "A ray-tracing algorithm for microcellular and indoor propagation modeling" Ninth International Conference on Antennas and Propagation, ICAP 95, vol. 2, no. 407, pp. 231 – 235, April 1995.

[13] K. Rizk, J. F. Wagen, F. Gardiol, "Two-dimensional ray-tracing modeling for propagation prediction in microcellular environments," IEEE Transactions on Vehicular Technology, vol. 46, no. 2, pp. 508 – 518, May 1997.

[14] E. Costa, “Ray-tracing based on the method of images for propagation simulation in cellular environments” Tenth International Conference on Antennas and Propagation, vol. 2, no. 436, pp. 204 - 209, April 1997.

[15] J. W. McKown, R. L. Hamilton Jr., “Ray-tracing as a design tool for radio networks,” IEEE Network Magazine, vol. 5, no. 6, pp. 27 – 30, Nov. 1991.

[16] M. C. Lawton, J. P. McGeehan, “The use of ray-tracing techniques for modelling of the radio LAN environment,” IEE Colloquium on Radio LANs, pp. 7/1 - 7/6, May 1992.

[17] W. K. Tam and V. N. Tran, “Multi-Ray Propagation Model for Indoor Wireless Communications,” IEE Electronic Letters, vol. 32, no. 2, Jan. 1996.

[18] Z. Ji, B. Li, H. Wang, H. Chen, and T. K. Sarkar, “Efficient Ray-Tracing Methods for Propagation Prediction for Indoor Wireless Communications,” IEEE Antennas and Propagation Magazine, vol. 43, no. 2, April 2001.

[19] H. R. Anderson, “A ray-tracing propagation model for digital broadcast systems in urban areas,” IEEE Transactions on Broadcasting, vol. 39, no. 3, pp. 309 – 317, Sep. 1993.

[20] H. Ling, R. Chao, and S. Lee, “Shooting and Bouncing Rays: Calculating the RCS of an Arbitrarily Shaped Cavity,” IEEE Transactions on Antennas and Propagation, vol. 37, no. 2, Feb. 1989.

[21] S. Y. Seidel and T. S. Rappaport, “A Ray-tracing Technique to Predict Path Loss and Delay Spread Inside Buildings,” Proceeding of the IEEE Globecom92, pp. 649- 653, Dec. 1992.

[22] Y. Liu and C. D. Sarris, “Efficient Propagation Modeling for Communication Channels with Reconfigurable Intelligent Surfaces,” in IEEE Antennas and Wireless Propagation Letters, vol. 21, no. 10, pp. 2120-2124, Oct. 2022.

[23] E. Björnson, Ö. Özdogan and E. G. Larsson, “Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions,” in IEEE Communications Magazine, vol. 58, no. 12, pp. 90-96, December 2020.

[24] N. Bernadas, “Reconfigurable Intelligent Surfaces: Optimal Positioning and Coverage Improvement,” KTH Dissertation, 2023.