Multiple Diffraction Shadowing Simulation Model

Rubén Fraile, Jad Nasreddine, Narcís Cardona, and Xavier Lagrange

***Abstract*— This article presents a shadowing simulation model based on multiple-edge diffraction. Such model provides an appropriate tool for simulating shadowing in cases where over-obstacle diffraction is the main propagation mechanism. Results show that the model is in good agreement with literature in terms of its statistical parameters. Moreover, its capability for dealing with variations in antenna height makes it appropriate for simulating a wide range of wireless systems.**

***Index Terms*— Fading channels, land mobile radio, land mobile radio propagation factors, modeling, radio propagation, radio propagation terrain factors, simulation.**

I. Introduction

SHADOWING modelling is one of the key issues when performing system-level simulation of wireless networks. It is typically implemented through generation of sequences of random values with an adequate distribution. These sequences are processed afterwards so as to achieve desired correlation properties. This can be done either for individual mobile units [1] or for a whole simulation area, if shadowing maps are generated, as in [2]. In both cases, only site-to-mobile shadowing with fixed antenna heights is considered and it is commonly generated considering both spatial autocorrelation and site-so-site cross correlation. This is because in typical cellular networks interference occurs only within the same link, be it either uplink or downlink. Nevertheless, interaction between links (cross-link) has to be analysed in some systems such as UTRA-TDD [3]. Since this can only be achieved if the simulation model considers the impact of antenna height on shadowing, a new modelling approach is needed.

This letter presents a shadowing model based on over-obstacle propagation that is able to account for uplink-to-downlink interaction, since it allows for modelling variations in antenna height from ground. The model is appropriate for urban wireless networks in which site antenna heights are either similar or greater than mean rooftop height, where propagation mainly occurs above buildings [4]. Yet, such approach may easily be extrapolated to any other environment in which site antennas are situated either at a similar height or above obstacles. In fact, the dominance of over-obstacle propagation has been confirmed even for low antennas in urban environments [5]. The structure of the paper is as follows: section II describes the main aspects of the proposed model, section III reports on model validation and results while section IV includes the conclusions.

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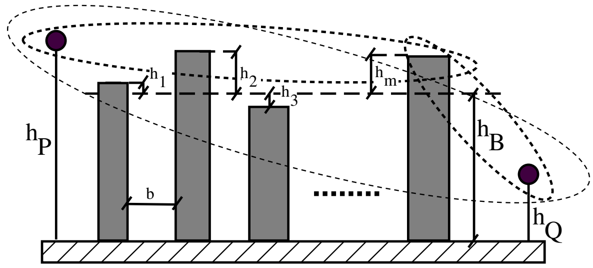

Fig. 1. Height variation profile obtained from sampling of matrix $\mathbf{H}$.

II. Model Description

Mobile radio propagation is usually modelled as the effect of three simultaneous contributions: path loss, shadowing and fast fading [6]. Path loss represents dependence on distance for a specific environment described by its average parameters, such as mean obstacle height. Since no parameter of the real environment is constant, real propagation losses correspond to a statistical distribution whose average is given by the path-loss model. Shadowing accounts for this variability for a spatial resolution of a few meters while shorter-range variations are modelled by fast fading. The model herein proposed consists in modelling shadowing as a function of variations in obstacle height over the simulation area. The model has two parts: a geometric part, partly based on [7], and a diffraction part that is an extension of the model in [8].

A. Geometric Part of the Model

Let's suppose that we want to simulate a wireless network within an area of $R \times R$ (m^2) (the form of the area is assumed to be square without loss of generality). Let's also assume that there are obstacles within this area above which propagation occurs; the mean height of obstacles is h_B (m) while b (m) is their mean width. The first step of shadowing simulation consists in generating a random map grid $\mathbf{H}_{n\times n}$ (as in [7]) that models obstacle height variations around h_B for the whole area. Given R and b, the size of the grid is:

$$n = \frac{R}{b} + 1 \tag{1}$$

and its values follow a Gaussian distribution, as in [9].

Now, let $P(x_p, y_p, h_p)$ and $Q(x_q, y_q, h_q)$ be two points between which shadowing is to be generated. In order to do so, a set of equally spaced samples $\{h_1, h_2 \dots h_m\}$ between P and Q are obtained from height map $\mathbf{H}$ so as to get a profile of obstacle height variations around their mean value h_B (Fig. 1). The sampling distance is made equal to b and values for every h_i, $i = 1, 2 \dots m$, are obtained through bilinear interpolation.

B. Diffraction Part of the Model

From [8], diffraction loss due to a set of m regularly spaced obstacles between points P and Q can be written (in dB) as the sum of the effects of individual obstacles:

$$L_{diff} = \sum_{i=1}^{m} L_i \left(h_p, h_q, h_B, h_i, b, r\right) \tag{2}$$

where $h_B + h_i$ is obstacle height, r is propagation distance and the rest is as defined before. (2) becomes a path-loss model if $h_i = 0\ \forall i$. However, if there is any i for which $h_i \neq 0$, variations over path-loss model occur, thus shadowing appears. Assuming that height variations around their mean value are small and zero-averaged, (2) may be approximated as:

$$L_{diff} \approx \sum_{i=1}^{m} L_i|_{h_i=0} + \sum_{i=1}^{m} \left.\frac{\partial L_i}{\partial h_i}\right|_{h_i=0} \cdot h_i = L_0 + \sum_{i=1}^{m} w_i \cdot h_i \tag{3}$$

Thus, shadowing (second term of (3)) can be estimated as a linear combination of obstacle height variations along the propagation path. [8] proposes to compute combination weights w_i as explained next. Let's define ν_i as the clearance of the first Fresnel zone for i-th obstacle position if $h_i = 0$:

$$\nu_i = \left(h_B - \frac{r_{pi}(h_p - h_q)}{r}\right) \cdot \sqrt{\frac{2r}{\lambda \cdot r_{pi}(r - r_{pi})}} \tag{4}$$

where r_{pi} is the distance from point P to obstacle i and λ is the wavelength. From this, if the i-th obstacle were the only one along the propagation path, it would produce a diffraction loss equal to:

$$\begin{aligned} l_i &= \left[0.5\left(0.5 + C^2(\nu_i) - C(\nu_i) + S^2(\nu_i) - S(\nu_i)\right)\right]^{-1} \\ L_i &= 10 \log l_i \end{aligned} \tag{5}$$

where $C(\cdot)$ and $S(\cdot)$ are the Fresnel integrals. Last, according to (3):

$$w_i = \frac{\partial L_i}{\partial h_i} = \frac{\partial L_i}{\partial \nu_i} \cdot \frac{\partial \nu_i}{\partial h_i} = \frac{10}{\ln 10 \cdot l_i} \cdot \frac{\partial l_i}{\partial \nu_i} \cdot \frac{\partial \nu_i}{\partial h_i} \tag{6}$$

Therefore, computation of w_i as proposed in [8] involves numerical evaluation of Fresnel integrals, which is computationally expensive. In order to avoid this, we propose to use the following approximation [10]:

$$L_i \approx 6.9 + 20 \cdot \log_{10}\left(\sqrt{1 + (\nu_i - 0.1)^2} + \nu_i - 0.1\right) \tag{7}$$

And, from it:

$$\begin{aligned} \frac{\partial L_i}{\partial \nu_i} = &\frac{20}{\log 10 \cdot \left(\sqrt{1 + (\nu_i - 0.1)^2} + \nu_i - 0.1\right)} \times \\ &\times \left(\frac{\nu_i - 0.1}{\sqrt{1 + (\nu_i - 0.1)^2}} + 1\right) \end{aligned} \tag{8}$$

hence avoiding any evaluation of integrals. The main drawback of both approaches, the one in [8] and our approximation, is that inadequate values of w_i are produced if $\nu_i < -0.5$. This means that height variations in points with a good clearance of the first Fresnel zone may have more impact on shadowing than obstructing points, which is nonsense. To overcome such difficulty we propose to multiply (8) by an exponential term $e^{0.6 \cdot (\nu + 0.5)}$ when $\nu < -0.5$.

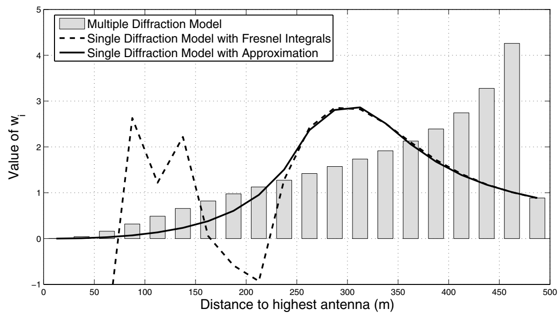

Fig. 2. Values for w_i calculated as in [8] (dashed line), substituting Fresnel integral evaluation with an approximation (continuous line) and multiple diffraction model (bars). Other parameter values are mainly taken from [1]: $h_p = 27\ m$ (leftmost point of the x-axis), $h_q = 1.5\ m$ (point on the right end), $h_B = 12\ m$, $b = 25\ m$, $f = 2\ GHz$ and $r = 500\ m$.

Figure 2 shows the variation of weights w_i as a function of distance to the ending point with the highest antenna both according to [8] and with the above-mentioned modification. The approximation produces a good estimate and, at the same time, avoids undesired oscillations for negative values of ν_i (left half of the plot). Another relevant aspect of the figure is that obstacles with the highest impact on loss variability are in the middle of the profile. This is not coherent with the assumption that shadowing is mostly affected by obstacles close to the lowest antenna [8]. Such incoherence comes from the fact that the model considers the influence of each obstacle within the propagation path as if it were the only one.

An alternative approach consists in regarding the problem as a multiple diffraction. A simple, yet suitable, approach to model multiple diffraction as a series of single diffractions is Deygout's model [11]. This is a recursive method that consists in evaluating the influence of the most obstructing obstacle in the radio link (i.e. obstacle with highest value of ν_i). Afterwards, the link is divided into two sublinks: first between transmitter and obstacle and second between obstacle and receiver (this has been depicted in Fig. 1). Then, evaluation of both sublinks is done similarly, as if each of them were the main link.

The set of weighting coefficients obtained with this recursive, multiple-diffraction model is also plotted in Fig. 2. It can be noticed how this model overcomes limitations of single diffraction model, that is, obstacles with higher impact on shadowing are closer to the lowest antenna.

III. Model Validation

For validation purposes, shadowing maps have been calculated with spatial resolution equal to 10 m for three sites placed on the vertices of a regular triangle of 833 m long edges within a square area of $2000 \times 2000\ m^2$. Other propagation parameters are the same as for Fig. 2. Statistical distribution, spatial autocorrelation and site-to-site cross-correlation of results have been analysed.

Shadowing is expected to follow a Gaussian distribution in decibel domain [6]. According to (3), shadowing is calculated as a linear combination of zero-mean Gaussian values h_i. Consequently, shadowing also has zero mean and Gaussian distribution. As for standard deviation σ_L, its typical values

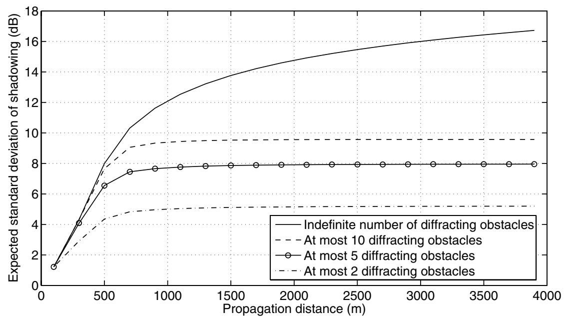

Fig. 3. Dependence of expected standard deviation of shadowing on propagation distance for an unlimited number of obstacles and for a number of obstacles limited to 10, 5 and 2.

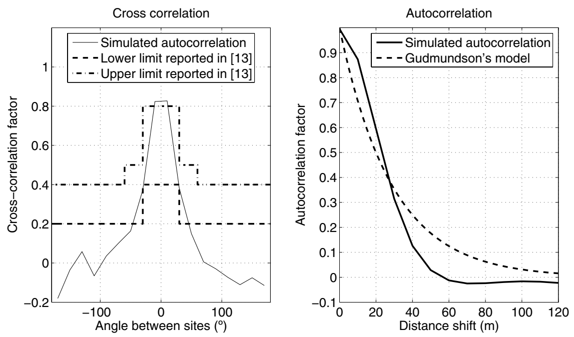

Fig. 4. Correlation of simulated shadowing maps and comparison to other models: cross correlation (left) and autocorrelation (right).

range from 7 dB to 10 dB, but such values are distance-dependent and tend to stabilise, or even to decrease, as propagation distance grows [5]. Recalling (3), and provided that standard deviation of h_i equals unity:

$$\sigma_L = \sqrt{\sum_{i=1}^{m} w_i^2} \tag{9}$$

Figure 3 shows a plot of the evolution of σ_L as propagation distance increases. It can be observed that the values for σ_L does not stabilize as distance grows if the number of obstacles m is not limited. However, far from being a drawback of the model, this fact is in coherence with [4], that assumes that loss variability mainly depends on a limited number of obstacles. We may limit this number by taking only h_i samples corresponding to most obstructing obstacles in the radio path. For instance, in the case of 5 obstacles the convergence of the standard deviation occurs at propagation distances between 500 and 1000 m, which agrees with [4], and the values of σ_L fall within the expected range of 7-10 dB.

As for distance autocorrelation, figure 4 shows its mean values, as calculated for all three sites and for both vertical and horizontal shifts. For the purpose of comparison, the plot also includes Gudmundson's function [12]. It can be appreciated how a fair fit between simulated data and theoretical model is achieved even without specifically including autocorrelation issues in the shadowing model. Namely, simulated data exhibit decorrelation distance around 20 m and a decreasing shape similar to the exponential decay of Gudmundson's model.

Regarding cross-correlation between different links, it is assumed to have a two-fold dependence: on the one hand it depends on angle between links and, on the other, on ratio between propagation distances [13]. Figure 4 shows the dependence of cross-correlation of simulated shadowing on angle difference. For a wide range of angles (between -50^o and 50^o) the experimental values are inside the bounds proposed in [13], which are also plotted.

IV. Conclusions

This paper presents a shadowing simulation model whose results reach a good level of agreement with existing models while maintaining a fair degree of complexity. The main advantage of this approach is its adaptability to different environments, ranging from rural environments to small urban macrocells, due to modelling of obstacle size and height, and from medium wave radio broadcasting to networks operating in the 2 GHz band, due to the diffraction model on which it is grounded. Also, the model accounts for cross-link correlation in shadowing since it uses a single random matrix to produce all shadowing values for the simulation area, no matter the values of the antena heights. Its limitation is related to the dominant propagation mechanism, which is assumed to be over-obstacle propagation.

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