A SITE-SPECIFIC MODEL FOR PROPAGATION PREDICTION IN INDOOR WIRELESS COMMUNICATIONS

Model rasprostiranja elektromagnetskog signala u bežičnim komunikacijama specifičnog prostora

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UDK 004.72 : 654.16

Abstract

Indoor wireless communications transport the vast information capacity using millimetre wave frequency band. Accurate characterization of the propagation channel is an important requirement for design and implementation of a local area network inside buildings. A tool for prediction of electromagnetic filed strength in indoor communications has been presented. A 3D ray tracing model is developed based on accurate electromagnetic theories that incorporate polarization characteristics. Propagation mechanisms for reflection and transmission are included in the model. The developed software enables prediction of the signal strength at any receiving point of the specific indoor environment. This deterministic model is compared with Motley-Keenan model. The obtained results from both models are compared with measured data. The ray tracing model is used with measured electromagnetic parameters. Non-destructive free space measurement method for the measurement of complex dielectric constant of the walls and other obstacles is used. The accuracy of the model enables the usage of it for characterization of a typical indoor environment for the performance evaluation of wireless local area network.

Keywords: indoor propagation, signal strength prediction, ray tracing, Motley-Keenan method, complex dielectric constant.

Sažetak

Bežične komunikacije u zatvorenom prostoru moraju omogućiti prijenos velikih količina informacije. Važna je točna karakterizacija prijenosnog kanala pri dizajniranju i instalaciji lokalnih mreža u zgradama. U ovom radu prezentira se alat za predviđanje snage elektromagnetskog polja u takvim komunikacijskim mrežama. Razvijen je trodimenzionalni model slijeđenja zrake zasnovan na elektromagnetskoj teoriji, koja uključuje polarizacijske karakteristike. U model su uključeni propagacijski mehanizmi refleksije i prijenosa. Razvijeni software daje predviđenu vrijednost snage

ISSN 0469-6255 (202-212)

signala u bilo kojoj točki specificiranog prostora. Ovaj deterministički model se uspoređuje s empirijskim Motley-Keenanovim modelom. Rezultati dobiveni od oba modela uspoređeni su s izmjerenim podacima. Model slijeđenja zrake upotrijebljen je za specifični prostor s izmjerenim elektromagnetskim parametrima. Korištena je nedestruktivna metoda za mjerenje kompleksne dielektrične konstante zidova. Točnost modela omogućuje njegovu uporabu za vrednovanje bežične lokalne mreže tipičnoga zatvorenog prostora.

Ključne riječi: rasprostiranje u zatvorenom prostoru, predviđanje snage signala, slijeđenje zrake, Motley-Keenanova metoda, kompleksna dielektrična konstanta.

INTRODUCTION / *Uvod*

The design of personal communication networks in buildings required detailed study of propagation properties of indoor communication channels. The complex environment encountered in indoor wireless communication makes it very difficult to obtain exact field strength distribution. Signals are reflected from the walls, the floor, and the ceiling, and human movement producing distorted versions of transmitted signals at the receiver. This phenomenon is known as multipath fading. The performance of the wireless communications inside building will be seriously degraded by multipath fading. Signal strength in any point of the indoor environment is needed for quality design of local area network. The direct measurements provide accurate propagation characteristics, but these are very expensive and time consuming. It is thus necessary to develop an efficient and reliable model to facilitate the study of putting transmitters in specific places so to achive good coverage by signal strength. It is much easier to develop computer models than to make measurement for every different transmitter position for studying its optimum position. By using electromagnetic modelling it is possible to develop a reliable on-site propagation model for predicting path loss, signal strength at any arbitrary receiving point and delay spread. These parameters predicted by the developed propagation model give very valuable information for designing indoor wireless communication system. On the same way the optimum access point locations can be obtained to ensure the capability of high speed data transmission.

In this work the problems and limitations of site-specific indoor electromagnetic propagation have been examined. It has been developed a variety of theoretically based models to predict signal propagation in various frequency bands as wall as for various types of environment [1]. These models can be categorized into two types: statistical models [2], [3], and deterministic models [4], [5]. The approach of this paper can be categorized as deterministic one. In our case we use 3D ray tracing method to determine the signal strength at predefined receiving points.

The ray tracing technique is based on a simplified layout of a building providing relatively simple approximate solution for indoor propagation. This method has been proven to be suitable for radio propagation modelling in indoor environments. It enables fading and delay characteristics of multipath rays. Two general approaches in calculation the paths in ray tracing method are known.

The first approach is based on the optical images of the transmitters and receivers [2]. The reflections of the transmitted signal by the walls and other objects are presented as the images of the transmitter. These images help to find paths to the receiver. The insertion between the given object and the line from the image location of the receiver determines the point of reflection. Considering primary images as sources, secondary images can be created to determine second order reflection paths. In the similar way multiple reflection paths can be determined. It is very difficult to determine image points of all reflections of transmitted signal. Therefore, it is enough accurate to consider a few dominant reflections.

The second approach uses ray shooting technique [5], where the progress of each ray is traced through the environment. At the end of its path, ray intersects the receiving antenna and contributes to the total signal to the receiver. It is impossible to trace infinite number of rays, so it is not sure that every path between the transmitter and the receiver is considered. Many researchers showed that ray tracing technique is very promising for indoor radio propagation modelling. However, some unresolved problems still exists.

Some of the existing simulation tools lack enough accuracy, because of a lot of coarse assumptions. Also, some haven't ability to model polarization characteristics. For instance in [6] , it is assumed that rays hit the floor or ceiling in TM mod, while rays that hit the walls are in TE mod. Next assumptions take the same dielectric constant and loss tangent for all walls regardless of material. In [ ] the transmission loss assumed to be 2 dB for each obstacle and for the each ray incident angle. The influence of the furniture

ISSN 0469-6255 (202-212)

is usually omitted. In existing ray tracing algorithms walls, ceilings and floors are, usually, modelled as homogeneous dielectric slabs. Inhomogeneities inside the material may have a significant effect on signal coverage in indoor environments [ ].

A deterministic model based on the ray tracing algorithm with full propagation parameters has been proposed in this article. Three dimensional ray tracing model is developed based on the accurate electromagnetic theories, that incorporates polarization characteristics. Predicted and measured electromagnetic parameters are used in the ray tracing algorithm. A non-destructive free space method for complex dielectric constant measurement is, also, presented. Through measurement of the reflection and transmission coefficients the complex dielectric constant is obtained. The model is applied to real indoor environment in which the measurements are carried out in WLAN (Wireless Local Area) frequency band of 2.4 GHz. The ray tracing results with predicted and measured electromagnetic parameters are compared with measured ones. A method based on data of empirical origin is, also, used for propagation characteristics prediction. The Motley-Keenan method is chosen, because it includes constructional obstacles, so it approaches to the deterministic methods. These results are compared with the results obtained by ray tracing model for its validating. The appropriate software for ray tracing algorithm is developed.

RAY TRACING FOR RADIO PROPAGATION MODELLING / *Modeliranje radiopropagacije slijeđenjem zrake*

The approach in this work is based on the principles of geometrical optics, where an electromagnetic wave is considered as a ray [6]. Every ray is determined by its origin and direction. The starting point of each ray is determined by transmitter position, while the directional vector determines the direction of electromagnetic wave propagation. This model assumes the electromagnetic wave as a particle that passes different paths from the transmitter to the receiving point. On its way the ray meets different obstacles and it can be reflected, transmitted refracted or scattered. All these mechanisms don't contribute equally to the total field strength at the receiving point. Some of these contributions to total field strength can be neglected. Transmitted ray through obstacle (wall) represents new source of electromagnetic radiation. The paths between transmitter and receiver can be classified as direct path and paths with one and more reflections. The rays with more reflections on its way to the receiver have smaller contribution to the total power at the input to the receiver. The contribution to the total receiving power for the rays with three or more reflections with operating frequencies above 2 GHz is negligible, what is, also, our assumption.

The first step in the development of 3D ray tracing model is determination of transmitter (T_x) receiver (R_x) positions. The receiver needs to change its position. This model assumes direct ray and the rays with one and two reflections. Next step includes development of the data base with geometrical and constructional data of the specific environment. For the lengths of each ray we need the points of reflections (transmissions).

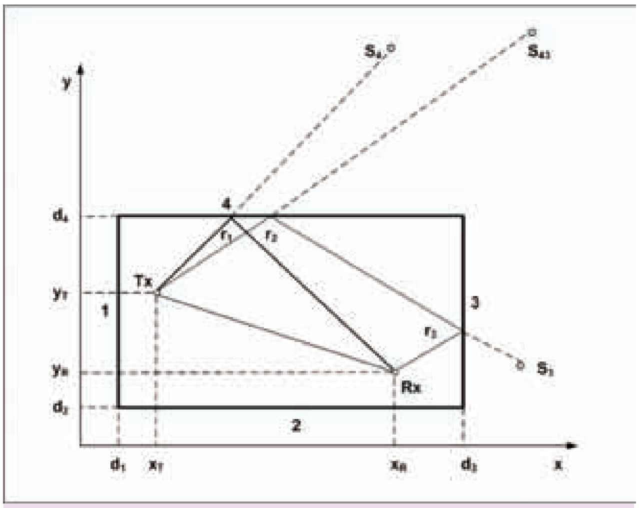

Figure 1. Determination of reflection points

Slika 1. Utvrđivanje točaka refleksije

Using the general principles of geometrical optics [6] and repeating reflections of receiver antenna across obstacles (walls in fig. 1), the coordinates of the receiving points can be found. According to the fig. 1 one trace path from transmitter to the receiver is reflecting from the walls 4 and 3, while another one is reflecting only from the wall 4. To find coordinates of the reflection point's r_2 and r_3 we need to find coordinates of the images S_{43} and S_3. The same is for the reflection point r_1, where the coordinates of the image S_4 need to be found. First, S_4 is obtained by reflecting coordinates of the receiver (x_R, y_R, z_R) across the wall 4, so its coordinates are $(x_R, 2d_4 - y_R, z_R)$. The coordinates of the reflection point r_1 is found to be insertion point of the line T_x - S_4 with wall 4. On the similar way reflection points r_2 and r_3 can be found. The coordinates of the image S_3 $(2d_3 - x_R, y_R, z_R)$ are obtained by reflecting the coordinates of the receiver point across the wall 3. Similarly the coordinates of the image S_{43} $(2d_3 - x_R, 2d_4 - y_R, z_R)$ are obtained by reflecting the coordinates of

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image S_3 across wall 4. Finally, the coordinates of the reflection point r_2 are located at insertion of line T_x-S_{43} and wall 4, while the coordinates of the reflection point r_3 are located at insertion of line r_2-S_3 and wall 3. Now it is simple to find total length of the rays with one and two reflections.

The total power of the received signal for the direct ray, N rays with one reflection and M rays for two reflections can be expressed as

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \left| \frac{1}{d_0} + \sum_{i=1}^{N} \frac{\Gamma_i}{d_i} e^{-j\Delta\varphi_i} + \sum_{k=1}^{M} \frac{\Gamma_{1k}\Gamma_{2k}}{d_k} e^{-j\Delta\varphi_k} \right|^2, \quad (1)$$

where P_t is the transmitter power, G_t and G_r are transmitter and receiver antenna gains respectively, d_0 is the length of the direct ray, d_i and d_k are lengths of the rays with one and two reflections respectively, Γ_i, Γ_{1k} and Γ_{2k} are reflection coefficients of the rays with one and two reflections respectively. Phase differences between direct and reflected rays

$$\Delta\varphi_i = \frac{2\pi}{\lambda}\Delta l_i \qquad \Delta\varphi_k = \frac{2\pi}{\lambda}\Delta l_k, \quad (2)$$

where Δl_i and Δl_k are length differences between direct path and the reflected paths.

Reflection and transmission coefficients are calculated according to the same ray optic theory of propagation. In our case we assumed $\mu = \mu_0$, so according the Fresnel formula [7] for horizontal and vertical polarization reflection coefficients are

$$\Gamma_h = \frac{\cos\theta_i - \sqrt{\varepsilon_r' - \sin^2\theta_i}}{\cos\theta_i + \sqrt{\varepsilon_r' - \sin^2\theta_i}} \quad (3)$$

and

$$\Gamma_v = \frac{-\varepsilon_r'\cos\theta_i + \sqrt{\varepsilon_r' - \sin^2\theta_i}}{\varepsilon_r'\cos\theta_i + \sqrt{\varepsilon_r' - \sin^2\theta_i}}. \quad (4)$$

θ_i = incident angle

The complex permittivity ε_r' is given by

$$\varepsilon_r' = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0} \cong \varepsilon_r - j60\sigma\lambda, \quad (5)$$

where σ is the conductivity of the reflecting surface, and λ is the wavelength of the incident ray [7].

The roughness of the reflecting surface is included in reflection coefficients by Fresnel equation

$$\Gamma_s = \Gamma e^{-j\frac{4\pi\Delta h\cos\theta_i}{\lambda}} \quad (6)$$

where Δh is the standard deviation of surface height variation.

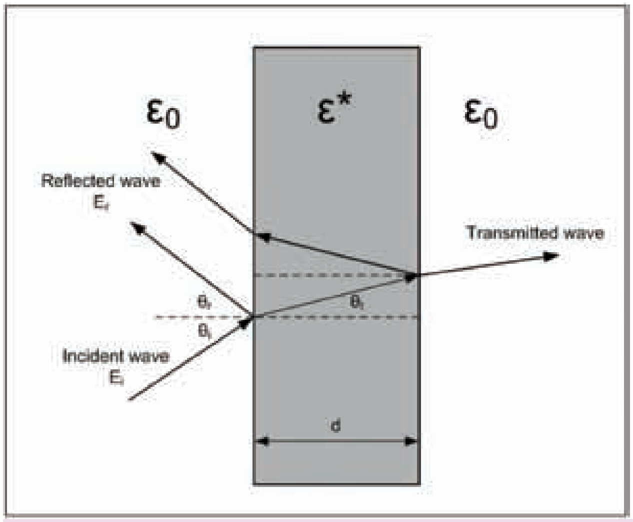

Figure 2. Reflection and transmission mechanism in slab

Slika 2. Mehanizmi refleksije i prijenosa u zidu

The Fresnel expressions are suitable to be used in indoor environments to model reflection mechanism. This model doesn't include width of obstacles, like slab model in Fig. 2. The wave transmitted through the first layer of the slab is reflected more times from both edges inside the slab and each ray reflected from either side of the slab causes another transmission to the air. Therefore, each incident ray results in multiple reflected and transmitted rays. The strength of these rays are function of the electromagnetic properties and thickness of the slab as well as the frequency and incident angle. Applying the Fresnel equation to the geometrical optics as in the Fig. 2 reflection and transmission coefficients can be obtained [7]:

$$\Gamma = \frac{E_r}{E_i} = \frac{1 - e^{-2\gamma d/\cos\theta_i}}{1 - \Gamma_0^2 e^{-2\gamma d/\cos\theta_i}}\Gamma_0 \quad (7)$$

Γ_0 = reflection coefficient for the first reflection according Fresnel equation for vertical or horizontal polarization.

γ is the propagation constant expressed as

$$\gamma = j\omega\sqrt{\varepsilon_r'\mu_0} \quad (8)$$

Complex dielectric constant ε_r' can be expressed in terms of the tangens of loss angle:

$$\varepsilon_r' = \varepsilon_r(1 - j\tan\delta) \quad (9)$$

According to the relation between reflection and trasmission coefficients: $T_0 = 1 + \Gamma_0$, the transmission coefficient is expressed by equation:

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$$T = \frac{E_t}{E_i} = \frac{\left(1-\Gamma_0^2\right)e^{-\gamma d/\cos\theta_i}}{1-\Gamma_0^2 e^{-\gamma d/\cos\theta_i}} \qquad (10)$$

The reflection and transmission coefficients depend on frequency, polarization of incident wave, incident angle, width of the obstacle (wall), and dielectric constant. Dielectric constant of composite materials as walls in the buildings, can be obtained by the measurement of the reflection coefficient as it is described in [8].

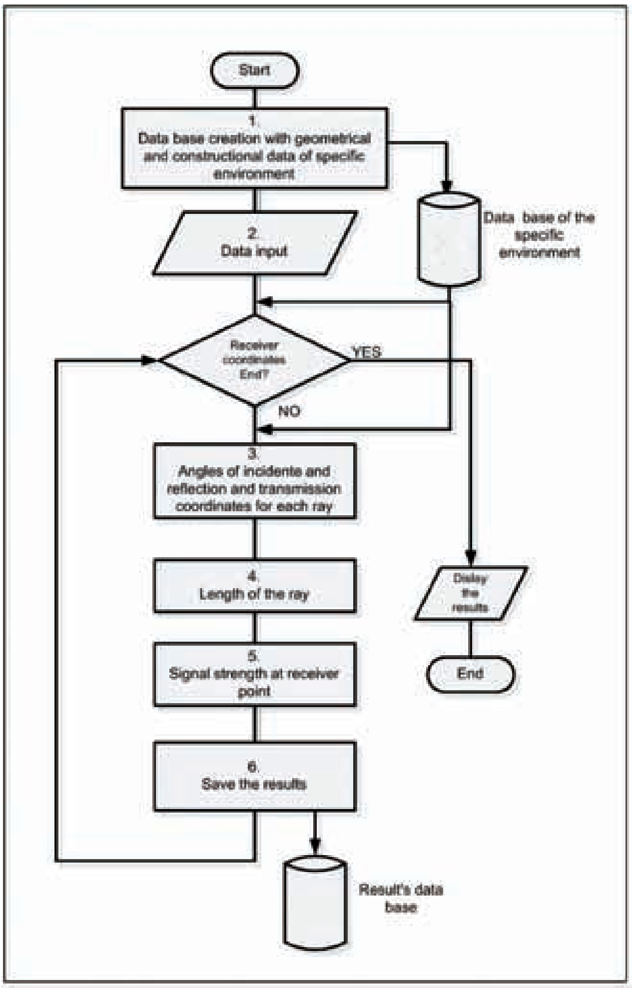

Figure 3. Algorithm for ray tracing model

Slika 3. Algoritam modela slijeđenja zrake

Appropriate software is developed for signal strength calculation at any receiving point of specific indoor environment. The main steps of the ray tracing algorithm are presented in the fig. 3. In the first step the data base is created with geometrical data (coordinates of significant points) and appropriate values of relative dielectric constant. The variable data, like frequency, power of the transmitter and antenna characteristics, are entered in the second step. In the next step each receiver point is determined and reflection points are calculated for the each ray. The total length of each ray is calculated in the strep four. The signal strength at each receiving point is calculated next, and results are saved in the appropriate file. The user interface of the ray tracing software with the results obtained for transmitter-receiver separation is shown in the fig.4.

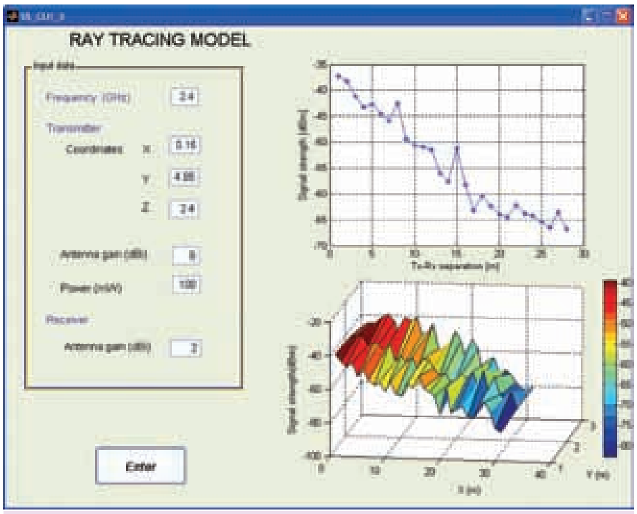

Figure 4. User interface and graphical representation of the results

Slika 4. Korisničko sučelje i grafička prezentacija rezultata

IMPLEMENTATION OF THE RAY TRACING ALGORITHM / *Primjena algoritma slijeđenja zrake*

The second floor of Dubrovnik University building is selected as test environment for the ray tracing model presented in previous chapter (Fig. 5). The area under consideration includes the corridor and offices on both sides of the corridor. The coordinate axes are visible in the fig. 5. The environment under consideration is bordered by points ABCD (fig. 5) and its area is 34x13 = 442 m^2. The height of the ceiling is 2.4 m. The width of the corridor is 3 m, while the area of the offices is 4.5x5m. The ceiling is made of concrete and floor is covered by stone plates in the corridor, and the offices floors are covered by parquet. The walls that separate the offices are made of some composite construction material, while the doors are made of wood. As it is shown in the fig. 5, measurement setup consists of access points transmitted at 2.4 GHz that are located at three locations (AP1, AP2 and AP3) and 28 receiving points as it can be seen in the fig. 5. Transmitters are Cisco Aironet 1100 that supports 802.11g standard with

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data rates up to 54 Mbps. Locations (coordinates) of the access points are shown in the Table 1. The each WLAN access point was operating on the 4th channel at 2.427 GHz (100mW) with omni-directional antenna (gain 8 dBi).

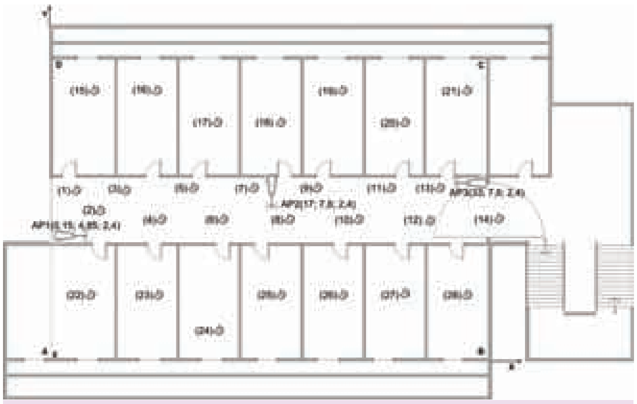

Figure 5. Plan of the University buliding second floor

Slika 5. Tlocrt drugog kata sveučilišne zgrade

The signal strength measurements were made by laptop computer with PCMCIA wireless card positioned 1.2 m above the floor. There were made three measurements for each receiver location and mean value was saved with location coordinates.

Table 1. Coordinates of the access points

Table 1. Koordinate pristupnih točaka

Access point	x	y	z
AP1	0,15	4,85	2,4
AP2	17,0	7,6	2,4
AP3	33,0	7,6	2,4

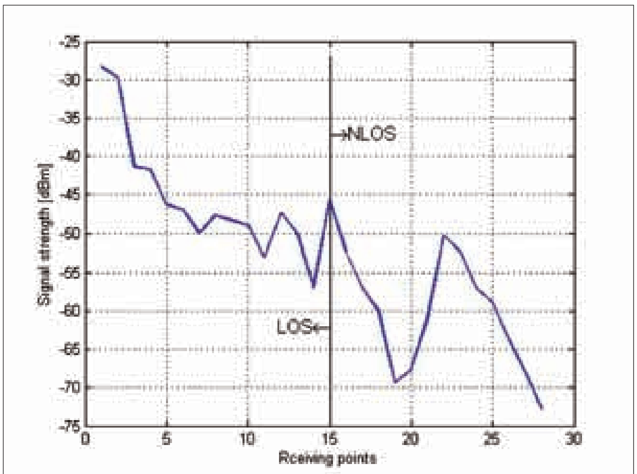

Figure 6. Signal propagation for the access point AP1

Slika 6. Rasprostiranje signala za pristupnu točku AP1

The propagation of electromagnetic signal is presented by the figures 6 to 8 for the three access points. The first 14 receiving points are in the corridor i.e. in line of sight (LOS) area, while other receiving points are out of the area with the line of sight (NLOS). Signal strength in the area of LOS has predictable behavior, while in the offices that is full with different furniture, behavior of signal propagation is very difficult to predict.

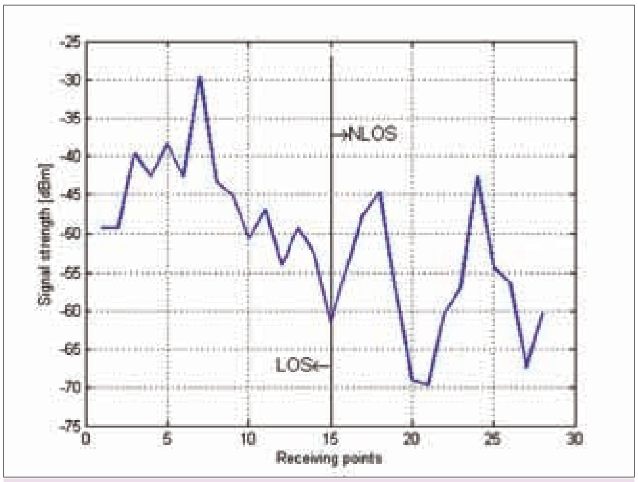

Figure 7. Signal propagation for the access point AP2

Slika 7. Rasprostiranje sigala za pristupnu točku AP2

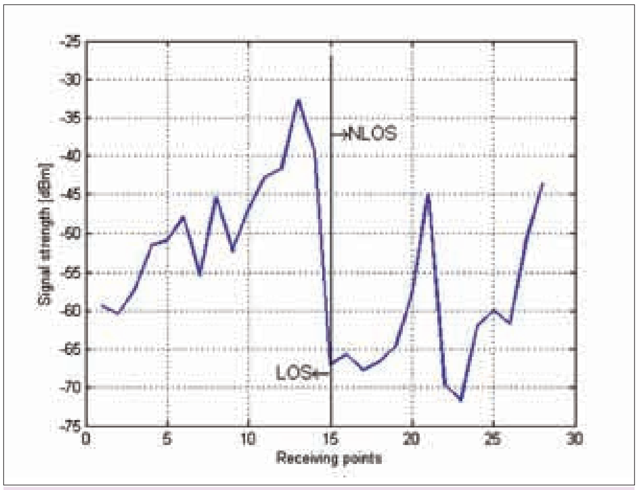

Figure 8. Signal propagation for the access point AP3

Slika 8. Rasprostiranje signala za pristupnu točku AP3

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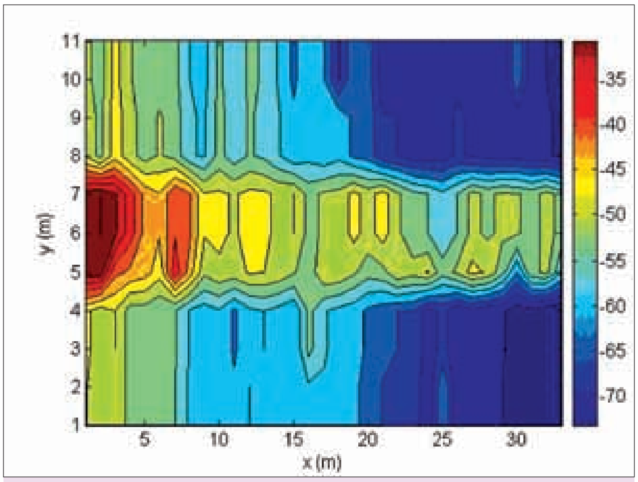

Figure 9. Contour map of the measured receiver power strength for access point AP1

Slika 9. Konturni dijagram izmjerene snage prijama za pristupnu točku AP1

The coverage with signal strength is the best presented by the contour map as it is in the fig. 9 for the acces point AP1. The units on colorbar are dBms.

The multi-ray model described by the equation (1) is used for the simulation of the signal propagation in the environment presented above. In our case we use direct ray and two additional rays with one and two reflections as it illustrates fig. 10 for the horizontal and vertical plane. The following assumptions are introduced:

- The rays with more than two reflections are not taken into account since their contribution to the total received power is insignificant for the signal frequency of interest.
- The diffraction phenomenon at the frequency above 2 GHz is almost negligible.
- There is no significant contribution to total received power produced by scattering caused by the non-uniformities of the surface materials.
- There is no need to take atmospheric propagation losses since in indoor environments the attenuation is very small (0.00116 dB/m).
- The perpendicular reflection coefficient is used for the rays reflected from the vertical walls, while the parallel reflection coefficient is used for the rays reflected from the ceiling and floor surfaces.

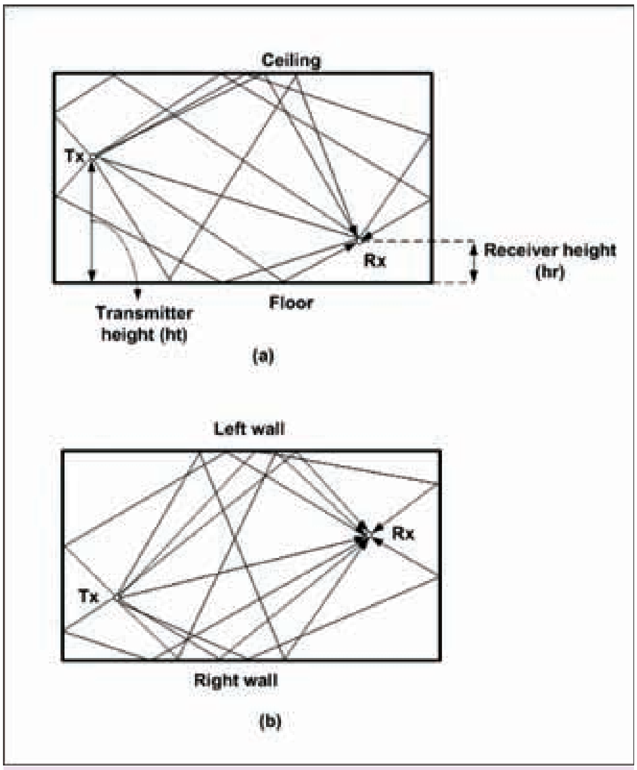

Figure 10. Propagation geometry, paths of the chosen rays: a) vertical plane, b) horizontal plane

Slika 10. Putanje odabranih zraka: a) u vertikalnoj ravnini, b) u horizontalnoj ravnini

The dielectric constant of the main materials is obtained by the measurement described in [8], as it has been already mentioned in the preceding chapter. These values are shown in the Table 2 along with values of the material condutivity.

Table 2. The electrical properties of material

Tablica 2. Električke karakteristike materijala

Material	Dielectric constant (ε_r)	Conductivity (S/m)
Concrete	6.8	0.005
Composite material of the walls	3.8	0.005
Wood	2	$0.4 \cdot 10^{-4}$
Glass	5.75	$1 \cdot 10^{-5}$

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RESULTS / *Rezultati*

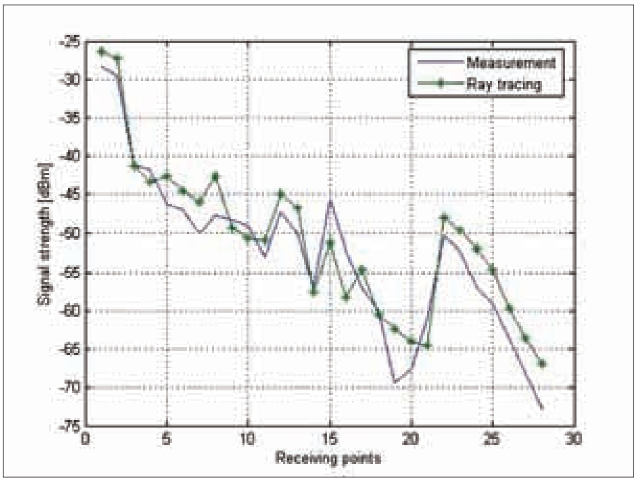

Figure 11. Comparison of the results between the measurement and raytracing model for AP1

Slika 11. Usporedba rezultata dobivenih mjerenjem i modelom slijeđenja zrake za AP1

Received signal strengths predicted by the ray tracing model are examined by comparing them with measured data. Figure 11. shows comparison of the predicted and measured results for the access point AP1 and the figures 12 and 13 show the same for the access points AP2 and AP3. The results obtained by ray tracing model are little higher of those obtained by measurement. This is acceptable because ray tracing method didn't include all mechanisms of multipath propagation, so these results show lower losses.

The differences between measured and predicted results are expressed in terms of absolute mean error, standard deviation and root mean squared (RMS) error. Absolute mean error is calculated according the following expressions

$$e = \left| P_{measured} - P_{calculated} \right|$$

$$\bar{e} = \frac{1}{N} \sum_{i=1}^{N} e_i , \tag{11}$$

where *P* denotes measured or calculated power, and *N* is total number of the results. Standard deviation is the difference between each result and mean absolute value:

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left(e_i - \bar{e} \right)^2} \tag{12}$$

$$RMS = \sqrt{\sigma^2 + \bar{e}^2} \tag{13}$$

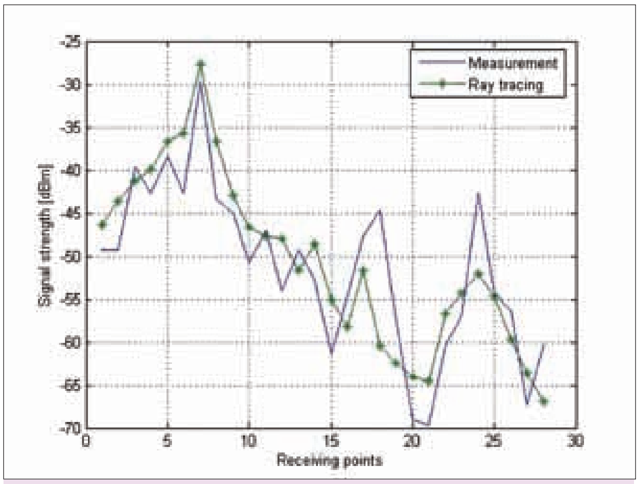

Figure 12. Comparison of the results between the measurement and raytracing model for AP2

Slika 12. Usporedba rezultata dobivenih mjerenjem i modelom slijeđenja zrake za AP2

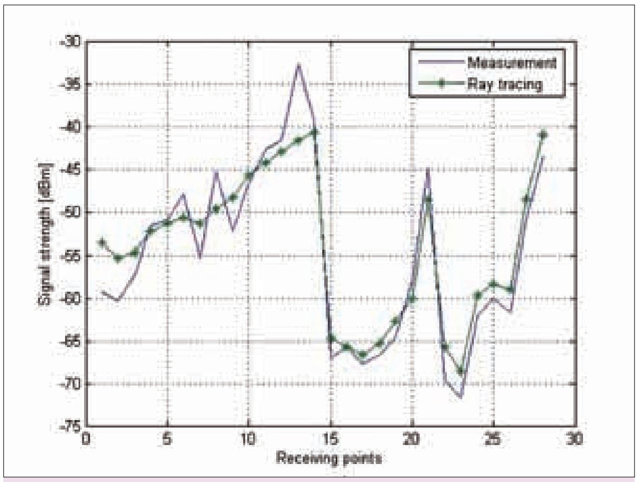

Figure 13. Comparison of the results between the measurement and raytracing model for AP3

Slika 13. Usporedba rezultata dobivenih mjerenjem i modelom slijeđenja zrake za AP3

The differences between measured and results predicted by ray tracing model are presented in the Table 3 for three access points. The best result is obtained for access point AP3, and the worst one for access point AP2.

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Table 3. Errors of the ray tracing model

Tablica 3. Pogreške modela slijeđenja zrake

Access point	Absolute mean error [dB]	Standard deviation [dB]	RMS [dB]
AP1	3.1867	1.7741	3.6472
AP2	4.4220	3.0541	5.3741
AP3	2.6667	1.8703	3.2572

The differences between measured and predicted values are higher for the receiving points with NLOS for access points AP1 and AP2. It is very difficult to include all reflected and diffracted rays that contribute to total receiving power in rooms full of furniture. In the case of the access point AP3 the highest difference between measured and predicted results is in the proximity of the transmitter, what can be caused by the influence of the near field.

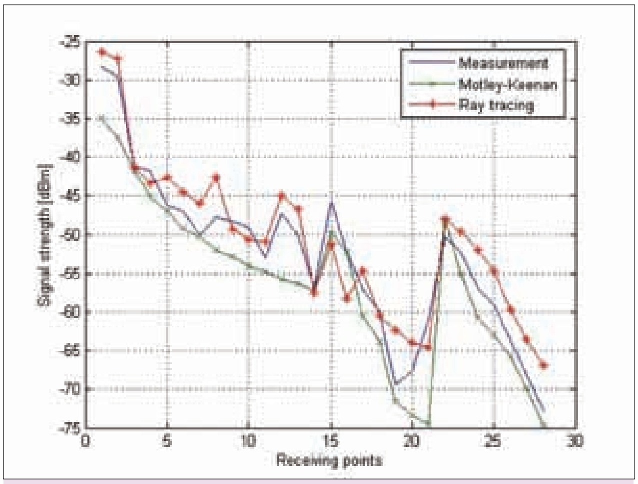

Figure 14. Comparison between signal strength prediction using measurement, ray tracing and Motley-Keenan model for AP1

Slika 14. Usporedba rezultata dobivena mjerenjem i modelima slijeđenja zrake i Motley-Keenan za AP1

COMPARISON BETWEEN THE RESULTS FROM THE RAY TRACING AND EMPIRICAL MODEL / *Usporedba između rezultata dobivenih slijeđenjem zrake i empirijskog modela*

Motley-Keenan method [3] is introduced for predicting receiving signal strength in 28 receiving points that were described above (fig. 5) to check validity of the ray tracing model. According to the geometrical and constructional characteristics of the indoor environment, Motley-Keenan model enables prediction of the signal strength at any arbitrary point of the environment expressed by signal power:

$$P_r = P_t + G_r + G_t - L_{fs} - \sum_{i=1}^{N} k_{wi} L_{wi} - \sum_{j=1}^{M} k_{cj} L_{cj} \qquad (14)$$

where *kL* pairs are products of the losses and number of walls and ceilings located in the path from transmitter to receiver, while L_{fs} is the loss in free space. In our case the walls and other obstacles are presented in the table 4. All values

Table 4. Type of the obstacles

Tablica 4. Vrste prepreka

Type of the wall - obstacle	Width (m)	Loss (dB)
Concrete	0.27	13
Multilayered wall	0.12	8
Metallic surface	0.045	47
Wood	0.04	1

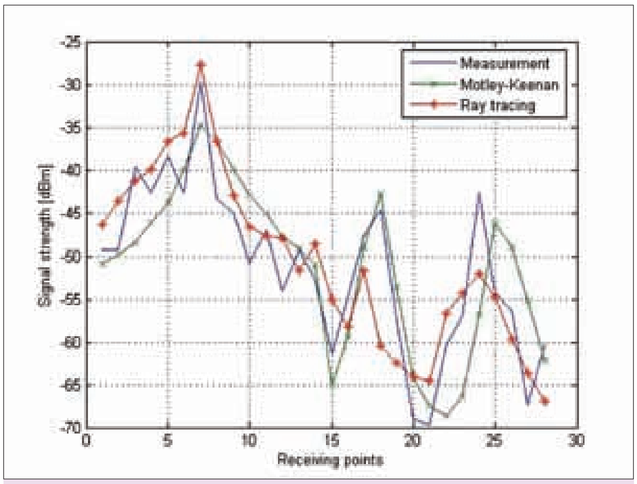

Figure 15. Comparison between signal strength prediction using measurement, ray tracing and Motley-Keenan model for AP2

Slika 15.Usporedba rezultata dobivena mjerenjem i modelima slijeđenja zrake i Motley-Keenan za AP2

ISSN 0469-6255 (202-212)

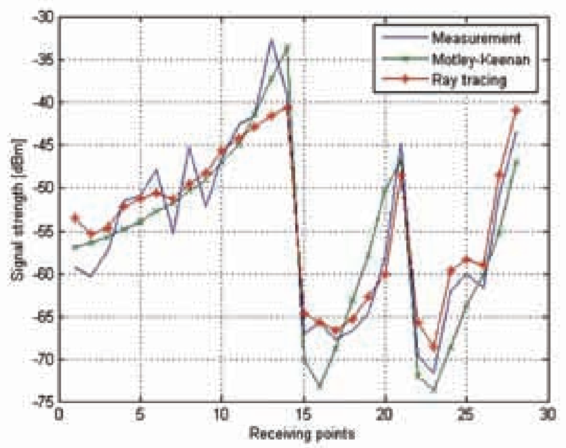

Figure 16. Comparison between signal strength prediction using measurement, ray tracing and Motley-Keenan model for AP3

Slika 16. Usporedba rezultata dobivena mjerenjem i modelima slijeđenja zrake i Motley-Keenan za AP3

The figures 14, 15 and 16 shows comparison between signal strength values obtained on three ways. There is good coverage of the curves obtained by Motley-Keenan and ray tracing model. The differences between results obtained by Motley-Keenan method and measurement are higher than in case of the ray tracing model. The errors of the Motley-Keenan model are summarized in the table 5. It is obvious that errors are for 1 dB higher than those obtained by ray tracing method what can be expected. The Motley-Keenan model, as any empirical model, shows lower accuracy, but it is useful for qualitative check of our ray tracing model.

Table 5. Errors of the Motley-Keenan model

Tablica 5. Pogreške za Motley-Keenanov model

Access point	Absolute mean error [dB]	Standard deviation [dB]	RMS [dB]
AP1	3.6927	2.9641	4.7352
AP2	5.0261	3.5186	6.1353
AP3	3.5416	2.0273	4.0808

CONCLUSION / *Zaključak*

The site-specific ray tracing model for propagation prediction has been presented. The signal can propagate with 3 rays for a satisfactory contribution to the total received signal. Hence the computation is much faster. This method requires the measurement of the electromagnetic parameters, such as relative dielectric constant. It is possible to take these values from literature available, but they can't be accurate for the materials particularly in buildings. The developed software can be commonly used for any environment; only specific data base must be created with geometrical and electrical data.

The results obtained with proposed ray tracing model are compared with data measured for any particular receiving point. It has been found that ray tracing model had an RMS error bound of 3.5 dB related to the measurement data what is an acceptable value. The comparison has also been made between the results obtained by empirical Motley-Keenan method and ray tracing model. The ray tracing model has been qualitatively proved by Motley-Keenan results that show significant higher differences from measured data. This model can be used for improving the performance of the existing indoor wireless networks, as well as for planning future networks.

The diffraction from the edges has been ignored, although the contribution of the diffracted rays from the door edges can be significant. Furniture is not easy to be included in the model, but scattering from the furniture edges can contribute to total receiving power. Nevertheless, the ray tracing model based on geometrical optics provides useful insights into the propagation characteristics of the specific environment. The advantage of the model is in the computational simplicity. As a future task, this ray tracing model can be extended further to include diffracted and scattered rays which will lead to more accurate results. Furthermore, the model can be extended to the prediction of the receiving power in multistorey buildings.

ACKNOWLEDGMENT

This material is based upon work supported by the Ministry of Science, Education and Sports of Republic Croatia, under Project No. 036-0361566-1570, Project No. 275-0361566-3136 and Project No. 275-0000000-3260.

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Rukopis primljen: 17. 7. 2009.

ISSN 0469-6255 (202-212)