Chapter 5

Radio Network Planning and Propagation Models for Urban and Indoor Wireless Communication Networks

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Additional information is available at the end of the chapter

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Abstract

As the growing demand for mobile communications is constantly increasing, the need for better coverage, improved capacity, and higher transmission quality rises. Thus, a more efficient use of the radio spectrum and communication systems availability are required. This chapter presents EM propagation models most commonly used for the design of wireless communication systems, computer networks WLAN and WPAN for urban and/or in indoor environments. The review of commercial or University computer codes to assist design of WLAN and WPAN networks were done. An example of computer design and simulation of indoor Bluetooth and WLAN communication systems, in the building of Wroclaw University of Science and Technology, Wroclaw, Poland is shown in Chapter 8.

Keywords: EM wave propagation, urban, outdoor, indoor, deterministic model, empirical model, one-slop, multi-wall, ray tracing, ray lunching, dominant path, mobile communication system, WLAN, Wi-Fi, Bluetooth

1. Introduction

In recent years, a substantial increase in the development of broadband wireless access technologies for evolving wireless Internet services and improved cellular systems has been observed. Because of them, it is widely foreseen that in the future an enormous rise in traffic will be experienced for mobile and personal communications systems. This is due to both an increased number of users and introduction of new high bit rate data services. This trend is observed for third-generation systems, and it will most certainly continue for fourth- and fifth-generation systems.

Wireless communication systems, as opposed to their wireline counterparts, pose some unique challenge:

a. allocated spectrum limitation results in a limited levels of system capacity;

b. radio propagation environment and the mobility of users give rise to signal fading and spreading in time, space, and frequency; and

c. expired battery life at the mobile device poses DC power constraints.

In addition, cellular wireless communication systems have to cope with interference due to frequency reuse. Research efforts investigating effective technologies to mitigate such effects have been going on for the past years, as wireless communications are experiencing rapid growth.

The rise in traffic will put a demand on both manufacturers and operators to provide sufficient capacity in the networks. This becomes a major challenging problem for the service providers to solve, since there exist certain negative factors in the radiation environment contributing to the limit in capacity.

A major limitation in capacity is co-channel interference caused by the increasing number of users. The other impairments contributing to the reduction of system performance and capacity are multipath fading and delay spread caused by signals being reflected from structures (e.g., buildings and mountains) and users traveling on vehicles (**Figure 1**).

To aggravate further the capacity problem, in 1990s, the Internet gave the people the tool to get data on-demand (e.g., stock quotes, news, weather reports, e-mails, etc.) and share information in real time. This resulted in an increase in airtime usage and in the number of subscribers, thus saturating the systems' capacity.

Wireless carriers have begun to explore new ways to maximize the spectral efficiency of their networks and improve their return on investment. Research efforts investigating methods of improving wireless systems performance are currently being conducted worldwide.

In the design of wireless networks for companies and institutions, there is no room for chance. Failure to even potentially the smallest factor can cause errors that will make our project become useless. To organize the design process, the concept of splitting the process into three phases is introduced [1]: *initial phase*—collects information about the requirements and expectations of the client; *design phase*—identifying the best access point, AP, location by application of simulation based on the EM wave propagation models; and *measurement phase*—implementation of the project and the introduction of any amendments arising from the difference between the results of measurements (the real behavior of the network), and simulation.

In the circumstances in which radio waves are many phenomena, the designation of a useful signal level is extremely complex and requires the introduction of appropriate propagation models. Such model is a collection of mathematical expressions, graphs, and algorithms used to produce propagation characteristics of EM waves in chosen environment. Propagation models can be divided into empirical (statistical) such as One-Slope (O-S), Multi-Wall (M-W)—linear and nonlinear, dominant path model (DPM), etc., the deterministic (e.g., Ray Tracing, RT, Intelligent Ray Tracing, IRT, Ray Lunching, RL, etc.). There are also models which are a combination of both of these types.

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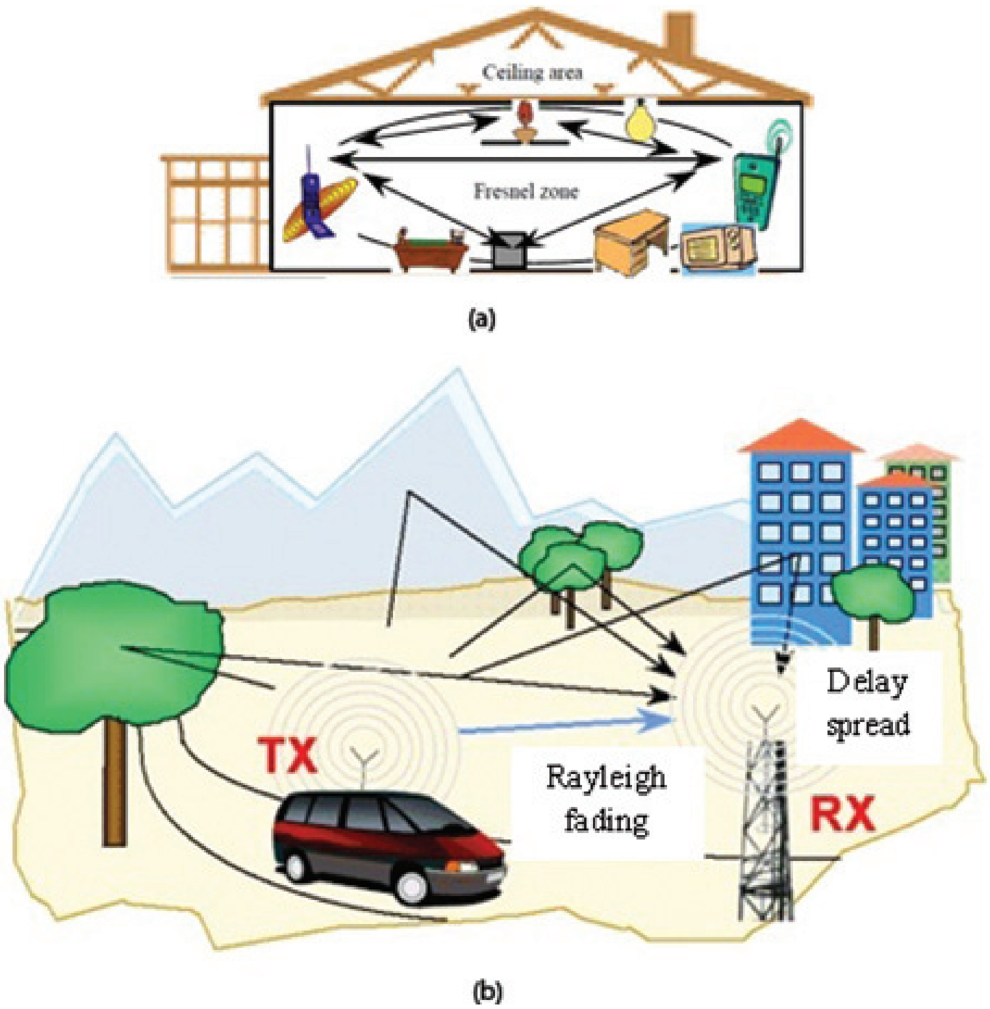

Figure 1. Wireless systems impairments in: indoor (a) and outdoor (b) environments.

Presented models allow streamlining the design process for wireless networks. On the market, there are a lot of solutions, commercial computer codes, based on these concepts.

2. Radio link budget

Wireless network design requires that you specify the size and shape of the areas covered by the access points. To this end, the link budget is performed:

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - (L_{Tx} + L_{Rx} + L) \tag{1}$$

where P_{Rx} is the received power (dBm), P_{Tx} is the broadcast power (dBm), G_{Tx} is the power gain of transmitting antenna (dB), G_{Rx} is the power gain of receiving antenna (dB), L_{Tx} is transmitting antenna cable attenuation, L_{Rx} is receiving antenna cable attenuation, and L is the route of EM wave propagation attenuation (dB).

The most difficult to determine the part of the link budget is the attenuation loss *L* of the propagation route. Typical wireless systems environment is located inside the buildings filled with walls, furniture, peoples, and other objects. In such conditions, the mechanism of propagation of the EM waves is very complex. A number of EM waves distributed inside buildings belong to different physical phenomena [2]:

- ***Diffraction***: when signal encounters on the road, an impermeable barrier, whose dimensions are larger than the wavelength. At the edges of the obstacles is the deflection of the wave causing the attenuation, dispersion, and a change in the direction of EM wave propagation,
- ***Dispersion***: when on the road the wave contains obstacles, whose dimensions are comparable to the wavelength. In this case, the radio waves are directed in more directions, which is difficult to predict and model,
- ***Reflection***: when radio wave on the way encounters an obstacle, whose dimensions are much larger than the wavelength of the incident EM wave, they reflect itself from the obstacle. In cases when at the receiving end, there are many of reflected waves signal can be very unstable,
- ***Penetration over obstacles***: when radio wave encounters an obstacle, which is to some extent transparent for radio waves, allowing the reception of radio signals inside buildings (waves penetrate through walls and ceilings),
- ***Absorption***: caused by the appearance of the plants on the propagation route, peoples with high absorption capacity. Radio waves are absorbed also by other obstacles, such as walls, furniture, and painting of the walls, curtains on the windows, etc.,
- ***Running along the tunnels and corridors***: guided wave phenomenon can be dealt with as a special mechanism to describe the propagation in tunnels or corridors, arising as a result of multiple reflections and interference of the EM waves along the route.

The designation of the attenuation of a route in such conditions is extremely difficult. Having regard to these mechanisms of propagation, the propagation models have been developed. The propagation model is an algorithm to analyze the propagation of radio waves in the environment taking into account the mechanisms described above. The algorithm described it in the proper order by means of the specified mathematical expressions, charts, and tables of some coefficients, and they are most frequently served in the form of recommendations of the ITU, IEEE and others worldwide standardizing institutions.

The propagation models permit to determine the average value of the propagation loss in a proper place. For the complete modeling of the propagation environment, the statistics of the received signal should be provided, which lets you include slowly variable and quick-exchange of signal dropouts. The slowly variable dropouts are understood as fluctuations in the average value of a signal over a distance of several wavelengths. Studies have shown that the lognormal distribution with standard deviation of values $\sigma = 2.7/5.3$ dB is the best model of the phenomenon of slow signal fade [8]:

$$p(x) = \frac{1}{x \cdot \sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{\frac{-(\log x - \log m)^2}{2 \cdot \sigma^2}} \tag{2}$$

where *p(x)* is the probability of the appearance of the signal with a value of x, σ is the standard deviation of the distribution, and m is the mean value of the signal.

The quick-exchange dropouts shall be understood as fluctuations in the average value of the signal caused by changes in the propagation environment, for example, the movement of people in the building. These fluctuations at the small number of moving people best describes the Rice distribution with a value of σ = 7/14 dB [8]:

$$p(x) = \frac{x}{\sigma^2} \cdot e^{\frac{-(x^2 + A^2)^2}{2 \cdot \sigma^2}} \cdot I_0\left(\frac{A \cdot x}{\sigma^2}\right) \tag{3}$$

where *p(x)* is the probability of the appearance of the signal with a value of x, σ is the standard deviation of the lognormal distribution with mean value m, and A is the strongest signal component amplitude, I_0 is a modified Bessel function of the first kind of order 0.

In order to facilitate the description of the Rice distribution, the k parameter is used [8]:

$$k = 10\log \frac{A^2}{2 \cdot \sigma^2} \tag{4}$$

In the case of a large movement of people in buildings, it is advisable to use the Rayleigh distribution [8]:

$$p(x) = \frac{x}{\sigma^2} \cdot e^{\left(\frac{-x^2}{2 \cdot \sigma^2}\right)} \tag{5}$$

where *p(x)* is the probability of the appearance of the signal with a value of x and σ is the standard deviation of the lognormal distribution with mean value m.

Analysis of the introduced distributions has allowed determining that the value of the signal exceeded at a given point in the 90% of the time in the conditions inside the building is smaller by about 6 dB from the mean value.

3. Empirical models

Empirical models are based on measurements and observations made under different conditions. Their accuracy depends not only on the results of measurements but also from the similarity of the present environment and the environment in which the modeling measurements were conducted. The propagation environments inside buildings are strongly differentiated. The use of empirical models in such conditions can lead to less accurate results relative to other promotional environments. Therefore, for indoor environments, more accurate models are considered to be deterministic models. Despite this, the easy implementation and fast calculation time that empirical models are not lost in popularity [8].

3.1. The one-slope model

The one-slope model is the simplest model used in the indoor environment. It does not take into account the details of the structure of the building but only the distance and n parameter describing an environment [8]:

$$L = L_0 + 10 \cdot n \cdot \log(d) \tag{6}$$

where L_0 is the attenuation at a distance of 1 m, n is the coefficient of the power distribution, and d is the distance between the transmitter and the receiver.

The parameters of the L_0 and n are empirical parameters assigned to the specified environment. By appropriate selection of their values, we can adjust the model to a specific type of building, for which we design a wireless network. Examples of model values for different propagation environments are shown in **Table 1.**

Building 1 represents buildings introducing the large attenuation (with high density of users, furniture, walls, and other obstacles). Building 2 represents the typical office buildings of medium attenuation. Building 3 represents the big empty spaces of exhibition halls, warehouses, and large offices with a small amount of furniture and other obstacles of the generally small damping. Parameter n in the case of propagation in the corridor is only 1, 2—what is apparent from the account of the phenomenon of driving in the tunnel (waveguide), which amplifies the signal. Due to the small accuracy of the model O-S has been used in a small number of computer tool applications: I-PROP (Technical University of Prague) and WinProp (AWE).

f, GHz	L_0, dB	n	Application
2.45	40	3.5	Building 1
2.45	40	4.5	Building 2
2.45	40	2	Building 3
2.45	40	1.2	Corridor in the building
5.25	46.8	3.5	Building 1
5.25	46.8	4.5	Building 2
5.25	46.8	2	Building 3
5.25	46.8	1.2	Corridor in the building

Table 1. Sample parameters of the one-slope model.

3.2. The multi-wall model

The most popular models of empirical studies to take into account the effect of the walls and ceilings are multi-wall models. Linear multi-wall model (also called the Motley-Keenan model) specifies the attenuation on the direct route between transmitter and receiver, taking into account the attenuation by walls and ceilings of the building [8]:

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$$L = L_0 + 10 \cdot n \cdot \log(d) + \sum_{i=1}^{I} N_{wi} \cdot L_{wi} + \sum_{j=1}^{J} N_{fj} \cdot L_{fj} \quad (7)$$

where L_0 is the attenuation at distance of 1 m, n is the index that depends on the adopted model, d is the distance between the transmitter and receiver, N_{wi} is the number of walls of equal attenuation value, N_{fj} is the number of floors with equal attenuation values, L_{wi} is the attenuation of the i-th walls- kind, and L_{fj} is the attenuation of j-th ceilings value.

Based on measurements, the parameter values are designated as [8]: L_0 = 37 dB, L_f = 20 dB (for typical slabs thickness < 30 cm), L_w = 3.5 dB (for plaster walls), and 7 dB (for concrete walls), n = 2.

Conditions of the propagation inside the building more accurately reflects, so called, nonlinear model of multi-walls, which was developed within the framework of the European project COST 231 and approved by the ITU as recommended for third generation of cellular mobile systems projects. Attenuation of radio link referred to the model is given by following equations [4]:

$$L = L_{FS} + L_0 + \sum_{i=1}^{I} N_{wi} \cdot L_{wi} + N_f^{\left(\frac{N_f+2}{N_f+1} - b\right)} \cdot L_f \quad (8)$$

$$L_{FS} = 32,4 + 20\log\left(f_{[MHz]}\right) + 20\log\left(d_{[km]}\right) \quad (9)$$

where L_{FS} is the free space loss, L_0 is the attenuation at distance of 1 m, N_{wi} is the number of i-type walls on the propagation route, N_f is the number of floors on the propagation route, L_{wi} is the attenuation of the i-type walls, L_f is the slab attenuation, b is the empirical parameter, f is the channel center frequency (MHz), and d is the distance between the transmitter and the receiver (km).

Some of model parameters were determined empirically [4]: L_0 = 37 dB, L_f = 18.3 dB (for ceilings constructed of reinforced concrete with a thickness < 30 cm), L_{w1} = 3.4 dB (for plaster walls with lots of window openings), L_{w2} = 6.9 dB (for concrete walls and constructed from bricks, perforated in the form of holes in their design), and b = 0.46.

The M-W models are used in computer programs (commercial and academic). Examples of computer codes are: WinProp (AWE Communication), ACTIX Analyzer, and I-Prop (University of Prague). **Figure 2** shows a comparison of the simulation results obtained in the building type 1 by applying the model of one-slope (b) and nonlinear model of multi-walls (c).

Simulations were made using the demo version of the I-Prop program for the transmitter with a power of 10 dBm and at a frequency of 2.45 GHz [3]. The M-W model in indoor environments takes into account the impact of the walls on the suppression of radio wave but only on the direct of transmission transmitter to receiver route. As mentioned earlier, the specificity of phenomena in indoor environments causes if a direct signal is often not the

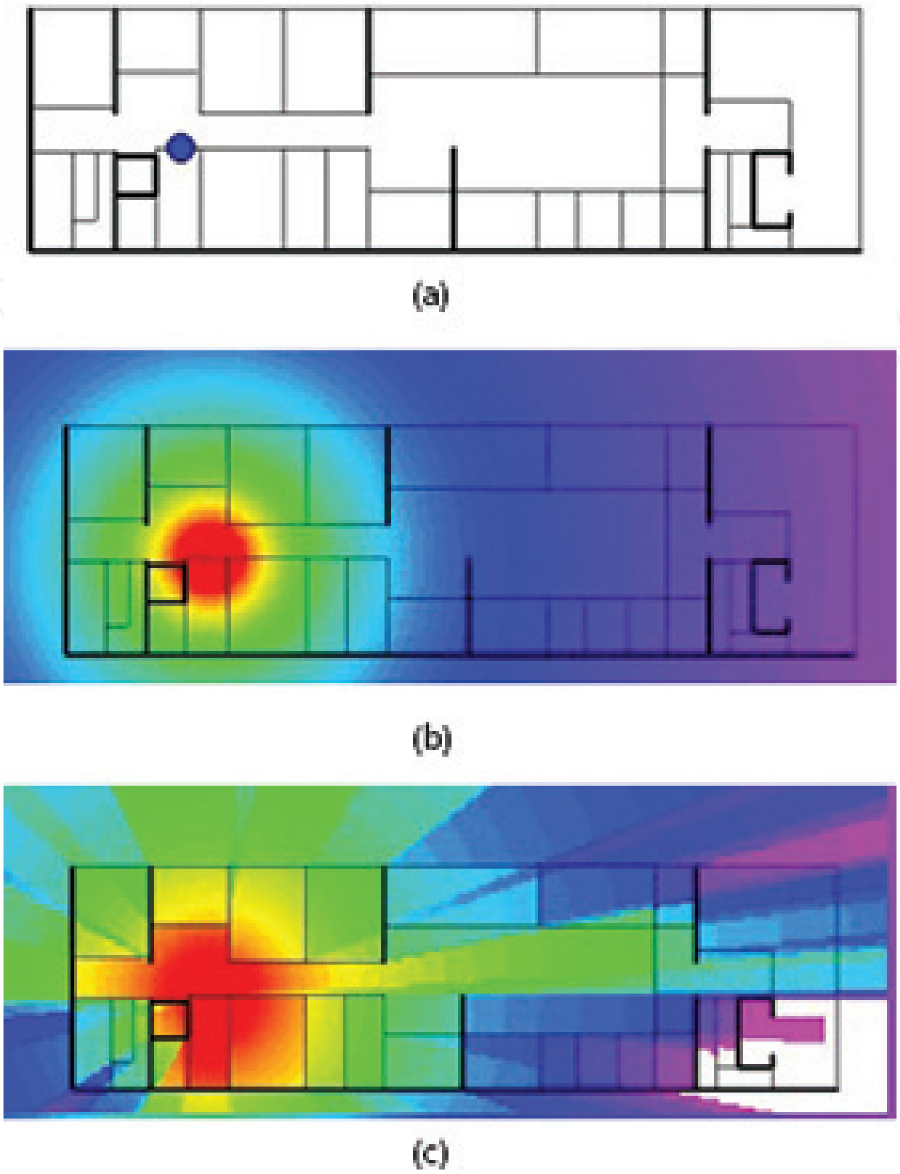

Figure 2. The projection of floors and location of the access point (a), the distribution of the signal for one-slope model (b), and for nonlinear model of multi-walls (c) [3].

strongest one. In that cases in the received signal the reflected as well as the diffraction rays should also be considered [4].

3.3. Dominant path model

In the dominant path model (D-P), the losses shall be determined for several wave propagation routes. As shows experience, in most cases, only two or three rays carry more than 95% of the signal energy. Analysis of the results of measurements also showed that the adjacent rays decompose the same phenomena and are almost identical. This fact was used in the D-P model, which is looking for the routes with the smallest attenuations. In **Figure 3**, the concept of the D-P model is shown.

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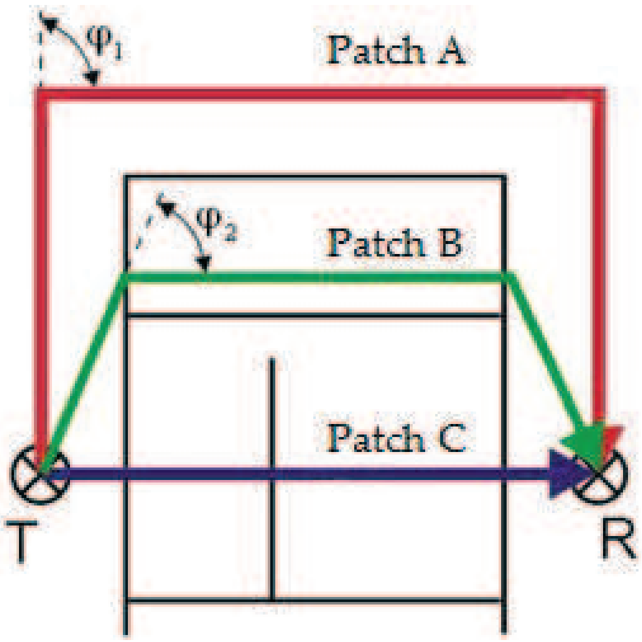

Figure 3. Routes of the wave propagation in dominant path model [5].

The losses on selected routes shall be, according to [5]:

$$L = 20 \cdot n \cdot \log(d) + \sum_{i=1}^{I} f(\varphi_i, i) + \sum_{j=1}^{J} L_j - W \tag{10}$$

where n is the factor depending on propagation conditions for direct radius, d is the length of the propagation route, W is the factor of the conduct of wave which grows for the smaller distance between the faces on the propagation route, $f(\varphi_i,i)$ is the function determining the loss depending on the number of phenomena, i specifies the following phenomena, φ_i is the angle between the new and the previous direction of propagation, and L_j is the attenuation caused by the transition of the wave by j-wall (or ceiling).

The D-P model allows you to take into account the situation, when the dominant radius is not the dominant one, it means the attenuation of EM waves is not lowest one. So, on the beginning the attenuations for some few routes are determined, for which are expected to be the smallest. On further analysis, only those routes have been taken into account. It is important that the exact designation of the losses is associated with some encountered phenomena (reflection and diffraction) and strengthening related to the phenomenon of the driving waves in the corridors (the waveguide effect). The designation of a wave driving factor W and suppression caused by diffraction and reflection can greatly vary depending on the type of building. For each environment before the calculations, it is recommended that measurements should be arranged, the results of which will allow for the designation of a function $f(\varphi_i, i)$ and parameter W. Parameter W that specifies the contribution to the phenomenon of the conduct of the wave in the D-P model depends on: the width of the corridor/tunnel, the material from which the walls are built, the walls' orientation relative to the designated path, and the continuity of the phenomenon of the conduct of the wave.

Determination of the coefficient W starts the analysis of three parameters for each of the walls and at the point of x. The factor $w_i(x)$ that represents the interim impact of the i^{th} wall on the conduct of the wave at the point x, can be appointed from [5]:

$$w_i(x) = A_i \cdot D_i(x) \cdot L_i \tag{11}$$

$$A_i = \begin{cases} 1 - (\varphi_i/45^\circ) & 0 \leq \varphi \leq 45^\circ \\ 0 & \varphi > 45^\circ \end{cases} \tag{12}$$

$$D_i(x) = \begin{cases} 1 - (d_i(x)/3m) & 0 \leq d_i \leq 3m \\ 0 & d_i > 3m \end{cases} \tag{13}$$

$$L_i = \begin{cases} 1 - (L_{Ri}/10dB) & 0 \leq L_{Ri} \leq 10dB \\ 0 & L_{Ri} > 10dB \end{cases} \tag{14}$$

where d_i is the distance between the wall and the path of propagation; L_{Ri} are losses resulting from reflection, depending on the material of the wall is built; and φ_i is the angle between the wall and the path of propagation.

The factor $w(x)$ that represents the partial effects of all N walls in section x specifies the pattern [5]:

$$w(x) = \frac{1}{w_0} \min\left(w_0, \sum_{i=1}^{N} w_i(x)\right) \tag{15}$$

The factor is normalized relative to the w_0—maximum value of the conducted wave. Resultant factor wave driving is the superposition of all partial coefficients in the way of propagation [5]:

$$W = \frac{1}{x_R - x_T} \cdot \int_{x=x_T}^{x_R} w(x)dx \tag{16}$$

where x_R is the receiver position and x_T-the position of the transmitter.

The value of the coefficient W can range between a value of 0 (the conducting of EM wave phenomenon does not exist) and 1 (the ideal case of the conducting EM wave phenomenon).

The second essential and difficult to model parameter of the D-P model is the attenuation caused by the changing direction of propagation of the angle φ_i. This parameter is determined as a factor W of the wave driving.

Besides, you should also know the suppression resulting from the transition of the wave by an obstacle and the distance between the transmitter and the receiver. Based on the difficulties in the designation $f(\varphi_i, i)$ and W in the result, this model is used in a small number of computer codes (e.g., WinProp) [5].

Figure 4 shows a comparison of the simulation results obtained from: (a) only the direct radius (nonlinear of M-W model, (b) the strongest ray (the dominant path D-P model), and (c) the ray tracing, 3D RT, approach (c).

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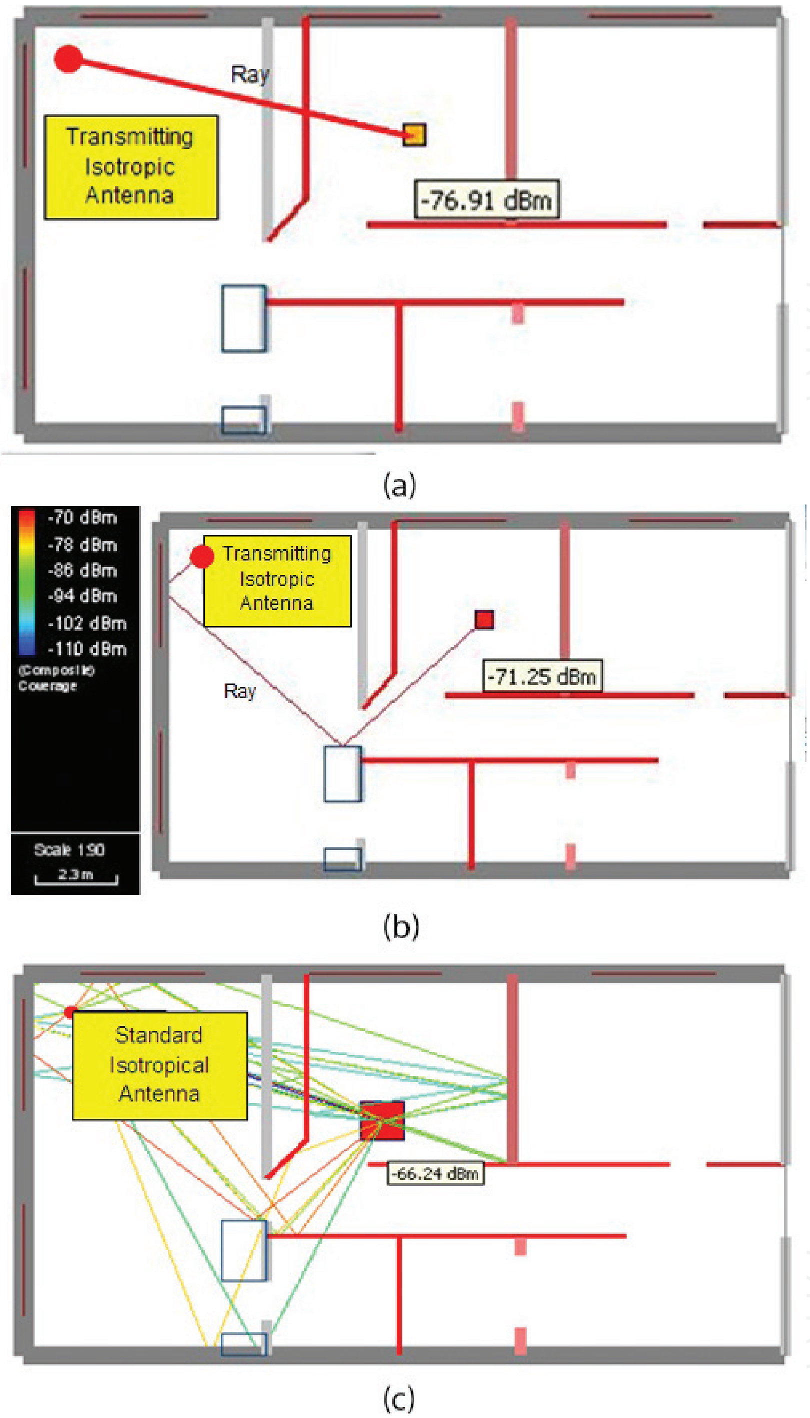

Figure 4. Simulation results obtained using: only the direct radius (nonlinear of M-W model) (a), of the strongest ray (the dominant path D-P model) (b), and ray tracing, 3D RT, approach (c).

Both results were obtained by means of ACTIX Analyzer for the transmitter with a power of 10 dBm at frequency of 2.45 GHz [6]. In this example, the direct radius is weaker than the strongest radius of about 5.66 dB, or almost 3.7 times. This result proves the superiority of the D-P model over the M-W model. Unfortunately, the very complex initial calculations make D-P model difficult to implement.

4. Deterministic models

Deterministic models are based on physics laws and allow for precise modeling of the propagation of electromagnetic waves. These models take into account the phenomena such as reflection, diffraction, absorption, and wave running, which are essential in the conditions inside buildings as well as in the outdoor area of dense building centers. Unlike the empirical models, the deterministic models are not based on measurements and thus it accuracy does not depend on the similarity of the standard environment and concerned one. To accurately model the phenomenon of propagation of electromagnetic waves, deterministic models require accurate rendering of environment propagation periods. In addition to the level of the model of the environment and on the quality of results, calculation has the effect of repeat accuracy phenomena, which are subject to the electromagnetic waves. The EM waves propagation environments inside buildings are strongly differentiated. Therefore, for these environments, deterministic models are considered to be more accurate in comparison with models of empirical studies.

In order to wave propagation modeling, two concepts were developed. The first is a technique for FDTD (finite-difference time-domain) and the other is a technique GO (geometrical optics) also known under the name of ROM (ray optical method).

4.1. FDTD method

The FDTD method is to solve the boundary conditions of the Maxwell's equations for the analyzed area by means of frequency differences method in the time domain. The method requires a transition from continuous space and time distribution of electromagnetic field to a discrete spatially grid that contains in its nodes of the field values in a certain moment of time. The transition from derivatives for odds ratios differential allows you to create an algorithm to calculate the distribution of the field in the next time step of the fields at the time of the previous one. The distribution of the structure given by the material constants is specified in each of the nodes of the grid. This algorithm has been provided by Kane Yee. In accordance with the algorithm EM field value in the node of the grid depends only on the values of the EM field at this point in the previous time step, as well as of the values of other EM fields in the adjacent nodes of the grid, and of the known features of magnetic and electrical sources. FDTD simulation results are more precise relative to GO. It requires a large amount of CPU memory and of the computer microprocessor power for fast calculation of the large Maxwell's equations. For this reason, it is rarely used in computer programs that support design of the wireless networks. An example of such a program is the Wireless InSite of the Remcom Company. The FDTD method is limited in suburban environments, in which the structures are situated close to antennas with complex material properties [7, 23–27].

4.2. Method of geometrical optics GO

Deterministic models are based primarily on methods of geometrical optics (ray optical method (RO), or geometrical optics (GO)), which are based on the assumption of rectilinear propagation of electromagnetic waves. Each of the rays carries the part of the radiated power.

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If it encounters obstacles, the wave is: reflected, refracted, diffracted, or dispersed. At the beginning, all possible routes between the transmitter and the receiver are determined. In several recent years, the largest popularity won two techniques to determine the possible paths of propagation: method of images (image method, IM) and method of the rays shooting (ray lunching, RL). These methods allow you to recreate the three-dimensional spread of the waves by taking into account of losses on the transmitter-receiver road. The accuracy of the two methods depends largely on the number of phenomena that are included in the models. The more the phenomena will be included, we can get more accurate results.

The image method IM lets you designate all possible routes of the signal propagation between the transmitter and the receiver (the center of the pixel) with regard to the phenomena of reflection and transmission. To find a ray route, the mirrors of transmitter relative to the illuminated surrounding surfaces are created. The intersection of the straight line connecting the virtual source and receiving point of the illuminated plane designates the place of reflection of the rays (**Figure 5a**).

In the case of multiple reflections, the following mirrors of virtual source are generated and the algorithm is repeated. The analysis can be carried out in three dimensions, or separately in the vertical and horizontal planes. Method of images allows you to designate the exact routes of the reflected rays. The direction of the rays invading to the obstacle shall be determined according to the Snell's law. Method of images can be used to find the routes of diffracted rays [8].

In the RL method, the created rays are shooting directly from the source. The azimuth (elevation) angle of rays increases gradually at constant values (**Figure 5b**).

For the 3D model at 1°, discretization of both shooting angles more than 32,000 rays are generated. The route of each of the ray is tracked independently of the other. For each of ray is allocated a part of the sphere forming the wave front (**Figure 6b**).

In the simplest solution, an excerpt of the sphere is approximated by a circle. Then, the circle creates the so-called received sphere (**Figure 6a**), in which the ray for 2D model is expressed by (17), and for the 3D model by (18) [8]:

$$R_S = \frac{\gamma \cdot d}{2} \tag{17}$$

$$R_S = \frac{\gamma \cdot d}{\sqrt{3}} \tag{18}$$

where γ is the angle between the directions of launching rays and d is the distance the center of the sphere to the signal source.

This method introduces errors of interpretation arising from the limited geometrical possibility of approximation of a sphere by concentric circles. In order to increase the accuracy, portions of a sphere are approximated by the rectangles (**Figure 6**). The sizes of the υ_i and ψ_i determine the coordinates of the launched ray, and $\Delta\psi_i$ and $\Delta\upsilon_i$ are the sides of the rectangle and are described by [8]:

$$\Delta\psi_i(\vartheta_i) = \frac{\Delta\vartheta}{\sin\vartheta_i} \tag{19}$$

$$\vartheta_i = \frac{\Delta\vartheta}{2} + (i-1)\cdot\Delta\vartheta, \qquad i = 1\ldots N_\vartheta, \qquad \Delta\vartheta = const. \tag{20}$$

The intensity of the electric field at the receiving end is the sum of the intensities of all rays, whose distances from a receiving point are less than R_S. The direction of the rays, penetrating

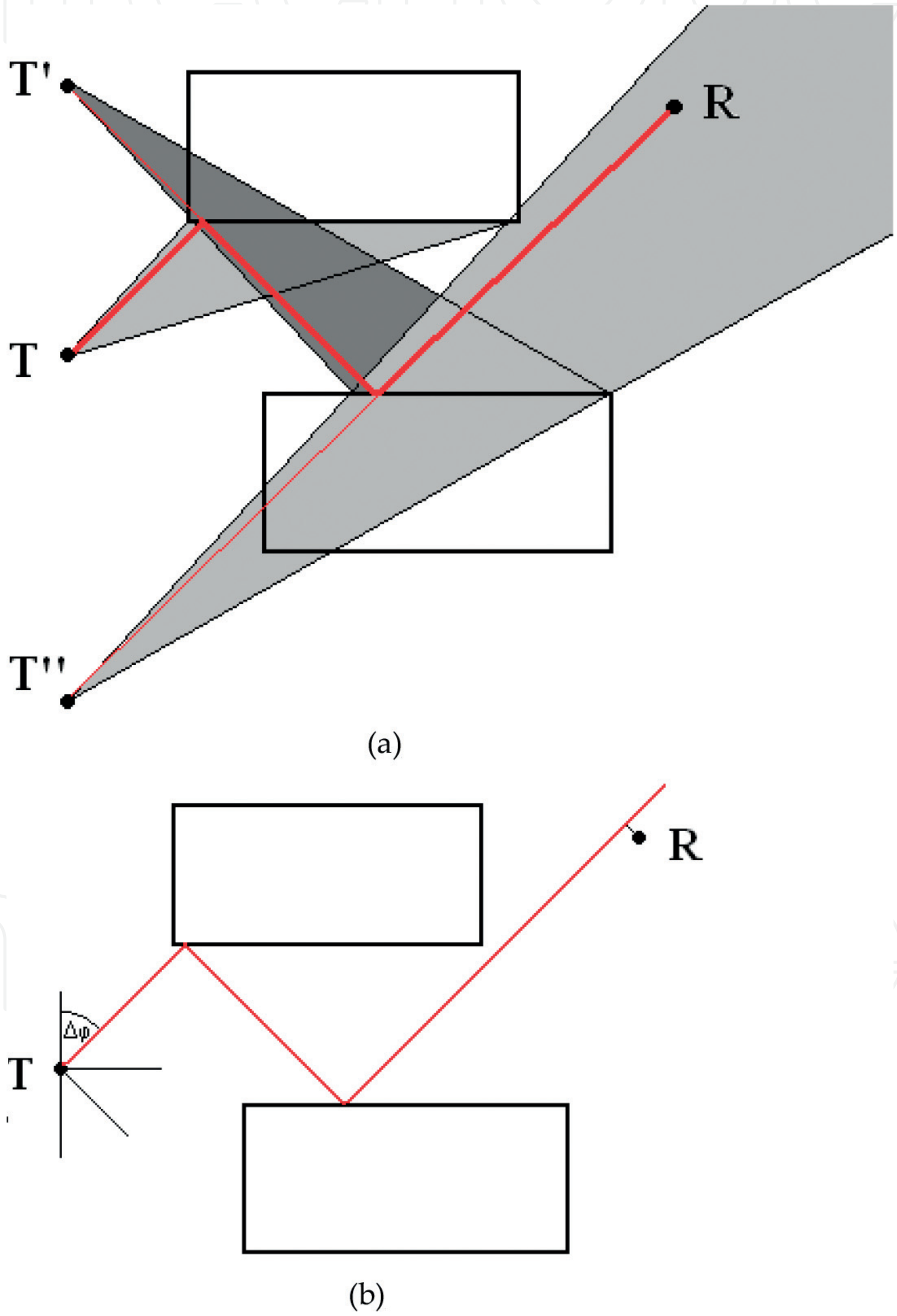

Figure 5. Routing of the reflected rays in the method of images IM (a), and routing of the reflected rays in the rays launching R-L method [1].

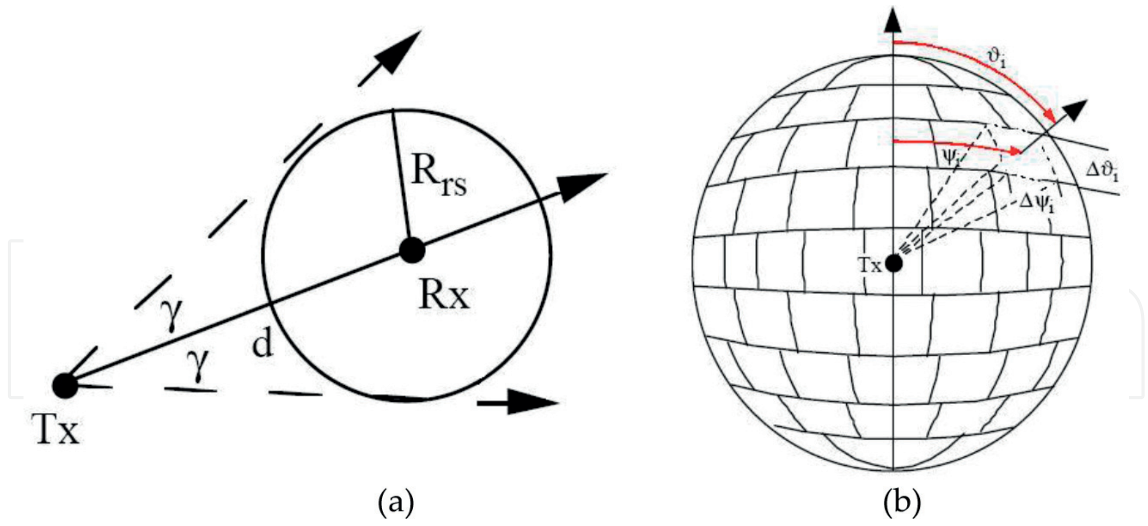

Figure 6. Cross-section of the receiving sphere (a) and rays launching method concept (b) [11].

the obstacle shall be determined with the law of Snell. The RL method can be used to find the routes of diffracted rays. The source of diffracted rays may be found when the rectangle (or circle) associated with the ray crosses the diffraction edge [8].

The RL method has a disadvantage in relation to the IM method because it may neglect the very narrow obstacles lying on the extension of transmitter, which can be placed between two rays. To ensure satisfactory resolution of the simulation, the technique of rays splitting RS was introduced, which allows you to split the rays when the radius of the receiving sphere (or side of the rectangle) reaches its maximum size (**Figure 6**).

The RL method is easier to implement with respect to the IM method. It is characterized by the weaker resolution and longer time of computation. Currently, the IM and RL methods are called the ray tracing, RT, method.

In several recent years, research to refine the method of RT has been conducted. Thus the smart method of ray tracing, that is, intelligent ray tracing (IRT) (**Figure 8b**) has been developed. It is based on simple assumptions [10, 14, 15]: (1) only a few rays takes an essential part of the energy of the electromagnetic field, (2) visibility of faces and edges do not depend on the position of the of transmitter antenna, (3) often the bordering receiving points (pixels) are reachable by the rays with a very similar the properties. In accordance with the objectives the calculation were optimized. Pretreatment process of database processing with a collection of information about the obstacles encountered in the model shall be carried out only once. The idea is that each of these obstacles is divided into small pieces called tiles and on the borders in the form of episodes.

Mutual relations of visibility between objects are calculated once and stored in the database. The tiles and the edges are represented only by their center points. The idea of the relationship of visibility center points of the edges or tiles is that if the two center points are in the zone, direct visibility defines the rays from the center of the first tile to the corners of the next one (**Figure 7a**).

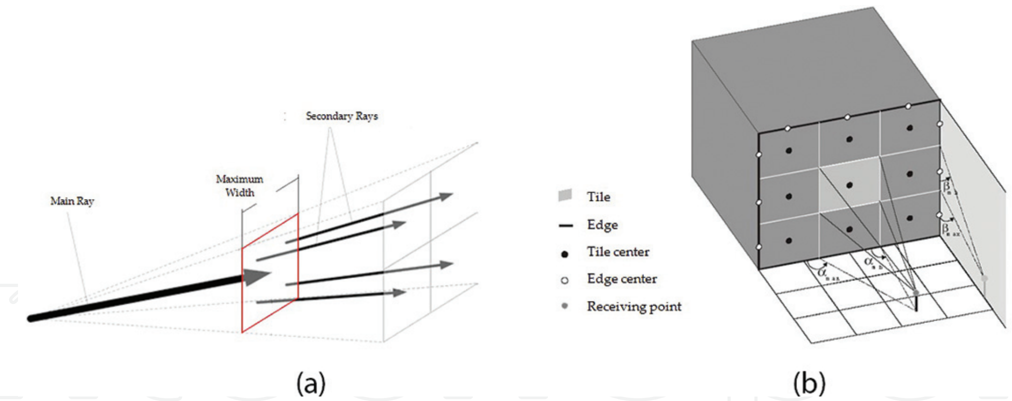

Figure 7. The division of the rays in the RT method [12] (a) and the geometry of the inteligent method of ray tracing IRT [10].

These rays and the throw of their angles are data indicating the relationship prevailing between the two center points. Such relationships are created also between edges, as well as in the case of the edge of the tiles. Important are the angles that define the angular distance of possible diffraction and reflection. During the process of routing, the propagation links the information about the relationship of visibility are readily available and you do not need to set dependencies between the obstacles for each ray, which greatly increase the computation speeds [10].

The introduction of the 3D model is associated with the growth of databases and considerable complexity of algorithms. This causes prolongation of the calculation time. To reduce this time, instead of 3D method, the 2 × 2D, so called 2.5D method of modeling has been introduced. In this solution, two independent analyses are carried out: in vertical and horizontal planes [8]. In order to further reduce the calculation time proposed the division of the algorithms in the class due to the number of the relevant phenomena for each of the waves (**Table 2**).

Further increasing the maximum number of, at issue, propagation phenomena takes longer simulation time. In order to reduce calculation time the receiving coverage surface is divided into smaller portions, called the pixels. Each pixel is represented by its center point. The route of the rays is determined only between source and any center point. Increasing the size of the pixels will reduce the resolution of the simulation and the calculation time.

After you specify all the routes between the transmitter and receiver, the components of the electrical field strength E_i at the receiving end originating in from each of the rays are determined [9]:

$$E_i = \frac{\sqrt{Z_0 \cdot P_0 \cdot G_{Ti}(\theta_{Ti}, \varphi_{Ti})}}{4\pi \cdot d_i \cdot L_{Di}(d_i)} \cdot \prod_m D_{mi} \cdot \prod_j R_{ji} \cdot \prod_k T_{ki} \cdot \prod_n e^{-\alpha_{ni} \cdot d_{ni}} \cdot e^{-j\frac{2\pi \cdot d_i}{\lambda}} \tag{21}$$

where G_{Ti} is the energetic gain of receiving antenna for the i^{th} ray, Z_0 is the characteristic impedance (≈ 377 Ω), P_0 is the power input to the transmitting antenna, λ is the of the transmitted wavelength, d_i is the length of the route and of the i^{th} ray, L_{di} is the geometric coefficient depending on the position of the diffraction edge on the route of the i^{th} ray, D_{mi} is the diffraction

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Class of algorithm	Direct ray	Maximum number of reflections in the absence of diffraction	Maximum number of diffraction in the absence of reflections	The maximum number of reflections (o) and diffraction (d)
1	Yes	—	—	—
2	Yes	1	—	—
3	Yes	2	—	—
4	Yes	2	1	—
5	Yes	3	1	—
6	Yes	3	1	1 o + 1 d
7	Yes	3	2	1 o + 1 d
8	Yes	3	2	2 o + 1 d
9	Yes	4	2	2 o + 1 d
10	Yes	5	2	2 o + 1 d
11	Yes	6	2	2 o + 1 d

Table 2. Division of algorithms due to the number of the relevant phenomena.

coefficient of m^{th} edge for the i^{th} ray, R_{ji} is reflection coefficient from j^{th} object for the i^{th} ray, T_{ki} is the coefficient for k^{th} border for the i^{th} ray, α_{ni} is attenuation constant of the n^{th} object for the i^{th} ray, and d_{ni} is the length of the route of the i^{th} ray by n^{th} object of attenuation constant of α_{ni}.

The intensity of the electric field from the all rays arriving at the receiver is calculated according to the formula [8]:

$$E = \sum_{i=1}^{n} E_i \tag{22}$$

Power P_R delivered by the receiving antenna to receiver depends on the effective area (or the effective length) A_{SK} of the receiving antenna and power density S [8]:

$$P_R = S \cdot A_{SK} = \frac{|E|^2 \cdot A_{SK}}{Z_0} \cdot \sum_i G_{Ri}(\theta_{Ri}, \varphi_{Ri}) \tag{23}$$

where G_{Ri} is a energetic gain of receiving antenna for the i^{th} ray.

The coefficients in the expression (21) are defined by the modeling techniques of propagation phenomena used in the RT method.

In the methods of geometrical optics, GO, reflection phenomenon of reflection of electromagnetic waves describes the Fresnel coefficients, expressing ratios of electromagnetic fields strengths of the reflected (R) and incident (I) waves. The two Fresnel coefficients are different for the EM vectors intensities, namely the parallel and perpendicular components to the plane of incidence. The degree of reflection and transmission of both Fresnel vectors are varying quite different. The plane of incidence is defined as the plane determined by the wave vector of the incident and the normal to the boundary of separation. **Figure 8** shows the mechanism of the reflection phenomenon [8].

Coefficients of reflection (R) and transmission (T) of both components are expressed by the following expressions [11]:

-the parallel component reflection coefficient

$$R_{II} = \frac{tg(\theta_1 - \theta_2)}{tg(\theta_1 + \theta_2)} \tag{24}$$

-reflection coefficient of perpendicular component

$$R_{\perp} = -\frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)} \tag{25}$$

-transmission coefficient of the parallel component

$$T_{II} = \frac{2 \cdot \cos(\theta_1) \cdot \sin(\theta_2)}{\sin(\theta_1 + \theta_2) \cdot \cos(\theta_1 - \theta_2)} \tag{26}$$

-coefficient of perpendicular transmission component

$$T_{\perp} = \frac{2 \cdot \cos(\theta_1) \cdot \sin(\theta_2)}{\sin(\theta_1 + \theta_2)} \tag{27}$$

Knowing the material properties of both media: conductivity σ, permeability μ, and permittivity ε for an angular frequency ω, we can designate an angle θ_2 using Snell's law [11]:

$$\theta_2 = \arcsin(\sin(\theta_2)) \tag{28}$$

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \sqrt{\frac{\mu_2 \cdot \left(\varepsilon_2 - j\frac{\sigma_2}{\omega}\right)}{\mu_1 \cdot \left(\varepsilon_1 - j\frac{\sigma_1}{\omega}\right)}} \tag{29}$$

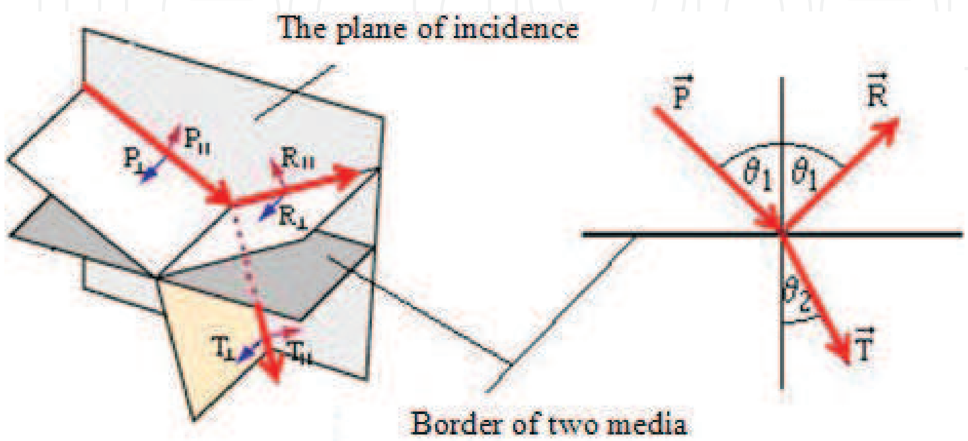

Figure 8. The EM wave reflection and transmission phenomenon.

In real terms, the walls are constructed of several layers. On each border of the wall layers the wave is splitting on two components, the reflected wave from the surface of layer and transmitted wave to the layer. The result is that the actual coefficients of transmission and reflection depend on the angle of incidence [9].

The incident wave is dissipated as a result of surface roughness. To determine the surface roughness, the criterion of Rayleigh is used [12]:

$$\Delta\varphi = \frac{\pi}{2} \tag{30}$$

where $\Delta\varphi$ is the difference of phase between the two rays as shown in **Figure 9**.

For small angles, the height H of Rayleigh and minimum distance between inequalities S determine the following equations [12]:

$$H = \frac{\lambda}{8 \cdot \theta} \tag{31}$$

$$S = \frac{\lambda}{4 \cdot \theta^2} \tag{32}$$

where λ is the length of a scattered wave and θ is the angle between the incident wave and reflecting plane.

According to the Rayleigh criterion, if the height surface roughness is greater than H and the distance between them is greater than S, then consider the surface that causes the dispersion of incident wave [12].

The phenomenon of EM wave scattering can be taken into account by reduction of the reflection coefficients (transmission coefficients are not changed). These coefficients can be multiplied by the value of slightly less than unity, where the exact value depends exponentially on the level of surface roughness calculated in accordance with the theory of Rayleigh:

$$R'_{II,\perp} = R_{II,\perp}\exp\left[-8\left(\frac{\pi \cdot H \cdot \cos\theta}{\lambda}\right)^2\right] \tag{33}$$

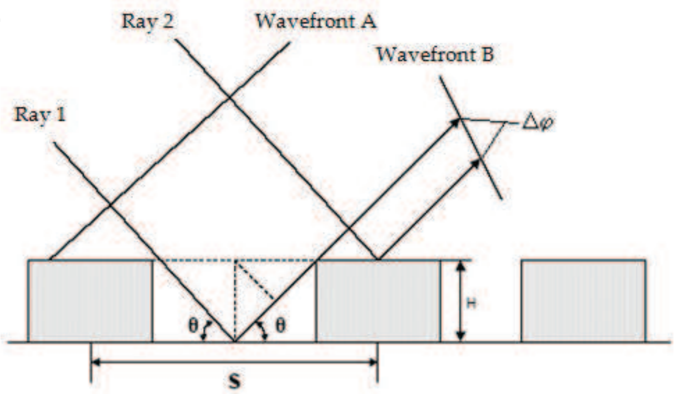

Figure 9. Determination of surface roughness [12].

where $R_{II,\perp}$ is the reflection coefficient from the perfectly flat surface, $R'_{II,\perp}$ is the reflection coefficient taking into account the scattering phenomenon, λ is the length of the wave, H is the Rayleigh's height, and θ is the angle of incidence.

Studies have proven that the absorption of the wave by different types of objects (first of all living beings) is very difficult to model. Knowing the obstacle dimensions and material properties: conductivity σ, permeability μ, and $\varepsilon = \varepsilon' - j\varepsilon''$, given the frequency of the EM wave, using a general description of the EM plane wave, we can determine the impact of absorption on changing the wave parameters [11]:

$$U \cdot e^{j\cdot\omega\cdot t} = A \cdot e^{-\alpha\cdot d} \cdot e^{j\left(\omega\cdot t - \beta\cdot d\right)} \tag{34}$$

where α is a attenuation constant, β is a phase constant, U is the wave amplitude after absorption, A is the wave amplitude before absorption, d is the dimension of obstacles, and ω is angular frequency of the wave.

The attenuation constant α and the phase constant β are expressed in the following equations [11]:

$$\alpha = \omega \cdot \sqrt{\varepsilon' \cdot \mu'} \cdot \sqrt{\frac{1}{2} \cdot \left[\sqrt{1 + \left(\frac{\sigma/_{\omega} + \varepsilon''}{\varepsilon'}\right)^2} - 1\right]} \tag{35}$$

$$\beta = \omega \cdot \sqrt{\varepsilon' \cdot \mu'} \cdot \sqrt{\frac{1}{2} \cdot \left[\sqrt{1 + \left(\frac{\sigma/_{\omega} + \varepsilon''}{\varepsilon'}\right)^2} + 1\right]} \tag{36}$$

The ray tracing method RT does not take diffraction into account. In order to model this phenomenon, the deterministic models based on ray tracing method are enhanced with correct techniques. There are several methods for modeling a phenomenon of diffraction: PAW (perfectly absorbing wedge), GTD (geometrical theory of diffraction) and UTD (uniform theory of diffraction). One of the biggest problems of modeling of diffraction is the precise definition of diffraction edges of the buildings and other objects. The most commonly used method is the UTD, which takes into account the wave polarization and the material properties of the diffraction edge. The EM wave coming on the diffraction edge is scattered on a cone whose vertex is at the diffraction point. In **Figure 10a**, the example of a diffraction cone is shown [8].

Figure 10b shows the transmission of the ray, which includes the phenomenon of diffraction by means of the UTD method.

The intensity of the electric field at the point of reception can be designated from [13]:

$$E_{UTD} = E_0 \frac{e^{-jks'}}{s'} \cdot D_{II}^{\perp} \cdot \sqrt{\frac{s'}{s + s'}} \cdot e^{-jks} \tag{37}$$

where E_0 is the wave field intensity emitted at the transmitting point, $k = \frac{2\cdot\pi}{\lambda}$ is the wavenumber, $\sqrt{\frac{s'}{s+s'}}$ sets the geometric relationship necessary for the determination of L_{Di} in an

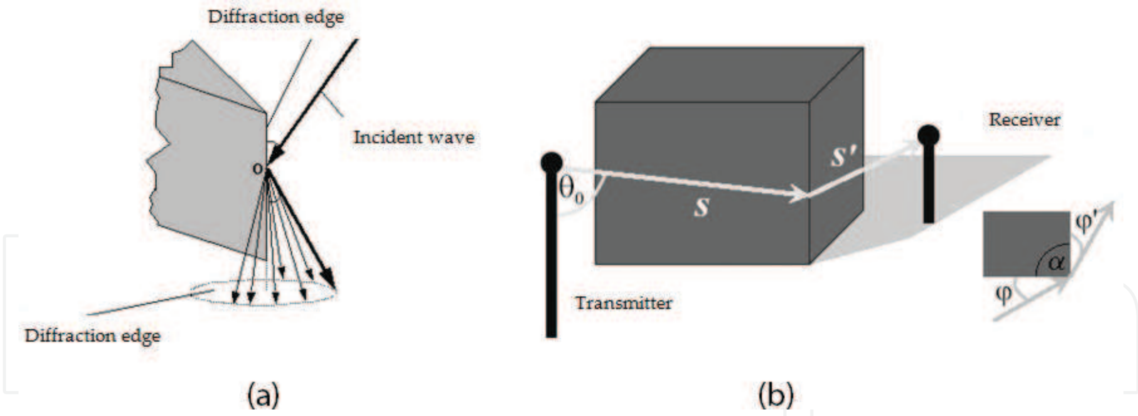

Figure 10. Diffraction cone in the UTD method (a) and an example of the radius diffracted on the edge (b) [13].

expression (21), and $D_{II}^{\perp}$ is the diffraction coefficient of the UTD method which is defined as follows [13]:

$$D_{II}^{\perp} = \frac{e^{-j\pi/4}}{2 \cdot n \cdot \sin\theta_0 \cdot \sqrt{2 \cdot \pi \cdot k}} \times (D_1 + D_2 + D_3 + D_4) \tag{38}$$

$$D_1 = \cot\left(\frac{\pi + (\varphi - \varphi')}{2 \cdot n}\right) \cdot F\left(k \cdot L \cdot a^+\left(\varphi - \varphi'\right)\right) \tag{39}$$

$$D_2 = \cot\left(\frac{\pi - (\varphi - \varphi')}{2 \cdot n}\right) \cdot F\left(k \cdot L \cdot a^-\left(\varphi - \varphi'\right)\right) \tag{40}$$

$$D_3 = R_0^{\perp, II} \cdot \cot\left(\frac{\pi - (\varphi + \varphi')}{2 \cdot n}\right) \cdot F\left(k \cdot L \cdot a^-\left(\varphi + \varphi'\right)\right) \tag{41}$$

$$D_4 = R_n^{\perp, II} \cdot \cot\left(\frac{\pi + (\varphi + \varphi')}{2 \cdot n}\right) \cdot F\left(k \cdot L \cdot a^+\left(\varphi + \varphi'\right)\right) \tag{42}$$

where $R_n^{\perp, II}$ and $R_0^{\perp, II}$ are the reflection coefficients of sides of diffraction edges at a given EM wave polarization, and $a^{\pm}, \beta^{\pm}, L,$ *and* $F(\cdot)$ (Fresnel transition function) are expressed in the following expressions [13]:

$$a^{\pm}(\beta) = 2 \cdot \cos^2\left(\frac{2 \cdot n \cdot \pi \cdot N^{\pm} - \beta}{2}\right) \tag{43}$$

$$\beta^{\pm} = \varphi \pm \varphi' \tag{44}$$

$$L = \frac{s \cdot s'}{s + s'} \cdot \sin^2\theta_0 \tag{45}$$

$$F(x) = 2 \cdot j \cdot \sqrt{x} \cdot e^{j \cdot x} \int_{\sqrt{x}}^{\infty} e^{-j \cdot \tau^2} \cdot d\tau \tag{46}$$

where $N^{\pm}$ is the integer closest to the fulfillment of the following equations [13]:

$$2 \cdot \pi \cdot n \cdot N^{+} - \left(\varphi \pm \varphi^{'}\right) = \pi \tag{47}$$

$$2 \cdot \pi \cdot n \cdot N^{-} - \left(\varphi \pm \varphi^{'}\right) = -\pi \tag{48}$$

$$n = \frac{2 \cdot \pi - \alpha}{\pi} \tag{49}$$

Figure 4c shows the results obtained by RT 3D method. Results were obtained by means of the ACTIX Analyzer computer code [6] for the 10 dBm transmitter power at a frequency of 2.45 GHz.

Method of geometrical optics, GO, is used to model the distribution of electromagnetic fields inside the buildings. On the basis of GO, the computer programs developed are: ACTIX Analyzer (by ACTIX) [6], WinProp (by AWE) [10], WiSE (by Lucent Technologies), Wireless InSite (by Remcom) [33], Cindoor (by Cantaberia University, Spain), Volcano (by Siradel) [28], and SitePlanner (by Motorola), and others for designing the indoor and outdoor wireless communication systems.

5. Review of computer programs for wireless networks planning

The EM wave propagation models presented previously have been used in computer programs for planning wireless communication networks. The most commonly used method is the ray tracing RT. Methods based directly on the Maxwell's equations (e.g., FDTD) have not adopted in the design of wireless networks inside buildings, they are rather more attractive for outdoor propagation scenes simulation (e.g., Wireless InSite by Remcom [33]). An empirical model most commonly used in computer programs is a non-linear model of multi-walls MW developed within the framework of the COST 231 project and adopted in the ITU Recommendation. The one slope I-S model is not the exact and therefore rarely used, while the dominant path model (D-P) is difficult to implement. Showcased programs allow you to simulate for the frequency range from 0.05 to about 300 GHz. **Table 3** summarizes the basic characteristics of the mostly used computer programs.

In addition to the presented programs on the market, there are several third-party products. These include, for example, Volcano (Siradel) [28], ADTI ICS online [29], iBWAVE DE [30], TAP™MAPPER [31], SitePlanner (Motorola), EDX Signal Pro (EDX Wireless Technologies) [32], CelPlanner™ [34], etc. The commercial computer solvers of the EM wave propagation models are complemented by the computer tools implemented by academic centers. The examples are the program I-Prop (Technical University of Prague, Czech Republic) [3], Cindoor (University of Cantaberia, Spain), etc.

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	ACTIX Analyzer	Wireless InSite	WiSE	WinProp	I-Prop
Firm	**ACTIX An Amdocs Company**	**Remcom**	**Lucent Technologies**	**AWE Communications**	**Czech Technical University in Prague**
Frequency (GHz)	0.3/300	0.05/40	*/	>0.6	*/
Propagation models	- MW - 2.5D RT - 3D RT	- 2.5D RT - 3D RT	- 2.5D RT - 3D RT	- OS - Linear MW - Non-linear MW - D-P - 3D RT - 3D IRT	- OS - Non-linear MW
Modeled phenomenon	- Reflection - Diffraction - Absorption	- Reflection - Diffraction - Absorption - Dispersion	- Reflection - Diffraction - Absorption	- Reflection - Diffraction - Absorption	- Absorption
Parameters of materials	- Permittivity ε	- Permittivity ε - Conductivity σ	- Permittivity ε - Conductivity σ	- Permittivity ε - Conductivity σ - Attenuation L (for D-P model)	- Attenuation L
Result of the simulation	- The EM power - Delay - The angular span the rays received - Interference - The range of access points	- The EM power - Change of power in time - Delay - The angular span the rays received - Interference - The range of access points	- The EM power - Change of power in time - Delay - The range of access points	- The EM power - Delay - The angular span the rays received - Interference - The range of access points - Transmission speed	- The EM power - The range of access points
The characteristics of the codes	- Possibility of introducing the own propagation models - Data base of people and trees models - To take into account the depolarization - Dynamic simulations (of receivers mobility)	- Data base of trees models - Incorporate of phase of received rays - The application of FDTD method (only in urban environments) - Simulation of power changes in time	- Multi-layer structure models	- The applicability of the IRT model - Simulation of the impact of the environment on the system parameters - The ability to compare with the results of the measurements	- The ability to compare with the results of measurements

*No details.

Table 3. Basic characteristics of mostly used the EM wave propagation modeling computer programs.

The EM wave propagation models presented allow you to streamline the process of designing wireless networks of mobile communication systems like WLAN, Bluetooth RFhome, ZigBee, and WPAN inside buildings as well as the outdoor urban environment. Allow you to specify the most appropriate location of access points and their minimum number of required covering a given area. In the case of a large diversification of the propagation environment (e.g., shopping center) it is recommended that you use the more accurate but at the same time dealing with more time simulation based on deterministic models.

6. Planning for wireless communication networks

Planning of the wireless communication systems, for example, LAN and PAN is not simple. Committed design errors can significantly reduce its final performance. Each project is influenced by many factors, which makes the implementation of ready-made scenarios not useful and, as a result, affecting the final result. Due to the complexity of the implementation of projects, short-range wireless networks can be divided into three stages: preparation of the data to the project, the design and implementation of the project and the measurements. Each phase requires the use of an appropriate approach, since errors made in any one of them can undermine efforts in working on the project. **Figure 11** shows the proposed design algorithm [16, 17].

6.1. Data preparation for the project

Preparation of the data to the project is an important part of planning wireless networks, because the mistakes made at this stage influence the next steps to the implementation of a wireless network. At the stage of the initial project, you must obtain the following information: range of communication system, number and locations of the supported users (or devices), their mobility, and types of used applications. You need to collect and draw up the technical documentation, the design area and parameters the obstacles which prevent the propagation of electromagnetic waves. Knowledge of the infrastructure of an existing wired network will allow the use of it in a wireless network in the project as a bridge/transition to the users of different communication systems. Based on these data and the financial capacity of the client, we select the appropriate wireless network technology. Most popular solutions for WPAN is the Bluetooth system, and in the case of the WLAN, the IEEE 802.11 standard [16].

6.2. Collection and development of technical documentation

The first step in the initial stage is to collect and develop the technical documentation of the design area. On its basis in the design phase, the environment model used in simulations of the EM wave distribution power is built. You must specify the obstacles parameters properties which prevent the propagation of electromagnetic waves, such as location, geometrical shape and dimensions, and material properties (conductivity σ, permeability μ, and permittivity ε).

6.3. Define assumptions of the project

In the initial stage, we need to gather information about the range of the proposed network, estimated the number and location of users (or devices) and their mobility as well as a traffic profile. To do this, you must carry out a survey or environmental interview. In the case of a

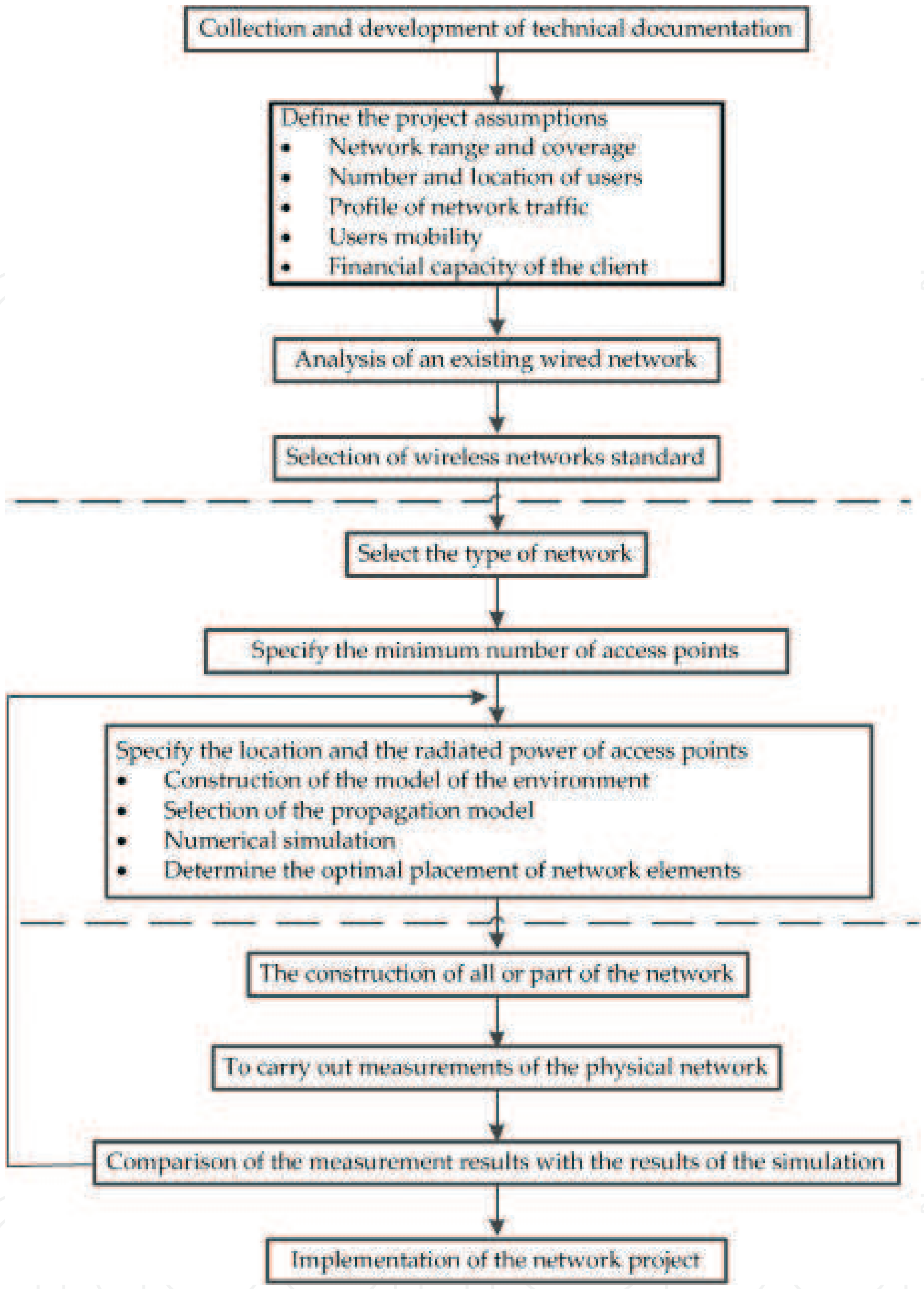

Figure 11. Design algorithm of wireless communication networks.

wireless network project such as the alarm system or multimedia communication, you should refer to the specification of a specific system. On the basis of specific requirements and expectations, you must specify the maximum number of simultaneous connections, which is to ensure the proposed network. Fixed number should be greater than the estimated number of calls occurring most of the time (e.g., by 95% of the time within 1 hour). In order to facilitate the analysis and take into account the diversity of needs of all traffic, it is divided into three categories: video a1/a2/a3-duplex services (video conferencing – MPEG4

Area	Degree of coverage [%]	Number of concurrent connections			Mobility	Communication with another network	System selection
		Video $a_1/a_2/a_3$	Audio a_4/a_5	Data a_6			
1	90	1/2/0	8/6	34	+	+	IEEE 802.11 g
2	90	0/0/0	0/2	8	–	+	Bluetooth
3	100	0/0/0	0/0	22	–	–	ZigBee

Table 4. A set of project assumptions of sample wireless communication system [17].

640 × 480 25 frames per sec)/unilateral (streaming MPEG-4, 640 × 480, 25 frames/sec)/ unilateral (streaming-MPEG 2, 720 × 576, 25 frames/sec); audio a4/a5-duplex services (voice chat-g.711)/unilateral (streaming-G. 711), and data a6-FTP, mail, Web, p2p [18]. Mobility users understand the need to move to the area covered by another cell of the network while preserving the connection. This is possible only when both access points are on the same subnet. Often it is not possible to provide coverage of the entire area or associated it with a big financial effort. Therefore, network design requires that you specify the degree of its coverage. In the situation of the area covered with a mesh wireless sensors (e.g., alarm burglar alarm or fire), 100% coverage is required. In the case of the area in which users can easily move (e.g., WLAN at the airport) you can accept less coverage, for example, 90%. It happens that the collected information is not the same throughout the area. This is due to the characteristic features of the area (e.g., conference room or the library of the University). You then need to separately specify the design intent for each of the specific areas.

Table 4 provides a set of project assumptions sample wireless system for the Bank. The project provides for the 3 areas: (1) area 1 – lobby, corridors, rooms (providing access to the network of the Bank); (2) area 2 – Conference Room (multimedia presentations setup); and (3) area 3-around doors and windows (network sensors of high security locks).

6.4. Analysis of exiting wire network

In most cases, wireless networks are designed as an extension to the wired LAN. Then you should be familiar with the topology and the capabilities of the network. It is important to specify the ability to increase her workload resulting from the join of the proposed wireless network, and the ability to support its security mechanisms (e.g., VPN network, IEEE 802.1 X authentication). Analysis of the wired network topology allows you to specify the possible spots to join the proposed network. On the basis of the initial information, we select for each of the areas of wireless technology.

7. Network design and simulation

The next step in the process of deploying a wireless network is a design phase. At this stage, on the basis of the information gathered in the initial phase of the project is created. The design phase is discussed on the example of Bluetooth and IEEE 802.11 b/g wireless systems.

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7.1. Selecting the type of network

The first step in the design phase is to select the type of network. There are two main types of network: range coverage and capacitive. Range coverage wireless network designs due to the largest coverage with the fewest number of access points. In this type of networks not optimizes to *QoS* parameters. It is assumed that users will benefit from the services of low-speed of packet transmission (e.g., barcode scanning and database query). These installations are used in warehouses or retail stores for inventory control and purchasing in real time purchases. An example of a range coverage network is a wireless sensors network of anti-theft system. You can deploy the range coverage WLAN networks in small- and medium-sized companies instead of wired Ethernet. When designing the capacitive network to ensure QoS parameters is required, that is, capacity, duration, and variation of delay as well as a bit error rate, *BER*. The sizes of the cells in the capacity networks are smaller, which means that the system must be equipped with a greater number of access points. The size of the cells is determined based on the number of users supported by a single access point. The maximum number of users that are associated with the access point is determined on the basis of the type of services to be available on the network.

7.2. Specifying the minimum number of access points

Specifying the minimum number of access points is extremely difficult. The problem is due to complications related to the precision of the estimates of the anticipated traffic generated by the users in the proposed wireless network. This, in turn, makes it difficult to estimate the impact of the number of users on the access point load, and thus the determination of areas of coverage. The Bluetooth system is designed for the implementation of broadcast audio and data. It provides a guarantee of quality of the services offered by granting higher priority connections audio relative to data transmission. Moreover a movement within pico-network is coordinated by the Master device, which eliminates the problem of collisions of packages. Therefore, to ensure the quality of the services offered on the network based on Bluetooth system comes down to minimize the probability of overloading. It is implemented by specifying the maximum number of connections the devices associated with one access point on the basis of the type of generated traffic. For this purpose, referred to in the previous stage of the types of traffic are attributed to the following the weight: audio w_4/w_5–2/1, – date w_6–1. The sum of the products of consecutive weights by the number of connections does not exceed the value of the $O_B = 7$ for one Master Bluetooth system [19]:

$$\sum_{i=4}^{6} w_i \cdot a_i \leq 7 \tag{50}$$

This value results from the specification of the Bluetooth system (7 slots).

IEEE 802.11 networks analysis is more complicated [20–22]. In the case of this type, the effective capacity decreases with each client connected. The DCF access mechanism provides equitable access to BSS. To ensure the quality of the services offered on the network based on IEEE 802.11 g comes down to minimize the probability of overloading. It is implemented by specifying the maximum number of connections the devices associated with one access point on the basis of the type of generated traffic. For this purpose, referred to in the previous stage of the types of traffic is attributed to the following weights: video $w_1/w_2/w_3$–7/3.5/10, audio w_4/w_5–2/1.5, data w_6–1. The sum of the products of consecutive weights by the number of connections does not exceed the value of the O_I = 22 for one AP of IEEE 802.11 g network:

$$\sum_{i=1}^{6} w_i \cdot a_i \leq 22 \tag{51}$$

The minimum number of devices needed to cover a given area determines the quotient of the sum of the weights by the numbers subsequent connections in that area by the maximum load of the access point. For the Bluetooth (L_B) and WLAN (L_I) systems the minimum number of access points is an expression (rounding up):

$$L_{B\,or\,I} = \frac{\sum_{i=4\ or\ 1}^{6} w_i \cdot a_i}{O_{B\ or\ I}} \tag{52}$$

8. Implementation of the project

Determination of the optimal location for the deployment of the wireless system access points is a result of the consideration of the position resulting from the numerical simulation of the EM propagation models, as well as taking into account the experimental verification, under real conditions, of the implemented project. In most cases, wireless networks are designed as an extension to the wired LAN. Typically, the access points connect to the LAN network through a combination of their Ethernet cable UTP 5e with the appropriate port of the switch. This combination allows, in addition to access to this network, extension of the existing security in wireless network on the security available in a wired network above all security protocols related to virtual private networks VPN and authentication protocols such as 802.1 X [16, 17].

The information provided has been used to design a wireless network multimedia transmission in the building C-5 Faculty of Electronics the Wroclaw University of Science and Technology (**Figure 12**).

8.1. Propagation model selection

Before start of the simulation examined, the usefulness of various propagation models available in the ACTIX ANALYZER computer code [6], in order to select the most suitable for the present environment, compares the results of the propagation models: non-linear multi-wall, MW (COST 231), 2.5D, and 3D models.

Figure 12 shows the model of the ground floor of the building C-5 of the selected location for the access point, and **Figure 13a–c** – the EM radio wave propagation simulation results using different propagation models for the transmitted power − 10 dBm, and frequency - 2.45 GHz.

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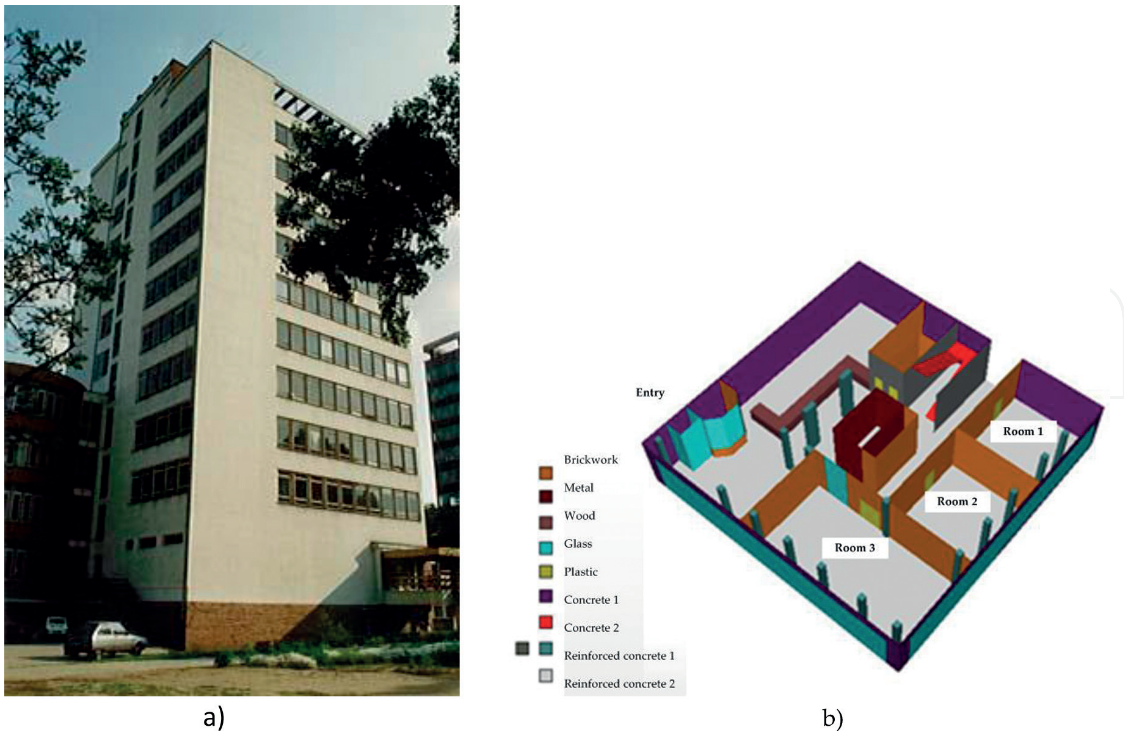

Figure 12. Photo of the Wroclaw University of Science and Technology building C-5 (a) and the numerical model of the ground floor with use of defined construction materials an example (b).

Simulations were performed on a computer with an AMD Athlon processor, XP 2000+, and 768 MB of RAM. The duration of the simulation depends on the specific case and propagation model parameters. With the same propagation models parameters settings, the shortest time 1 s of simulation was obtained for MW model, 7 minutes and 14 seconds for the 2.5 RT model, and 16 minutes and 33 seconds for the 3D RT model. The ratio between the durations of the simulation the tested models also depends on the specific example. In the present environment MW model due to metal elevator shaft cannot be used, which is an obstacle for electromagnetic wave (**Figure 13**). In this case, the direct rays of the electromagnetic waves in the MW model are shielded. Comparison of simulation results 2.5D and 3D RT models has shown that theoretically worse 2.5D RT model almost in no way inferior the 3D version, but the computation time is two times longer. In highly complex environments with a large number of obstacles, the 2.5 RT model can be too big simplification, then you must apply the 3D model.

8.2. Deployment of network devices

A number of simulation based on 2.5D and 3D RT models, the objective of which was to find the optimal deployment of WLAN AP points in the room 1, and the Bluetooth access points in rooms 2 and 3 implementing the project. The 2.5D RT model used in power distribution simulations on the ground floor. On the basis of simulation, it was found that for the area on one floor you must put only one AP of 10 dBm radiated power, mounted at a height of 3 m. The WLAN AP locations on the ground floor and the simulation results the EM wave power distribution is shown in **Figure 14**.

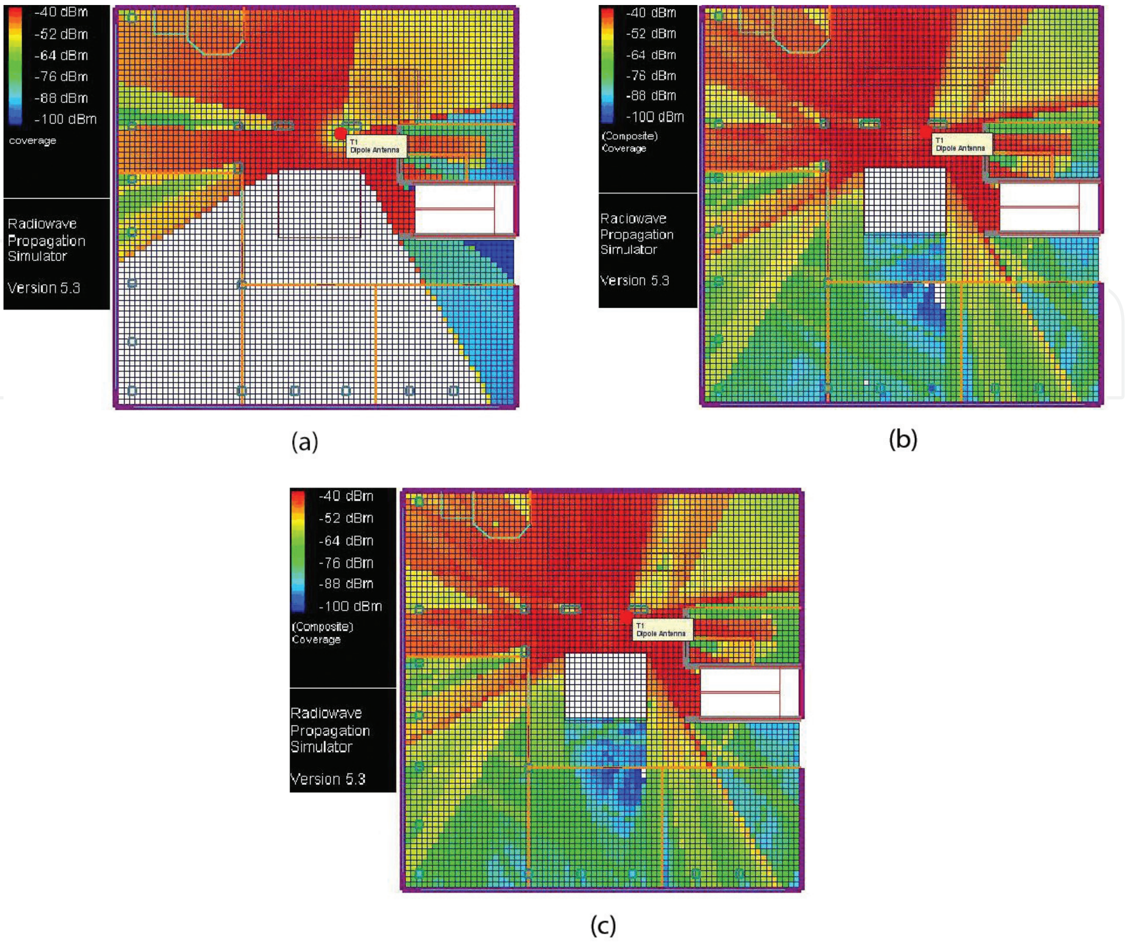

Figure 13. The simulation results of signal power distribution in a MW model (a), the 2.5 D RT model (b), and the 3D RT model (c) for radiated power 10 dBm at f = 2.45 GHz on the ground floor of building C-5 of WRUoS&T.

You have selected the points where the power values shown in **Table 5** were read.

Empty areas in the grid of receivers (e.g., inside an elevator shaft) indicate areas where signal strength is lower than the established system sensitivity (−94 dBm for IEEE 802.11 g). Model of a lift shaft turned out to be a screen for electromagnetic waves. Analysis of the simulation results showed that the AP does not cover the whole floor area. AP coverage areas on adjacent floors enough overlap to provide users with the ability to change the AP without losing the connection to the network. Analysis of the results of the simulation of power distribution showed that the vast majority of the coverage area, it is possible to obtain the maximum transmission speed of 54 MB/s.

Bluetooth network simulations were carried out for the room 3 (lecture halls on the ground floor). Assume that the master devices are PCs placed on desks lecture halls at a height of 1 m above the floor. The Bluetooth access point locations in the room 1, on the ground floor, and the simulation results of the EM wave power distribution are shown in **Figure 14b**. The power values selected read at points are shown in **Table 5**. Simulations have shown that full coverage has been achieved already at the radiated power 4 dBm of access points (class 2). Pico networks areas overlap themselves which allows you to combine them to form a distributed

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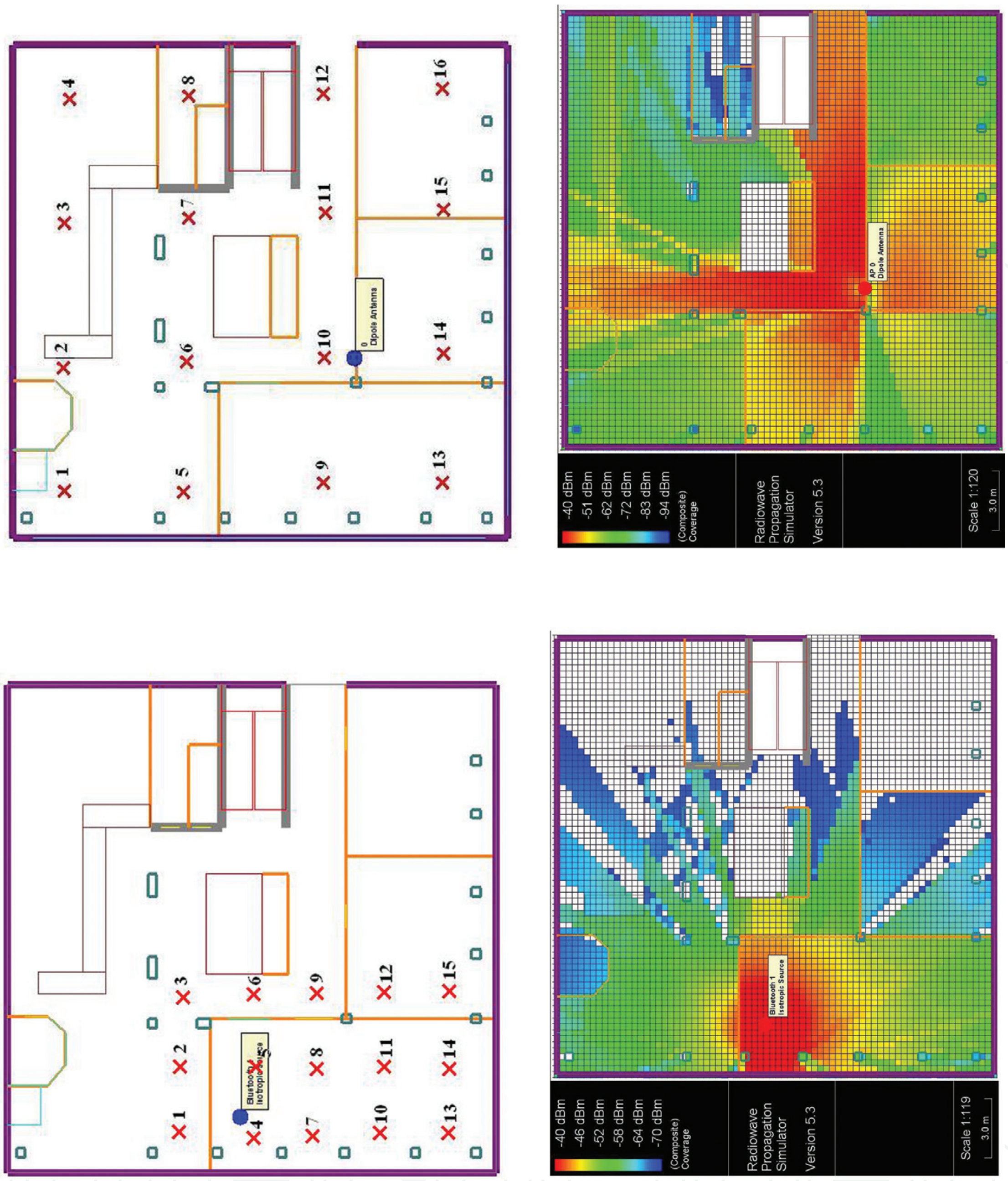

Figure 14. Distribution of AP IEEE 802.11 g (a), the simulation results of EM wave power distribution (b), the arrangement of the master point of Bluetooth system (c), and the simulation results for the room 3 on the ground floor of building C-5.

network, which will consist of a device with 3th pico network. Because the area of these networks covers part of the corridor in front of the entrance to each of the rooms, it is possible to move users between meeting rooms without losing the connection.

8.3. Calculation of the interference impact

Selected Bluetooth and IEEE 802.11 g systems work in this same frequency 2.4 GHz band ISM (*Industry Scientific Medicine*). In addition, in IEEE 802.11 g are the only three non-overlapping

Parameter		Value	Attention
RL	Range of elevation (°)	−90/90	The full range
	Angular resolution in elevation (°)	1	
	Azimuth angle range (°)	0/360	The full range
	Angular resolution in azimuth (°)	1	
	Maximum distance between the rays (m)	0.1	
Maximum number of reflections		2	
Maximum number of penetration		2	
Maximum number of diffraction		1	
Minimum signal level (dBm)		−94	IEEE 802.11 g
		−70	Bluetooth
Maximum number of rays on the route of the transmitter-receiver		4	Negligible impact of the rest of the rays
Frequency (GHz)		2.45	
Transmitting antenna power gain (dBi)		2.2	Half-wave dipole
Receiving antenna power gain (dBi)		0	Isotropic antenna
Suspended height of receiving/transmitting antennas (m)		1/3	
Size of the receivers grid sets (m)		0.3	

Table 5. The2.5D and 3D RT propagation models parameters applied in the simulation.

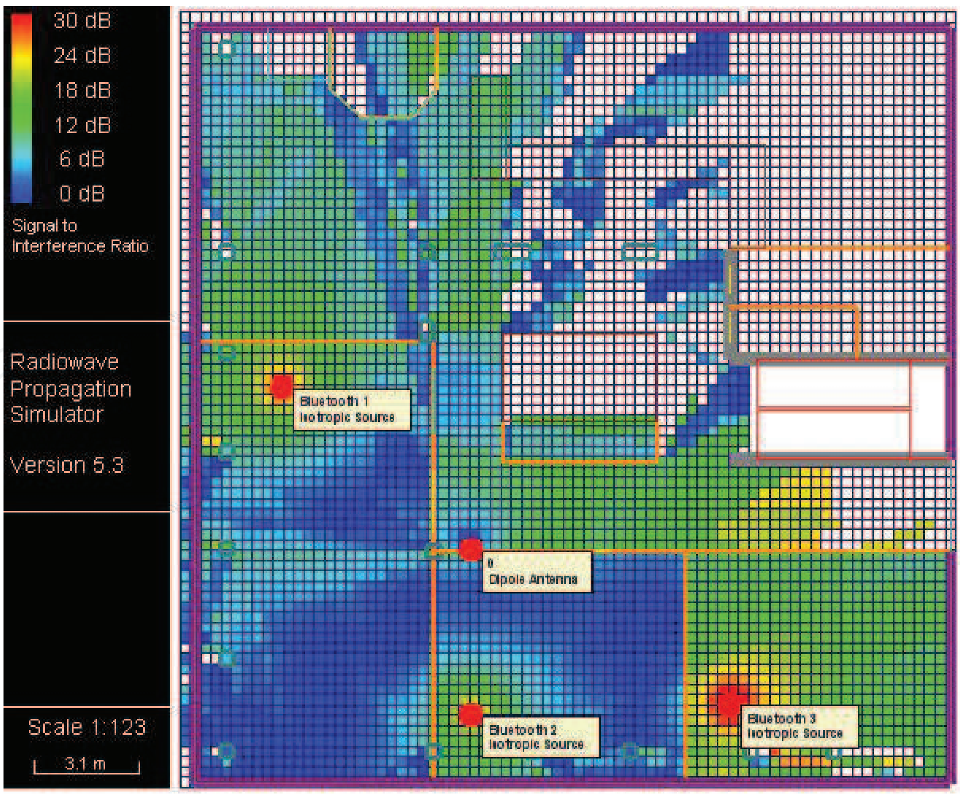

Figure 15. Levels of interference between Bluetooth and IEEE 802.11 g systems on the ground floor of the C-5 building.

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channels. Therefore, in order to evaluate the possibility of the coexistence of Bluetooth and IEEE 802.11 g systems, and the impact of inter-system interference in both systems, a number of simulations were carried out. For 10 WLAN AP in the network, each frequency channel repeats at least three times. For one AP per each floor on the same frequency channels, AP will work every 3rd floor. The ACTIX ANALYZER program allows you to estimate the level of interference on a given area. Selected is the dominant transmitter and then calculated the ratio of the power of its signal to the power of the signals of the other transmitters. The result is expressed in dB. The simulations allowed said there are no significant interference inside the WLAN system for room one.

Interference between Bluetooth and IEEE 802.11 g systems can affect the work of the two systems. **Figure 15** shows the interference between AP (*EIRP* = 10 dBm) located on the ground floor and three Bluetooth master devices (*EIRP* = 4 dBm) forming 3 piconets in the halls 1, 2, and 3.

The analysis of the results indicates a strong interference signal, above all within the hall 2 and 3. In view of the above, the project should examine methods that co-exist in both systems at the same time and space.

8.4. Impact of humans in the area of Bluetooth and WLAN systems operation

The ACTIX Analyzer program allows you to simulate taking into account the impact of the people on the EM wave propagation phenomenon. To do this, in the propagation model of the environment are inserted the human models (**Figure 16a**) recognized as the additional obstacles for the EM waves. In ACTIX Analyzer, it is possible to scale the standard human model in order to obtain models representing people of different growth. The man is a complicated living organism and it is difficult to simulate its effects on electromagnetic field. However, studies have shown that the best substance simulating human tissue (a large generalization) is a solution of water with salt in varying degrees of saturation depending on the conditions in question. In the project to simulate human tissue, the solution about the contents of the 4 gram NaCl per liter of water has been chosen. The properties of the substance at frequency 2.4 GHz are $\varepsilon' = 77$ and $\varepsilon'' = 13$ ($\varepsilon = 77\text{-}j13$) [14]. **Figure 16b** shows the arrangement of a dozen models of people on the ground level of building C-5 to simulate their effects on the AP IEEE 802.11 g (area 1) and the Bluetooth master device in the areas 2 and 3. **Figure 16c** shows the results of the simulation taking into account and without taking into account the impact of people on the network coverage in the area 1 with the active AP IEEE 802.11 g networks on the ground floor of the C-5. The AP parameters are set as in previous simulations. The analysis of the results showed that the presence of people on the route of the transmitter-receiver can significantly degrade received power. In order to reduce the impact of humans on the power level of the received signal, install access points so that the route of the transceiver as little as possible was divided by areas with a high concentration of people.

Figure 16d shows the results of the simulation, taking into account the impact of people on the network coverage in the area 3 with the active Master device in the Bluetooth system # 3. The analysis of the results shows that the people have a strong effect on the propagation of the signal in the pico-network. In the case of a large number of people in the room radiated power

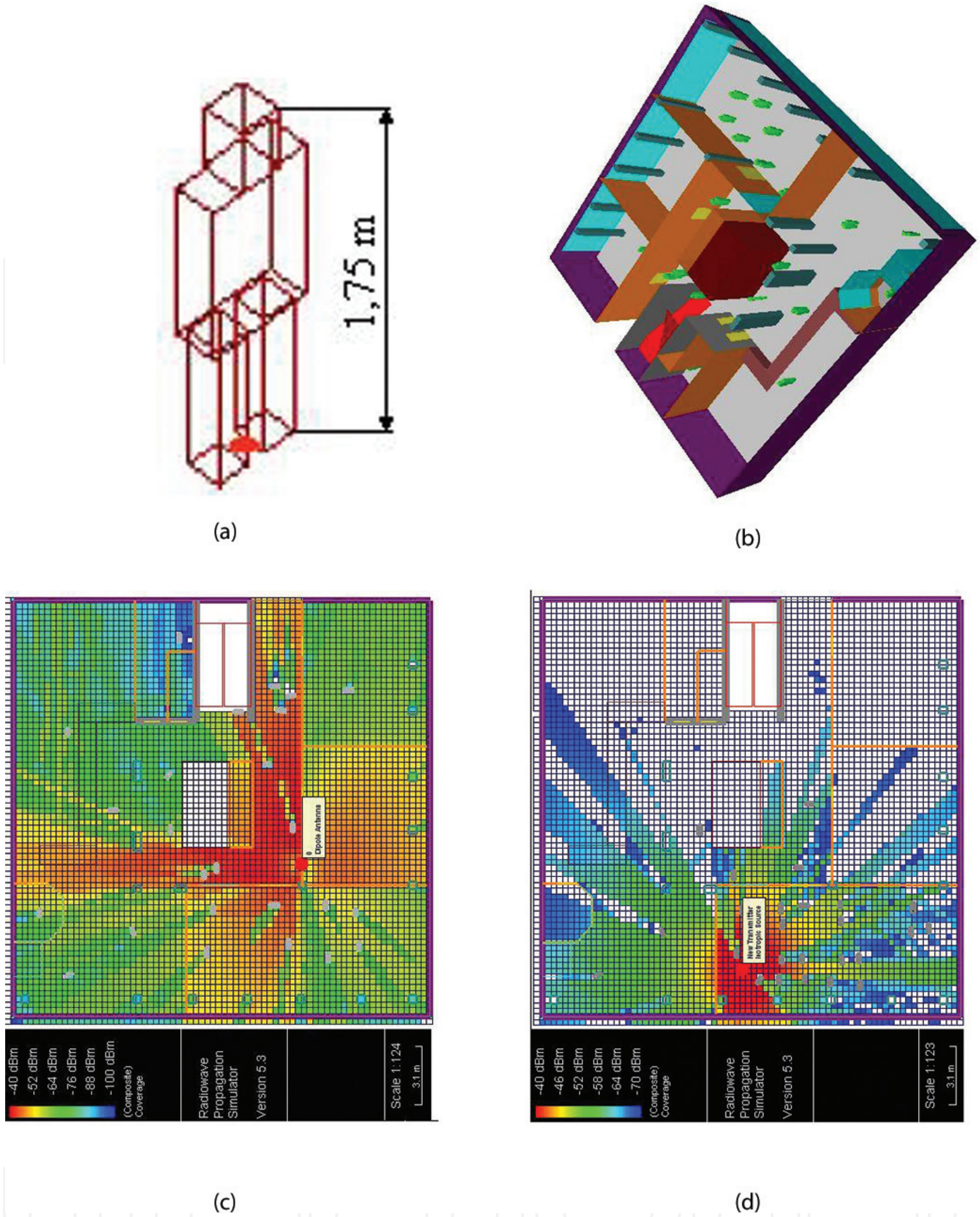

Figure 16. The deployment of several human models (a) on the ground floor (b) of the C-5 to simulate their effect on the extent of IEEE 802.11 g (c) and Bluetooth networks (d).

of 4 dBm of master is insufficient to cover the entire area (room 3). Therefore, rooms 2 and 3 are applied the master of first class-Bluetooth system with a higher maximum radiated power.

9. Conclusion

The EM wave propagation models presented allow you to streamline the process of designing wireless networks of mobile communication systems like WLAN, Bluetooth RFhome, ZigBee, and WPAN inside buildings as well as the outdoor urban environment. Allow you to specify the most appropriate location of access points and their minimum number of required covering a given area. In the case of a large diversification of the propagation environment (e.g., shopping center) it is recommended that you use the more accurate but at the same time dealing with more time simulation based on deterministic models.

This chapter presents the concepts, methods, and algorithms that were used to design a wireless system for indoor as well as outdoor mobile communication systems. The project supported simulations carried out using ACTIX Analyzer computer code. Indoor propagation environment is very complex (reflection, diffraction, refraction, etc.) while maintaining high accuracy digital model was built. In most cases, reduce the applied version of computer code that are not influenced significantly on the simulation results. A very interesting option of simulation is possibility taking into account of the impact of humans on the propagation of the signal. Typically, wireless networks are used in places with a high concentration of people (e.g., airports, universities, hotels, libraries, etc.) that is why skipping in simulations of the impact people can turn out to be a very serious mistake.

Designed a network allows users to wireless access in the building of the C-5 to the Internet and Intranet networks of the Wroclaw University of Science and Technology based on the IEEE 802.11g standard. It also allows the implementation of data transfer and audio and video connections with the guarantee of quality of offered services. For conference and lecture-seminar rooms, a separate network of Bluetooth system to ensure that the combination of elements of the multimedia presentations setups is designed. Part of the position includes a host computer, multimedia projectors, cameras, sound system, printers, monitors, wireless microphones, and listeners equipment (e.g., laptops, palmtops, and mobile phones).

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