A Review of the Applicability of the Main EM Field Calculation and Assessment Models in Wireless Communications Design

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Abstract - **A brief review of the basic large-scale propagation models used in the network planning tools is made and their limitations and areas of application are pointed out. Demonstrated and discussed is the applicability of the 2D parabolic equation method in UHF/VHF propagation prediction.**

Keywords - **radiowave propagation prediction models, parabolic equation, numerical methods, network planning tools.**

I. INTRODUCTION

The increasing demand for mobile communication services has led to the need of more efficient propagation prediction models as one of the essential parts of the radio network planning tools. On the other hand, since UMTS radio network is more sensitive to the propagation environment than is the GSM network, [1], the more accurate the radio propagation prediction is, the closer the system performance will be to the expected one. At present it exists a great variety of commercially available network planning tools that implement classical and/or more sophisticated propagation prediction models for open areas, urban and indoor planning. During the last years, in order to meet the increasing importance of accurate coverage and interference estimations, some of these models have been extensively tested under operational conditions [1-3] and their advantages, drawbacks, limitations and accuracy have been documented.

The aim of the present work is to outline the essential characteristics and area of validity of the main classical outdoor propagation models widely used in different planning tools. Demonstrated and discussed is also the applicability of the 2D parabolic equation (PE) method in UHF/VHF propagation prediction.

II. BASIC LARGE-SCALE PROPAGATION MODELS

The large-scale propagation models give results as path loss versus range. Below follow the characteristics of the basic area-to-area and point-to-point path loss prediction models widely used in generating signal coverage map, co-channel interference area map, handoff occurrence map.

Log-distance path loss model, [4]. Theoretical and experimental propagation models indicate that the average received signal power decreases logarithmically with distance and:

$$PL(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma, \qquad (1)$$

where path loss, PL, is in dB, n indicates the rate at which the path loss increases with distance d, d_0 is the reference distance which is determined by measurements close to the transmitter, X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ. X_σ accounts for the variation in average received power due to the shadowing. The values of n and σ are derived from measured data. A smaller value of σ means more accurate path loss prediction. Typical values for n are: n =2 (free space), n =2.7 to 3.5 (urban area), n =3 to 5 (shadowed urban area).

Lee's path loss model, [5]. Lee proposes a simple point-to-point model that encompass the following three cases:

1) Received power P_r (dB expression) for non-obstructed by terrain path (the major factor here is the effective antenna height h_e):

$$P_r = P_{r_0} - \gamma\log\frac{r}{r_0} + 20\log\frac{h_e}{h_1} + \alpha, \qquad (2)$$

where P_{ro} is the power at the r_0=1.6 km point of interception, γ is the path loss slope, r - the transmitter-receiver distance, h_1 – the transmitter antenna height;

2) Received power P_r for shadowed path: P_r(from (2) with h_e replaced by h')+L+α, where α is the correction term (see [5], Sec.4.2.1), h' is a height derived from the obstacle and L accounts for the diffraction loss (Lee's model uses single or double knife-edges diffraction).

3) Land-to-mobile over water path = free space formula.

The described model can be used in suburban and urban areas for frequencies above 30 MHz. The differences between predicted by the model and measured values have been determined for many areas and have shown its usefulness and applicability. Drawbacks of the model: it does not account for the orientation of streets and the foliage loss has to be added. This is a macrocell model not applicable within the 2 km area from the cell site.

Egli's model, [6]. This is a plane-earth model. The median transmission loss is given by:

$$L = 139.1 - 20\log h_t + 40\log d, \qquad (3)$$

where h_r is assumed 1.5 m, h_t is in m and the distance d is in km. The model uses some perturbation factors to improve the results. Its validity is up to d=60 km and frequency between 40 MHz and 900 MHz.

Blomquist-Ladell model, [6]. The median transmission loss is calculated as:

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$$L = L_0 + \left\{ \max\left(L_p, L_k\right) \text{or} \sqrt{\left(L_p{}^2 + L_k{}^2\right)} \right\}, \quad (4)$$

where L_0 denotes the free space loss, L_p – plane earth loss, L_k accounts for knife-edge loss. This formula is valid for $5<d<22$ km and $30<f<900$ MHz. Better results are obtained using the squire term.

Ibrahim-Parsons model, [6]. This model was especially designed for estimating the path loss in the city of London. The model is based on data collected by measurements and assumes plane earth. The model includes a clutter correction factor and a degree of urbanization factor. This model has been applied for other cities, [7], where the model demonstrated strong similarity of the urbanization factor to the one reported for London.

Epstein-Peterson (diffraction) model, [6]. This is a multi knife-edges model. It considers each knife-edge individually and approximates the total loss as a sum of the individual losses. The first loss is calculated considering the path "transmitter-first obstruction-second obstruction", the second path loss is for the path "first obstruction-second obstruction-third obstruction" and so on until the receiver is reached. This model gives bad results if the obstructions are situated close to each other.

Bullington's (diffraction) model, [6]. In this model the *n*-dimensional problem is reduced to one-dimensional by replacing the *n* obstruction by one equivalent knife-edge. The method requires finding of an equivalent height that will produce the same effect as the series of obstacles between the transmitter and the receiver. The best result is obtained with two-obstruction path loss. With the increase of the number of the obstacles the result gets worst.

Deygout's (diffraction) model, [6]. The model initially estimates the diffraction path loss by considering the dominant obstruction of the environment. The losses due to the remaining knife-edges are determined with respect to this dominant edge. Deygout's model is one of the most widely used diffraction models.

Hata-Okumura model, [4]-[6]. This model is of very common use in signal prediction modeling. It is based on extensive measurements in urban area over a quasi-smooth terrain using vertical omni-directional antennas at the base and mobile stations assuming h_t=200 m and h_r(mobile)=3 m. The median attenuation relative to free space *A(f,d)* was presented by Okumura as a family of curves plotted as function of frequency (100 MHz<f<1920 MHz) and as function of distance from the base station (1 km<d<100 km). The model previews correction factor accounting for the terrain type, G_{area}, which is given in another set of curves, as well different expressions for antennas height gain factors, $G(h_t)$, $G(h_r)$, and for values of h_t, h_r, others than the assumed in the curves (the antenna pattern is not taken into account). The median value of the path loss following the model can be expressed as:

$$L = L_0 + A(f,d) - G(h_t) - G(h_r) - G_{area}, \quad (5)$$

where L_0 is the free space propagation loss. Hata provided empirical formulation of the path loss curves, given by Okumura. The formula for median path loss is given by (6), where f is in MHz, h_t is the effective base station height in meters ($30<h_t<200$ m), h_r is the effective mobile antenna height ($1<h_r<10$), the distance d is in km, $a(h_r)$ is a correction factor related to the mobile antenna height. The values of $a(h_r)$ for small to median sized cities can be found in [6]. The model is applicable for frequencies from 150 MHz to 1500 MHz and $1<d<100$ km.

$$L = \begin{cases} 69.55 + 26.16\log f - 13.821\log h_t - a(h_r) \\ + \log d\left(44.9 - 6.55\log h_t\right), \text{for urban area;} \\ L(urban) - 2\left[\log\left(\frac{f}{28}\right)\right]^2 - 5.4, \text{for suburban area;} \\ L(urban) - 4.78(\log f)^2 - 18.33\log f - 40.98, \\ \text{for open rural area.} \end{cases} \quad (6)$$

The above-described model is among the best (and simplest) models, it has standard deviation between predicted and measured path loss value about 10 to 14 dB, [7], and is used in practically all cellular and land mobile radio systems planning tools. The model is well suited in urban and suburban areas. Disadvantages: the model does not reflect the rapid terrain variations and has not to be used in small cells (d<1 km).

Walfisch-Bertoni model, [4], [8]. Urban models need the inclusion of the impact of rooftops and buildings height in the path loss models. The average signal strength is predicted considering the path loss to be a product of three factors: $L=P_0Q^2P_1$, where P_0 stands for the free space path loss, Q accounts for the influence of the rooftops of the buildings that immediately shadow the receiver, P_1 is a diffraction term related to the losses from the rooftop to the street. It is to note that this model assumes h_t above the rooftops.

Some of the above-referred models have been subjected to extensive measurements assessments during the COST action 231, [3], and a number of improvement have been introduced in them especially for applications in urban areas at 900 and 1800 MHz bands.

COST 231 Hata model. COST 231 has extended Hata´s urban path loss formula to the frequency band 1500 ≤ f MHz ≤ 2000:

$$L_b = 46.3 + 33.9\log f - 13.82\log h_t - a(h_r) + \log d\left(44.9 - 6.55\log h_t\right) + C, \quad (7)$$

where L_b is the basic transmission loss, $a(h_r)=h_r(1.1\log f-0.7)-(1.56\log f-0.8)$ and C is given by:

$$C = \begin{cases} 0 \text{ dB for medium sized city and suburban centers with} \\ \text{medium tree density;} \\ 3 \text{ dB for metropolitan centers.} \end{cases}$$

This model is valid for flat terrain. Its application is restricted to the case of base station antenna heights, h_t, above rooftop levels (large and small macro-cells). Restrictions: formula (7) must not be used for micro-cells.

COST 231 Walfisch-Ikegami model. In comparison with Walfisch and Bertoni model COST model allows for improved path-loss estimation by considering more data to describe the character of the urban environment, namely: a) heights of buildings, b) widths of roads, c) building separation distance and d) road orientation with respect to the direct radio path. However, the model does not consider topographical database of the buildings. The Walfisch and Bertoni model is extended by COST 231 for base station antenna heights below the rooftop levels using an empirical function based on measurements. The COST 231 model distinguishes also between line-of-sight (LOS) and non-line-of-sight (NLOS) situations. The formulas for both cases may be found in [3]. This COST model is restricted to f between 800 and 2000 MHz, 0.02 km $\leq d \leq$5 km, 4 $\leq h_t \leq$50 m and 1$\leq h_r \leq$ 3 m. The model has also been accepted by the ITU-R and is included into Report 567-4. The standard deviation is in the range 4-8 dB, [3]. Restrictions: the model has large prediction error for $h_t \approx h_{roof}$ and for $h_t << h_{roof}$; the model is not designed for micro-cells; the prediction is poor in case of grazing incidence; the model assumes flat terrain and does not consider multipath propagation.

Longley-Rice model, [9]. This is a terrain-based propagation model. The Longley-Rice model predicts long-term median transmission loss over irregular terrain relative to free-space transmission loss. The model was designed for frequencies between 20 MHz and 10 GHz and for path lengths between 1 km and 2 000 km. It accounts for tropospheric refraction and troposcatter over long distances. A background of the model, as well as a comparison to other models, may be found in [9]. Longley-Rice model can be used in two modes: when detailed terrain profile is available the model performs point-to-point prediction mode; otherwise the model estimates the path-specific parameters and provides an area prediction mode. Shortcomings: Longley-Rice model does not provide techniques to predict the influence of the environment in the immediate vicinity of the mobile receiver or to include corrections related to the effects of buildings and foliage; the multipath is not considered. The model has many modifications and corrections, some of them introduce an urban factor, accounting for the urban clutter, thus making it applicable in urban area. The model is widely used in the available propagation prediction tools.

Durkin's model, [4]. This model is similar to the above described, that is, it predicts large-scale phenomena over irregular terrain. The model predicts well LOS and some NLOS cases (it is good in accounting of diffraction losses) but excludes the reflection from objects not situated on the radial joining the transmitter and the receiver. The method can be used with digital elevation maps and provides site-specific calculations (deviation of the predicted field strength from the measured is within few dB), [4]. Disadvantages: the model does not predict adequately effects due to buildings and foliage and excludes multipath propagation.

Ray tracing based models. These models compute radio ray propagation accounting correctly for the reflection, diffraction and scattering. Ray tracing provides several advantages over traditional prediction methods: accurate site-specific field strength prediction, possibility to incorporate 3D antenna patterns and to obtain wide-band radio channel characteristics such as direction of arrival and multipath time delay. There is a grate variety of ray tracing based prediction techniques, [1], [10]-[12], but normally they perform the following: 1) reading of a detailed environment data file; 2) finding of (possibly) all reflective and diffractive surfaces and identifying (dynamically) all ray-paths between the transmitter and the receiver; 3) processing of the results to obtain radio channel characteristics. Typically ray trace based models account for the following propagation mechanisms, [10]: 1) direct ray (LOS propagation); 2) ray-paths with arbitrary (or limited) number of reflections from vertical walls; 3) ray-paths with arbitrary (or limited) number of diffractions on vertical edges; 4) diffractions on horizontal edges may be included as well combinations of diffracted and reflected ray-paths; sometimes scattering from different adjacent to the mobile objects as trees is also included.

The ray tracing based propagation prediction methods are well suited in the propagation prediction both for open and urban areas. They are known to avoid the erroneous planning with less than expected quality of service and unacceptable interference, [1]. Nevertheless, these techniques have some weaknesses: they are unreliable under ducting conditions, suffer difficulties when transiting from one type of region/cell to an other, when treating the back-scattering problem they require field input on the building surfaces which is difficult to obtain within simple assumptions. Solution to these problems is sought in the PE based methods, [13]-[18].

PE based methods. The PE approximation to the wave equation is a full-wave method, combining terrain diffraction, atmospheric ducting and great flexibility in the specification of the building geometry and electrical parameters, thus accounting simultaneously and accurately for the diffraction, refraction and scattering. As paraxial approximation, PE assumes the problem has some preferred propagation direction, say, the x-axis in a Cartesian co-ordinate system, and transforms the scalar wave equation in a 3D PE, [13]:

$$\frac{\partial u(x,y,z)}{\partial x} = \frac{i}{2k}\left(\frac{\partial^2 u(x,y,z)}{\partial z^2} + \frac{\partial^2 u(x,y,z)}{\partial y^2}\right) + \frac{ik}{2}\left(n^2(x,y,z)-1\right)u(x,y,z), \qquad (8)$$

where k is the free-space wave number, n is the refractive index of the troposphere, $u(x,y,z)$ is the reduced function related to a field component E as $E(x,y,z)=u(x,y,z)exp(ikx)$. Equation (8) accounts only for forward propagating field and is very accurate at angles within 15^0 of the direction of x-axis, [13]. A more general form of PE allows calculation of back-scattered field and application of larger angles, [15].

The advantage of equation (8) is that it can be easily marched in range provided the field is known on an initial plane and adequate boundary conditions on the outer boundaries of the integration domain are given. To solve the PE different numerical techniques are used: Fourier/split-step method, finite-difference, and finite-element based schemes. The Fourier/split-step technique, [14], allows for larger range step, thus speeding up the calculations, but the implementation of the boundary conditions is not

straightforward. The finite-difference, [15], and finite-element schemes, [16], allow better description of scatterers and easier boundary conditions implementation but are computationally intensive. Due to its simplicity, the 2D form of (8) is the most widely used, [14-16], [18]. The 2D PE falls when steep transverse terrain gradients exist between the transmitter and the receiver, [13]. The accurate accounting for building scattering also requires 3D methods. The scalar 3D PE does not account for the depolarization effects occurring in a 3D environment. The full treatment of 3D electromagnetic scattering effects is provided by the vector PE, [17].

Examples of the application of the 2D PE are given for the region of Sofia using the terrain data provided by the USA NIMA product DTED (Level 0). Horizontally polarized Gaussian beam antenna with 2 000 MHz frequency is used. The terrain data are combined with the Terrain Parabolic Equation Model (TPEM), [14], to obtain the coverage diagrams under standard troposphere conditions (Fig. 1) and surface based duct conditions (Fig. 2).

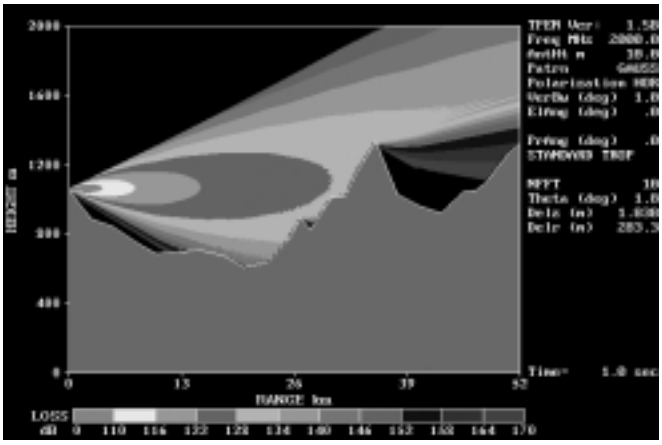

Fig. 1 Coverage for 2 000 MHz under standard troposphere

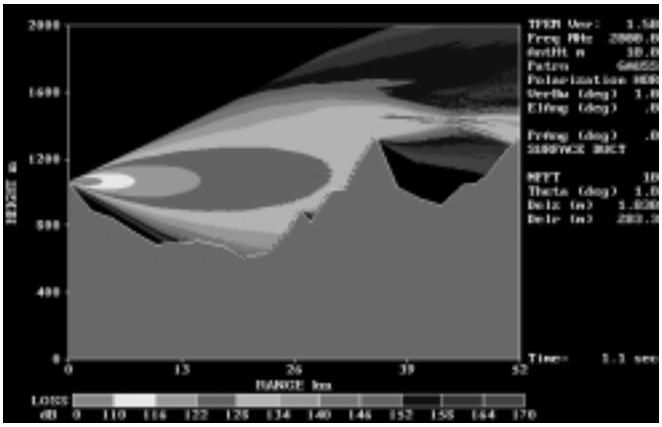

Fig. 2 Coverage for 2 000 MHz under surface duct conditions

III. Conclusion

A brief review of the basic large-scale propagation models indicating their limitations and areas of application is made. Pointed out is the need of more accurate propagation prediction models to reach better network planning. The PE provides the possibility to use one and the same method for very accurate field calculations in rural (with Fourier/split-step) and urban (with finite-element scheme) areas. The drawbacks of the method (longer computational time and greater memory resources required in comparison to traditional techniques) can be avoided by using the PE only when fine structure scatterers have to be described passing the results as input for other method, say, ray-tracing, to perform the calculations in larger zone.

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