Analysis and Validation of a Shadowing Simulation Model Suited for Dynamic and Heterogeneous Wireless Networks

Rubén Fraile
Universidad Politécnica de Madrid, Spain
Email: rfraile@ics.upm.es

José F. Monserrat, Daniel Calabuig and Narcís Cardona
Universidad Politécnica de Valencia, Spain
Email: jomondel,dacaso,ncardona@iteam.upv.es

***Abstract*—Complete shadowing modelling is one of the key issues when performing system level simulation of wireless networks. So far, models have been defined considering fixed antenna heights and a cellular deployment of base stations over roofs. However in multi-hop networks, like vehicle-to-vehicle systems, mobile equipments can be in constant three-dimensional mobility and the height of transmitter and receiver may vary depending on the moment or the specific hop. Therefore a new modelling approach is needed to take into account the impact of antenna height on shadowing. This paper presents and validates 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. In a classical scenario, 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.**

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 that 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, and one of the ends of this link is static. Nevertheless, in some modern wireless networks, such as TD-CDMA or any other TDD system, interaction between links has to be analysed [3] and in others, such as relay/ad-hoc networks, both ends of the link may be mobile and links among close mobile units may even be dynamically established and released; for these systems the classical approach to shadowing modelling is not valid [4] and its extension to consider mobility of both ends of the link would lead to a highly dimensional problem (four dimensions if movement is restricted to a plane [5]). Therefore, a different modelling approach is required.

In [6] an alternative proposal was presented. Such proposal offers two advantages over other shadowing modelling schemes. On the one hand, shadowing values are generated from a random matrix that models the whole simulation area. As a result, correlated values of shadowing can be generated for nearby links, even if they do not share any of their ends. This capability is remarkably interesting both for relay/ad-hoc networks, where a mesh of links is established throughout the same area and links may be established between moving units, and for TDD systems, where cross-link interference has to be modelled. On the other hand, this simulation model includes antenna heights and carrier frequency as adjustable parameters. Such flexibility of the model allows modelling cellular networks in which antennas are not placed at the same height, which is very usual, and heterogeneous networks that consist of several interworking technologies operating in different frequency bands. The mentioned model achieves these two advantages while preserving the most relevant statistical behaviour of shadowing, namely probability density function [7], standard deviation of its values and dependence of such standard deviation on propagation distance [8], autocorrelation function [9] and cross-correlation between links [10].

Within this article a review of the model in [6] is presented (section II). After the review, an analysis of its behaviour, complementary to that included in [6], is reported (section III). Thirdly, an assessment of the validity of the model is provided in section IV. The assessment is based both on well-known characteristics of shadowing processes and on the comparison of UMTS radio access simulation results with those obtained with other models. Last, section V includes the conclusions.

II. Model Description

In any propagation model, the average logarithmic dependence of propagation loss with distance is commonly called path loss while shadowing accounts for loss variability with respect to path loss within spatial resolutions of a few meters. Bearing this in mind, [6] considers that path loss is a function of the average characteristics of the propagation scenario and shadowing is a function of variations in such characteristics.

In this framework, obstacle size and separation is assumed to be the most relevant aspect of the propagation scenario affecting propagation loss. This approach is coherent with the assumption that over-obstacle diffraction is a dominant propagation mechanism in many environments [11] [8].The model has two parts: a geometric part, partly based on [12], and a diffraction part that is an extension of the model in [13].

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 for this area we have obstacles above which propagation occurs and the mean height of obstacles is h_B (m) while b (m) is their mean width. The first step of the model consists in generating a random matrix $\mathbf{H}_{n\times n}$ that simulates obstacle height variability for all the simulation area. The size of the matrix is given by:

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

and Gaussian distribution is a suitable option for it [14].

Coherently with (1), coordinates of the first row correspond to the upper limit of the simulation area and coordinates of the last row correspond to the lower limit (similarly for columns). For simplicity, we will assume that $(0, 0)$ are the coordinates of the lower left corner and (R, R) correspond to the upper right corner (see figure 1).

Now, let $P(x_p, y_p, h_p)$ and $Q(x_q, y_q, h_q)$ be two points within the simulation area between which shadowing is to be generated. In order to do so, a set of samples $\{h_1, h_2 \ldots h_m\}$ of the height profile between P and Q must be obtained from matrix $\mathbf{H}$ (see also figure 1). If r is the distance between P and Q:

$$r = \sqrt{(x_q - x_p)^2 + (y_q - y_p)^2} \tag{2}$$

then the number of samples of the height profile is:

$$m = \left[\frac{r}{b}\right] \tag{3}$$

where [ ] means rounding to the closest integer. If $m = 0$ then transmitter and receiver are so close that no shadowing has to be considered. In fact, either a line-of-sight propagation model or the simple free-space propagation loss should be more appropriate. As for the coordinates of the profile samples, they are given by:

$$x_i = x_p + \frac{(x_q - x_p) - (m-1)\cdot\Delta x}{2} + (i-1)\cdot\Delta x \tag{4}$$

$$y_i = y_p + \frac{(y_q - y_p) - (m-1)\cdot\Delta y}{2} + (i-1)\cdot\Delta y \tag{5}$$

where $i = 1 \ldots m$ and:

$$\Delta x = b \cdot \cos\alpha \tag{6}$$

$$\Delta y = b \cdot \sin\alpha \tag{7}$$

$$\alpha = atan\left(\frac{y_q - y_p}{x_q - x_p}\right) \tag{8}$$

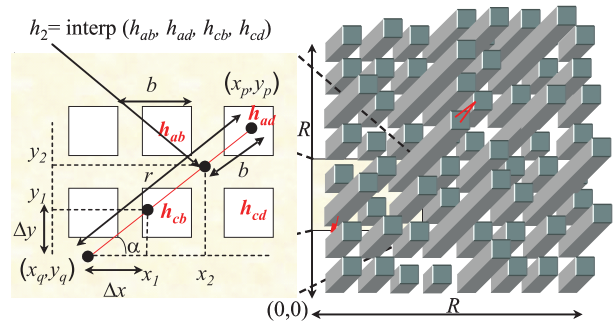

Fig. 1. Simulation area and height matrix. Sampled height profile between two points.

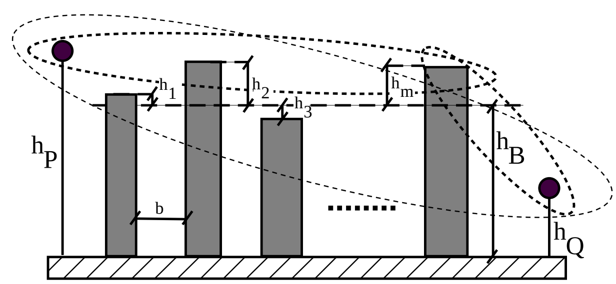

Fig. 2. Height variation profile obtained from sampling of matrix $\mathbf{H}$.

that is, b is the sampling distance for the height profile.

Last, values for every h_i are obtained through bilinear interpolation of elements in matrix $\mathbf{H}$. As a results, a profile of height variations around their mean value h_B is obtained (figure 2).

B. Diffraction Part of the Model

The model in [6], referred to as multiple diffraction shadowing simulation model, assumes that diffraction loss is due to a set of m regularly spaced obstacles between points P and Q. Such loss can then be written (in dB) as the sum of the effects of individual obstacles:

$$L_{diff} = \sum_{i=1}^{m} L_i\left(h_p, h_q, h_B, h_i, b, r\right) \tag{9}$$

where $h_B + h_i$ is obstacle height, r is propagation distance and the rest is as defined before. (9) 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, (9) may be approximated as:

$$L_{diff} \approx \sum_{i=1}^{m} L_i|_{h_i=0} + \sum_{i=1}^{m} \left.\frac{\partial L_i}{\partial h_i}\right|_{h_i=0} \cdot h_i = L_0 + \sum_{i=1}^{m} w_i \cdot h_i \tag{10}$$

Thus, shadowing (second term of (10)) can be estimated as a linear combination of obstacle height variations along the propagation path. Such combination is computed as explained next. Let's define ν_i as the clearance of the first Fresnel zone for i-th obstacle position if $h_i = 0$:

$$\nu_i = \left(h_B - \frac{r_{pi}(h_p - h_q)}{r}\right) \cdot \sqrt{\frac{2r}{\lambda \cdot r_{pi}(r - r_{pi})}} \qquad (11)$$

where r_{pi} is distance from point P to obstacle i and λ is wavelength. Then, according to (10):

$$w_i = \frac{\partial L_i}{\partial h_i} = \frac{\partial L_i}{\partial \nu_i} \cdot \frac{\partial \nu_i}{\partial h_i} = \frac{10}{\ln 10 \cdot l_i} \cdot \frac{\partial l_i}{\partial \nu_i} \cdot \frac{\partial \nu_i}{\partial h_i} \qquad (12)$$

In order to avoid the computational load of calculating $\frac{\partial l_i}{\partial \nu_i}$ the following approximation is used:

$$L_i \approx 6.9 + 20 \cdot \log_{10}\left(\sqrt{1 + (\nu_i - 0.1)^2} + \nu_i - 0.1\right) \qquad (13)$$

And, from it:

$$\frac{\partial L_i}{\partial \nu_i} = \frac{20}{\log 10 \cdot \left(\sqrt{1 + (\nu_i - 0.1)^2} + \nu_i - 0.1\right)} \times \\ \times \left(\frac{\nu_i - 0.1}{\sqrt{1 + (\nu_i - 0.1)^2}} + 1\right) \qquad (14)$$

To avoid some numerical drawbacks of the approximation, (14) is multiplied by the exponential term $e^{0.6 \cdot (\nu + 0.5)}$ when $\nu < -0.5$.

The multiple diffraction is modelled as a series of single diffractions according to Deygout's model [15]. This is a recursive method for computing the clearance ν_i at each obstacle that consists in the following steps: first, ν_i is computed for 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: the first one between transmitter and obstacle and the second one between obstacle and receiver (this has been depicted in figure 2). Then, evaluation of both sublinks is done similarly, as if each of them were the main link.

III. Analysis of model behaviour

The main adjustable parameters of the shadowing model described in the previous section are the standard deviation of obstacle heights that is used to generate matrix $\mathbf{H}_{n \times n}$ (let's call it σ_h) and the sampling distance b in (1). Obviously, wavelength λ, mean obstacle height h_B and antenna heights h_P and h_Q are adjustable too, but it is assumed that their values are chosen in agreement both with the simulated system and the propagation scenario. Thus, only σ_h and b remain free to adjust shadowing characteristics.

Since shadowing loss is modelled as a linear combination of obstacle height variations, as expressed in (10), and such variations are assumed to have a Gaussian distribution, the resulting distribution for shadowing is also Gaussian and its standard deviation will be linearly related to σ_h. This is illustrated by figure 3. Specifically, for a simulated environment with two base stations and a carrier frequency of 2 GHz, the figure shows both the mentioned linear dependence and the independence between shadowing correlation (both autocorrelation and cross correlation) and σ_h.

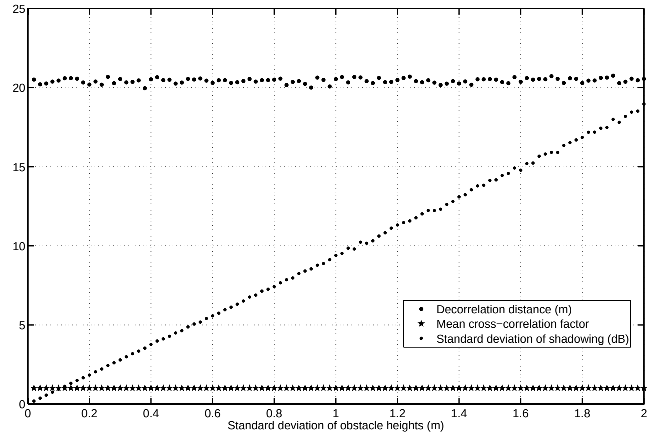

Fig. 3. Dependence of shadowing parameters(σ, decorrelation distance and mean cross-correlation factor) on the standard deviation of obstacle heights σ_h.

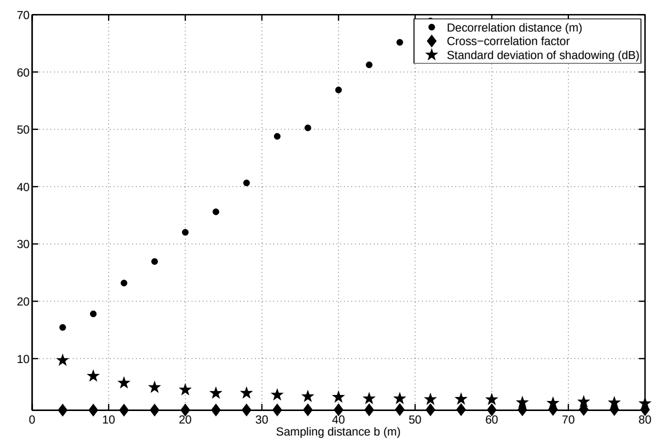

Fig. 4. Dependence of shadowing parameters (σ, decorrelation distance and mean cross-correlation factor) on the sampling distance b of the obstacle height map $\mathbf{H}_{n \times n}$.

Conversely, decorrelation distance is significantly affected by the choice of b, as depicted in figure 4. In this case, b also affects standard deviation of shadowing by means of a inverse relation. Cross correlation remains fairly independent of b too. Considering both figures, the most reasonable way to proceed is to adjust b in order to obtain the desired decorrelation distance and, afterwards, choose the value of σ_h that provides the desired standard deviation of shadowing. Both adjustments are expected to be fairly straightforward due to the linear nature of dependences.

IV. Model Validation

A. Statistical Analysis

Some validation tests of the described shadowing model were reported in [6]. These included analysis of the dependence of standard deviation of shadowing with propagation distance, decorrelation distance and dependence of cross correlation with angle between links.

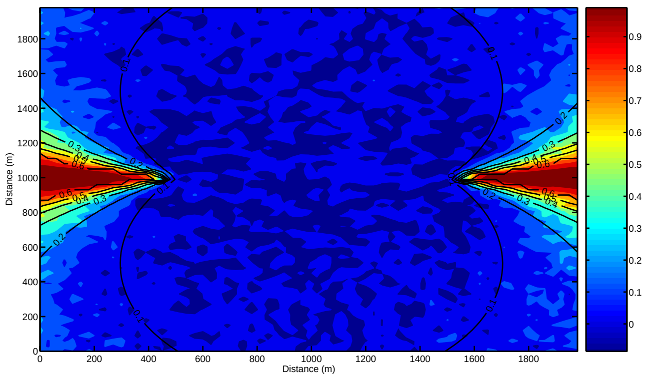

Fig. 5. Cross correlation of simulated shadowing maps (coloured map) and comparison to Saunders' model (contour lines).

Regarding cross-correlation between different links, [6] demonstrated the good agreement of the model results with the measurements behaviour described in [10]. In this paper an additional test has been performed comparing the cross correlation obtained by the herein presented model with the model proposed by Saunders [16]. This model considers the cross correlation between links ρ_c to be a function of the angle between links ϕ as follows:

$$\rho_c = R \cdot \left(\frac{\phi_c}{\phi}\right)^{\gamma} \quad (15)$$

when $\phi < \phi_c$ and $\rho_c = R$ otherwise. From simulation results it has been found that $R = 1$, $\phi_c = 7^o$ and $\gamma = 1.22$ provide a good fit between Saunders' model and those results. Figure 5 allows qualitatively assessing the goodness of this fit.

Finally in [6] it was also shown that, for a wide range of angles (between -50^o and 50^o), the experimental values of cross-correlation are inside the bounds proposed in [10].

B. Impact on System-level Simulations

A second validation strategy has consisted in simulating a downlink UMTS scenario, comparing the performance of different shadowing models, including the model described in this paper. In these simulations only web browsing service has been considered, using the model described in [17] with a non-strict deadline of 30 s.

The scenario consists of seven cells with radius 0.5 km, with the cell under study in the centre. The maximum available power is 43 dBm, and the transmitted power of the interfering cells is 40 dBm (a 50% load factor is considered). Users are continuously moving with a constant speed of 50 km/h. The path loss for each user is calculated using the model described in [18]. The thermal noise power level is -102 dBm. The orthogonality factor is set to 0.5. The scheduling algorithms are run every 0.5 seconds. The maximum power load factor is set to 0.6 for the cell being studied.

Four shadowing modelling techniques with an increasing level of complexity and accuracy have been compared with the multiple diffraction shadowing simulation:

- *Model 1*: One-dimensional with spatial correlation. This model fits with the proposal of Gudmundson [9] and is widely used by the research community. Each user is characterized by means of a specific one-dimensional shadowing model with spatial autocorrelation.
- *Model 2*: Two-dimensional with spatial correlation. This model was proposed in [2]. The correlation model distance-dependent is the same as in the case of the first model. However, a two-dimensional filter is used, allowing the creation of shadowing maps corresponding with each transmitter.
- *Model 3*: Complete shadowing model. This is also a bi-dimensional shadowing model but it introduces both the spatial correlation and the cross-correlation present in real systems. The model proposed by Saunders [16] is used to calculate the cross-correlation matrix between all the base stations of the systems.
- *Model 4*: Multiple diffraction shadowing simulation model. Analysed in this paper and previously described in Section II. It is worth noting that for fair comparison Saunders' model has been properly adjusted to fit this model (see (15)).

TABLE I
MAIN PARAMETERS OF THE SHADOWING MAPS

x size	1000 m
y size	1000 m
Sampling distance	5 m
Decorrelation distance	20 m

For those models based on shadowing maps, namely 2, 3 and 4, table I summarizes the main parameters considered in their generation. For each shadowing model, ten system-level simulations executed with different random seeds have been run during one hour of emulated time. All reported results have been obtained averaging over the whole set of 10 simulations.

Table II shows a set of system performance metrics obtained with the four shadowing models. From among all the analyzed parameters, the total power is, without doubt, the one that is mostly affected by the selection of the shadowing correlation model. The reason for this effect is that, intuitively, the more correlation introduced, the lower the total power since increasing correlation favours channel stability and therefore power control is able to follow changes in the signal to noise plus interference ratio, reducing the noise rise of the system. In agreement with the previous reasoning, the lowest power consumption is achieved by the multiple diffraction shadowing simulation model (M4) and the complete shadowing model (M3). Recall that in models M3 and M4 all interferers and the useful signal are correlated in accordance with Saunders' model. In models where shadowing cross correlation is not included (M1 and M2) the total power increases.

Table II also shows that the reduction of the total power comes with an slight improvement in the performance of the resource allocation tasks, what, in the end, entails a lower number of users with data pending for transmission and a remarkable reduction in the mean object and web page delay.

TABLE II
AVERAGE RESULTS

	M1	M2	M3	M4
Total power (W)	12.85	12.83	12.74	12.66
Number of active users	14.11	13.95	13.57	13.53
Effective throughput (kb/s)	1026.4	1028.5	1031.7	1032.1
Throughput per user (kb/s)	77.58	78.39	80.29	80.65
Object delay (s)	1.21	1.22	1.18	1.16
Web page delay (s)	7.12	7.17	6.91	6.83

According to these results, models considering all shadowing features produce performance indicators better than those models only including spatial correlation.

Comparing models M3 and M4, only a slight difference is detected, being the multiple diffraction shadowing simulation model the one which achieves the best performances. This fact corroborates the validity of the proposed model. It can be conclude that the multiple diffraction shadowing simulation model outperforms the other models found in the literature, since it is valid for conventional scenarios and is also flexible enough to be employed in other 'non-classical' systems.

V. CONCLUSIONS

This paper has revised a shadowing simulation model whose results reach a good level of agreement with existing statistical models while maintaining a fair degree of complexity. The main interest of this model is its adaptability to different environments, ranging from rural environments to small urban macrocells, due to its modelling of obstacle size and height, and from medium wave radio broadcasting to networks operating in the 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 antenna heights. These features makes the model specially interesting for cases in which there is a diversity of antenna heights, interference between uplink and downlink may occur or both ends of the wireless link move. Moreover, as the influence of the wavelength is also consider, the model can also be appropriate in the case of heterogeneous networks consisting of different technologies operating in different frequency bands. Its limitation is related to the dominant propagation mechanism, which is assumed to be over-obstacle propagation. However, this seems to be a dominant mechanism for many outdoor environments, even in the case of low antennas [8].

As for the impact of the model on simulations, the results reported in this paper have shown that the performance of the model is comparable to that of other models in the case of standard wireless cellular networks, thus confirming the validity of the model.

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