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Radiowave Propagation Over an Irregular Surface – The GO and UTD Approach

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***Abstract*—The paper presents a proposal of a method used to calculate path loss over an irregular terrain in an open, rural environment. The proposed method is based on the analysis of three basic types of wave: direct, reflected and diffracted. The assumptions of Geometrical Optics (GO), which is used in reflection analysis, as well as diffraction phenomena, have been described. The diffraction phenomena is analysed according to the Uniform Theory of Diffraction (UTD) and the reflection is calculated according to the Ray Tracing (RT) method. In addition, the irregular surface model used for the simulation and analysis of results for various cases have been presented. All results were compared to propagation loss calculated by the well-known two-ray model.**

***Index Terms*—Diffraction, geometrical optics, radiowave propagation, ray tracing, surface roughness.**

I. INTRODUCTION

In an open, rural environment the two-ray model is very often used for the calculation of path loss of radiowave propagation. This model, however, assumes that the reflecting surface is perfectly flat. In the real environment, the reflecting surface generally indicates some degree of irregularity, in particular for shorter wavelengths. Because of that, during radiowave propagation scattering and diffraction also occur in addition to reflection. A model presented in the article is an attempt to answer the question about the impact of the surface irregularity on the wave propagation above it. Geometrical Optics (GO) was chosen as a method of analysis. It is also used in the mentioned two-ray model. GO shows high accuracy in calculations of the propagation path loss and it is relatively easy to compute. The Uniform Theory of Diffraction (UTD) was chosen for diffraction analysis. UTD has a very high accuracy according to other full wave methods, e.g. Method of Moments (MoM) [1], [2]. The presented model is based on the Ray Tracing (RT) method, which is widely used for the calculation of propagation loss. It is very often combined with UTD, especially in an urban environment or with other methods e.g. FEM (Finite Element Methods) indoors [3]. The simulation results, based on a combination of GO and UTD, are in very good agreement with measurements and with other calculation methods (e.g. Physical Optics combined with Physical Theory of Diffraction), which are very often used in an outdoor [4]–[7], as well as an indoor environment [8]–[10]. Propagation over an irregular surface can be seen as a very actual statement. For this kind of analysis approximate methods should be used, because full wave methods for electrically large cases are too complicated and too time consuming. An attempt of using Physical Optics to analyse propagation over an irregular surface could be found e.g. in [11] (without taking into account polarization). In [12], authors show this kind of calculation using the Small Perturbation Method, but only for slightly rough surfaces. This paper presents the proposal of a model based on the GO/UTD approach. The basics of the GO approach are shown in [13].

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II. TWO-RAY MODEL FOR A FLAT SURFACE

The common, well-known and widely used two-ray model is used in calculations of wave propagation over a flat terrain. The visualization of this situation is shown in Fig. 1. According to GO, the propagation area is divided into three regions. In region 1 the total field is calculated as a superposition of direct and reflected rays. Region 2 is determined by RSB (Reflection Shadow Boundary) and ISB (Incident Shadow Boundary) lines and only a direct ray can propagate within it. Region 3 which is called shadow area is, according to GO, free from the field.

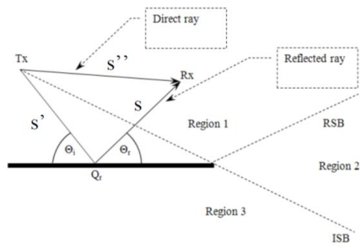

Fig. 1. Geometry of the two-ray model.

The path-loss calculation according to the two-ray model can only be made in region 1. Due to the existence of direct and reflected waves, the field intensity at a particular point near the reflecting plane is obtained as a sum of both components, including their phases, according to (1)

$$\vec{E}_{Rx} = \vec{E}_r + \vec{E}_i, \tag{1}$$

where $\vec{E}_r$ – field intensity of reflected wave, $\vec{E}_i$ – field intensity of incident wave.

The field intensity of both the reflected and directed rays is calculated according to GO. The field intensity of the direct ray is given by

$$\vec{E}_i\left(s''\right)=\vec{E}_i\left(0\right)\sqrt{\frac{\rho_1\cdot\rho_2}{\left(\rho_1+s''\right)\left(\rho_2+s''\right)}}e^{-j\frac{2\pi}{\lambda}s''}, \qquad (2)$$

where $\vec{E}_i\left(0\right)$ – field intensity at the Tx point, ρ_1, ρ_2 – principle radii of wave curvature, s’’ – distance between Rx and Tx points.

The value with the root is a factor determining the space attenuation. Depending on the wave type (plane, cylindrical or spherical wave) it takes a different value. The field intensity of the reflected ray is given by

$$\vec{E}_r\left(s\right)=\vec{E}_{Q_r}\cdot\overline{R}\sqrt{\frac{\rho_1^r\cdot\rho_2^r}{\left(\rho_1^r+s\right)\left(\rho_2^r+s\right)}}e^{-j\frac{2\pi}{\lambda}s}, \qquad (3)$$

where $\vec{E}_{Q_r}$ – field intensity at the reflection point Q_r, R – complex reflection coefficient, ρ_1^r, ρ_2^r – principle radii of curvature of the reflected wave, s – distance between Rx and Q_r points.

The field intensity at the reflection point E_{Qr} is calculated according to (1), where the parameter *s’* is used instead of *s’’* as the distance between the Tx and Qr points [14]–[18].

III. THREE-RAY MODEL FOR AN IRREGULAR SURFACE

The analysis of radiowave propagation over an irregular surface is more complicated than for a flat surface. For this case the diffraction phenomenon occurring on the wedges and scattering should be taken into account. During scattering a part of energy is directed in a different direction than in the case with a specular reflection from a flat surface. In this case three types of rays can reach the receiver: direct, reflected and diffracted. This situation is shown in Fig. 2 (the figure is only illustrative and therefore Snell’s law for the reflected ray is not preserved).

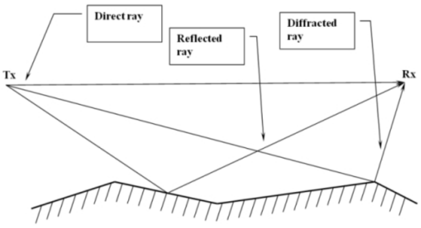

Fig. 2. Three-ray model for the irregular surface.

Due to the presence of surface irregularities, a ray, double-reflected from different planes, may also reach the Rx point. It should also be noted that two different double-reflected rays might exist for one pair of planes. These rays overcome various distances on the way from the transmitter to the receiver, and they also reflect from the surfaces at different angles, hence their field strength is different from each other and must be calculated separately.

The reflecting surface may be treated as flat if it satisfies the Rayleigh criterion, which says that the difference in phase of two reflected rays should not be greater than π/2 [19]. According to this criterion for the 2.4 GHz (wavelength 12.5 cm) for angle Θ_i = 45°, the maximum amount of irregularities, for which the area can be considered as a flat, should not exceed about 2.2 cm. This is a relatively small value, beyond which the scattering should be taken into account in the analysis of propagation of electromagnetic waves.

The field strength at the Rx point for an irregular surface is calculated according to (4). The total value is the sum of the intensities carried out by three types of rays. It should be noted that for a flat surface only two rays (direct and reflected) reach the Rx point. For an irregular surface the number of these rays can be much greater. Their number depends on the degree of the surface unevenness and the amount and degree of the irregularity slope

$$\vec{E}_{Rx}=\vec{E}_i+\sum\vec{E}_i+\sum\vec{E}_d+\sum\vec{E}_{rr}, \qquad (4)$$

where $\vec{E}_d$ – field intensity of diffracted wave, $\vec{E}_{rr}$ – field intensity of double-reflected wave.

The edge diffraction phenomenon can be observed during the wave incidence at the top of the wedge. The incident rays on the edge (wedge top) create a diffraction cone as shown in Fig. 3. Waves are diffracted in all directions due to the law of diffraction – an angle between the incident ray and the edge (β_0) is equal to the angle between the edge and the diffracted ray.

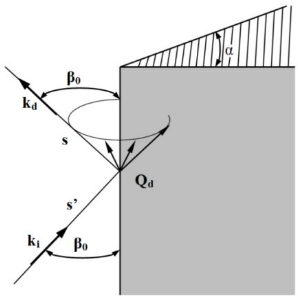

Fig. 3. Diffraction cone at the edge.

The field intensity of the diffracted ray is calculated using UTD according to (5). It is worth noting that the relationship (5) is very similar to (3) for a reflected ray, because the UTD method is also based on the ray concept

$$\vec{E}_d\left(s’,s\right)=\vec{E}_{Q_d}\cdot\overline{D}\cdot A\left(s’,s\right)\cdot e^{-j\frac{2\pi}{\lambda}s}, \qquad (5)$$

where $\vec{E}_{Q_d}$ – field intensity at the diffraction point Q_d, D – complex diffraction coefficient, A(s’,s) – the factor of space attenuation, s – distance between the Rx and Q_d point, s’ – distance between the Tx and Q_d point.

The field strength at the diffraction point is calculated according to (5), in which the parameter *s″* means now the distance from point Tx to Q_d. The factor of the space attenuation takes different values depending on the type of wave (plane, cylindrical or spherical). The diffraction coefficient determination is quite complicated and depends on many parameters [17], [20], [21].

IV. IRREGULAR SURFACE MODEL

It is necessary to build a model of an irregular (uneven) surface in order to simulate the reflection and diffraction phenomena of electromagnetic waves. The surface is modelled as a series of small planes and their cross section is shown in Fig. 4. According to the assumptions of geometrical optics, the size of the reflecting plane must be greater than the wavelength. Therefore, the size of each plane L_i is referenced to a multiple of the wavelength described as parameter *"n"* ($L_i \approx n\cdot\lambda$ see Fig. 4).

The surface model should imitate the real structures as thoroughly as possible. Therefore parameters h_i and L_i are generated according to the normal distribution [22] and they are defined locally for each irregularity. These parameters characterize the randomness of the real irregular surfaces and they have been generated with the mean value $\mu_h = h_{mean}$ and $\mu_L = n\cdot\lambda$ and with variation $\sigma_L^2 = 1$ m^2 (σ_h is changed for different simulations). Different values of L_i give the possibility to change the location of the top of the irregularity (according to the x axis), so it defines the irregularity inclination in relation to the horizontal axis. Generating h_i and L_i for each irregularity separately gives a pseudo-random change in height and inclination of irregularities within particular limits. Parameters *"h_{mean}"* and *"n"* are constant for all surface irregularities.

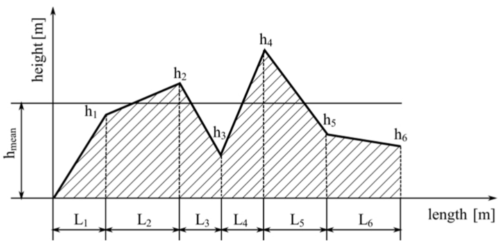

Fig. 4. Model of the irregular surface.

V. Simulation Results

The entire analysis was performed for a reflecting surface with a total length of 500 m and a width of 10 m. The e-m wave source was placed in the middle of the left edge of the surface at a height of 5 m. The field strength values and subsequently the path loss between the transmitter and the receiver were calculated on a straight line (parallel to the front surface edge) at a height of 2 m above the surface (Rx line in Fig. 5). The simulation scenario is shown in Fig. 5. Note that this figure is only for the scenario illustration, so the scale is not visible.

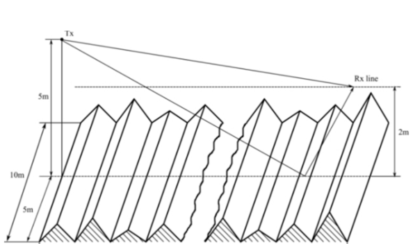

Fig. 5. Simulation scenario.

Electrical parameters of the surface, that were used to calculate the reflection coefficient, have been set as for a medium dry ground for 2.4 GHz ($\varepsilon_r = 15$, $\mu_r = 1$, $\sigma = 0.005$ S/m) [23]. For the simulation a wave frequency equal to 2.4 GHz (wavelength 12.5 cm) and horizontal polarization (parallel to the flat surface) of the wave was chosen. The frequency 2.4 GHz was chosen because it belongs to the 2.4 GHz ISM band, so it is a frequency widely used by wireless systems. Receiving points on the line of analysis were placed at a distance of $\lambda/4$ from each other. All simulations were performed with taking into account shadow areas.

Simulation results with and without diffraction are shown in Fig. 6. The simulation was performed in the Matlab environment for an irregularity with mean height equal to 10 cm and for *"n"* parameters equal to 40. As it can be seen, the difference between calculation results with and without diffraction is significant, especially for the large distance between Rx and Tx points. Both values were referenced to the path loss calculated for a flat surface. It can be noted that the path loss calculated with diffraction (for an irregular surface) is smaller than for a flat surface. This is a quite interesting result, which confirms that for such a surface diffraction analysis cannot be neglected during the propagation calculation.

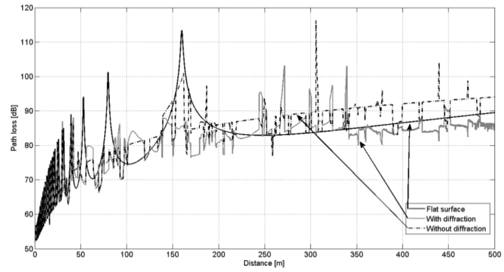

Fig. 6. Path loss calculated with and without diffraction.

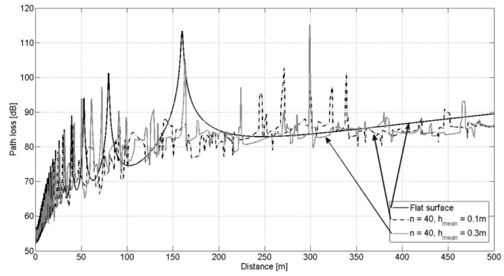

Fig. 7. Path loss calculated for different values of parameter h_{mean}.

Simulation results for different values of the mean value of the irregularity height are shown in Fig. 7. Calculations were performed for n=40. As one can see, for a greater value of the distance between Rx and Tx points there is practically no difference in simulation results for two different values of h_{mean} parameter. An increase of the h_{mean} parameter, where the value of σ_h is constant, gives only a slight reduction of the distance between Tx and Rx points (for reflected and diffracted rays), so the results are comparable for different values of h_{mean}. Calculation results for the case without diffraction are shown in [24].

The calculation results for different values of parameter "n" are shown in Fig. 8. Simulations were performed for two different values of parameter": 20 and 40. The greater number of diffraction edges and reflection planes coincides with a greater number of diffracted and reflected rays reaching the Rx points. In each Rx point, the rays superposition is calculated with taking into account theirs phases. So, two rays can be summed with amplification of total energy or reduction (fading). Superposition with amplification is more probable because of a predominance of diffracted rays with the small phase difference. So the total energy in the Rx point for a higher number of rays is greater and the propagation loss is lower.

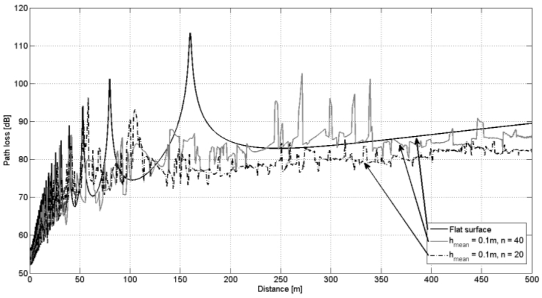

Fig. 8. Path loss calculated for different values of parameter "n".

Figure 9 shows simulation results for different values of standard deviation of irregularity height σ_h. Increasing the value of this parameter causes an increase in the difference between heights of succeeding irregularities, which in turn causes transitions of plane inclinations. For a higher σ_h, rays are reflected in various directions, so in a particular Rx point their number is smaller (in comparison to surfaces with a smaller σ_h). A smaller number of rays represent a smaller value of field intensity and a higher value of path loss in the point Rx. It should be noted, that for a surface with a high value of irregularity, standard deviation path losses are significantly higher than for path losses obtained for a flat surface.

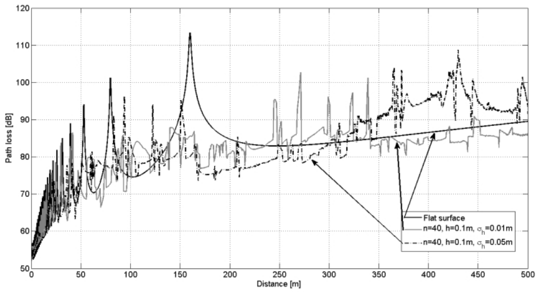

Fig. 9. Path loss calculated for different values of parameter σ_h.

VI. Conclusions

This paper presents the proposal of a new model, which is used for e-m wave path loss evaluation above an irregular surface. It can be noted that simulation results obtained for a flat and an irregular surface differ from each other. An interesting issue is that results for the slightly irregular surface with taking into account the diffraction phenomena are better than for a flat surface in opposite to highly irregular surfaces, for which the achieved path loss is higher. The calculated path-loss for the three ray model is smaller than for the results achieved for a flat surface. Therefore, obtained results should be confirmed by measurements in real conditions to determine the scale of a prediction accuracy of the field intensity or to determine the necessity of calculating the diffraction component. The proposed model only takes into account single and double ray reflection from a surface. Probability of higher-order reflection is very small for the described situation so those rays have practically no meaning. In addition, taking higher-order reflection into account would significantly increase the duration of simulations. These two reasons mean that they are not included in the calculations. Therefore, for further analysis the combination of reflections with diffraction will be also calculated to answer the question of which phenomena are dominant in such a kind of propagation.

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