3D Coverage Mapping with UTD and Geometrical Optic Model

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Abstract: - Transmitter placement is critical to improve communication service quality, and 3D coverage estimation is required to optimize this placement. In this study, a 3D coverage mapping tool based on Uniform Theory of Diffraction (UTD) and Geometric Optics (GO) models is developed to determine transmitter placement and coverage. This tool, created in MATLAB environment, estimates the total electric field by calculating the direct, reflected and diffracted rays with a ray-tracing algorithm and generates 2D electric field maps, and converts them into 3D coverage maps. Analyses for different frequencies (100 MHz, 1800 MHz, 4000 MHz and 6000 MHz) show that as the frequency increases, the signal loss increases and the coverage area shrinks. These results make the optimization of transmitter placement even more important, especially in high frequency communication technologies such as 5G. The study provides a solution for radio planning and transmitter placement that is both time efficient and suitable for large-scale simulations.

Key-Words: - 3D coverage mapping; ray tracing; propagation; Uniform Theory of Diffraction.

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1 Introduction

Nowadays a very large number of people use mobile phone to communicate to each other. Service quality of communication is very important and suffers from non-line-of-sight (NLOS) situations. To enhance the service quality of the communication, transmitters should be deployed in correct places. In order to deploy the transmitter into correct place some software like Atoll [1], Wavesight [2] and Winprop [3] are used. With increasing of the carrier frequency especially in 5G technology path loss increases and so the coverage of the transmitter decreases and more number of transmitters are needed [4].

Almost all the tools developed for radio planning based on ray theoretical or numerical electromagnetic wave propagation models. Even though the numerical models [5, 6] are ultimate in accuracy, their computation time is so much. On the contrary, ray theoretical based models [7-14] have much less elapsed time for computation [15]. GO and UTD models are ray theoretical and can be used for calculating the direct, reflected and diffracted rays. In order to predict the electric field strengths accurately in a point where all the direct, reflected and diffracted rays have to be determined. Radio planning tools use the GO and UTD models to predict the field strength. These calculated fields are used to create coverage maps so that transmitters can be placed in correct places.

In this study, a tool that can be used to optimize transmitter placement, especially in high frequency communication systems (such as 5G) is developed. This MATLAB-based 3D coverage mapping tool is designed to be integrated into radio planning processes and aims to improve service quality by precisely determining transmitter placement. The developed method offers a significant advantage in terms of predicting signal interruptions due to dense construction and various obstacles in urban areas. In high-frequency systems such as 5G technology, such tools play a critical role in transmitter placement optimization, as more transmitters are needed over short distances. By modeling the terrain in detail, signal loss can be predicted more accurately, thereby expanding the coverage area and significantly improving communication service quality. With the developed ray-tracing algorithm, all the direct, reflected and diffracted rays between the transmitter and receiver are determined. Multiple diffraction and reflection scenarios such as diffraction + reflection + diffraction, diffraction + diffraction + reflection + diffraction are calculated for the diffracted beam from the obstacle.

The rest of this paper is organized as follows. The second section describes ray-tracing, electric field calculation and coverage map generation. In the third part, generation of 3D coverage map is given. At the last part, conclusions are presented.

2 Materials and Methods

In this section detailed information is given about ray tracing, electric field calculation and coverage map generation.

2.1 Ray Tracing

In order to predict the field strength in a receiving point all the contributing direct, reflected and diffracted rays should be determined as illustrated in Figure 1.

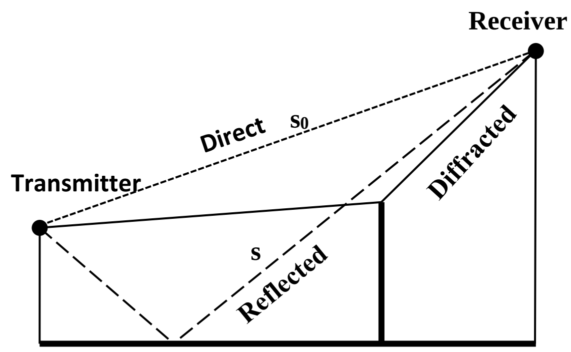

Figure 1. Direct, reflected and diffracted rays.

In this study a 3D terrain map is drawn in MATLAB according to Cartesian coordinates of the terrain of west of Turkey as it is demonstrated in Figure 2.

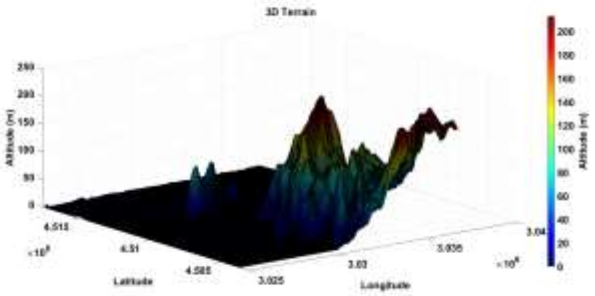

Figure 2. Terrain map

After drawing the terrain map, a point is determined as the transmitter position and a 2D transform window is considered starting from the transmitter to the edge of the terrain as depicted in Figure 3 and 4.

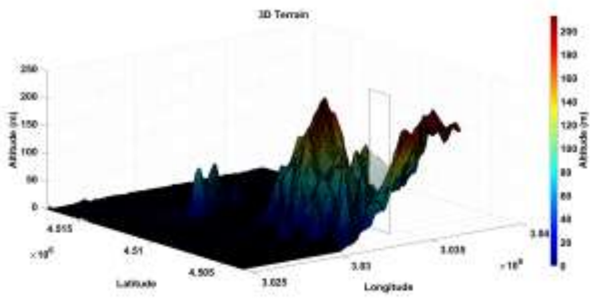

Figure 3. 2D transform window

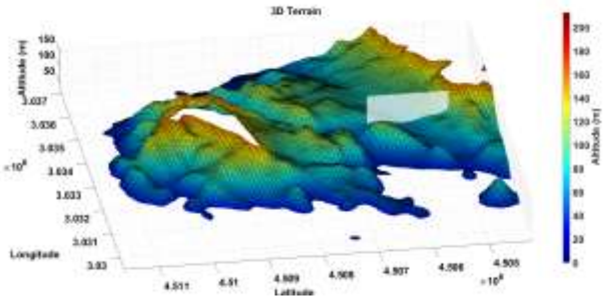

Figure 4. Zoomed view of the 2D transformation window

By using transform window as it is illustrated in Figure 3 and Figure 4, a 2D profile is obtained as shown in Figure 5.

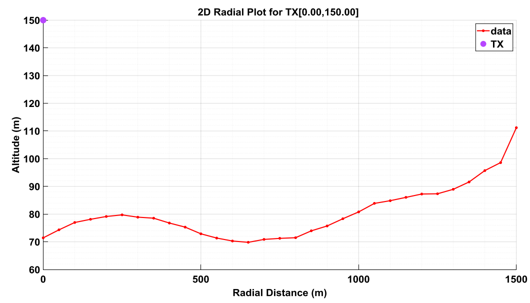

Figure 5. 2D profile after transform window

In this profile, a transmitter is placed at the [0,150] point and all the direct, diffracted and reflected rays are determined by the ray-tracing algorithm in 1800 MHz. With using GO and UTD models electric field is calculated as described in the next section.

2.2 Electric Field Calculation and Coverage Mapping

In order to generate the coverage area of the transmitter, it is necessary to calculate the total electric field of the direct, reflected and diffracted rays. The electric field of the direct rays can be calculated by,

$$E = \frac{E_0}{s_0} e^{-jks_0} \qquad (1)$$

where k is wave number, s_0 is the distance between the transmitter and receiver. E_0 is initial electric field and it taken as 1 V/m. The coverage map of the direct rays for the scenario in Figure 5 is illustrated in Figure 6.

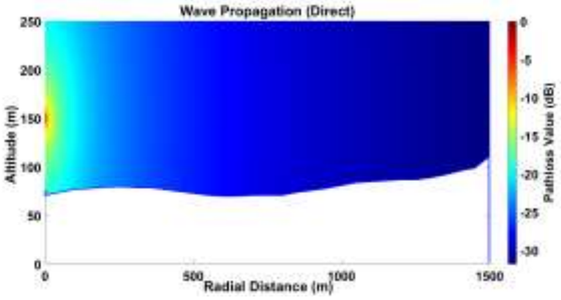

Figure 6. Coverage map of the direct rays

As it is shown in Figure 6, the direct electric field is decreased as far away from the transmitter. The electric field of the reflected rays can be calculated by [16],

$$E = R\frac{E_0}{s}e^{-jks} \tag{2}$$

where R is the reflection coefficient of the surface, k is the wave number and s is the total distance between the transmitter, surface and ground. The reflection coefficient is taken as 1 for the superconductor surfaces. The coverage map of the reflected rays for the scenario in Figure 5 is depicted in Figure 7.

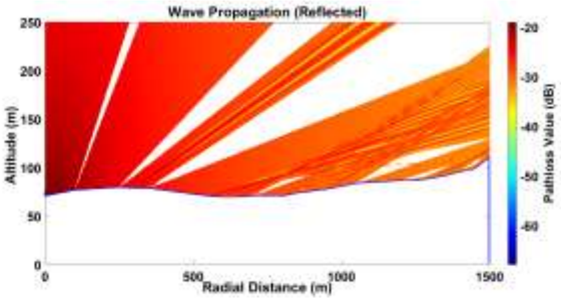

Figure 7. Coverage map of the reflected rays

As it is shown in Figure 7, the reflected electric field is decreased as far away from the transmitter. Moreover, there is no reflected rays in some part of the coverage map due to the terrain profile. The electric field of the diffracted rays can be calculated by [17],

$$E = E_i DA(s)e^{-jks} \tag{3}$$

where, Ei is the incident electric field, D stands for the amplitude diffraction coefficient, A refers to spreading factor, k is the wave number and s is the propagation distance of the wave. The amplitude diffraction coefficient is expressed by [18],

$$D(\alpha) = -\frac{e^{-\frac{j\pi}{4}}}{2\sqrt{2\pi k\cos\left(\frac{\alpha}{2}\right)}}F[x] \tag{4}$$

where α is the diffraction angle between the incident and diffracted rays. F(x) is the transition function resulting between 0-1. The coverage map of the diffracted rays for the scenario in Figure 5 is demonstrated in Figure 8.

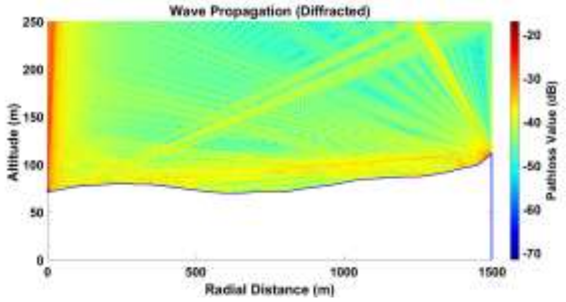

Figure 8. Coverage map of the diffracted rays

As it is demonstrated in Figure 8, there are scattered rays in sharp region on the terrain. The total coverage map of the terrain for the determined transmitter position is obtained by adding all the direct, reflected and diffracted rays as illustrated in Figure 9.

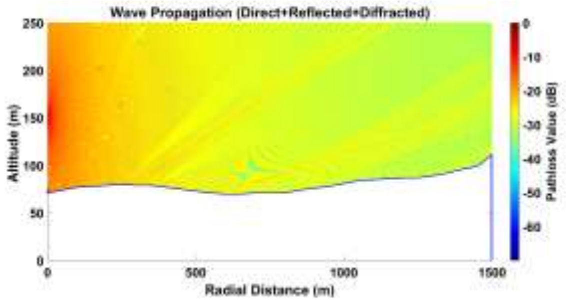

Figure 9. Total coverage map for 1800 MHz

As shown in Figure 9, the reddest region of the coverage map is the transmitter position and vicinity of it. Average minimum values of the electric fields of the direct, reflected and diffracted rays are -27.26 dB, -27.38 dB and -42.71 dB, respectively. Moreover, as far away from the transmitter, electric field strength decreases. Furthermore, there are interference patterns on the coverage map. At the transmitter level, electric field strength is shown in Figure 10.

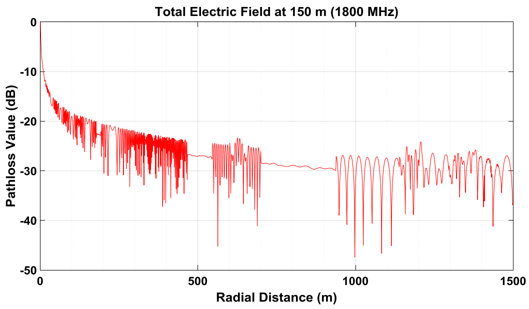

Figure 10. Electric field strength at the transmitter level

As it is shown in Figure 10, electric field strength decreases far away from the transmitter. There are some fluctuations thanks to contribution of reflected and diffracted rays. The above mentioned steps are repeated for 100 MHz, 4000 MHz and 6000 MHz frequencies. The coverage maps including all rays because of the calculations are shown in Figure 11-13 for the relevant frequencies respectively.

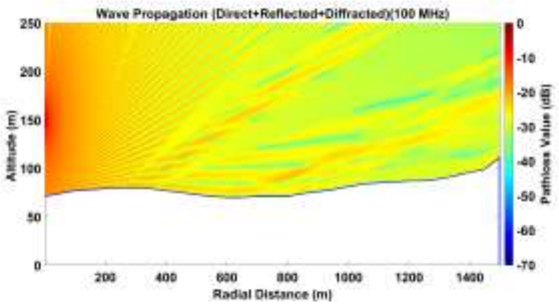

Figure 11. Total coverage map for 100 MHz

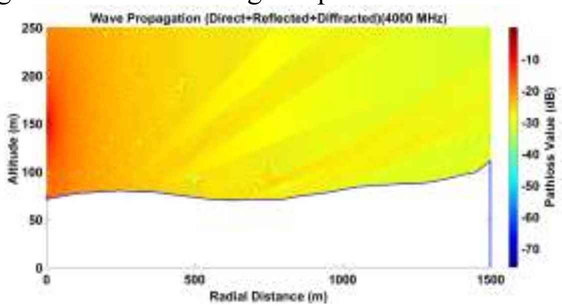

Figure 12. Total coverage map for 4000 MHz

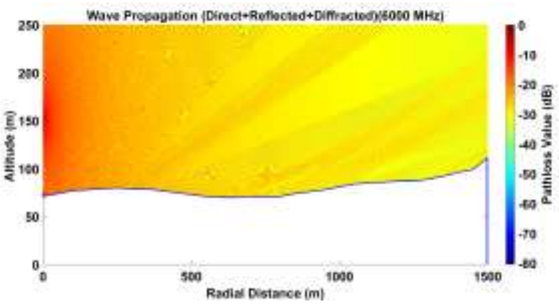

Figure 13. Total coverage map for 6000 MHz

Table 1 shows the average path loss values calculated for the four different frequency values mentioned previously. It can be observed that the average path loss value increases slightly as the frequency increases. This is related to the fact that signal attenuation becomes more pronounced over shorter distances, especially in high-frequency communication systems (e.g. 5G), and can be said to be one of the main reasons why more transmitters are needed in these systems.

Table 1. Frequency - Average path loss value table.

Frequency Value (MHz)	Average Path Loss Value (dB)
100	-26.9240
1800	-27.1951
4000	-27.1988
6000	-27.2151

3 3D Coverage Map

In the previous section, 2D coverage map is obtained by using the direct, reflected and diffracted rays. In this section firstly possible transmitter point is determined and then 2D profile window is applied for the transmitter position as depicted in Figure 14.

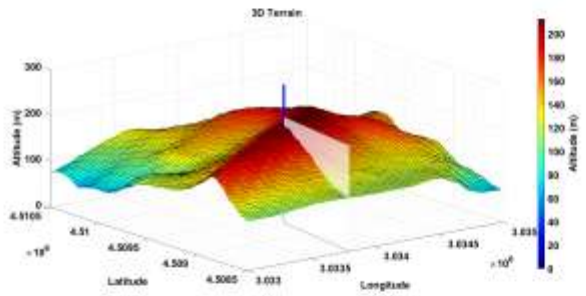

Figure 14. Transmitter position and 2D profile window

For the profile given in Figure 14, coverage map is generated as shown in Figure 15.

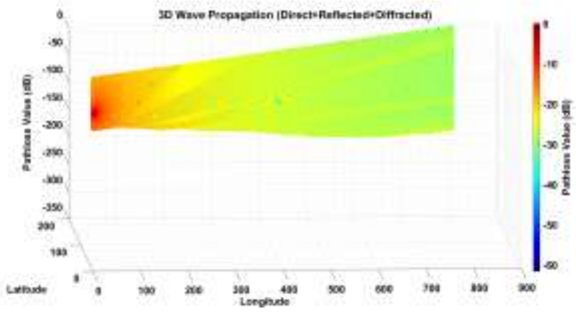

Figure 15. Transmitter position and 2D profile window

As shown in Figure 15, the coverage map is given above the terrain borders. Afterthat 2D profile windows are run for all other directions as shown in Figure 16.

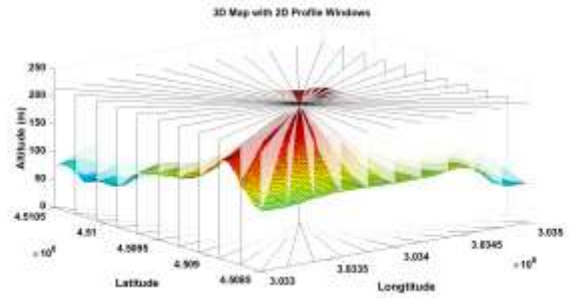

Figure 16. 2D profile windows in all directions

All 2D profile windows are run for the transmitter position, and all the electric fields are calculated for these windows and then 3D coverage map is obtained as illustrated in Figure 17.

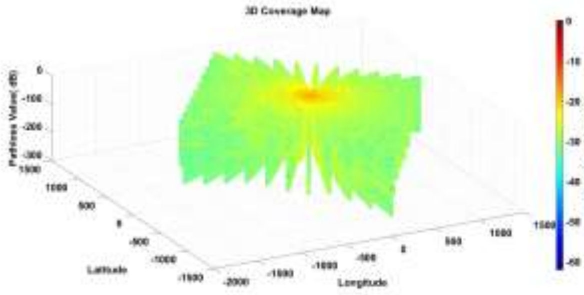

Figure 17. 3D coverage map

As it is illustrated in Figure 17, the 3D coverage map is successfully generated, with the reddest region representing the location of the transmitter. As the angle difference between the 2D planes is reduced, the accuracy of the coverage maps increases significantly. Reducing the angle difference allows terrain structure and obstacles to be computed at more frequent intervals, enabling more precise modeling of topographic details and obstacles on the signal. This makes it possible to estimate more accurately the effects of buildings or natural obstacles on signal propagation, especially in urban areas and complex topographic regions. As a result, a more precise calculation of direct, reflected and diffracted signals contributes to the creation of more realistic and reliable coverage maps. This method allows optimization of transmitter placement and makes a significant contribution to improving service quality, especially in high-frequency communication systems such as 5G.

4 Conclusions

This paper presents an efficient method for the generation of 3D coverage maps based on UTD and GO models. UTD and GO models have long been used in electric field calculations and provide significantly shorter computation times compared to numerical models. Communication service quality is a critical parameter and to improve this quality, transmitters need to be placed in the right places. Analyses at different frequencies show that especially in high-frequency communication systems (e.g. 5G), path loss increases and therefore the coverage area shrinks. In this study, 2D coverage maps are generated for four different frequencies between 100 MHz and 6000 MHz and the effect of frequency is analyzed in detail. Moreover, to ensure the threshold electric field to communicate 3D coverage map is generated via developed program in MATLAB.

The developed tool provides a practical solution for improving transmitter placement and service quality. However, the study has some limitations. The simplification of complex geometric structures in the terrain and the modeling of obstacles only as wedges with knife-edges are the factors that limit the accuracy of the results obtained. These simplifications can negatively affect the performance of the model, especially in densely urbanized areas with complex and multi-surface buildings. Furthermore, although this model provides shorter times compared to numerical models, the processing times are still quite time-consuming.

Future work could be improved to include more complex terrain and building models. Also, incorporating the effects of different surface materials and building types into the model will improve the accuracy of the results. In this context, the use of modern methods such as deep learning or artificial intelligence models can be useful to overcome current limitations and reduce processing times. Such improvements will provide more comprehensive solutions to optimize communication quality, especially in high-frequency systems, by enabling transmitter placement and coverage predictions to be made in less time and with higher accuracy.

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