RADIO WAVE PROPAGATION IN URBAN ENVIRONMENTS

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Abstract - This work consists on the investigation and analysis of some aspects related to electromagnetic wave propagation in presence of the Earth and atmosphere. To accomplish that, MATLAB® simulations are developed to allow a better comprehension of the different radio wave propagation phenomena that occur in certain environments. The simulations are based on the following features: representation of the electric field interference pattern due to ground reflection, representation of the electric field close to obstacles, ray tracing in a horizontally stratified atmosphere, visualization of the effects caused by the inversion of the refraction index in the atmosphere (mirages), and evolution of the electric field in an urban environment (mobile communications scenario), according to an empirical and theoretical model.

I. INTRODUCTION

Since the proliferation of wireless devices in the 1990s, the study of radio wave propagation has received much attention. As a form of electromagnetic radiation, radio waves are affected by different phenomena when they are transmitted or propagated from one point on the Earth to another, such as reflection, refraction, diffraction, absorption, polarization and scattering [1].

The studies of all these phenomena are of great relevance for the development of wireless and mobile communications systems.

To support the continuously increasing number of mobile telephone users around the world, mobile communications systems have become more advanced and sophisticated in their designs. As a result of the great success with the second generation mobile radio networks, deployment of the third and fourth generations, the demand for higher data rates to support available services, such as internet connection, video streaming, video telephony, personal navigation systems, and others, is growing dramatically. Although new technologies in theory provide increased network capacity, in order to have a successful mobile communication system, a deep knowledge of radio wave propagation behaviour in complex environments is required. Therefore, due to the ever increasing demand for personal products and services incorporating wireless technology, the need for research on radio wave propagation and mobile communication models in urban, suburban and rural environments has come to the forefront and became crucial for the development, planning and design of new and more sophisticated systems.

A theoretical approach along with simulations developed in MATLAB® are presented in this paper. These simulations are based on propagation models, and are designed to allow the visualization and analysis of many factors related to radio wave propagation, and lead to a better comprehension of several phenomena in propagation, such as reflection, diffraction and refraction of electromagnetic waves in macro-cell environments as well as in point-to-point long distance communication systems services.

This paper is composed by four topics related to radio wave propagation. The first consists in the ground reflection analysis. Simulations are made to represent the field strength due to the interference of the free space and reflected waves through a colour graphic reproducing different intensities, along a certain distance and height for the reception antenna. The influence of the frequency in the field is demonstrated as well as the influence of an array of antennas and the contribution of the polarization on the field. The second topic is about diffraction, with the Knife-edge model being used to simulate an obstacle and the field attenuation due to the obstacle. The influence of the frequency in the model is demonstrated as well. The next topic corresponds to the refraction of radio waves in the atmosphere, where the influence of the refraction index of an atmosphere is demonstrated in the ray tracing. It is also demonstrated the duct effect and the distortion of images due to the mirage effect in special refraction situations that occur in the atmosphere. In the final topic a theoretical and an empirical model, Waldisch-Bortoni and Okumura-Hata, respectively, are analyzed. Simulations are made to represent the field strength in urban macro-cell environments according to each model.

II. GROUND REFLECTION

Due to the presence of the Earth, several phenomena might occur during the radio wave propagation and reflection is one of them. This chapter focus on the effect that a reflected ray on the ground has in the electric field. The interference between the direct ray and the reflected ray produces amplitude oscillations in the resulting electric field around a mean value, the free-space field. The polarization is another factor analyzed in this section as well as the frequency and the use of an array of antennas as a transmitter.

The considered scenario is shown in Fig. 1.
The electric field due to the interference of the direct and reflected rays is given by

\[ E = E_d[1 + |\Gamma|e^{i\Delta\phi}] \]

where \( E_d = \sqrt{60P_G}\) represents the maximum amplitude of far field free-space, \( \Gamma \) the reflection coefficient of the ground and \( \Delta\phi \) the phase difference between both rays. The reflection coefficient depends on the polarization, which can be horizontal or vertical as represented in Fig. 2.

The reflection coefficients are given by

\[ \Gamma_H = \frac{\sin\psi - \sqrt{n^2 - \cos^2\psi}}{\sin\psi + \sqrt{n^2 - \cos^2\psi}} \]

for horizontal polarization and

\[ \Gamma_V = \frac{n^2\sin\psi - \sqrt{n^2 - \cos^2\psi}}{n^2\sin\psi + \sqrt{n^2 - \cos^2\psi}} \]

for vertical polarization. The phase difference is related with the trajectory difference between the direct ray and the reflected ray (Fig. 1), and is represented by

\[ \Delta\phi = \arg\{\Gamma\} - 2\pi \frac{\Delta r}{\lambda} \]

where \( \Delta r = r_r - r_d \).

In the interference zone, the electric field oscillates between maximums and minimums. A maximum occurs when \( e^{i\Delta\phi} = 1 \) and a minimum for \( e^{i\Delta\phi} = -1 \). From the electric field equation, these are given by

\[ \left( \frac{E}{E_d} \right)_{\text{max}} = 1 + |\Gamma|, \quad \text{even } n \]

\[ \left( \frac{E}{E_d} \right)_{\text{min}} = 1 - |\Gamma|, \quad \text{odd } n \]

and they occur when

\[ \frac{2\pi\Delta r}{\lambda} - \arg\{\Gamma\} = n\pi \]

The Fig. 3 represents the simulation results for the electric field variation in a given distance, using a half-wave dipole and vertical polarization. There’s no height variation on the reception.

Proceeding to the analysis of the Fig. 3, it is possible to distinguish the maximums and minimums of the electric field (blue line) around the free-space field (red line), due to the interference between the direct and the reflected rays. The Brewster angle, which represents the incidence angle where \( |\Gamma_V| \) is approximately zero, is visible. At this distance, the electric field coincides with the red line, i.e., it is approximately equal to the free-space field.

In Fig. 4 the interference phenomena between both rays is demonstrated for a given distance and in this case also for different reception heights. It is possible to see how the electric field varies in distance and height, as well as the maximums and minimums. From this simulation it is also possible to see that there are certain points in...
distance and height where the receiver antenna can have a stronger signal.

In Fig. 6 the influence of an array of two antennas is introduced in the variation of the electrical field. The antennas used are half-wave dipoles separated by $\lambda/2$ with the currents in phase. For a better comprehension of the effects and consequences that an array has in wave propagation, four situations were simulated exhibiting different behaviours as shown in Fig. 5.

The image in the upper left corner shows the variation of the electric field in free-space using only one antenna. In the upper right corner it is used an array of two antennas separated by $\lambda/2$ with the currents in phase. The array generates a narrower main lobe and raises the electric field intensity. In the bottom the antennas are separated by $2\lambda$ but in the left the currents are in phase while in the right they are lagged 45°. With a higher separation between the antennas, the main lobe becomes narrower and secondary lobes begin to appear. The lag in the current with a higher separation causes the growth of the smaller secondary lobes and the main lobe becomes even narrower. The Fig. 6 shows the change in the electric field intensity due to the use of the array.

III. DIFFRACTION

In this chapter it is analyzed how the orography of the terrain intervenes in propagation. Usually in communication systems the path between the antennas has an irregular nature, with mountains and other obstacles that cause interference and generate additional attenuations on the transmitted signal. To study the behaviour of electromagnetic waves in these environments, several models were created. The Knife-edge model is the chosen one in this article.

The Knife-edge model considers the obstacle as a semi-infinite plan. The geometry of the model is represented in Fig. 7.
where

\[ \bar{x} = \frac{x_d d_r + x_r d_e}{d} \]

\[ h_e = \frac{kd}{\pi d_r d_e} \bar{x} \]

The gap \( \bar{x} \) is the distance between the ray and the top of the obstacle. The attenuation is strongly dependent of this parameter. When the gap (\( \bar{x} \)) is higher than the radius of the first Fresnel ellipsoid on the top of the obstacle, the obstacle won’t interfere with the signal. The attenuation generated by the interference of the obstacle is given by

\[ A(h_e) = \frac{1}{2} \left[ 1 + C(h_e) \right]^2 + \frac{1}{2} \left[ 1 + S(h_e) \right]^2 \]

where \( C(h_e) \) and \( S(h_e) \) are the Fresnel integrals. Fig. 8 represents the variation of the attenuation added by a Knife-edge, as function of \( v = -h_e \).

As we can see in Fig. 8, if the gap (\( \bar{x} \)) is negative, the penetration \( v \) is positive and the attenuation increases. On the other hand, if the gap (\( \bar{x} \)) is positive, then the penetration becomes negative because the ray doesn’t pass through the obstacle. In case the first Fresnel ellipsoid is not obstructed, i.e., if the radius of the ellipsoid at the top of the obstacle is at least equal to the gap (\( \bar{x} \)) of the ray, then the attenuation will be very low or zero.

So, in order to obtain the electric field received when the signal passes the obstacle, we add the attenuation due to the obstacle to the electric field expression of the ground reflection chapter. We get the following equation

\[ E = E_d [A_d + A_r |\Gamma|^2 e^{i\Delta\phi}] \]

where \( A_d \) and \( A_r \) are the direct and reflected ray attenuations, respectively. The following figures represent the electric field variation in the presence of an obstacle by using the previous equation as a function of the distance and height of the receiver antenna.

By analyzing Fig. 9 we can immediately verify that the electric field drops dramatically in an observation point deeply immerse in the shadow zone caused by the obstacle. The higher the height of the receiving antenna, the stronger the received signal will be.

The frequency of the signal is a very important factor that influences wave propagation, especially under these circumstances. The higher the value of the frequency the higher the attenuation caused by the obstacle, as shown by Knife-edge model in Fig. 10.

The electric field shows lower values after the obstacle and the shadow zone increases.
IV. REFRACTION

Another very important factor that influences actively the trajectory of electromagnetic waves is the refraction index variation in the atmosphere. By using the modified refractivity to characterize different atmosphere layers, it was possible to simulate the trajectory of the rays in different situations and to demonstrate the influence of the index in them.

The modified refractivity is given by

\[ M = N + 10^6 \frac{h}{a} \]

where \( N \) is the refractivity, \( h \) is the height in the atmosphere and \( a \) the Earth radius. The refractivity is given by

\[ N = N(0) + \left( \frac{dM}{dh} - 157 \right) h \]

with \( N(0) = 315 \) being the refractivity at the surface.

With these equations it is possible to define the nature of the atmosphere for the following ray tracing simulations. The simulations are based on two cases. The case of a standard atmosphere and the case where rays are trapped inside a duct, due to special conditions that occur in the atmosphere. A standard atmosphere is characterized by a linear variation of the modified refractivity and that profile doesn’t change in height.

The analytical model used to represent the trajectory is given by

\[ z = \frac{2}{\pm A \mu} \left( \sqrt{\mu h + b} - \sqrt{\mu h_0 + b} \right) \]

where \( A = \sqrt{2} \times 10^{-3} \), \( b = (10^6/2)\alpha_0^2 - \mu h_0 \), \( \mu = dM/ dh \), \( h_0 \) represents the height of the transmitter and \( \alpha_0 \) is the departure angle of each ray relative to the horizontal.

The next figure represents the behaviour of the rays in a standard atmosphere, with different departure angles.

As we can see, when \( dM/ dh \) is positive the rays tend to rise and move away from the surface of the Earth. On the other hand, if \( dM/ dh \) is negative the rays tend to fall to the surface (Fig. 12).

Under special meteorology conditions favorable to the formation of inverted layers where \( dM/ dh \) becomes negative, a duct is generated. In these circumstances rays travel longer distances and may cause interference in other systems. This behaviour is due to the fact that ducts act like waveguides where propagation losses are minimized. The duct takes place when the atmosphere is structured by two or three layers. Each layer presents a different modified refractivity and the signals of \( dM/ dh \) in two consecutive layers are opposed.

The Fig. 13 and Fig. 14 demonstrate the effects of surface ducts and raised ducts, in a two and three layer atmosphere, respectively.

From the analysis of the figures we can verify that the rays are contained in the layer where \( dM/ dh \) is negative. As a consequence, rays can travel longer distances as opposed to normal conditions.

Fig. 11 – Ray trajectories for \( dM/ dh > 0 \), with ground reflection.

Fig. 12 – Ray trajectories for \( \alpha_0 \geq 0 \) and \( dM/ dh < 0 \).

Fig. 13 – Surface duct.
As a consequence of the atmosphere being stratified in layers with different refraction indexes in height, super-refraction situations of light rays may occur, resulting in the distortion of images captured by the human eye. This phenomena is called a mirage. A superior mirage occurs when the atmosphere is stratified in two layers and it is common in places where the air close to the surface is cold like the sea. An inferior mirage occurs if the atmosphere is stratified in three layers and it is common in deserts and road asphalts where the air temperature close to the ground is very high. The normal and distortion situations are represented in Fig. 15 and Fig. 16.

The Fig. 16 gives us an example of how an image captured by the human eye can be deformed due to the different trajectories of the rays in a stratified atmosphere.

In reality light rays travel through the atmosphere, reach the human eyes and the brain builds an image. To simulate the mirage effect we follow an opposite approach, i.e., in order to take advantage of the ray tracing method utilized in this chapter, the rays travel from one point to an image in study.

An image is divided in equal vertical intervals, depending on the number of lines in the image. Each line corresponds to a ray, and after the ray tracing they arrive to a certain interval in the image. The rays are numbered in an increasing order of the departure angle. The arrived point is stored in a matrix. The original image is then divided in two halves. The superior half corresponds to the vertical plan and the inferior half corresponds to the horizontal plan. The Fig. 17 represents the image splitting.

Now using the stored information in the previous matrix, if a ray reaches the maximum distance he is in the vertical plan, otherwise he is in the horizontal plan. After defining where each ray belongs, the ray lengths and heights are converted to a scale according to the number of rays. These values are then stored in a position matrix and converted in a new image.

The Fig. 18 represents the simulation of a superior mirage. In superior mirages the human eye sees an inverted image of the object, above its real position. In the simulation it is represented the variation of the modified refractivity for the atmosphere and the resulting ray tracing. The bottom left image is the original image and the bottom right image is the mirage image, i.e., the result of the ray tracing due to the super-refraction situation.
The next figure shows the simulation for an inferior mirage. In this case we see an image of the sky on the ground and this kind of mirage is usually confused with a puddle.

In mobile communication systems and other wireless services, the urban, suburban and rural environments are divided in cells, according to three classes: macro-cell, micro-cell and pico-cell.

The macro-cells are used in mobile communications systems to cover areas in the order of 1-3 km, where the base stations are usually on the top of buildings and the mobile terminals are in the shadow zones of the obstacles. These cells are common in urban environments. Typically in rural environments these cells have superior dimensions due to the lower population density.

Propagation models are needed for signal estimation. In general, a model can be empirical or theoretical.

An empirical model takes all environment influences implicitly into account. It is based on measured data and may be applied in environments similar to where the measurements were performed. The main advantage of empirical models is their simplicity and computational efficiency. The model accuracy depends on the measurement accuracy and the similarity between the environments where the measurements and predictions are taking place.

Theoretical models on the other hand, are based on the principals of physics, they represent an approximation to reality. As a consequence, it doesn’t take all environment influences into account and thus, large and detailed topographic data bases and extensive modelling are needed to describe the environment where the model is to be applied, in detail.

Two basic families of outdoor models are analyzed in this article: the Okumura-Hata empirical model and Walfisch-Bertoni theoretical model.

In 1968 the now known Okumura model was published [2] where a set of curves was empirically derived from extensive measurements performed in Tokyo. The measurements were performed in environments that were classified as urban over quasi-smooth terrain. The model has the disadvantage of being slow in response to rapid terrain changes, and for that reason, the prediction accuracy is generally better in urban and suburban areas compared to rural areas. Nevertheless, the model is one of the simplest and most accurate path loss models to be used in cluttered areas, hence, it has become a benchmark with which other models are compared to.

The Okumura-Hata model is an empirical formulation of the graphical path loss data provided by Okumura. The median path loss formula given by Hata [3] is expressed for urban areas as

\[
L_{P_{[dB]}} = 69.55 + 26.16 \log(f_{[MHz]}) - 13.82 \log(h_{c[m]}) + [44.90 - 6.55 \log(h_{c[m]})] \log(d_{[km]}) - J(h_r, f) - \sum K_{correction}
\]

where \( f \) is the carrier frequency ranging from 150 to 1500 MHz, \( d \) is the antenna separation distance between 1 and 20 km, \( h_r \) is the effective base station antenna height in the range of 30-200 m, \( J(h_r, f) \) is the mobile antenna correction factor and \( \sum K_{correction} \) represents the environment and terrain correction factors to be applied if the scenario in study differs from the standard conditions (urban environment over quasi-smooth terrain).

The mobile antenna correction factor for small to medium sized cities is given by

\[
J(h_r, f)_{[dB]} = [1.10 \log(f_{[MHz]}) - 0.70]h_{r[m]} - [1.56 \log(f_{[MHz]}) - 0.80]
\]

and for large cities, the correction factor is expressed as

\[
J(h_r)_{[dB]} = \begin{cases} 
8.29 \log^2 (1.54h_{r[m]}) - 1.10, f \leq 200 MHz \\
3.20 \log^2 (11.75h_{r[m]}) - 4.97, f \geq 400 MHz
\end{cases}
\]

Correction factors related to terrain and environment are also given in [2] as curves, and can be applied to improve the model’s accuracy. The following equations are approximate expressions of some of these curves:

- Terrain undulation

\[
K_{th}(\Delta h)_{[dB]} = -8 \log^2 (\Delta h_{[m]}) + 12 \log (\Delta h_{[m]}) - 3
\]

where \( \Delta h \) is the terrain undulation height. This expression is based on measurements done for 453 MHz.
- Position in terrain undulation
  \[ K_{hp}(\Delta h)_{[dB]} = -2 \log^2(\Delta h_{[m]}) + 16 \log(\Delta h_{[m]}) - 12 \]
  The computed field will increase for receiver locations at or near the top of the hill (+K_{hp}) and reduced for locations in the valley (−K_{hp}).

- Street orientation
  \[ K_{ae}(d)_{[dB]} = 2.1 \log(d_{[km]}) - 6.3 \]
  The computed field will be decreased in streets that are across (perpendicular to) radial paths from the base station.

\[ K_{ai}(d)_{[dB]} = -2.7 \log(d_{[km]}) + 8.6 , d \leq 40 \text{ km} \]
  The computed field will be increased if streets are along (parallel to) the radial paths from the base station.

- Average terrain slope
  \[ K_{sp}(\theta)_{[dB]} = -0.0025\theta_{[mrad]}^2 + 0.204\theta_{[mrad]} , d < 10 \text{ km} \]
  The computed field will be increased for uphill paths, or reduced for downhill paths. In this correction factor, the path slope is limited to values between ±20 mrad.

- Mixed land-sea paths
  \[ K_{mp}(\beta)_{[dB]} = \begin{cases} 
    -8.0\beta^2 + 19.0\beta , & d < 30 \text{ km} \\
    7.8\beta^2 + 5.6\beta , & d < 30 \text{ km}
  \end{cases} \]
  The computed field increases with the \( \beta \) parameter, which represents the ratio between the water surface length and the antenna separation distance. In scenery A the water surface is closer to the receiving antenna, in B the water surface is closer to the base station.

- Open areas and quasi-open areas
  \[ K_{oa}(f)_{[dB]} = 4.78\log^2(f_{[MHz]}) - 18.33 \log(f_{[MHz]}) + 40.9 \]
  \[ K_{qo}(f)_{[dB]} = K_{oa}(f)_{[dB]} - 5 \]

- Suburban areas
  \[ K_{su}(f)_{[dB]} = 2.00\log^2\left(\frac{f_{[MHz]}}{28}\right) + 5.40 \]
  The Fig. 20 and Fig. 21 represent the simulations of the Okumura-Hata model for different environments and terrains. The average value of the computed electric field in dB (\( \mu V/m \)) is given by

\[ E_{[dB \mu V/m]} = P_e_{[dBW]} + G_a_{[dB]} + 20 \log(f_{[MHz]}) - 20 \log\left(\frac{c_{[m/s]}}{4\pi}\right) + 10 \log(30) + 240 - L_p_{[dB]} \]

where \( P_e \) is the transmitted power, \( G_a \) is the gain of the transmitting antenna, \( c \) is the speed of light in vacuum and \( L_p \) is the path loss median value according to the Okumura-Hata model. In the following simulations, correction factors are used to determine the model’s median path loss in different scenarios. The specifications are: \( P_e = 10 \text{ dBm}, \ G_a = 2.15 \text{ dB}, f = 450 \text{ MHz}, h_t = 30 \text{ m}, h_b = 5 \text{ m} \) and \( d: 1 – 10 \text{ km} \).

As we can see in Fig. 20, when the density of buildings and obstacles increases, the model predicts that the path loss will increase as well.

In Fig. 21 the Okumura-Hata model is simulated for different terrains and paths in a suburban environment, with the addition of the following specifications: \( \beta = 0.5, \ \theta_1 = 10 \text{ mrad} \ (\text{uphill path}), \ \theta_2 = -10 \text{ mrad} \ (\text{downhill path}), \ \Delta h: 50 \text{ m} \).
In Fig. 21 we immediately conclude that the worst situation is the reception in the valley which represents a shadow zone. The second worst case is when the receiver is located in a street perpendicular to the emitted signal from the base station, i.e., there is no line of sight and the signal arrives through reflections (multi-path) and diffractions in the nearby buildings and obstacles. On the other hand, in line of sight situations like an uphill path or reception on top of hill, or along the street, the signal attenuation decreases.

A theoretical model for urban propagation was proposed by Walfisch and Bertoni in 1988 [4]. According to the Walfisch-Bertoni model, the biggest contribution for the received field comes from the diffracted waves on the top of the buildings. There are two types of attenuation considered in this model. The first is the attenuation introduced by multiple obstacles that interfere from the transmitter to the obstacle that precedes the receiver. The second is the attenuation associated with the diffraction from the top of the building to the street.

The second attenuation is associated with the multi-path effect caused by two adjacent buildings. The mobile terminal is reached by several rays but only two have preponderant contributions. These are the direct ray that comes directly from the top of the building to the receiver and the ray that reflects once in the front building. The Fig. 22 represents the geometry of the multi-path.

![Multi-path geometry](image1)

**Fig. 22 – Multi-path geometry [1].**

Considering the buildings as semi-infinite plans and the inclination (\(\alpha\)) of the wave relative to the horizontal plane, the attenuation (\(A_E\)) is given by

\[
A_E(h_e) = \left[ 1 + \frac{1}{2} C(h_{e1,2})^2 + \frac{1}{2} S(h_{e1,2})^2 \right]^{1/2}
\]

where \(C()\) and \(S()\) are the Fresnel integrals, \(h_{e1}\) and \(h_{e2}\) are the equivalent heights of the direct diffracted wave and reflected wave in the front building, respectively. These are given by

\[
h_{e1} = \frac{2 \sin \phi}{\lambda z} \left( h_r - h_e + 2 \frac{\sin \alpha}{\sin \phi} \right)
\]

\[
h_{e2} = \frac{2 \sin \phi}{\lambda (2w - z)} \left( h_r - h_e + 2 (2w - z) \frac{\sin \alpha}{\sin \phi} \right)
\]

The street angle (\(\phi\)) is considered 90° because the wave is in line with the buildings.

The electric fields for each ray are given by

\[
E_1^2 = E_0^2 |A_E(h_{el})|^2
\]

\[
E_2^2 = E_0^2 |A_E(h_{e2})|^2 |I_{ed}|^2
\]

where \(E_1\) is the diffracted ray field, \(E_2\) is the reflected ray field and \(|I_{ed}|\) is the reflection coefficient of the building.

This model is applied when the buildings are replaced by semi-infinite plans and have the same height and the same spacing between them. The Fig. 23 shows the geometry used to calculate the attenuation due to a row of buildings.

![Attenuation model for multiple obstacles](image2)

**Fig. 23 – Attenuation model for multiple obstacles [1].**

The inclination \(\alpha\) is given by

\[
\alpha = \tan^{-1} \left( \frac{h_b}{N_{ed} w} \right)
\]

where \(h_b\) is the base station height on top of the building.

The attenuation \((A_{N+1})\) induced by the multiple obstacles is obtained by the following expression

\[
A_{N+1} = 2.35 g_p^{0.9}
\]

with \(g_p = \sqrt{w/\lambda \sin \alpha}\).

The expression used to calculate the attenuation \((A_{N+1})\) can only be applied when \(0 < g_p < 0.5\) and \(N_{ed} > 0.1 N_0\), where \(N_{ed}\) is the number of buildings and \(N_0 = \text{Int}(\lambda/\sin^2 \alpha)\).

The total electric field with the additional attenuations, is given by

\[
E = A_{N+1} \sqrt{E_1^2 + E_2^2}
\]

To simulate the field at any distance and height we divide the figure in three zones. In the first zone, which is the one over the buildings, the free-space expression is used because there’s no interference of the reflected ray. The second is the zone between buildings, where the Walfisch-Bertoni model is used. The third zone is after the
last building and the field is calculated using the Knife-edge model without the reflected ray. The Fig. 24 represents the simulation of the field in these three zones. The specifications are: $P_e = 10\, W$, $G_e = 15\, \text{dBi}$, $f = 600\, \text{MHz}$, $h_E = 45\, \text{m}$, $h_b = 5\, \text{m}$, $w = 70\, \text{m}$, $N_{ed} = 20$.

![Electric field (dBm)](image)

**Fig. 24** – Walfisch-Bertoni model for 600 MHz.

Proceeding to the analysis of the Fig. 24 it is possible to verify that the electric field decreases progressively between the buildings and is very low after the last building. The frequency influences the model in the same way it does in the Knife-edge model, i.e., the higher the frequency the higher the attenuation due to the obstacles.

The blue and red lines represent the region where the multi-obstacle attenuation of the Walfisch-Bertoni model is valid. The validation parameters $(g_p, N_b)$ are also influenced by the frequency, as shown in the Fig. 25.

![Electric field (dBm)](image)

**Fig. 25** – Walfisch-Bertoni model for 1800 MHz.

**VI. CONCLUSIONS**

The last few years have witnessed a phenomenal growth in the wireless industry. The main goal of this work is to investigate and analyze the influence that certain environments can have in wave propagation. To provide the needed results a series of simulations of propagation models studied in the course were made. The addressed aspects are the reflection, refraction, diffraction and propagation models in complex environments.

In the reflection topic, the interference of the reflected ray on the ground with the direct ray was demonstrated through the existence of maximums and minimums of the electric field. The influence of an array of antennas was shown as well. The electric field with ground reflection is influenced by the frequency, the distance and height of the receiving antennas and by polarization, all causing variations of the field around a mean value.

The Knife-edge model was analyzed in the diffraction chapter. In this model the obstacle is seen as a semi-infinite plane. If the penetration is positive, i.e. the ray passes through the obstacle, then the attenuation is high. Otherwise, the attenuation is low. The obstacle creates a shadow zone where the field is very low. The model also shows the influence of the frequency. The higher the frequency the higher the attenuation.

In the refraction chapter the ray tracing was demonstrated with a standard atmosphere and for atmospheres with special conditions. When the modified refractivity gradient is negative the ray goes down, otherwise, the ray goes up. Under special conditions in a stratified atmosphere a duct is formed and the trapped rays can travel longer distances in the layers where the gradient is negative. The mirages phenomena was demonstrated too. Due to different indexes in the atmosphere an image gets deformed in the human eye.

The last topic is about propagation models in urban environments. The Okumura-Hata empirical model was simulated for different environments and types of terrain to predict the median path loss. The model shows that the higher the density building and terrain irregularities, the higher is the attenuation. The best situation is when there’s line of sight between the antennas. In Walfisch-Bertoni model two types of attenuation are considered. One due to multiple obstacles and the other due to multi-path between two buildings close to the mobile terminal. In the multi-path attenuation two rays have preponderant contribution, the direct ray and the reflected ray in the front building. The electric field decreases along the buildings and after the last building the Knife-edge model was used. The frequency influences the Walfisch-Bertoni model the same way as the Knife-edge model, i.e., the higher the frequency the higher the attenuation will be.

**VII. REFERENCES**


