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MODERN APPROACHES IN MODELING OF MOBILE RADIO SYSTEMS PROPAGATION ENVIRONMENT

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ABSTRACT

In this article a review of popular propagation models for wireless communication channels is given. Macrocell, microcell, and indoor prediction methods are considered separately. Advantages and disadvantages of these models are discussed. Also, some practical improvements of the existing models as well as some new models are given.

Over the few past decades, radio communication systems underwent extensive development. The demands that a radio system must fulfill are greater by the day. Having in mind good quality and cost effective solutions, a new radio system must be designed carefully from the very beginning. The first step in the process of a new radio system design is to determine base station arrangement and a frequency plan, both of which are chiefly dependent on environmental characteristics.

One of the most important characteristics of the propagation environment is the path (propagation) loss. An accurate estimation of the propagation losses provides a good basis for a proper selection of base station locations and a proper determination of the frequency plan. By knowing propagation losses, one can efficiently determine the field signal strength, signal-to-noise ratio (SNR), carrier-to-interference (C/I) ratio, etc.

An accurate prediction of the field strength level is a very complex and difficult task. To date, various field strength prediction methods have been proposed in the literature. This article presents an overview of popular prediction models and describes some useful algorithms that are based on the authors' experience, to improve their accuracy. It should be noted that in most cases the models presented predict a local average value (median, mean, slow fading) which is of particular interest for those system engineers who are putting radio-systems in operation. Otherwise, models of time dispersion parameters, which are very important for device designers, are not considered.

The main propagation mechanisms of the radio signal are described. Definitions and some basic characteristics of the propagation models are given. Macrocell, microcell, and indoor propagation models are considered in detail in the later sections. In these sections, an overview of popular prediction models is given. Their advantages and disadvantages are discussed, and in addition, some practical improvements of these models, along with some new models, are described.

PROPAGATION PHENOMENA

Propagation mechanisms are very complex and diverse. First, because of the separation between the receiver and the transmitter, attenuation of the signal strength occurs. In addition, the signal propagates by means of diffraction, scattering, reflection, transmission, refraction, etc.

Diffraction occurs when the direct line-of-sight (LoS) propagation between the transmitter and the receiver is obstructed by an opaque obstacle whose dimensions are considerably larger than the signal wavelength. The diffraction occurs at the obstacle edges where the radio waves are scattered, and as a result, they are additionally attenuated. The diffraction mechanism allows the reception of radio signals when the LoS conditions are not satisfied (NLoS case), whether in urban or rural environments.

Scattering occurs when the propagation path contains the obstacles whose dimensions are comparable to the wavelength. The nature of this phenomenon is similar to the diffraction, except that the radio waves are scattered in a greater number of directions. Of all the mentioned effects, scattering is the most difficult to be predicted.

Reflection occurs when the radio wave impinges the obstacle whose dimensions are considerably larger than the wavelength of the incident wave. A reflected wave can either decrease or increase the signal level at the reception point. In cases where many reflected waves exist, the received signal level tends to be very unstable. This phenomenon is commonly referred to as multipath fading, and the signal is often Rayleigh distributed.

Transmission occurs when the radio wave encounters an obstacle that is to some extent transparent for the radio waves. This mechanism allows the reception of radio signals inside buildings in cases where the actual transmitter locations are either outdoors or indoors.

Refraction is very important in macrocell radio system design. Due to an inconstant refractive index of the atmosphere, the radio waves do not propagate along a straight line, but rather along a curved one. Therefore, the coverage area of an actual transmitter is usually larger. However, as a result of the fluctuations of the atmosphere parameters, the received signal strength level is fluctuating as well.

Since there is frequently no LoS between the transmitter and the receiver, the received signal is a sum of components that often stem from several previously described phenomena. Therefore, the received signal level is quite variable with respect to time and especially with respect to the receiver or transmitter displacement. Even a displacement of just a fraction of the wavelength can cause the signal level to change by more than 30dB. These fluctuations are known as short-term (or multipath) fading. On the other hand, the local average of the signal varies slowly with the displacement. These slow fluctuations depend mostly on environmental characteristics, and they are known as long-term fading. Both slow and fast fading are illustrated in Fig. 1.

Since the short-term fading of the received signal is almost impossible to predict, all propagation models estimate either the average or median values. When averaging is performed, the width of the averaging window should be chosen carefully. A window that is too narrow results in uncertain averages, while a window that is too wide can wash out the detailed signal changes depending on the local environment. Typically, a suitable window width for applications in the bigger areas is $\pm 20\lambda$ [1], while in smaller areas the window must be narrower.

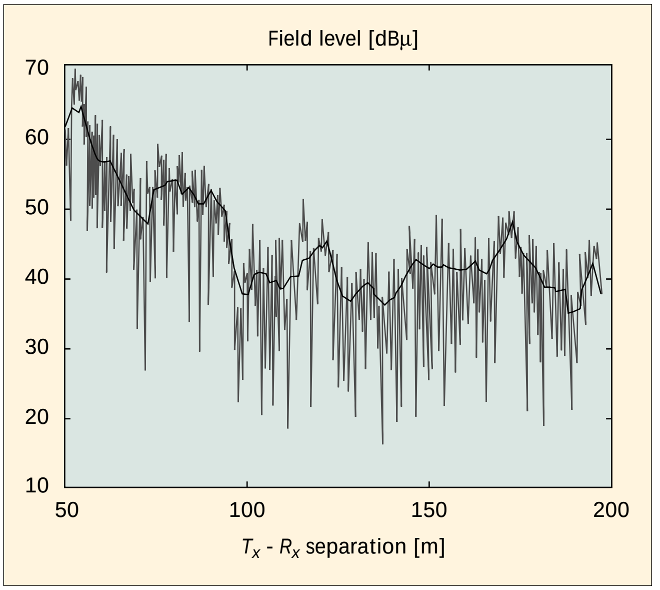


FIGURE 1. *Typical field level variations with respect to displacement. The signal level varies rapidly (short-term fading). Local average varies slowly (long-term fading).*

PROPAGATION MODELS

A propagation model is a set of mathematical expressions, diagrams, and algorithms used to represent the radio characteristics of a given environment. Generally, the prediction models can be either empirical (also called statistical) or theoretical (also called deterministic), or a combination of these two. While the empirical models are based on measurements, the theoretical models deal with the fundamental principles of radio wave propagation phenomena.

In the empirical models, all environmental influences are implicitly taken into account regardless of whether they can be separately recognized. This is the main advantage of these models. On the other hand, the accuracy of these models depends not only on the accuracy of the measurements, but also on the similarities between the environment to be analyzed and the environment where the measurements are carried out. The computational efficiency of these models is usually satisfying.

The deterministic models are based on the principles of physics and, due to that, they can be applied to different environments without affecting the accuracy. In practice, their implementation usually requires a huge database of environmental characteristics, which is sometimes either impractical or impossible to obtain. The algorithms used by deterministic models are usually very complex and lack computational efficiency. For that reason, the implementation of the deterministic models is commonly restricted to smaller areas of microcell or indoor environments. Nevertheless, if the deterministic models are implemented correctly, greater accuracy of the prediction can be expected than in the case of the empirical models.

On the basis of the radio environment, the prediction models can be classified into two main categories, outdoor and indoor propagation models. Further, in respect of the size of the coverage area, the outdoor propagation models can be subdivided into two additional classes, macrocell and microcell prediction models.

MACROCELL PROPAGATION MODELS

Macrocell design philosophy is based on the assumptions of high radiation centerlines, usually placed above the surroundings; transmitter powers on the order of several tens of Watts; and large cells whose dimensions are on the order of several tens of kilometers. Under these assumptions, LoS conditions are usually not satisfied and the signal from the transmitter to the receiver propagates by means of the diffraction and the reflection. Also, for large cells the effects of refraction are very important. All of these factors make the problem of field strength prediction very difficult. For years, a large number of researchers have been struggling with this problem. As a result a large number of models have been proposed. The list includes, but is not limited to: the Bullington model [2], the model of Okumura *et al.* [3], the ITU (CCIR) model [4], the Hata model [5], the "Clearance angle" method [6], the Polish Administration method [7], the Longley-Rice method [8], the Lee model [9], the EPM-73 method [10], the Deutche Bundest Post (DBP) method [11], the Ibrahim-Parsons model [12], the Atefi-Parsons model [13], the Joint Radio Committee (JRC) model [14], the TIREM model [10], the Walfish-Bertoni model [10, 15], the Ikegami method [16, 17], the IRT method [18], the ETF-ANN Macrocell Model [19], the Ericsson model 9999 [20], etc. In the following text, only a few very popular models are discussed.

MODEL OF OKUMURA *ET AL.*

The Okumura *et al.* method [3] is based on empirical data collected in detailed propagation tests over various situations of an irregular terrain and environmental clutter. The results are analyzed statistically and compiled into diagrams. The basic prediction of the median field strength is obtained for the quasi-smooth terrain in the urban area. The correction factor for either an open area or a suburban area should be taken into account. The additional correction factors, such as for a rolling hilly terrain, the isolated mountain, mixed land-sea paths, street direction, general slope of the terrain etc., make the final prediction closer to the actual field strength values.

In the present engineering practice, the Okumura *et al.* method is widely used. This is a method originally intended for VHF and UHF land-mobile radio systems and involves neither complex computations nor an elaborate theory. Much of its experimental data have been incorporated in the ITU (CCIR) reference curves as well as in other popular models.

However, many authors [9, 21, 23] show certain reserve toward the application of the Okumura model. They note that extensive data regarding its performance must be obtained before its use may be advocated. In addition, more careful interpretation of the definitions of various parameters needs to be made. When assessing the values of the model's parameters, the influence of the subjective factors is not easy to avoid, thus yielding different results for the same problem.

In order to make the Okumura technique suitable for computer implementation, Hata has developed the analytic expressions for the medium path loss for urban, suburban, and open areas [5, 22]. Although these expressions are only approximations and therefore have some limitations, they are almost always used in practice instead of the basic Okumura curves.

Location type	Urban transmitter site		Rural transmitter site	
	K_1* [dB]	σ_1 [dB]	K_2 [dB]	σ_2 [dB]
A	–8.9	13.9	–10.6	14.4
B	–4.5	11.4	–4.5	9.8
C	–6.9	11.4	–5.5	14.0
D	–4.2	10.3	–3.1	12.7
E	+0.6	9.7	–0.5	11.4
F	–5.8	19.5	–13.2	13.5
G	+8.4	11.7	+9.0	12.2
H	–12.4	5.5	–16.2	7.6

*) K - correction. σ - standard deviation of error

Table 1. *"Clearance angle" correction factors.*

ITU (CCIR) Model

The CCIR [4] method is based on the statistical analysis of a considerable amount of experimental data obtained by measurements in many countries. The curves for the field strength prediction refer to the kind of rolling irregular terrain found in many parts of Europe and North America, for which a value of parameter Δh, defining the degree of terrain irregularity of 50m, is considered representative. Parameter Δh is defined as the difference in the heights exceeded by 10 percent and 90 percent of the terrain over propagation paths in the range of 10km to 50km from the transmitter. To determine the field strength over any irregular terrain, the attenuation correction factor dependent upon Δh and given in the form of diagrams should be subtracted from the value read from the reference field strength curves. However, many papers ([4] Rep. 239, [8] and [23]) have demonstrated the single parameter Δh to be inadequate for precise determination of the attenuation correction factor. In addition, the local terrain effects in the region of the receiving area are in no way taken into account when applying the CCIR method. Finally, the field strength reference curves given in [4], Rep. 567 are deduced from the curves given in [4], Rec. 370. The original curves are intended for use in planning broadcasting services for the solution of interference problems over a wide area and not for point-to-point communications. Therefore, for rural environments it is not unusual to find the median field strength to differ by more than 20dB with respect to the predicted value. In urban areas the error can be even greater. As a consequence, the ITU model is used rarely in its basic form. However, due to its simplicity the model is used for frequency coordination and frequency planning purposes in the border areas (for example, between countries).

"Clearance Angle" Method

The "clearance angle" method [6] is proposed by the European Broadcasting Union (EBU), and adopted by CCIR ([4], Rep. 239). The main ideas of the method have been to retain the CCIR reference field strength curves given in [4], Rec. 370, the simplicity of application, and to improve the accuracy by taking into account the terrain effects in the region of the receiving area, since the latter are not always adequately represented by parameter Δh. These terrain effects are incorporated through the correction based on a "terrain clearance angle." This angle should be a representative of those angles in the reception area measured between the horizontal line at the receiving antenna, and that which clears all obstacles within 16km in the direction of the transmitter. The correction factor in terms of the "clearance angle" is given in the form of two curves, one for VHF and the other for the UHF band. The curves are derived through an optimization process and are the results of calculations of the field strength on more than 200 paths in Europe and their comparison to the results obtained by the CCIR method. This correction factor should be added to the field strength level obtained from the CCIR reference curves given in ([4], Rec. 370).

In its very nature the "clearance angle" model as well as many other models predict the field level in the rural environment. The effects of urbanization, forests, overpasses, underpasses, etc., must be taken into account through the appropriate additional correction factors. These corrections, which to a great extent depend on the specific environment, can be easily determined through measurements. An example of the "clearance angle" corrections determined for the area of the city of Belgrade (which is a typical Mediterranean city with a population of two million) is presented in Table 1 [24]. In this case, the eight location types are defined as:

A Dense urban areas (5-10 floor buildings)
B Urban areas with high buildings (15-25 floors) that are several hundred meters distanced from each other
C Suburban areas
D Residential areas
E Rural areas
F Forests and park lands
G Bridges and overpasses
H Tunnels and underpasses less than 50m in length

It should be noted that the signal in urban environments not only undergoes additional attenuation, but because of many obstructions, it also fluctuates more rapidly. As a result, the standard deviation of the prediction error is usually greater in urban environments than in rural ones [23, 24].

Based on numerous field strength measurements and laborious statistical processing, the "clearance angle" method achieves quite remarkable prediction accuracy [23, 24]. In addition, this model is very operative, not complex, deprived of the subjective factors, and exceptionally well suited for computer implementation. Therefore, many old analog systems (conventional systems, trunking systems, etc.) as well as digital mobile radio systems (paging, NMT, GSM, etc.) have been designed by employing the "clearance angle" model.

ERICSSON MODEL 9999

Model 9999 [20] was developed (and extensively used) by Ericsson engineers and engineers employed in companies supported by Ericsson for the purpose of designing a cellular system (especially for NMT, GSM, PCS, DCS, etc.). This prediction model is based on the Okumura-Hata model, and has the form of a very simple analytical expression containing several free parameters. In addition, the model takes into account extra losses due to "knife-edge" diffraction over a dominant obstacle and the earth's curvature. Also, Model 9999 requires clutter (land usage) database.

The model-free parameters and correction factors of each clutter type are determined empirically for any specific environment. Due to the simplicity of the model, its accuracy is very sensitive to the accuracy of measurement data to which the model is adjusted. Usually, prior to the implementation of the model, extensive test measurements are carried out in order to collect the data. It should be noted that Model 9999's main advantage is that it is very fast.

LEE MODEL

W. C. Y. Lee proposed this model in 1982 [9]. In a very short time it became widely popular among researchers and system engineers (especially among those employed in U.S. companies) mainly because the parameters of the model can be easily adjusted to the local environment by additional field measurements. By doing so, greater accuracy of the model can be achieved. In addition, the prediction algorithm is simple and fast. Various radio systems are designed by using this model (AMPS, DAMPS, GSM, IS-95, PCS, etc.).

The model consists of two parts. The first part, an *area-to-area* prediction, is used to predict a path loss over a general flat terrain without taking into account the particular terrain configuration. Obviously, the *area-to-area* prediction alone is inadequate for hilly regions. The second part of the Lee model uses the *area-to-area* prediction as a basis and then develops a *point-to-point* prediction, thus resolving the problem. Based on the terrain profile database, the *point-to-point* prediction considers whether LoS conditions exist or not. In the case of LoS existence, the influence of the reflected radio waves is carefully examined. On the other hand, when LoS existence is missing, the obstructions are modeled in the form of "knife-edges" and diffracted waves are computed.

The basic *area-to-area* model can be expressed in the following form:

$$P_r = P_{r0}\left(\frac{r}{r_0}\right)^{-\gamma}\left(\frac{f}{f_0}\right)^{-n}\alpha_0 \qquad (1)$$

Type of environment	P_0 [dBm]*	γ [dB/dec]*
Rural area	-57.0	40.3
Forest or parkland	-57.0	44.5
Residential area	-57.0	47.0
Suburban area	-59.2	47.3
Urban area (building height: up to 4 floors)	-61.5	35.4
Urban area with distant high buildings (15–25 floors	-61.5	37.3
Dense urban area (building height: up to 4 floors)	-61.5	55.8
Dense urban area (building height: over 6 floors)	-61.5	56.9
*) P_T = 10W, f = 900 MHz, r_0 = 1 mile, g_r = 6 dBd, g_r = 0dBd, h_T = 30m, h_r = 3m.		

Table 2. *Lee model attributes.*

where P_r is the signal power in W at distance r from the transmitter; for the signal frequency f, P_{r0} is the signal power at the point of interception at distance r_0 from the transmitter; for the reference frequency f_0, γ denotes path-loss slope, n denotes frequency dependence, while α_0 is an adjustment factor for antenna heights, transmitter power, and antenna gains. The basic area-to-area model can be extended to a more general case when the radio wave propagates along several different environments. In that case, the path loss slopes γ_i as well as the boundaries of each environment must be known. The parameters of Eq. (1) depending on the environment are P_{r0} and γ. For several specific environments, mostly in the United States, Lee found values of P_{r0} and γ [9]. It should be noted that the estimation accuracy mainly depends on these parameters and thus they must be as precise as possible. The parameters P_{r0} and γ for the particular environment can be easily determined through measurements of signal strength. The results of the extensive propagation study carried out in the area of Belgrade are shown in Table 2 [25]. The results for this urban environment are different from parameters obtained by Lee himself. This can be easily explained by the fact that the structure of a Mediterranean city is completely different from the structure of a typical American town.

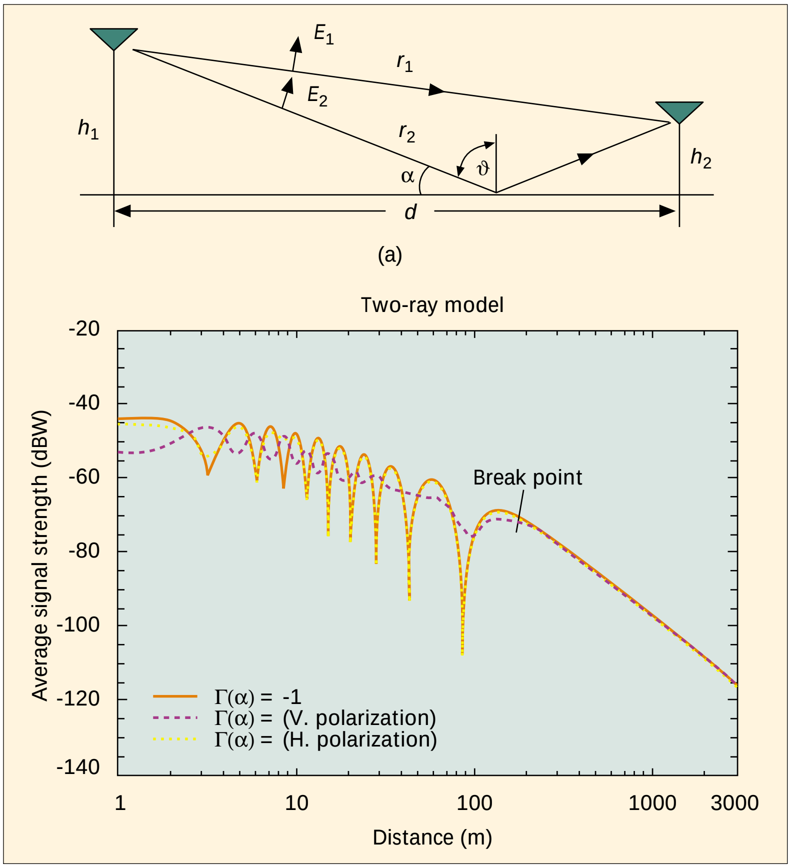
COST 231-WALFISCH-IKEGAMI MODEL

The COST 231-Walfisch-Ikegami model (COST 231-WI) [26] has been used extensively in typical suburban and urban environments where the building heights are quasi-uniform. It should be noted that the designers of public mobile radio systems (e.g., GSM, PCS, DECT, DCS, etc.) often use this model.

The model utilizes the theoretical Walfisch-Bertoni model [15] to obtain multiple screen forward diffraction loss for high base station antenna heights, whereas it uses measurement-based data for low base station antenna heights. This model also takes into account free-space loss, loss due to diffraction down to the street, and the street orientation factor.

Steep transitions of path loss occur when the base station antenna height is close to the height of the rooftops of the buildings in its vicinity. Therefore, the height accuracy of the base station antenna is especially significant if large prediction errors are to be avoided. Moreover, the performance of the Walfisch-Ikegami model is poor when the base station antenna height is significantly lower than the heights of the rooftops of adjacent buildings.

It was claimed, as the expected accuracy of the model, that the mean error is in the range of ±3dB and the standard deviation is about 4–8dB in the case when the base station antenna height is several meters above the highest rooftops of adjacent buildings within a radius of approximately 150m. However, recently it was found that the loss expression for the diffraction from the last rooftop to the street in the COST 231–WI model is over 8dB more optimistic than it is supposed to be [27].



■ **FIGURE 2.** *Two-ray model: a) the ray paths; b) the receiving power* $P_t = 1W$, $f = 900MHz$, $h_1 = 8.7m$ *and* $h_2 = 1.6m$ *[32].*

ETF-ARTIFICIAL NEURAL NETWORKS MACROCELL MODEL

Recently, several prediction models utilizing artificial neural networks (ANN) [19, 28] have been proposed. The main intention of the work presented in [19] was to form a good prediction model, i.e., the model that can ensure high accuracy (exceeding the accuracy of the most popular models) in real time that uses just ordinary (easily obtainable) databases.

The ANN model, proposed in [19], is based on a very popular feed-forward neural network architecture (precisely, multilayer perceptron) [29]. Feed-forward neural networks with sigmodial activation functions have demonstrated very good performance in solving problems with mild nonlinearities on the set of noisy data. That case fully corresponds to the problem of the field strength prediction. The data obtained by measurements are always noisy. Another key feature of neural networks is the intrinsic parallelism allowing for a fast evaluation of solutions. The process of learning may last for a couple of hours, but the process of field strength prediction is fast.

The proposed neural network has three groups of inputs. The first group consists of an input only and it is the normalized distance from the transmitter to the receiver. The second group of inputs (4 inputs) is based on the terrain profile analysis. These inputs are: 1) portion through the terrain; 2) and 3) modified "clearance angle" factors for both the transmitter and the receiver sites, respectively; and 4) the rolling factor. The third group of input parameters is based on the land category analysis along the straight line drawn between the transmitter and the receiver. There is a single input for each defined land use category. The network has one output and it is a normalized electric field level. The implementation of the proposed ANN model requires two databases. The first is the standard digital terrain elevation database; the other is the ground cover (i.e., land usage or "clutter") database.

In comparison to other popular prediction models, the ANN model demonstrated very good performance. The effects of urbanization are considered more subtly in the proposed model than in standard empirical models providing greater accuracy. On the other hand, the ANN model is not computationally as extensive as deterministic models.

The ANN model has been realized and used in 450MHz and 900MHz frequency bands for the purpose of TETRA and GSM system design, respectively.

MICROCELL PROPAGATION MODELS

A microcell is a relatively small outdoor area such as a street with the base station antenna below the rooftops of the surrounding buildings. The coverage area is smaller compared to macrocells and it is shaped by surrounding buildings. A microcell enables an efficient use of the limited frequency spectrum and it provides a cheaper infrastructure. The main assumptions are relatively short radio paths (on the order of 200m to 1000m), low base station antennas (on the order of 3m to 10m), and low transmitting powers (on the order of 10mW to 1W). Today, microcells are very often used in IS-95, PCS, DCS, GSM, DECT, etc.

There are many prediction models for a microcell situation. In this article, the authors present a review of some interesting models that are extensively used in the process of designing previously mentioned radio systems.

EMPIRICAL MODELS

The models proposed in [30, 31] describe the measured signal level along the line-of-sight path. According to these models, the road-guided waves are expected to exist only for short ranges. This situation can be described by two distinct path-loss slopes and a break point. The break point is the distance from the base station that is equal to the maximum distance that has the I Fresnnel zone clear. The break point can be used to define the size of a microcell because the signal level decreases more rapidly when the distance increases after the break point.

The form of the proposed propagation models is given by:

$$S = -20\log\{d^a \cdot (1 + d/g)^b\} + c \qquad (2)$$

where S is the signal level in dBμV/m, d is a distance from the transmitting antenna (m), a is the basic attenuation rate for short distances, b is the additional attenuation rate coefficient for the distance greater than 100 to 200m, g is the distance to the break point, and c is a scaleable factor. The expression is valid for 5 – 20m antenna heights and 200m – 1km distances.

This model, whose coefficients are relatively independent, has two boundary cases:

- At distances less than the break point, the form of the propagation model is:

$$S = -20\log d^a + c \qquad (3)$$

- At distances greater than the break point, the form of the propagation model is:

$$S = -20\log d^{(a+b)} + c + const. \qquad (4)$$

In addition, the signal around the corner decreases by 20 – 25dB in a short transition distance of only several tens of meters.

It was shown that for the same conditions, the results of the proposed models [30, 31] for a microcell situation are better than those of the normal linear regression and the Okumura model.

TWO-RAY MODEL

Numerous propagation models for microcells are based on a ray-optic theory. In comparison with the case of macrocells, the prediction of microcell coverage based on the ray-model is more accurate. One of the elementary models is the two-ray model. The two-ray model [32] is used for modeling of the LoS radio channel and it is described in Fig. 2a.

The transmitting antenna of height h_1 and the receiving antenna of height h_2 are placed at distance d from each other. The received signal P_r for isotropic antennas, obtained by summing the contribution from each ray, can be expressed as:

$$P_r = P_t\left(\frac{\lambda}{4\pi}\right)^2 \left|\frac{1}{r_1}\exp(-jkr_1)+\Gamma(\alpha)\frac{1}{r_2}\exp(-jkr_2)\right|^2 \qquad (5)$$

where P_t is the transmitter power, r_1 is the direct distance from the transmitter to the receiver, r_2 is the distance through reflection on the ground, and $\Gamma(\alpha)$ is the reflection coefficient depending on the angle of incidence α and the polarization.

The reflection coefficient is given by:

$$\Gamma(\theta) = \frac{\cos\theta - a\sqrt{\varepsilon_r - \sin^2\theta}}{\cos\theta + a\sqrt{\varepsilon_r - \sin^2\theta}} \qquad (6)$$

where $\theta = 90°-\alpha$ and $a = 1/\varepsilon$ or 1 for vertical or horizontal polarization, respectively. ε_r is a relative dielectric constant of the ground.

In Fig. 2b the received power given by Eq. (5) is shown as a function of the distance for the cases of horizontal and vertical polarizations as well as for the case assuming $\Gamma(\theta) = -1$. For large distances α is small, and $\Gamma(\theta)$ is approximately equal to –1. For short distances, the value of $\Gamma(\theta)$ decreases and it can even be zero for vertical polarization.

Also, there are more complex models based on the ray-optic theory. The four-ray model consists of a direct ray, ground-reflected ray, and two rays reflected by buildings. The six-ray model, besides the direct and the ground-reflected ray, takes four rays reflected by the building walls along the street. If a model considers a larger number of rays, the prediction tends to be more accurate, but the computational time is significantly increased. The problem deserving special attention is that of the corner diffraction. Two popular models considering this effect are the GTD (Geometrical Theory of Diffraction) model [33], and the UTD (Uniform Theory of Diffraction) model [34].

MODELS BASED ON UTD AND MULTIPLE IMAGE THEORY

One of the proposed models is quasi three-dimensional UTD propagation model [35], which functions well for microcellular applications. A multiple image concept and generalized Fermat's principle are used to describe the multiple reflections and diffractions. It is assumed that the building walls are much higher than the transmitter height so that the diffraction from the rooftops can be neglected. The model considers various line-of-sight propagation paths and, also, non-line-of-sight paths. The propagation paths taking a large number of corners and building walls are not necessarily coplanar. This model includes multiple reflections between wall-to-wall, wall-to-ground, ground-to-wall, the diffraction from the corners of buildings, and, also subsequent reflections from such diffracted signals. The relative contributions of the diffraction and reflection components to the total received signal along a side street depend on the parameters such as the widths of the main street, side streets, parallel streets, the distance from the transmitter to the junction, the reflectivity of the surfaces, etc.

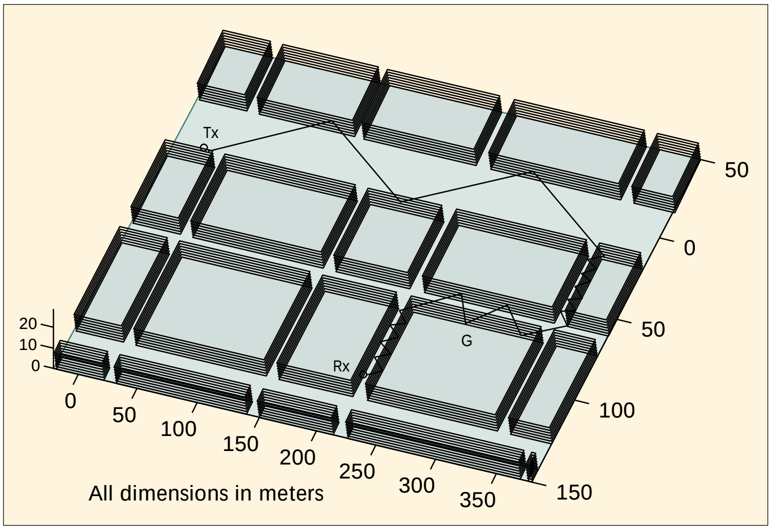


FIGURE 3. *Typical ray path of a street grid [35].*

The location and the sequence of all images have to be determined for making use of the multiple image concept. A "test ray," or ray-launching technique, is used on the plan view of the street grid (Fig. 3). The intersection of a ray with an object is the fundamental operation in the ray-launching technique. This image concept makes the determination of the exact point of reflection at a wall or at the ground surface. In the case of diffraction, the location of the point of diffraction at an edge has to be determined. The local ray-fixed coordinate system or edge-fixed coordinate system and appropriate reflection or diffraction coefficients are used for each reflection or diffraction. The accuracy of this model is limited mainly by the assumptions of characterizing the tall building walls as "smoothed-out" flat surfaces with average relative permittivity ε_r and conductivity σ.

The UTD mode considers a single ray at a time. Naturally, many rays will contribute to the received signal at a particular location R_x. The UTD approach takes the vector sum of all the reflected and diffracted rays. In general, a total of j multiple wall reflections from the main street, side streets, parallel streets, and, at most, one ground reflection, with or without diffractions from the building corners at the junctions can arrive at R_x. This is equivalent to including the multiple transmitter images. Since each reflection or diffraction causes a loss in signal strength, the value of j will depend on the values of σ and ε_r of the walls and ground surfaces as well as the geometry of the environment.

LEE MICROCELL MODEL

The Lee model for predicting the electric field in microcells [9] assumes that there is a high correlation between the signal attenuation and the total depth of building blocks along the radio path. This assumption is not entirely true because the signal received at the mobile unit comes from the multipath

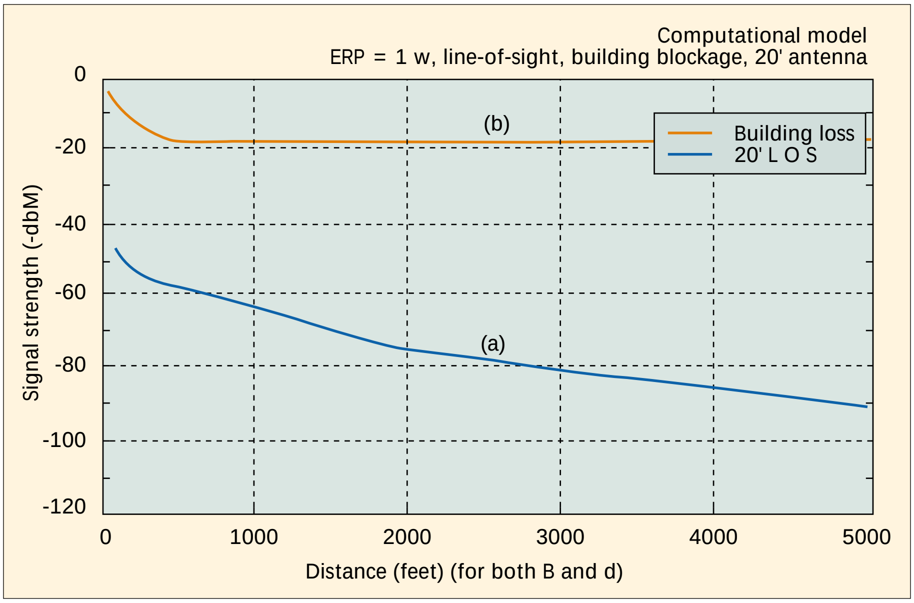


FIGURE 4. *Microcell prediction parameters: a) line-of-sight path loss P_{los}: b) the α_B due to the building blockage [9].*

reflected waves and not from the waves penetrating through the buildings. However, according to the assumption, if the building blocks are larger, the signal attenuation is higher. An aerial photograph can be used to calculate the proportional length of a direct wave path being attenuated by the building blocks. The line-of-sight signal reception curve P_{los} is determined from the measurement data along the streets in an open line-of-sight condition. The additional signal attenuation α_B curve due to the portion of building blocks over the direct path can be obtained in the following way:

- Calculate the total blockage length by adding the individual building blocks.
- Measure the signal strength P_{los} for a line-of-sight condition.
- Measure the signal strength P_{nlos} for a non-line-of-sight condition.
- If the signal level at a particular point is P_{nlos}, the distance from the base to the mobile unit is d_A, and B is the blockage length between the transmitter and the receiver, then the value of α_B for a blockage B can be expressed as:

$$\alpha_B(B) = P_{los}(d = d_A) - P_{nlos} . \quad (7)$$

The additional signal attenuation α_B curve based on the building blockage and the line-of-sight measured path loss are shown in Fig. 4. These curves are found experimentally [9]. A series of measurements have been done for different antenna heights in LoS conditions along many streets, and it is observed that the antenna height gain for different antenna heights is 30dB/dec.

In conclusion, in a microcell prediction model, two curves P_{los} and α_B are used to predict the received signal strength. Therefore, the microcell prediction model is given by:

$$P_r = P_{los} - \alpha_B \quad (8)$$

The original Lee model exhibits large errors in the following situations:

- When the prediction point is in the main street, but there is no direct LoS path.
- When the prediction point is in a side street near an intersection and large building blocks exist between the point of prediction and the transmitter (the case when the side street and the transmitter location are on the same side of the main street).

The accuracy of the model can be significantly improved by introducing specific corrections based on the arrangement of the streets and their types [36, 37]. There are significant differences in the propagation of radio waves in different types of streets. (For example, a main street under LoS conditions, a main street under NLoS conditions, a narrow side street, a wide side street, and a street parallel to the main). After these corrections are added to the model, the signal level in side streets and in the main street under NLoS conditions is given by:

$$P_{nlos}[\mathrm{dB}] = P_{los}(\mathit{LoS\text{-}distance}) - \alpha_{st}(\mathit{NLoS\text{-}distance}) \quad (9)$$

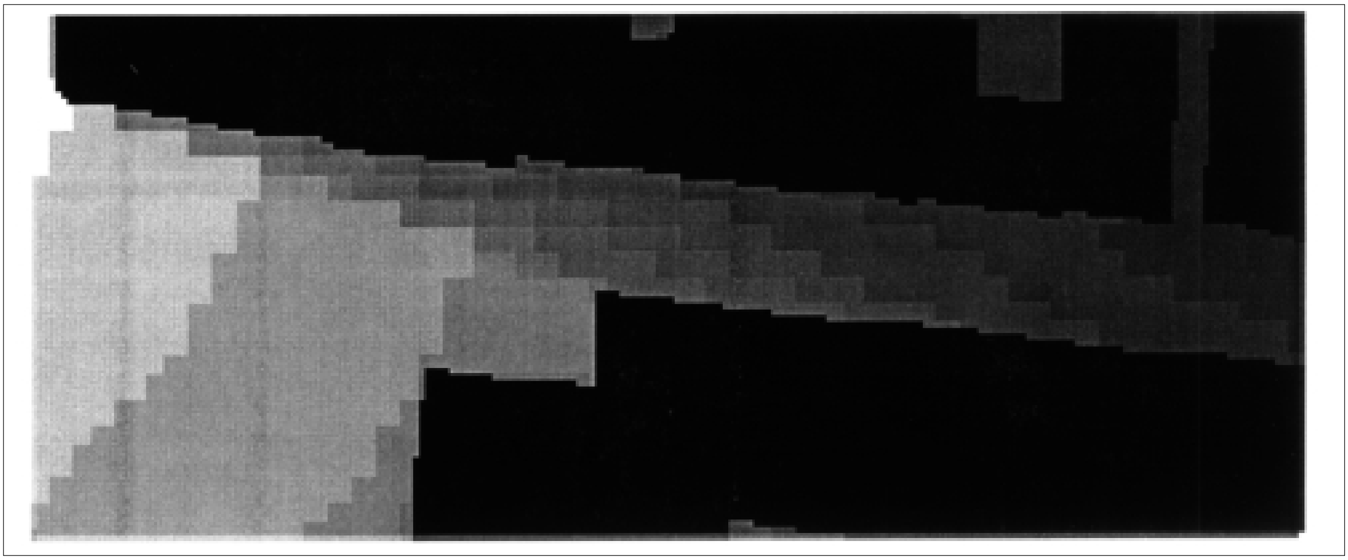
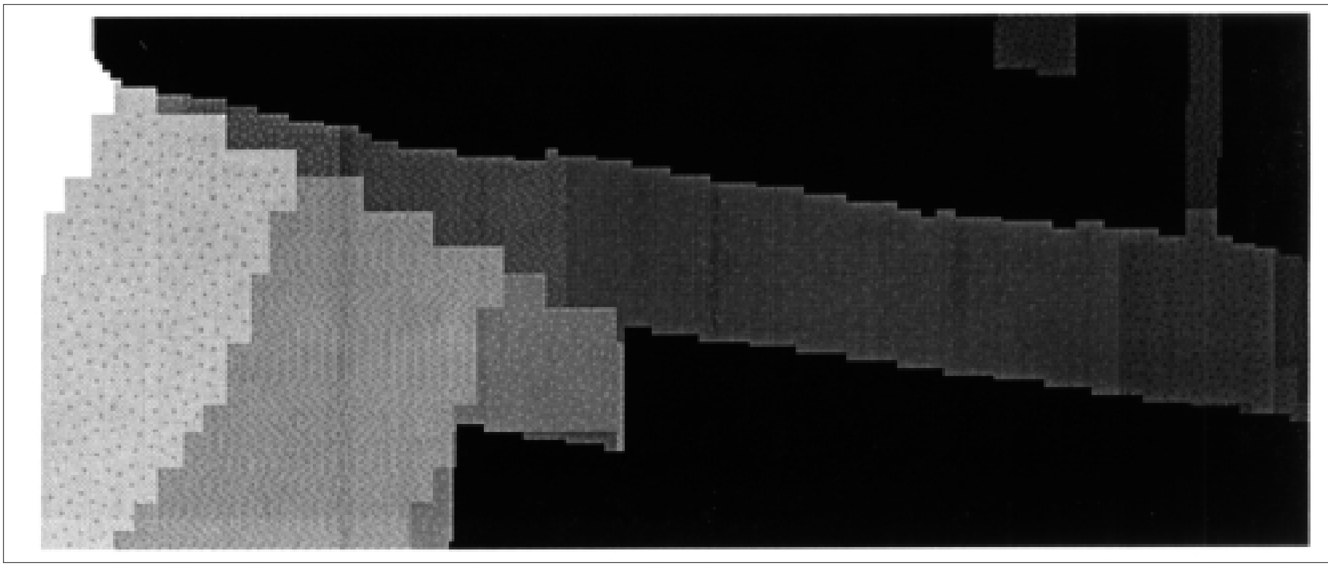


FIGURE 5. *The result of prediction based on the Lee model.*



■ **FIGURE 6.** *The result of prediction based on the improved Lee model.*

where P_{nlos} is the estimated signal level in the street under NLoS propagation conditions, P_{los} is the signal level on the LoS path at the intersection of the main and side street (at a *LoS-distance* from the transmitter), and α_{st} is the correction of the signal level in the side street at the *NLoS-distance* from the intersection.

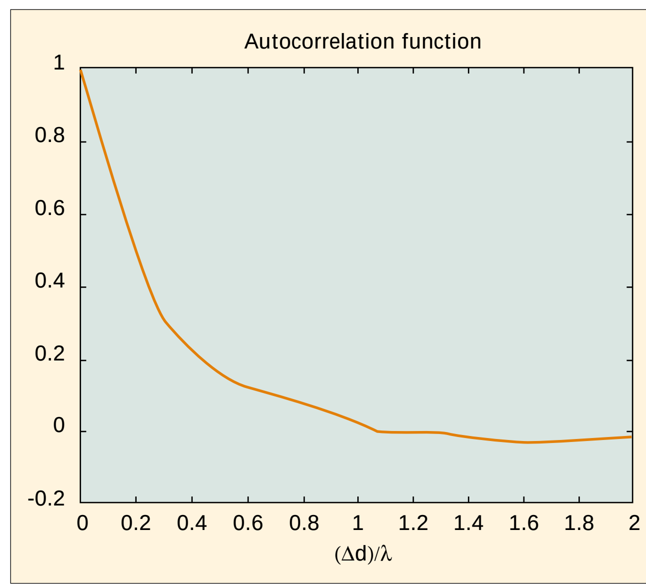
The results of the prediction in the side street based on the original Lee model and the improved model are shown in Fig. 5 and Fig. 6, respectively. On the figures, the black color represents the buildings while different shades of blue denote different signal levels. In the first part of the street, the signal level obtained by the improved model is greater than the signal level obtained by the primary Lee model for the same distance from the intersection. The estimated signal levels shown in Fig. 6 correspond more adequately to the real situation. Therefore, the improved model is more precise. At the same time, the algorithm is not overly complex.

INDOOR PROPAGATION MODELS

At first glance, the field strength prediction in indoor environments seems be to easier than the outdoor prediction. However, measurements [38] show that the field strength dynamics can be very high (over 80dB). Also, experimental autocorrelation has shown that a separation of 0.4λ is required for a correlation coefficient below 0.2 between two adjacent samples (Fig. 7) [38]. The same parameter for the outdoor environment is 0.8λ [9]. This difference can be explained by the fact that at a specific location, the electric field of the indoor environment is formed by a much larger number of indirect components than in the case of the outdoor environment. Therefore, the indoor signal level is more fluctuating than the outdoor signal level, and thus it is more difficult to predict.

The problem of the indoor field level prediction can be considered statistically or theoretically. While almost all statistical (empirical) models are based on the same general model, there are several distinguished theoretical models of which ray-tracing models and Finite-Difference Time-Domain (FDTD) models are the most popular. Some important disadvantages of both empirical and theoretical models can be overcome by an appropriate artificial neural network (ANN) model.

The general idea of each of the presented models can be easily applied to any specific frequency band. However, the 1.8-2GHz frequency band is of particular importance because the major indoor radio systems operate today in this band (DECT, PACS, PHS, etc.)



■ **FIGURE 7.** *Experimental autocorrelation function of the indoor radio channel.*

EMPIRICAL MODELS

The general empirical model can be expressed as [30]:

$$PL(d) = PL(d_0) + 10 \cdot n \cdot \log(d/d_0) + X_\sigma \qquad (10)$$

where $PL(d)$ is the path loss in dB at distance d, $PL(d_0)$ is the known path loss at the reference distance d_0 (usually d_0 = 1m), n denotes the exponent depending on the propagation environment, and X_σ is the variable representing uncertainty of the model. Based on this general formulation many empirical models have been derived [39–44].

These models are simple, efficient, and suitable for computer implementation. During implementation, the environmental database is unnecessary. Therefore, there is no requirement for investing time and resources in surveying building layouts. Due to model simplicity, great accuracy could not be expected. The main parameter n is very sensitive

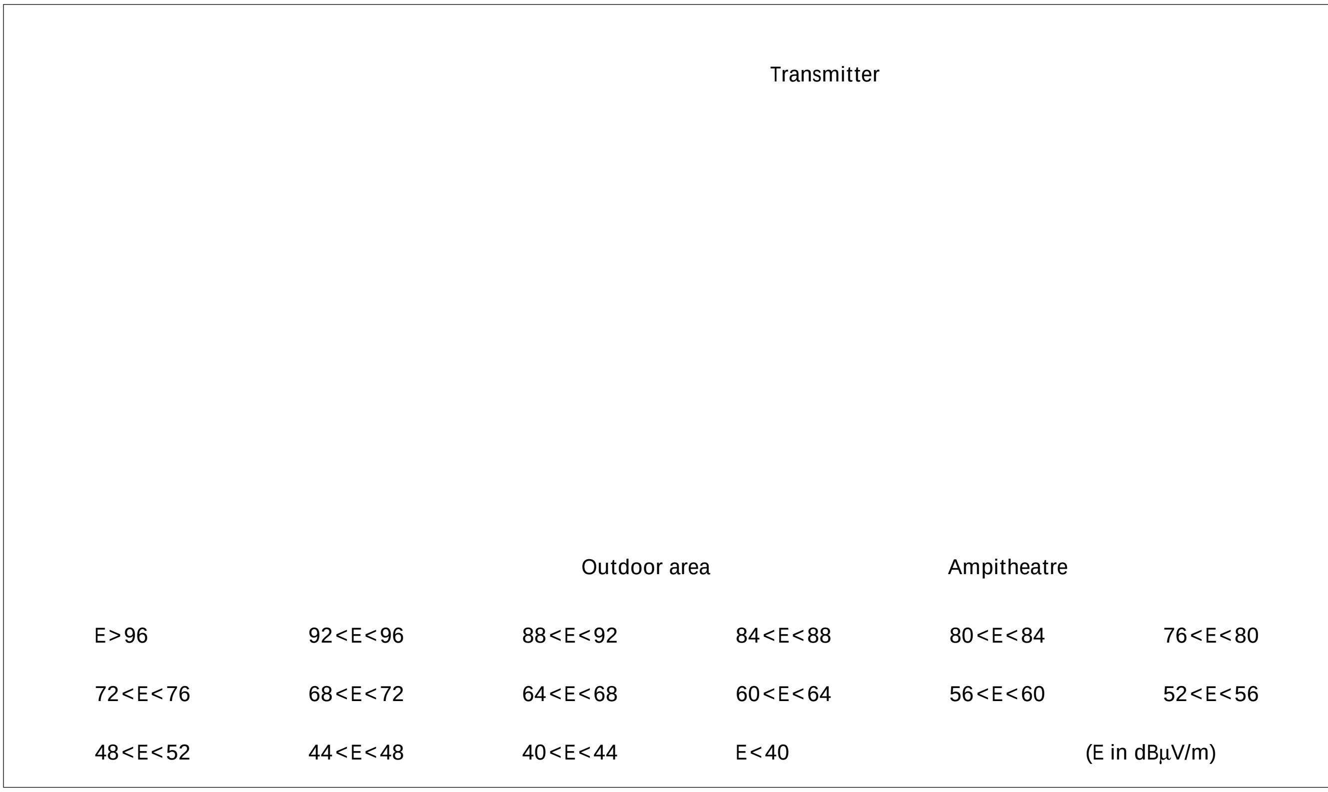


FIGURE 8. *Prediction results obtained by ETF-ANN model for the first-floor of the School of Electrical Engineering building (the size of the floor is 124.8m (41.4m).*

to the propagation environment, i.e., the type of construction material, type of interior, location within building, etc. The values of *n* range from 1.2 (waveguide effect) to 6. In addition, the value of *n* depends on the way the statistical analysis on measurement data is performed.

RAY-TRACING MODELS

The ray-tracing algorithm [33, 34, 41] calculates all possible signal paths from the transmitter to the receiver. In basic ray-tracing models, the prediction is based on the calculations of free-space transmissions and reflections from the walls. More complex ray-tracing algorithms include the mechanism of diffraction, diffuse wall scattering, and transmission through various materials. In the end, the signal level at any specific location is obtained as a sum of the components of all paths between the transmitter and the receiver. In addition to the propagation losses, the time dispersion of the signal can be successfully predicted by the ray-tracing models.

Today, the ray-tracing models belong to a group of the most accurate field strength prediction models. However, they require a very detailed layout of the area to be analyzed. The accuracy of the model depends on the accuracy and complexity of the area layout database. On the other hand, the implementation of these models requires extensive computational resources. Computational time depends exponentially on the details included in the layout of the area. Therefore, the computational time of a small area with plenty of details can be greater than that of a big area that is relatively poor in details.

Ray-tracing algorithms can also be used for signal level prediction in outdoor environments, but for relatively smaller areas.

FINITE-DIFFERENCE TIME-DOMAIN (FDTD) MODELS

Radio propagation characteristics can be derived solving directly Maxwell's equations of electromagnetic wave propagation. The FDTD method is probably the most popular method for a numerical solution of Maxwell's equations [41]. In this method, Maxwell's equations are approximated by a set of finite-difference equations. Prior to calculations, it is necessary to define a specific grid (regular or irregular) over the area of interest. After appropriate initial conditions are defined, the FDTD algorithm employs the central differences to approximate both spatial and temporal derivates. At the nodes of the grid, the solutions are determined iteratively. In this way, Maxwell's equations are solved directly.

Similarly to the ray-tracing model, the FDTD models are very computationally demanding. The computational time depends proportionally on the size of the area to be analyzed, but not significantly on the details involved. However, the number of nodes of the grid is exponentially related to the size of the area and the frequency of operation. The accuracy of the FDTD model is comparable to that of the ray-tracing models. The prediction is as accurate as the area layout database.

Due to computational complexity, FDTD models are suitable only for field prediction tasks in small areas. For large areas, ray-tracing models are more suitable.

ETF-ARTIFICIAL NEURAL NETWORK (ANN) MODEL

The main problem presented by empirical models is their unsatisfactory accuracy. On the other hand, the theoretical models lack computational efficiency. A compromise can be made by the artificial neural network model [38, 45].

Similar to the case of the ANN macrocell model, this model is based on multilayer perceptron feedforward neural networks. The implementation of an ANN model requires a database of the floor plan in which all particular locations are classified into several environmental categories, for example, wall, corridor, classroom, window, etc. The easiest way to do this is to make a color picture over the scanned floor plan.

The ANN model proposed in [45,38] has the form of the multilayer perceptron with three hidden layers. There are several inputs based on the number of previously defined environmental categories. One of the inputs is the normalized distance from the transmitter to the receiver. The remaining inputs are based on the analysis of the straight line drawn between the transmitter and the receiver with respect to environmental categories, e.g, how many doors, what percentage of the line passes through the classrooms, etc. The model has an output that is a normalized field level.

Determining the parameters of the ANN model is very simple. Statistical analysis is unnecessary. The neural network should just be trained with the measured data. Computationally the training process is very extensive, but it is done only once. In implementation, it was shown that the accuracy of the ANN model is comparable to the accuracy of the ray-tracing and FDTD models.

Figure 8 illustrates the prediction results obtained by the ETF-ANN model.

ADDITIONAL EFFECTS

Although previously described models do not take into account temporal fading and the effects of the human body, these phenomena must be carefully considered in a proper design of an indoor radio communication system.

Extensive measurements carried out at the School of Electrical Engineering in Belgrade [38] have shown that a portable terminal slowly moving through an indoor environment experiences Ricean or Rayleigh fading depending on whether LoS conditions exist or not. In the former case, Ricean K factor takes values in the range 2 to 10dB. Almost identical results are obtained by Alexander [42] and Rappaport and McGillem [43].

The influence of a human body on signal reception can be viewed through two main aspects [46]. The first is the influence of the user's own body and the second is the effect of bodies of the people who are in the vicinity of the user. On average, both effects cause a drop in the received signal level, while the latter, in addition, causes the received signal level to fluctuate more irregularly. These irregularities are very hard to predict due to their great dependence on the exact arrangement of the people near the user.

For fixed transmitter and receiver positions, the ambient motion causes temporal fading, which can be described as Ricean fading, with the Ricean K factor of about 10dB [40]. In this case, typical variations of the signal level are less than 15dB for 99.9 percent of the time, which is slightly greater than the variations typically obtained in an outdoor environment [9].

CONCLUSION

Today's fast growing radio communication market places stronger and stronger demands on the design of a radio system. A proper system design requires accurate and reliable radio channel models, among which the field strength prediction models are most important. Although many researchers have been working hard during the past few decades in the area of field strength prediction, there are still numerous problems to be solved. To date, a perfect propagation model has not been found. Instead, many different prediction tools have been proposed. Each of them has advantages and disadvantages and can be applied only to particular circumstances. Further investigations of methods for increasing accuracy and decreasing computational time are necessary. However, it should be noted that the progress in field strength prediction models depends to a great extent on the development of environmental databases as well as on the development of computational resources.

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