# A THREE-DIMENSIONAL RADIO COVERAGE PREDICTION MODEL FOR URBAN OUTDOOR ENVIRONMENT USING PHYSICAL OPTICS AND PHYSICAL THEORY OF DIFFRACTION

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### *Abstract*

*The objective of this paper is the presentation of a three-dimensional model which simulates the electromagnetic propagation in outdoor urban areas for GSM frequencies (900 - 1800 MHz), through the combination of separate propagation mechanisms. The simulation results of each propagation mechanism are analyzed in order to derive its contribution to the total received field. The simulation program is created using Matlab.*

*The mechanisms considered for evaluation are the Line-of-Sight, scattering and diffraction. The produced radiocoverage diagrams indicate the importance of scattering and diffraction as mechanisms of electromagnetic propagation in mobile telecommunications coverage in dense urban environments. They also provide a satisfactory radio coverage prediction for three-dimensional space taking into account the difference in height between the transmitter and the receiver.*

## 1. INTRODUCTION

The goal of our research is to create tools which provide accurate predictions of the electromagnetic field in urban areas in order to reach a required level of coverage.

For the creation of these algorithmic tools we took into account three distinct propagation mechanisms, Line-of-Sight, scattering and diffraction. The computation of the scattered field from planar surfaces was achieved with the use of Physical Optics theory, whereas the computation of the diffracted field from three-dimensional wedges was achieved with the use of Physical Theory of Diffraction.

In the case of scattering, the calculation of reflections from the ground is based on Geometrical Optics, while the calculation of scattering from the finite building surfaces is based on Physical Optics. Our model takes into account not only first but also second order phenomena. Consequently, it computes the field that is reflected from the ground surface and then scattered from a building facet, and vice versa.

In the case of diffraction, Ufimtsev's Physical Theory of Diffraction is used to perform simulation in two-dimensional space and subsequently Mitzner's theory, in order to expand that simulation to three-dimensional space.

## 2. SIMULATION CONSIDERATIONS

The following assumptions are made for the simulations:

- The buildings are considerably taller than the position of the transmitter.
- All buildings have four wedges.
- Buildings' shape: not necessarily rectangular.
- Only first order wall scattering and diffraction are taken into account.
- Phenomena of depolarization are not being examined.

## 3. ALGORITHM SIMULATION STEPS

### 3.1. Step 1: Data Input

The data inserted by the user to the simulation program are:

- the electromagnetic characteristics of the incident field, i.e. frequency, polarization, intensity,
- the geometry of the scene,
- the location of the transmitter,
- the height of the receiver.

### 3.2. Step 2: Identification of the Shadow Region

Based on our assumption that the buildings are considerably taller when compared to the height of the transmitter, we can assume that the shadow region remains unaltered independently of the position of the receiver, and therefore it can be calculated in 2-D space. To achieve that, the simulator separates the given space into pixels and runs through all of them sequentially to determine which are illuminated by the transmitter. The result of this step is demonstrated in Figure 1.

The shadowing algorithm also returns matrices containing the illuminated facets (edges and vectors) and illuminated wedges of the buildings. These will be used as input to the algorithms that compute the scattered and diffracted fields respectively.

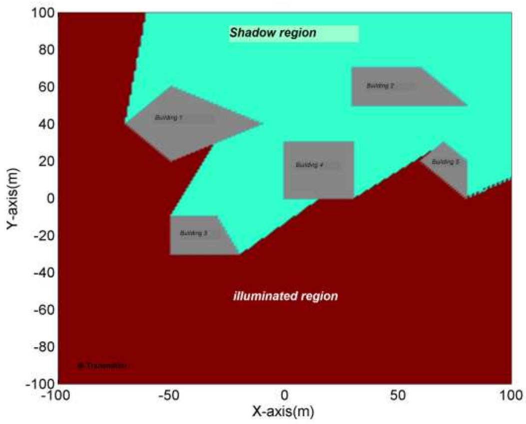


Fig. 1. Shadow region calculation

### 3.3. Step 3: Calculation of the LOS (Line-of-Sight) field

The LOS field is automatically calculated for all the pixels that the simulator determines as being illuminated by the transmitter. The following equation is used for the calculation:

$$E_{LOS-3D} = E_0 \frac{e^{-jkr}}{r} \tag{1}$$

where $k$ is the propagation constant, $E_0$ is a constant related to the emitted power given in V/m and $r$ is the propagation path length.

### 3.4. Step 4: Calculation of the Scattered field

The scattered field is computed as the sum of the complex vectors that arrive at the receiver antenna from the four paths, described in the following paragraphs.

In order to compute the scattered field, we used the 'Near to Far Field Transformation' method [4]. Specifically, we perform segmentation of the scattering surface into an appropriate number of small rectangles (cells), when the receiving antenna is located in the near or Fresnel zone of the scatterers. By such a subdivision of the electrically large scatterer, an observation point which is originally located in the near or Fresnel zone of the scatterer, is then transferred to the far region of the smaller cells.

#### *3.4.1. First order ground reflection*

In the case of first order ground reflection the Image Theory is applied, as demonstrated in Fig. 2.

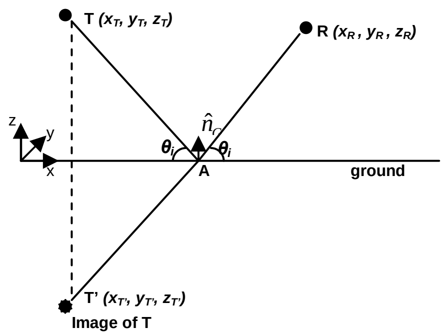


Fig. 2. First order ground reflection (T:Transmitter, R:Receiver)

The receiver field is:

$$E_R = E_T \cdot \overline{R} \cdot \frac{e^{-jk(T'R)}}{(T'R)} \tag{2}$$

where $\overline{R}$ is the binary Fresnel reflection factor. The Fresnel reflection factor acquires the following value for horizontal polarization of the electromagnetic field (vertical to the plane of incidence):

$$R_{\perp}(\vartheta_i) = \frac{\sin(\vartheta_i) - \sqrt{\varepsilon_c - \cos^2(\vartheta_i)}}{\sin(\vartheta_i) + \sqrt{\varepsilon_c - \cos^2(\vartheta_i)}} \tag{3}$$

In the case of vertical polarization of the electromagnetic field (parallel to the plane of incidence), the Fresnel reflection value is:

$$R_{\parallel}(\vartheta_i) = \frac{\varepsilon_c \cdot \sin(\vartheta_i) - \sqrt{\varepsilon_c - \cos^2(\vartheta_i)}}{\varepsilon_c \cdot \sin(\vartheta_i) + \sqrt{\varepsilon_c - \cos^2(\vartheta_i)}} \tag{4}$$

where angle $\vartheta_i$ is the angle of incidence at the reflection surface, and $\varepsilon_c = \varepsilon_r - i60\sigma\lambda$. The factor $\varepsilon_c$ depends both on the electrical characteristics of the surface and the frequency of the signal.

The steps followed for the simulation in this case are:

- Definition of the image of the transmitter
- Definition of the reflection point for every point of the receiver plane
- Calculation of the reflection angle from the ground
- Calculation of the Fresnel factor (equations (3) and (4))
- Calculation of received field (equation (2))

*3.4.2.. First order building scattering*

The geometry used for the calculation of the first order scattered field from a building facet is presented in Figure 3.

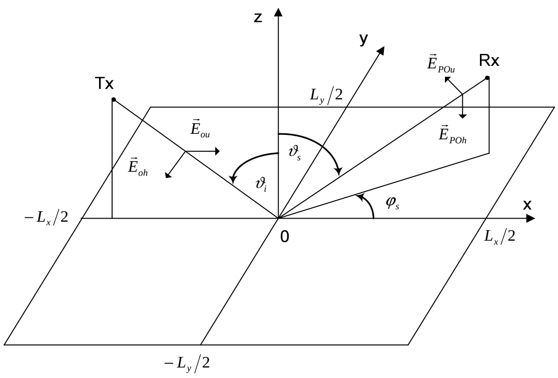


Fig. 3. Geometry for the calculation of scattered field from the building

The equation used for the calculation of the scattered field from a building facet is:

$$E_{PO} = E_0 \frac{jke^{jk(s'-s)}}{4\pi s's}[\cos(\vartheta_i)(1-\overline{R}) - \cos(\vartheta_s)(1+\overline{R})] \cdot L_x L_y \cdot \sin c[k(\sin(\vartheta_i) - \sin(\vartheta_s)\cos(\varphi_s))\frac{L_x}{2}] \cdot \sin c[k(\sin(\vartheta_s)\sin(\varphi_s))\frac{L_y}{2}] \quad (5)$$

where

$s = (T'S')$ is the distance of propagation between the transmitter and the scatterer,

$s' = (S'R)$ is the distance of propagation between the scatterer and the receiver,

$\overline{R}$ is the binary reflection Fresnel factor,

$k$ is the propagation constant, *k = 2π/λ,*

$\vartheta_i$ is the vertical angle of incidence,

$\vartheta_s$ is the vertical angle of scattering,

$\varphi_s$ is the horizontal angle of scattering,

$L_x, L_y$ are the dimensions of the scatterer,

$E_0$ is the emitted electric field (V/m)

$\overline{R}$ is the binary Fresnel reflection factor, given by equations (3) and (4).

The distances $s$, $s'$ and the angles of incidence and scattering, are measured from the center of the scatterer.

Equation (5) also contains the path loss for the examined case.

*3.4.3. First order building scattering followed by ground reflection*

Figure 4 presents the application of Image Theory in the case of first order scattering from a building facet followed by a second order reflection from ground.

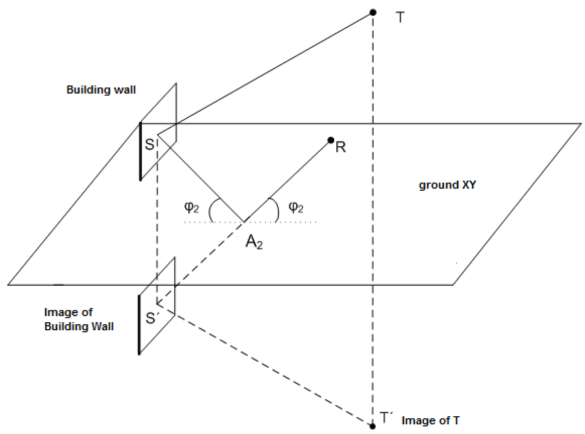


Fig. 4. Geometry for double reflection – Image Theory

Following the calculation of the scattered field from the building facet, the simulator multiplies that field with the Fresnel factor to derive the final received field.

In the case of second order scattering, we assume that the polarization of the incident wave on the ground is the same as that of the incident wave on the building facet, as we do not examine phenolmena of depolarization.

*3.4.4. First order ground reflection followed by building scattering*

Figure 5 presents the geometry applied for first order ground reflection followed by second order scattering. In this case an image of the scattering surface is not necessary, as the secondary source towards the scatterer is the ground surface.

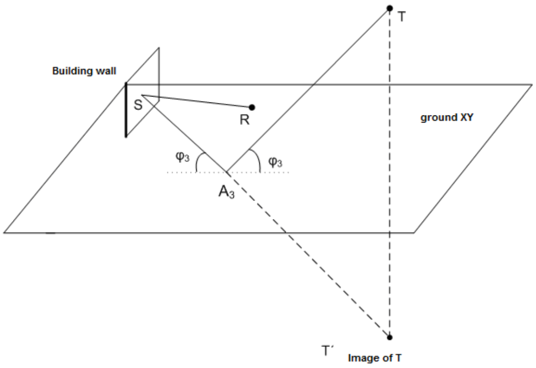


Fig. 5. Geometry for double reflection – Image Theory

Equation (2) is first applied to calculate the reflected field, and then equation (5) is applied to calculate the scattered field, where $s=(T'S)$ and $s'=(SR)$.

*3.4.6. Simulation Examples*

The following data were used for the simulation:
- Ground: $\varepsilon_r$=15, $\sigma$ =7 S/m
- Building: $\varepsilon_{r\_wall}$=7, $\sigma_{wall}$=0,2 S/m
- Building Surface dimensions: $l_y$=16m, $l_z$=12m
- Building Surface Position: x=15m, y=0m
- Transmitter position: x=100m, y=50m, z=6m
- Receiver height: 1,5m
- Frequency: 900MHz
- $E_0$ = 5 V/m
- Area dimensions: 200m x 200m

In Figure 6, we observe the simulation results of the first case, where we take into account only first order ground reflection.

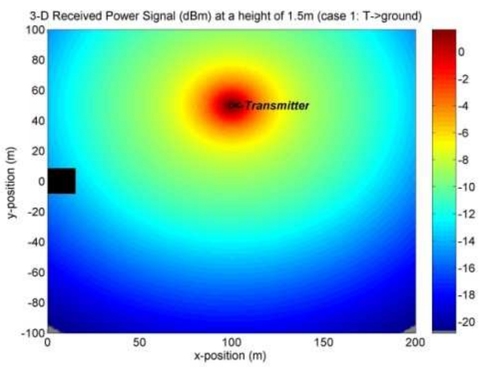


Fig. 6. First order scattering from the ground
(Power density in dBm)

In Figure 7, we observe the simulated field that results from first order scattering on the building, and subsequent second order reflection from the ground, for several positions of the transmitter. The building is coloured black, and we assume, for convenience, that there is no received field in the gray area behind the scattering surface.

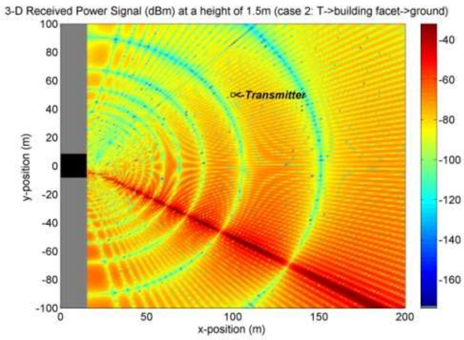


Fig. 7. First order scattering from the building followed by second order the ground reflection
(Power density in dBm)

Figure 8 presents the case of first order ground reflection followed by scattering on a building. The results are similar to those of the previous case.

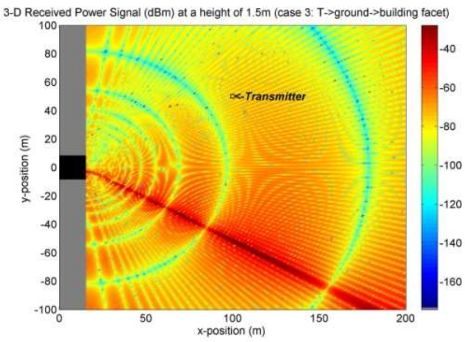


Fig. 8. Ground reflection followed by scattering from the building (Power density in dBm)

## 3.5. Step 5: Calculation of the Diffracted field

The diffraction algorithm is applied by the simulator on all those wedges returned by the shadowing algorithm, i.e. all those building wedges directly illuminated by the transmitter. It must be noted that only first order diffraction phenomena are taken into account. The simulation is based on Mitzner's theory, that uses Incremental Length Diffraction Coefficients (ILDC) to provide the approximation of the diffracted field by a wedge of any outline. According to this theory, the 3D diffracted field is given by the following expression [2,3]:

$$\overline{E_d}=2\mathrm{E}_0\psi_0 dt\begin{bmatrix}(D_\perp-D'_\perp)\hat{e}^s_\perp\cos\gamma-(D_\parallel-D'_\parallel)\dfrac{\sin\beta}{\sin\beta'}\hat{e}^s_\parallel\sin\gamma\\ -(D_x-D'_x)\dfrac{\sin\beta}{\sin\beta'}\hat{e}^s_\parallel\cos\gamma\end{bmatrix} \quad (6)$$

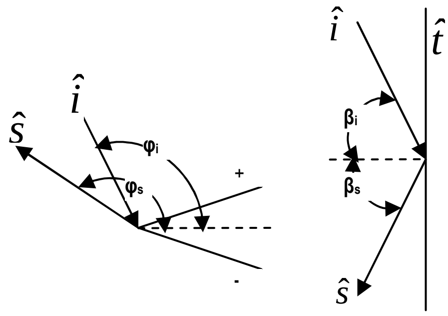


Fig. 9. Presentation of the angles for wedge diffraction in Mitzner's ILDC theory [2,3]

where the diffraction coefficients $D_{\perp}$, $D_{\parallel}$, $D_{\parallel\perp}$, $D'_{\perp}$, $D'_{\parallel}$, $D'_{\parallel\perp}$ are given by Mitzner's theory, and include special step functions which set on and off the respective diffraction physical optics coefficients depending on the facet of the wedge that is illuminated.

Figure 10 presents the diffracted field in the case where both facets of a rectangular wedge are illuminated.

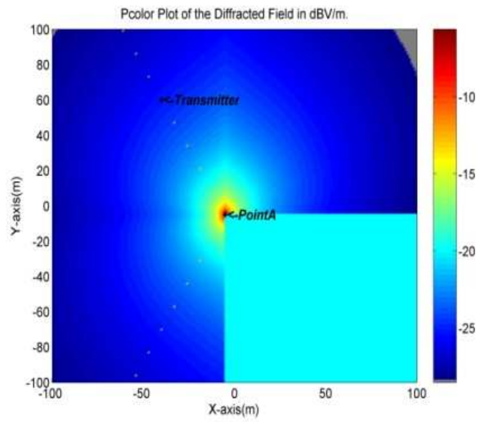


Fig. 11. Diffracted field in the case of illumination of both facets of the wedge (dBV/m)

### 3.5. Calculation of Total Field

The total received field is computed as the vector sum of the LOS, the scattered and the diffracted field :

$$E_{tot} = E_{LOS} + E_{PO\_scattered} + E_{PTD\_diffracted} \qquad (7)$$

This computation is performed by the simulator for each pixel into which the space is segmented. In every case the simulator takes into account the specific contributions by each propagation mechanism and applies the corresponding values to the sum of the received field in the specific pixel, generating the simulation diagram for a specific height (which is the height of the receiver).

The corresponding path loss in dB is:

$$L_{3-D} = -20 \cdot \log_{10}\left( \frac{\lambda}{4\pi} \cdot \frac{|E_{tot}|}{E_0} \right) \qquad (8)$$

## 4. CONCLUSION

On the basis of the aforementioned prediction data, concerning the simulated radio coverage derived through the combination of the particular contributions of LOS, scattered and diffracted field, we can conclude that scattering and diffraction mechanisms play a vital role in urban telecommunications. In environments with dense architectural structures it is not easily achievable to obtain an unobstructed propagation. In such circumstances, an accurate prediction of the received field under specific conditions is of paramount importance, as it eliminates the need for practical measurements. That kind of prediction is readily available through the use of the algorithmic tools described in this paper.

## References

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