ISSN 1330-3651
UDC/UDK 621.391.8 : 004.733 (497.13 Osijek)

RADIO WAVE PROPAGATION MECHANISMS AND EMPIRICAL MODELS FOR FIXED WIRELESS ACCESS SYSTEMS

Josip Milanović, Snježana Rimac-Drlje, Ivo Majerski

Original scientific paper

This paper provides a survey of the basic mechanisms which influence the propagation of electromagnetic waves at most. It also deals with features of empirical models often used in a process of fixed wireless access network planning and implementation. Four empirical models, SUI, COST 231-Hata, Macro and Ericsson, which are most suitable for path loss prediction for such a system, are presented. By using these propagation models the receiving signal levels are predicted for different types of environment for a WiMAX (Worldwide Interoperability for Microwave Access) system installed in the city Osijek, Croatia. Measurement results of receiving WiMAX power at 3,5 GHz are also presented and compared with the results predicted by using the propagation models.

Keywords: *empirical models, radio propagation, WiMAX*

Mehanizmi prostiranja radio vala i empirijski modeli za fiksne radijske pristupne sustave

Izvorni znanstveni članak

Ovaj rad daje pregled osnovnih mehanizama koji najviše utječu na prostiranje elektromagnetskih valova. Također se bavi značajkama empirijskih modela koji se često koriste u procesu planiranja i implementacije fiksnih radijskih pristupnih mreža. Predstavljena su četiri empirijska modela koja najbolje odgovaraju za predviđanje gubitaka za ove sustave: SUI, COST 231- Hata, Macro i Ericsson model. Korištenjem ovih modela prostiranja napravljena je predikcija razine prijemnog signala za različite tipove okruženja za WiMAX (eng. Worldwide Interoperability for Microwave Access) sustav postavljen u gradu Osijeku, u Hrvatskoj. Predstavljeni su i rezultati mjerenja prijemne snage WiMAX sustava na 3,5 GHz te su uspoređeni s rezultatima predviđenim uporabom modela prostiranja.

Ključne riječi: *empirijski modeli, prostiranje radio vala, WiMAX*

1
Introduction
Uvod

In wireless technologies information is sent by electromagnetic waves. During propagation an interaction between waves and environment attenuates the signal level. It causes path loss and finally it limits coverage area. The accurate path loss prediction is a crucial element in the first step of network planning. The capability of determining optimum base-station locations, obtaining suitable data rates and estimating coverage without conducting a series of propagation measurements (what is very expensive and time consuming) can be achieved with empirical propagation models. Empirical propagation models are designed for a specific type of communication systems, specific system parameters and types of environment. Therefore, selection of a suitable propagation model is the first step in the wireless network design. Okumura-Hata [1-2], COST 231-Hata [3] and COST 231 Walfisch-Ikegami [4] are widely used models for the path loss prediction in frequency bands below 2 GHz. However, new wireless systems are designed to operate on higher frequencies, i.e. 2,4 GHz, 3,5 GHz, 5 GHz. A new model (i.e. SUI model) for the band below 11 GHz has been developed by Stanford University, as an extension of the Hata model. In contrast to numerous publications that exist for path loss measurements for frequencies below 2 GHz, there are very few works that present experimental results for higher frequency bands. A comparison between a ray-tracing approach and empirical models for a frequency of 2,154 GHz is given in [5]. A modification of the ITU-R P.1411 model [6] to enhance prediction accuracy in urban environments is presented in [7], as well as measurement results at 2,17 GHz. In [8] experimental results for a system working at 3,5 GHz are compared against prediction made by different empirical propagation models. A simple empirical model based on measurements at 5,3 GHz is proposed in 9. Since accuracy of the path loss prediction significantly depends on the type of environment, as more experimental data for different environments are available, the better model fitting to real conditions can be done.

The paper is organized as follows: in Section 2 basic mechanisms of radio wave propagation are discussed. Characteristics of the radio wave propagation in built-up areas are given in Section 3. In Section 4 empirical propagation models suitable for the path loss prediction in a fixed wireless access system are presented. Section 5 gives experimental results for a WiMAX system on 3,5 GHz as well as a comparison between measured results and predictions obtained by different empirical propagation models. Concluding remarks are given in Section 6.

2
Basic mechanisms of electromagnetic wave propagation
Temeljni mehanizam elektromagnetskog prostiranja vala

During propagation between the transmitting and the receiving antenna, radio waves interact with environment, causing path loss. Path loss (*PL*) is defined as the difference between the transmitted and the received power as shown in (1):

$$PL = P_\mathrm{T} + G_\mathrm{T} + G_\mathrm{R} - P_\mathrm{R} - L_\mathrm{T} - L_\mathrm{R}, \qquad (1)$$

where P_T and P_R are the transmitted and the received power, G_T and G_R are gain of the transmitting and the receiving antenna and L_T and L_R are feeder losses, all in a dB scale. Propagation in free space path loss (FSL) can be expressed as [10]:

$$PL_\mathrm{freespace} = 32{,}4 + 20\cdot \lg d + 20\cdot \lg f,\ \mathrm{dB} \qquad (2)$$

where d is the distance between transmitting and receiving antennas given in kilometers and f is frequency in MHz. Expression (2) shows that free space loss increases by 6 dB for each doubling in either frequency or distance (or 20 dB per decade). In point-to-point communications the free space loss (FSL) model can be used only when there exists a direct ray between the transmitting and the receiving antenna. For point-to-surface type communications, even in LOS (line-of-sight) conditions, reflected and diffracted rays reach the receiving antenna together with a direct ray thus increasing calculation complexity.

The loss between two antennas can be less than its free space value only in highly anomalous propagation conditions. An example of such exception is when propagation is confined to some guided structure, such as street canyons.

2.1
Propagation of electromagnetic wave over smooth terrain
Prostiranje elektromagnetskog vala iznad glatkog terena

One of the fundamental situations that occurs when a propagation path is free of any kind of obstacles is illustrated in Figure 1. Here the transmitting and the receiving antenna are situated above a flat reflecting ground so that propagation takes place via both a direct path between the antennas and a reflection from the ground. These two paths sum at the receiver with a phase difference related to the difference in length between the two paths, giving the total field which can be presented as [11]:

$$E_{\mathrm{R}} = E_{\mathrm{T}}\left(1+\frac{r_1}{r_{\mathrm{reflected}}}R(\alpha)\mathrm{e}^{-jk\Delta r}\right), \qquad (3)$$

where r_1 and $r_{\mathrm{reflected}}=r_2+r_3$ are lengths of direct and reflected rays, respectively, $R(\alpha)$ is the reflection coefficient for horizontal and vertical polarization and $\Delta\varphi=k\Delta r$ is the phase difference between the reflected and direct waves which can be presented as:

$$\Delta\varphi = \frac{4\cdot\pi\cdot h_{\mathrm{R}}\cdot h_{\mathrm{T}}}{\lambda\cdot d}, \qquad (4)$$

where h_{R} and h_{T} are the receiving and transmitting antenna heights, λ is a wavelength and d is the distance between them.

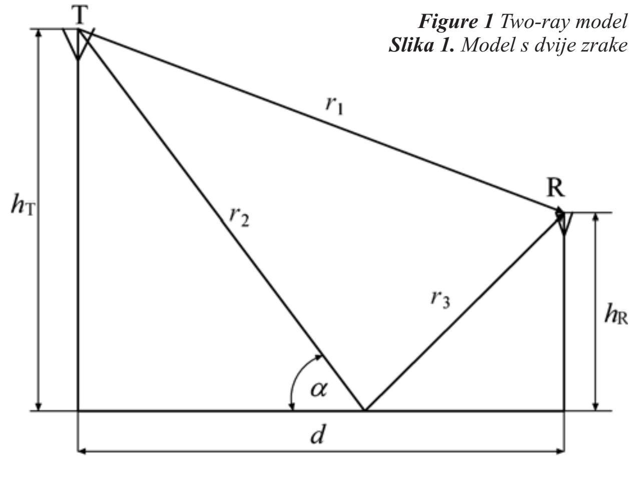

Figure 1 *Two-ray model*
Slika 1. *Model s dvije zrake*

If we assume that both antennas are omnidirectional and that they are far away from each other ($R(\alpha)$-1), then the absolute power value of the received signal can be defined as:

$$P_{\mathrm{R}} = \left|P_{\mathrm{T}}\right|\left(\frac{\lambda}{4\cdot\pi\cdot d}\right)^2 \sin^2\frac{k\Delta r}{2}, \qquad (5)$$

where P_{R} is received power, P_{T} is transmitted power and $\Delta r=(r_2+r_3)-r_1$.

Received power falls with d^2, but it also changes from the maximum to the minimum value due to $\sin^2(k\Delta r/2)$. As follows from (5), the largest distance from the transmitter for which there is some maximum of the received power occurs when:

$$\frac{k\Delta r}{2} \approx \frac{\pi}{2}, \quad \sin\frac{k\Delta r}{2} \approx 1. \qquad (6)$$

This distance is called the critical range and it can be presented as:

$$r_b \approx \frac{4\cdot h_{\mathrm{R}}\cdot h_{\mathrm{T}}}{\lambda}. \qquad (7)$$

This so-called Two-ray model can be applied in a case when communication between the transmitting and the receiving antenna occurs in LOS conditions and in small distances when Earth curvature does not significantly influence the wave propagation.

2.2
Radio wave propagation over irregular terrain
Prostiranje radio vala iznad neravnog terena

The previous section presupposed an ideal reflecting case when reflection occurs over a smooth surface. In reality, surface is usually rough what causes that the Two-ray model is no longer realistic since a rough surface presents many facets to the incident wave. A diffuse reflection therefore occurs and the mechanism is more akin to scattering.

In the case when surface is smooth, with a direct wave there exists only component of the reflecting wave. If reflection occurs over a rough surface, due to energy spreading, the component of a reflection will decrease while scattering component will increase. The total field at the receiving antenna will decrease since only a small fraction of the incident energy may be scattered in the direction of the receiving antenna. Therefore, in order to predict the propagation loss characteristics over the irregular terrain and estimate the role of each kind of wave component in the total field the surface roughness criterion must be defined. The method that defines the influence of surface roughness to the total field at the receiving antenna is known as Rayleigh method [12]. Because of simplification, this method idealizes a real surface with a quasiperiodical surface as shown in Figure 2.

Rayleigh method considers two rays (A and B) reflected from the top and bottom side of a rough surface in the points B and B', respectively. It is obvious that those two rays will pass over different paths and that they will have different phases at the receiving point (C and C'). The difference in phases and path lengths of these two rays when they reach

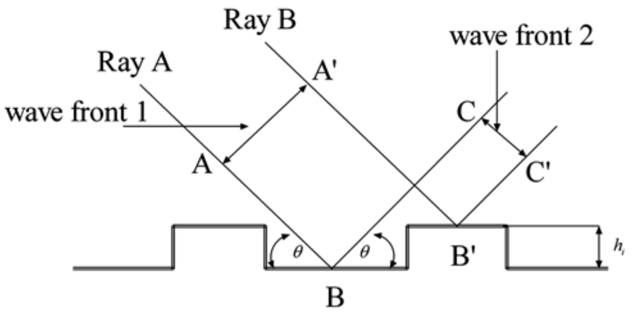

***Figure 2** Idealized quasiperiodical surface*
***Slika 2.** Idealizirana kvaziperiodična površina*

points C and C' after reflection is defined as [11]:

$$\Delta l = (\overline{AB} + \overline{BC}) - (\overline{A'B'} + \overline{B'C'}) = \\ = \frac{h_i}{\sin\theta}(1 - \cos 2\theta) = 2h_i \cdot \sin\theta . \tag{8}$$

$$\Delta\Phi = k \cdot \Delta l = \frac{2\pi}{\lambda}\Delta l = \frac{4\pi \cdot \sin\theta \cdot h_i}{\lambda} . \tag{9}$$

From equation (8) it can be seen that phase difference $\Delta\Phi$ will be small if the height of terrain irregularity h_i is small in comparison to wavelength. Every surface that satisfies criterion $\Delta\Phi \geq (\pi / 2)$ can be classified as a rough surface [10]. From equation (9) and considering the last criterion, critical height ($h_{R\max}$) can then be presented as:

$$h_i \geq h_{R\max} \equiv \frac{\lambda}{8\sin\theta} . \tag{10}$$

From equation (10) it can be seen that every surface where the height of terrain irregularity (h_i) is greater than critical height ($h_{R\max}$) can be considered as a rough surface. At the same time, the critical height is determined by the wavelength and angle θ with respect to the rough surface.

2.3
Radio wave propagation over terrain obstacles
Prostiranje radio vala iznad prepreka

Geometrical optics theory is very useful for many problems. However, such a description leads to entirely incorrect prediction when considering the area in the shadow region behind an obstruction, since it predicts that no field exists in the shadow region. It is well known that in many cases that is not true because some energy propagates into the shadow region. This effect is known as diffraction and it has been explained by Huygen's principle. This principle suggests that each point on a waveform acts as the source of a secondary wavelet and that these wavelets combine to produce a new wave front in the direction of propagation [12].

Diffraction causes path loss. The simplest case is when diffraction occurs over a single obstacle, where for determining diffraction loss the Single-knife edge diffraction model can be applied.

This model assumes that propagation occurs over a sharp and infinite long obstacle that blocks wave propagation around that obstacle. According to Huygen's principle, an infinite number of secondary sources in the region above the edge is summed, causing that the field in shadow region behind obstruction exists. Diffraction loss can be express as:

$$L(\nu) = -20 \cdot \lg \frac{1}{\pi\nu\sqrt{2}} , \tag{11}$$

where ν is Fresnel-Kirchhoff diffraction parameter defined as:

$$\nu = h \cdot \sqrt{\frac{2(d_1 + d_2)}{\lambda \cdot d_1 \cdot d_2}} , \tag{12}$$

where h is the obstacle height, d_1 and d_2 are distances between the transmitting and the receiving antenna respectively and obstacles.

A single knife-edge diffraction model can be applied only if the propagation path is obstructed with a single obstruction. If the path is obstructed with several obstructions then the multiple knife-edge diffraction models must be applied. These models simplify the propagation path using combinations of single edge diffractions between adjacent edges. Some examples are Deygout model, Bullington model, Epstein model and Giovanelli model.

3
Radio wave propagation in built-up areas
Prostiranje radio vala u izgrađenom području

During propagation in built-up areas electromagnetic waves interact with environment (trees, buildings, hills, etc.) what causes path loss. Different types of environment will cause a different attenuation level. In practice, because of better propagation conditions, it is possible that a system with less demanding parameters offers a better coverage area than a system with more demanding parameters. That is why it is very important to classify terrain as accurately as possible since propagation model selection as well as propagation model complexity strongly depend on environment.

3.1
Terrain type classification
Klasifikacija terena

A terrain profile may vary from a simple curved Earth to a highly mountainous region. Since the propagation model assumes that the characteristics of the environment are very similar to those where the system is operating, it is crucial to classify and choose the appropriate terrain type accurately. A simple classification of terrain is the result of practical research and experience of wireless networks designers which can be presented as [11]:

- open area,
- flat ground surface,
- curved, but smooth terrain,
- hilly terrain,
- mountains,

while built-up areas can be classified into three main categories [10]:

- Urban areas: Built-up city or large town with large buildings and houses with two or more stories or large villages with close houses and tall, thickly grown trees,

- Suburban areas: Village or highway scattered with trees and houses, some obstacles near the receiving antenna but not very congested,
- Rural areas: Open space, no tall trees or buildings in propagation path, plot of land cleared for 300-400 m ahead, e.g. farmland, rice fields and open fields.

Researchers have shown that the same categories definitions cannot be applied with the same accuracy in all countries, e.g. the term "urban", because building's density and building's average height have a different meaning in cities like Tokyo (Japan) and Zagreb (Croatia). That is why some countries use adapted categories which better describe the area of interest, e.g. British Telecom constructed ten categories of terrain configuration, which are presented in Table 1 [10].

Table 1 *Terrain configuration proposed by British Telecom*
Tablica 1. *Konfiguracija terena predložena od British Telecom-a*

Category	Description of the terrain
0	Rivers, lakes and seas
1	Open rural areas (e.g. fields and heathland with few trees)
2	Rural areas, similar to the above, but with some wooded areas
3	Wooded or forested rural areas
4	Hilly or mountainous rural areas
5	Suburban areas, low-density dwellings and modern industrial estates
6	Suburban areas, higher density dwellings (e.g. council estates)
7	Urban areas with buildings of up to four stories with gaps in-between
8	Higher density urban areas in which some buildings have more than four stories
9	Dense urban areas in which most of the buildings have more than four stories and some can be classified as "skyscrapers"

3.2
Multipath propagation
Višestazno prostiranje

Special attention in the process of designing wireless networks is dedicated to choosing an appropriate location where the transmitting antenna is going to be set up. These locations usually dominate with respect to the surrounding buildings by heights what increases the coverage area. But, the problem is usually present at the receiving side where the receiving antenna is surrounded by tall buildings or other objects which makes LOS (line of sight) communications impossible. In these cases radio waves arrive at the receiver from different directions with different amplitudes, phases and time delays, resulting in the phenomenon known as multipath propagation [13]. The radio channel is then obtained as the sum of the contributions from all of the paths.

The signal on these different paths can constructively or destructively interfere with each other and if the transmitter or the receiver moves electromagnetic field will be time varying and fading occurs. Researchers have shown that multiple propagation paths or multipath have both slow and fast aspects of fading [14]. When the transmitting or the receiving antenna moves in built-up areas, the measured signal contains both slow and fast fading components. Slow fading is a result of different propagation conditions which cause that some waves will suffer increased loss, while others will be less obstructed and have increased signal strength. Variation occurs over distances comparable to the widths of buildings and hills in the vicinity of the mobile station, which is usually tens or hundreds of meters and it varies with frequency, antenna heights and the environment.

The received signal is the sum of a number of signals reflected from local surfaces and objects in a constructive or destructive manner depending on the relative phase shift. Phase relations depend on the speed of motion, frequency of transmission and the type of environment.

The maximum level of the received signal will be achieved when the phase difference between received waves is at the minimum. In relation to this, an increasing phase difference will result in decreasing of the received total field level and the minimum level will be obtained when the phase difference is 180°.

Fast fading occurs if the channel impulse response changes rapidly within the symbol duration. In other words, fast fading occurs when the coherence time of the channel T_D is smaller than the symbol period of the transmitted signal T such as $T_D<T$ [14]. For fast fading estimation statistical models can be used. If communication is achieved in NLOS (non line of sight) conditions where reflection has a big influence, fast fading can be determined by Rayleigh distribution. In LOS propagation condition, where the influence of reflection is low, fast fading can be determined by Ricean distribution.

4
Empirical propagation models
Empirijski modeli prostiranja

Propagation models are main tools which are daily in use for designing, planning and analyzing wireless communication networks. It is important to point out that there is no general method or algorithm that is universally accepted as the best propagation model. Each model can be useful for some specific environment and the accuracy of any particular technique or algorithm depends on the fit between the parameters available for the area concerned and the parameters required by the model. Although there are lots of different kinds of models, none of them can be applied as a universal solution for all kinds of propagations situations. Choosing the appropriate propagation model depends on system parameters (e.g. frequency, antenna height, etc.) and terrain parameters (e.g. urban area, suburban area, rural area). According to time calculation, accuracy and the number of required parameters, propagation models can be divided into three main groups [8]: deterministic, statistical and empiric models. Deterministic models make use of the physical laws which determine radio wave propagation mechanisms for a particular location. These models require a 3-D data of the propagation environment. Accuracy of deterministic models is usually very high but on the expense of high computing complexity. Stochastic models, on the other hand, require the least information about the environment but provide the least accuracy [15]. They model the environment as a series of random variables. Empirical models are based on extensive measurements and mainly give prediction of path loss. They are more often used in practice than statistical and deterministic propagation models, because of low cost and model simplicity with acceptable accuracy. The empirical propagation models which are suggested as good solutions for fixed access signal calculation are: Cost 231-Hata model, SUI model, Macro model and Ericsson model.

4.1
Cost 231-Hata propagation model
Cost 231-Hata model prostiranja

One of the elementary propagation models many models are based on is the Okumura propagation model. This model gives a graphical expression for path loss between the receiving and the transmitting antenna for a frequency range between 200 MHz and 1920 MHz. The Okumura model is considered to be among the simplest and best in terms of accuracy in predicting path loss for early cellular systems. The major disadvantage of this model is that given graphical expressions are not practical what resulted in additional simplification given by a mathematical expression in Hata model [1]. The Hata model gives prediction of the median path loss for the frequency range from 150 MHz to 1500 MHz, from the distance d between antennas of up to 20 km, the transmitting antenna height between 30 m and 200 m and the receiving antenna height between 1 m and 10 m.

Application of the Hata model is restricted with upper frequency of up to 1500 MHz and therefore it is not applicable to GSM1800 and other similar systems operating on frequencies above 1500 MHz. Extension of the frequency range is achieved by the Cost231-Hata model which is usable in the frequency range from 500 MHz to 2000 MHz. The formula for the median path loss is given by:

$$\begin{aligned} L_{\text{COST 231-Hata}} &= 46,3 + 33,9 \cdot \lg f - 13,82 \cdot \lg h_{\mathrm{T}} - \\ &- a(h_{\mathrm{R}}) + (44,9 - 6,55 \cdot \lg h_{\mathrm{T}}) \cdot \lg d + c_m \end{aligned} \tag{13}$$

where d is the distance in meters, f is frequency in MHz, h_T and h_{R} are effective heights of the transmitting and the receiving antenna in meters. Parameter c_m is defined as 0 dB for suburban and rural environment and 3 dB for urban environment.

For a small or medium-sized city $a(h_{\mathrm{R}})$ is defined as:

$$a(h_{\mathrm{R}}) = (1,1 \cdot \lg f - 0,7) \cdot h_{\mathrm{R}} - (1,56 \cdot f - 0,8) \tag{14}$$

and for a large city, $a(h_R)$ is given by:

$$a(h_{\mathrm{R}}) = 3,2 \cdot (\lg(11,75 \cdot h_{\mathrm{R}}))^2 - 4,97. \tag{15}$$

4.2
Macro model
Makro model

A Macro model is based on the Hata model and it includes correction of each factor that influences propagation path loss [16]. Therefore, this model can be calibrated by changing parameters to fit propagation conditions better.

Path loss is given by the following formula (16):

$$\begin{aligned} L_{\text{Macro}} &= k_{\text{off}} + k_{\lg d} \cdot \lg d + k_{h_{\mathrm{R}}} \cdot h_{\mathrm{R}} + k_{\lg h_{\mathrm{R}}} \cdot \lg h_R + \\ &+ k_{\lg h_{\mathrm{T}}} \cdot \lg h_{\mathrm{T}} + k_{\lg h_T \lg d} \lg h_{\mathrm{T}} \cdot \lg d \end{aligned} \tag{16}$$

where k_{off} is a constant which regulates the absolute value of path loss, $k_{\lg(d)}$ regulates path loss dependence on the distance, $k_{h\mathrm{R}}$ is a correction factor for receiver antenna height gain, $k_{\lg(h\mathrm{R})}$ is the Okumura-Hata multiplying factor for h_{R}, $k_{\lg(h\mathrm{T})}$ is the transmitting antenna height gain factor and $k_{\lg(h\mathrm{T})\lg(d)}$ is the Okumura-Hata multiplying factor for $\lg(h_{\mathrm{T}})\lg(d)$.

4.3
Ericsson M*odel*
Eriksonov model

Ericsson model is Ericsson's implementation of Hata model [17]. In this model the modification of model parameters is possible according to propagation environment.

Path loss is given by expression:

$$\begin{aligned} L_{\text{Ericsson}} &= a_0 + a_1 \cdot \lg d + a_2 \cdot \lg h_{\mathrm{T}} + \\ &+ a_3 \cdot \lg h_{\mathrm{T}} \cdot \lg d - 3,2 \cdot (\lg(11,75 \cdot h_{\mathrm{R}}))^2 + g(f) \end{aligned} \tag{17}$$

where $g(f)$ is defined by

$$g(f) = 44,49 \cdot \lg f - 4,78 \cdot (\lg f)^2 . \tag{18}$$

Parameters a_0, a_1, a_2 and a_3 are constants, which can be modified for better fitting for specific propagation conditions. Default values are: a_0=36,2, a_1=30,2, a_2=–12,0 and a_3=0,1.

4.4
SUI (Stanford University Interim) propagation model
SUI (Stanford University Interim) model prostiranja

Upon development of a standard for a frequency band above 11 GHz, IEEE working group 802,16 was focused on the band below 11 GHz. That resulted in the SUI model which was developed by Stanford University. SUI model parameters depend on terrain type divided into three groups as shown in Table 2 where terrain type A represents hilly terrain with moderate to heavy tree densities with biggest path loss. Terrain type B represents either mostly flat terrain with moderate to heavy tree densities or hilly terrain with light tree densities, while terrain type C represents mostly flat terrain with light tree densities where path loss is minimal [18].

Table 2 *Terrain types for SUI model*
Tablica 2. *Vrste terena prema SUI modelu*

	Terrain type A	Terrain type B	Terrain type C
a	4,6	4,0	3,6
b, m^{-1}	0,0075	0,0065	0,005
c, m	12,6	17,1	20

This model is an extension of the Hata model for frequencies of up to 1900 MHz. To expand the frequency range, an additional correction factor is applied what enables the SUI model to be applied to the WiMAX system which works on 3,5 GHz. The SUI model can be used for transmitting antenna heights from 10 m to 80 m and the receiving antenna heights between 2 m and 10 m and the cell radius between 0,1 km and 8 km.

Equation for path loss calculation is given by expression:

$$L_{\text{SUI}} = A + 10\gamma \lg \frac{d}{d_0} + X_f + X_k + s \quad \text{for} \;\; d > d_0 , \qquad (19)$$

where d is the distance between the transmitting and the receiving antenna in meters, d_0=100 m, X_f is a correction factor for frequencies above 2 GHz, X_h is correction for the receivering antenna height, and s is a correction factor for shadowing because of trees and other clutters on propagation path. Parameters A and path loss exponent (γ) are defined as:

$$A = 20 \cdot \lg \frac{4\pi d_0}{\lambda} , \qquad (20)$$

$$\gamma = a - b \cdot h_{\text{T}} + \frac{c}{h_{\text{T}}} , \qquad (21)$$

where h_{T} is the transmitting antenna height in meters, and a, b and c are constants dependent on the terrain type, as given in Table 2. Path loss exponent depends on propagation environment and for free space path loss γ=2, in the urban NLOS area γ>3 and γ<5, and for indoor propagation γ>5.

The correction factors for the operating frequency and the receiving antenna height for the model are:

$$X_f = 6{,}0 \cdot \lg \left(\frac{f}{2000}\right) , \qquad (22)$$

and

$$X_h = -10{,}8 \cdot \lg \left(\frac{h_{\text{R}}}{2000}\right) , \text{ for terrain types A and B} \qquad (23)$$

$$X_h = -20 \cdot \lg \left(\frac{h_{\text{R}}}{2000}\right), \text{ for terrain type C} \qquad (24)$$

where f is the frequency in MHz and h_{R} is the receiving antenna height in meters. A disadvantage of the SUI model is the fact that it does not divide environment into the mostly used groups, namely rural, suburban and urban what can be additional source of calculation incorrectness.

5
Implementation of propagation models for WiMAX system on 3,5 GHz
Primjena modela prostiranja na WiMAX sustav na 3,5 GHz

WiMAX technology is the newest broadband wireless technology which is designed for offering DSL services in areas without an adequate telecommunication infrastructure or areas where there is no economical sense for putting in the operation height quality cables which are very expensive. Two main standards that are nowadays in use are 802.16d designed for fixed communications and 802.16e designed for mobile communications. Both of them have been defined by IEEE 802.16 working group.

This technology is based on OFDM (Orthogonal Frequency Division Multiplex) modulation offering communication between the transmitting and the receiving antenna in NLOS propagation conditions. In ideal conditions, WiMAX offers a bit rate of up to 75 Mbps, within the range of 50 km, which depends on radio optical visibility between antennas. So far, measurements in the field under real conditions have shown significant degradation of declared characteristics. For instance, the coverage range is between 5 and 8 km and the bit rate is up to 2 Mbps. In different countries WiMAX technology works at different frequencies and therefore WiMAX equipment must support at least five different frequencies to support interoperability. In the Republic of Croatia WiMAX works in a 3,5 GHz frequency range with channel width of 14 MHz or 21 MHz.

Considering the fact that empirical models are based on real measurements as well as the fact that WiMAX is a new technology which is in many countries in the installation process, it is obvious why the model which is specially defined for WiMAX does not exist at the moment. Recently, there has been considerable interest in the experimental verification of the coverage and the received power prediction for WiMAX system operating on different frequencies [19-22]. The following sections present some results of the comparison of receiving power predicted by propagation models and received powers measured under real propagation conditions.

5.1
Measurement setup
Mjerne postavke

Measurements were carried out at 60 locations in the city of Osijek (Croatia) and surrounding areas. Osijek is a medium-sized city with a high percentage of residential areas where around 120 thousand inhabitants live. Terrain in and around the city is flat with very rare vegetation. Measurement locations were selected carefully so that they can satisfy one of the propagation categories (urban, suburban and rural areas).

The WiMAX receiving signal level is measured in a 3,5 GHz frequency range (license WiMAX frequency range in Croatia) and a FSP40 Rohde&Schwarz analyzer was used for measurements. The transmitting antenna was mounted on the top of a building with height of 59 m above the ground level, while the receiving panel antenna was mounted on a 3 m high pole. At each location 33 measurements were taken to reduce the influence of the location variability on the receiving power level (which brings 1980 individual measurements in total). The mean value of those 33 measurements at each location was chosen as a referent receiving signal level for specific location (P_{measured}) and they were compared with predicted receiving levels ($P_{\text{predicted}}$) obtained with four empirical models: SUI, Cost231-Hata, Ericsson and Macro model.

For N locations we calculated differences between measured values (P_{measured}), and predicted ones ($P_{\text{predicted}}$), to obtain prediction error (Δx_i) for each location. Analysis is made for mean prediction error ($\overline{\Delta x}$), standard deviation (σ), and mean value of the absolute prediction error ($\overline{|\Delta x|}$), as given by expressions [19]:

$$\Delta x_i = P_{\text{predicted}_i} - P_{\text{measured}_i} , \qquad (25)$$

$$\overline{\Delta x} = \frac{1}{N} \sum_{i=1}^{N} \Delta x_i , \qquad (26)$$

$$\left|\overline{\Delta x}\right| = \frac{1}{N}\sum_{i=1}^{N}\left|\Delta x_i\right|, \qquad (27)$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta x_i - \overline{\Delta x})^2}\ . \qquad (28)$$

For calculations of the predicted receiving signal levels, commercial program Cellular Expert v.3.3. was used. Propagation model accuracy was analyzed according to LOS/NLOS propagation condition and according to different propagation environment (urban, suburban and rural areas).

5.2
Comparison of propagation models accuracy for LOS/NLOS location division
Usporedba točnosti modela prostiranja za LOS/NLOS podjelu lokacija

Location division to LOS/NLOS propagation condition was made according to clearance of the first Fresnel zone. It is known that locations where 60 % of the first Fresnel zone is clear of any kind of obstacles can be considered as locations where communications are achieved under LOS propagation condition. Contrary to this, locations where at least 60 % of the first Fresnel zone is not clear can be classified in the NLOS group as shown in the Figures 3 and 4.

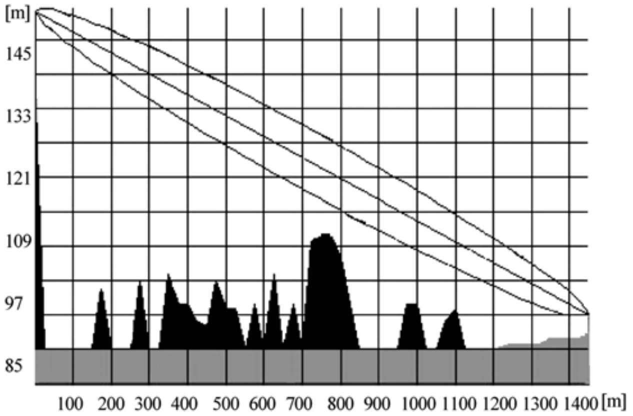

Figure 3 *LOS propagation condition by first Fresnel zone*
Slika 3. *LOS uvjeti prostiranja prema prvoj Fresnelovoj zoni*

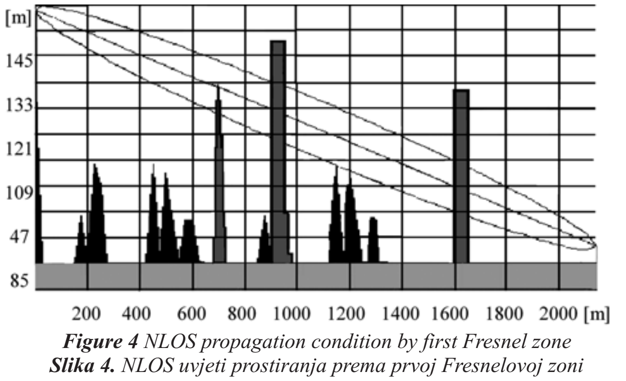

Figure 4 *NLOS propagation condition by first Fresnel zone*
Slika 4. *NLOS uvjeti prostiranja prema prvoj Fresnelovoj zoni*

Calculated values for mean prediction error, standard deviation and mean value of the absolute error for each terrain type in the SUI propagation model are given in Table 3.

Table 3 *$\overline{\Delta x}$, $\left|\overline{\Delta x}\right|$ and σ for SUI model*
Tablica 3. *$\overline{\Delta x}$, $\left|\overline{\Delta x}\right|$ i σ za SUI model*

	SUI A	SUI B	SUI C
$\overline{\Delta x}$, dB	−14,4	−11,0	−8,3
$\left|\overline{\Delta x}\right|$, dB	14,7	12,1	10,9
σ, dB	13,7	12,8	12,5

Table 3 shows that calculated results overestimate path loss for all SUI terrain types. Less overestimation occurred for terrain type C ($\left|\overline{\Delta x}\right|$=10,9 dB), what is an expected result, since terrain type C fits best to terrain in the Osijek region. Due to the fact that among all SUI models the best results are obtained with parameters given for terrain type C, further in the paper we present results only for SUI C model.

Measurement results as well as propagation models prediction are shown in Figures 5 and 6 while calculated values for mean prediction error, standard deviation and mean value of absolute error for each propagation model are given in Table 4.

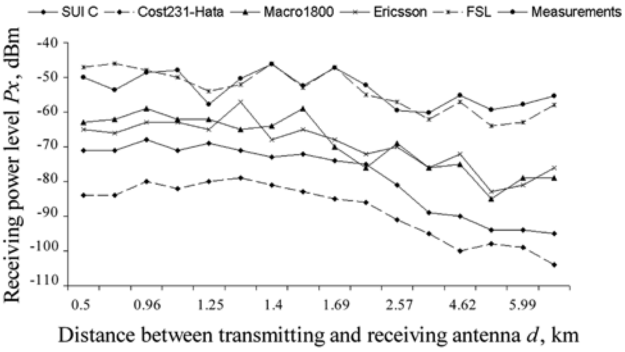

Figure 5 *Dependency of receive level on distance for different propagation models in LOS condition*
Slika 5. *Prijemna razina u ovisnosti o udaljenosti za različite modele prostiranja u LOS uvjetima*

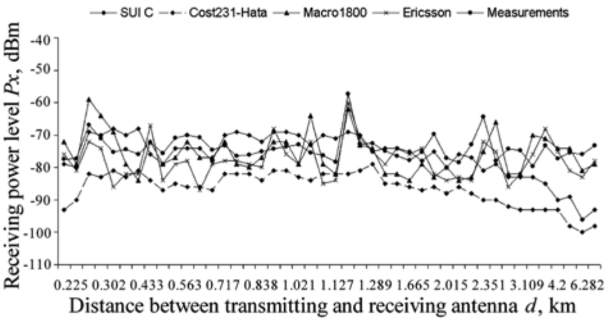

Figure 6 *Dependency of the receiving level on distance for different propagation models in NLOS condition*
Slika 6. *Prijemna razina u ovisnosti o udaljenosti za različite modele prostiranja u NLOS uvjetima*

Figure 6 shows a very interesting feature that the measured received power does not decrease with distance. This phenomenon can be explained by the fact that the OFDM system can effectively use multipath components because of the guard period incorporated in the signal. According to Table 4, all propagation models overestimate path loss. The best result in the LOS propagation condition is obtained with the Free space loss propagation model ($\left|\overline{\Delta x}\right|$ =2,6 dB), while the worst result is obtained with the Cost231-Hata ($\left|\overline{\Delta x}\right|$ =34,8 dB) propagation model. Much better prediction accuracy for all propagation models is

Table 4 $\overline{\Delta x}$, $\overline{|\Delta x|}$ *and σ for LOS and NLOS locations*
Tablica 4. $\overline{\Delta x}$, $\overline{|\Delta x|}$ *i σ za LOS i NLOS lokacije*

	SUI C		Cost231-Hata		Macro1800		Ericsson		FSL
	LOS	NLOS	LOS	NLOS	LOS	NLOS	LOS	NLOS	LOS
$\overline{\Delta x}$, dB	-25,3	-2,1	-34,8	-12,5	-15,7	-1,8	-16,0	-3,8	-0,3
$\overline{\lvert\Delta x\rvert}$, dB	25,3	5,7	34,8	12,5	15,7	5,1	16,0	5,5	2,6
σ, dB	7,6	7,1	6,2	5,7	6,5	5,8	5,2	5,2	3,2

obtained in the NLOS propagation condition, where the best result is obtained for the Macro1800 propagation model ($\overline{|\Delta x|}$ = 5,1 dB) and the worst result is obtained for the Cost231-Hata model ($\overline{|\Delta x|}$ = 12,5 dB). The greatest accuracy improvement was accomplished for the SUI model where absolute mean prediction error in the LOS propagation condition was $\overline{|\Delta x|}$ = 25,3 dB and in the NLOS environment it is usable $\overline{|\Delta x|}$ = 5,7 dB. This result is expected since the SUI model is designed for path loss calculation in built-up areas where propagation usually occurs under NLOS conditions.

To increase prediction accuracy, propagation models can be combined in a way that the model which suits best for a specific area is chosen. We have combined the FSL model with the Macro1800 model what resulted in increased accuracy ($\overline{|\Delta x|}_{\mathrm{Macro1800+FSL}}$= 4,4 dB). This result showed that model combination can provide usable accuracy that ensures designing a trouble-free and effective WiMAX network. A disadvantage of this approach is that it increases calculation time and calculation complexity.

5.3

Comparison of propagation models accuracy according to terrain type

Usporedba točnosti modela prostiranja prema vrsti terena

For location classification according to terrain type, ITU-R P.1411 recommendation was used. This recommendation distinguishes three main propagation areas which are characterized as:

- urban – streets lined with tall buildings of several floors each, buildings height makes significant contributions from propagation over roof tops unlikely, rows of tall buildings provide the possibility of long path delays,
- suburban – typified by wide streets, building heights are generally less than three stories making diffraction over roof-top likely, reflections and shadowing from moving vehicle can sometimes occur,
- rural – small houses surrounded by large gardens, heavy to light foliage possible, influence of terrain height (topography).

Since there is a wide variety of environments within each category the intention of the recommendation is not to model every possible terrain area but to give characteristics that are representative of frequently encountered environments [6].

We made terrain classification and calculation of the predicted receiver powers, as well as calculation of the difference (error) between predicted and measured values. Mean prediction error, standard deviation and mean value of absolute error are calculated (Table 5 and Table 6). Measurements results as well as propagation models prediction are shown in Figures 7, 8 and 9.

Table 5 $\overline{\Delta x}$, $\overline{|\Delta x|}$ *and σ for urban, suburban and rural areas for SUI C and Cost231-Hata model*
Tablica 5. $\overline{\Delta x}$, $\overline{|\Delta x|}$ *i σ za urbana, suburbana i ruralna područja za SUI C i Cost231-Hata model*

	SUI C			Cost231-Hata		
	Urban	suburban	rural	urban	suburban	rural
$\overline{\Delta x}$, dB	1,5	-0,1	-17,3	-9,7	-10,8	-26,6
$\overline{\lvert\Delta x\rvert}$, dB	3,8	4,0	17,9	9,7	10,8	26,6
σ, dB	3,9	4,3	11,7	3,4	3,8	10.8

Table 6 $\overline{\Delta x}$, $\overline{|\Delta x|}$ *and σ for urban, suburban and rural areas for Macro and Ericsson model*
Tablica 6. $\overline{\Delta x}$, $\overline{|\Delta x|}$ *i σ za urbana, suburbana i ruralna područja za Macro i Ericsson model*

	Macro1800			Ericsson		
	urban	suburban	rural	urban	suburban	rural
$\overline{\Delta x}$, dB	-2,3	-2,2	-8,8	-4,1	-3,9	-10,2
$\overline{\lvert\Delta x\rvert}$, dB	4,0	5,0	11,3	4,9	6,2	11,1
σ, dB	3,7	6,0	9,9	4,0	6,2	8,1

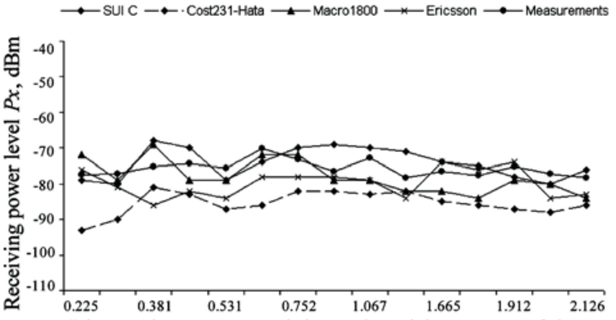

***Figure** 7 Measured and predicted receiving power level for urban areas*
***Slika** 7. Izmjerene i predviđene razine prijemne snage za urbana područja*

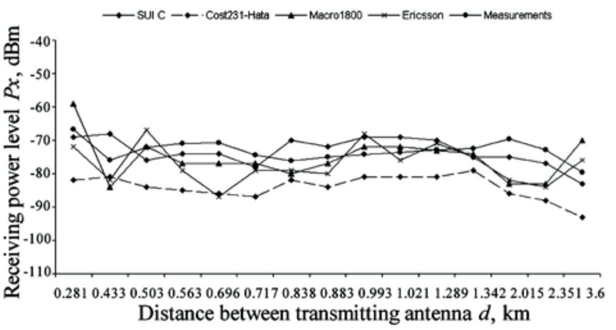

***Figure** 8 Measured and predicted receiving power level for suburban areas*
***Slika** 8. Izmjerene i predviđene razine prijemne snage za suburbana područja*

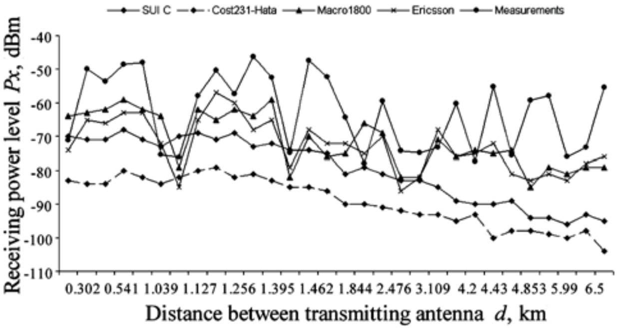

Figure 9 *Measured and predicted receiving power level for rural areas*
Slika 9. *Izmjerene i predviđene razine prijemne snage za ruralna područja*

Results show a quite different situation for different terrain types. In a rural area all propagation models overestimate path loss influence resulting in the fact that in a rural area all models give pessimistic results. A detailed analysis shows that the highest discrepancy between the predicted and the measured values is achieved for locations with LOS propagation conditions. Since there are lots of LOS locations in a rural area it is obvious why propagation models from Tables 5 and 6 cannot be successfully applied to WiMAX signal prediction in rural areas. This problem can be solved if models are combined with the FSL model. The worst result in all propagation conditions is obtained for the Cost231-Hata model where the absolute mean prediction error is between 9,7 dB for the urban area and 26,6 dB for the rural area. Such big differences between measured and predicted values can be explained by the fact that expression for path loss calculation by the Cost231-Hata propagation model was defined in the Tokyo city where the definition for urban, suburban and rural area is not the same as in the city of Osijek.

The situation for urban and suburban areas is much better and the best results are achieved for the SUI C model ($\overline{|\Delta x|}_{\mathrm{SUI\_urban}}$= 3,8 dB, $\sigma_{\mathrm{SUI\_urban}}$= 3,9 dB and $\overline{|\Delta x|}_{\mathrm{SUI\_suburban}}$=4,0 dB, $\sigma_{\mathrm{SUI\_suburban}}$=4,3 dB), while Ericsson and Macro models also gave satisfactory results which can be applied to WiMAX network planning.

To improve prediction in the rural area the Ericcson model was combined with the FSL model. This combination resulted in prediction that better fits propagation environment giving much better results since the mean prediction error is decreased from $\overline{|\Delta x|}_{\mathrm{Ericsson}}$=–10,2 dB to $\overline{|\Delta x|}_{\mathrm{Ericsson+FSL}}$=–1,8 dB, absolute prediction error from $\overline{|\Delta x|}_{\mathrm{Ericsson}}$ = 11,1 dB to $\overline{|\Delta x|}_{\mathrm{Ericsson+FSL}}$ = 3,9 dB and standard deviation from $\sigma_{\mathrm{Ericsson}}$=8,1 dB to $\sigma_{\mathrm{Ericsson+FSL}}$=4,4 dB.

Macro and Ericsson propagation models have parameters which can be calibrated to better describe propagation environment. These parameters were described in Sections 4.2. and 4.3. of this paper. A disadvantage of calibration is that it requires lots of experience, theoretical knowledge for the particular model and calibration time that will finally result in the propagation model which can be applied only to the area for which the model was calibrated.

6
Conclusion
Zaključak

Propagation models are main tools for path loss prediction in wireless systems what is the first step in network design. Although there are lots of different kinds of propagation models none of them can be applied as the universal solution for all kinds of propagation conditions, but choosing the appropriate propagation model depends on system and terrain parameters.

In this paper, we have presented the basic mechanism that theoretically describes propagation methods as well as the propagation models which have been mostly used for the fixed wireless access system signal level prediction. The receiving power level prediction for a WiMAX system at 3,5 GHz is made with four propagation models as an example of the empirical models implementation. To analyze propagation models accuracy depending on propagation conditions, extensive measurements are done on locations in different environments.

In LOS locations all propagation models, except the FSL model, gave very pessimistic results with a very big prediction error. Better results are achieved in NLOS locations where the best result was given by the Macro1800 model with $\overline{|\Delta x|}$ =–1,8 dB, $\overline{|\Delta x|}$ =5,1 dB and σ=5,8 dB.

Upon terrain classification according to terrain type the most accurate result in urban and suburban areas is achieved with the SUI model where the absolute mean prediction errors are $\overline{|\Delta x|}_{\mathrm{SUI\_urban}}$=3,8 dB and $\overline{|\Delta x|}_{\mathrm{SUI\_suburban}}$=4,0 dB. In a rural area all propagation models gave very pessimistic results and the worst result is obtained by the Cost231-Hata model with absolute mean prediction error $\overline{|\Delta x|}_{\mathrm{Cost231\text{-}Hata}}$=26,6 dB. Although SUI gave the best result in suburban and rural areas, a disadvantage of this model is that it does not classify terrain type according to mostly used category, but it has its own classification (terrain types: A, B and C).

This paper also showed that usage of the free space model (FSL model) for locations with the LOS condition as well as locations in a rural area can drastically improve prediction accuracy.

7
References
Reference

[1] Okumura, Y.; Ohmori, E.; Kawano, T.; Fukuda, K. Field strength and its variability in VHF and UHF land-mobile radio service. // Rev. Electr. Commun. Lab. 16, 9, 10(1968), pp. 825-873.

[2] Hata, M. Empirical formula for propagation loss in land mobile radio services // IEEE Trans. Veh. Tech. VT-29(1980), pp. 317-325.

[3] COST Action 231; Digital mobile radio towards future generation systems, final report. // Tech. rep. European Communities. EUR 18957(1999)

[4] Walfisch, J.; Bertoni, H. L. A theoretical model of UHF propagation in urban environments. // IEEE Trans. Antennas Propagation. 36,12(1988), pp. 1788-1796.

[5] Erricolo, D.; Uslenghi, P. L. E. Propagation path loss – a comparison between ray-tracing approach and empirical models. // IEEE Trans. Antennas Propagation. 50, 5(2002), pp. 766-768

[6] Propagation data and prediction methods for the planning of short-range outdoor radio communication systems and radio local area networks in the frequency range 300 MHz to 100 GHz. Rec. ITU-R P.1411-1

[7] Kwak, D. Y.; Lee, C. H.; Kim, S. C.; Lim, J. W.; Lee, S. S. Enhanced urban path loss prediction model with new correction factors. // IEICE Trans. Commun. E89-B, 4(2006), pp. 1459-1463.

[8] Abhayawardhana, V. S.; Wassell, I. J.; Crosby, D.; Sellars, M. P.; Brown, M. G. Comparison of empirical propagation path loss for fixed wireless access systems. // Proc. IEEE Veh. Tech. Conf. (2005), pp. 73-77.

[9] Zhao, X.; Rautiainen, T.; Kalliola, K.; Vainikainen, P. Path-loss models for urban microcells at 5.3 GHz. // IEEE Antennas and Wireless Propagation Letters. 5(2006), pp.152-154.
[10] Saunders, S. R. Antennas and propagation for wireless communication systems. John Wiley&Sons, Inc.1999.
[11] Blaunstein, N. Radio propagation in cellular networks, Artech House, Inc. 1999.
[12] Parsons, J. D. The mobile radio propagation channel, John Wiley&Sons, Inc. 2000.
[13] Sarkar, Z. K.; Ji, Z.; Kim, K.; Medouri, A.; Salazar-Palma, M. A Survey of Various Propagation Models for Mobile Communication. // IEEE Antennas and Propagation Magazine, 45, 3(2003), pp.51-82
[14] Belloni, F. Fading models. // Post. Course in Radio Commun.// Sign. Process. Lab., HUT, 2004., pp.1-4.
[15] Karasawa, Y. Statistical multipath propagation modeling for broadband wireless systems. // IEICE Trans. Commun. E-90-B(2007), pp. 468-484.
[16] Cellular expert tehnical reference, pp. 32-40
[17] EET-Ericsson Engineering Tool, User reference guide. Ericsson Radio System AB, 1997.
[18] Afric, W.; Matosic, N.; Vakante, D. WiMAX on 3,5 GHz cell size calculation. // Proc. of 48th Inter. Sympos. ELMAR, 2006. pp. 195-198.
[19] Milanovic, J.; Rimac-Drlje, S.; Bejuk, K. Comparison of Propagation Models Accuracy for WiMAX on 3.5 GHz. Proc. of IEEE 14th ICECS, 2007.
[20] Rimac-Drlje, S.; Milanovic, J.; Stresnjak, S. Receiving Power Level Prediction for WiMAX Systems on 3.5 GHz, Proc. of IEEE WCNC, 2009.
[21] Mach, P.; Bestak, R. WiMAX Performance evaluation. Proc. of IEEE 6th Conf. on Networking (ICN'07), 2007.
[22] Figueiredo, F. L.; Cardieri, P. Coverage prediction and performance evaluation of wireless metropolitan area networks based on IEEE 802.16. Journal of Commun. and Inform. Systems, 20, (2005), pp.132-140.

Authors' addresses
Adrese autora

Mr.sc. Josip Milanović
Croatian Post and Electronic Communication Agency
Osijek, Croatia
josip.milanovic@hakom.hr

Prof.dr.sc. Snježana Rimac-Drlje
University of Osijek, Faculty of Electrical Engineering
Osijek, Croatia
snjezana.rimac@etfos.hr

Ivo Majerski
Croatian Post and Electronic Communication Agency
Zagreb, Croatia
ivo.majerski@hakom.hr