Complete Shadowing Modeling and its Effect on System Level Performance Evaluation

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***Abstract*— Computer simulations are a common procedure for assessing the performance of new algorithms. To conduct a valid and accurate study, the models employed in such simulators need to be carefully selected. Regarding shadowing modeling, one-dimensional models are fairly commonplace in the literature. While simple and with low computational costs, these models can not produce correlated fading values for mobiles that are in nearby positions and, besides, do not include the cross-correlation effect. To overcome these limitations, this paper presents a bi-dimensional shadowing model which introduces both the spatial correlation and the cross-correlation present in real systems. Finally, the impact of considering different aspects of shadowing modeling for system level investigations is evaluated. For that purpose, the UMTS radio access technology has been considered as a case study.**

I. Introduction

The mobile radio channel is usually modeled as a combination of three effects: mean path loss, shadowing (referred to also as large-scale fading or slow fading) and fast fading. Of all the effects that exist in the actual channel, usually fast fading effect is included within link level simulations whereas mean path loss and shadowing are modeled for system level analysis. Since mean path loss depends simply on the distance between transmitter and receiver, the random variability of mobile radio channels is mostly affected by shadowing in system level simulations. For that reason, a careful selection of the simulated shadowing models is required to provide an appropriate and accurate system evaluation [1].

This paper proposes a realistic and complete shadowing model which simultaneously implements two very important characteristics of shadowing that Saunders [1] and Gudmundson [2] formulated by means of direct comparison with measurements. Moreover, this paper compares different models, analyzing their effect on the system performance evaluation, specifically in downlink UMTS.

With this aim, the shadowing characteristics are firstly analyzed. Starting from this study, several models with an increasing level of realism, hence complexity, are presented. Next, the results obtained considering each of these models are compared. Analysis of such results leads to a discussion on the most adequate complexity level of a shadowing model for system-level simulation of UMTS and similar systems.

II. Characteristics of Shadowing

Several experimental studies have shown that the statistical distribution of shadowing can be approximated by a lognormal law (e.g. [1],[2]) with zero mean and an environment-specific standard deviation. In addition, other works have demonstrated that shadowing is a random process with a certain spatial autocorrelation, which means that shadowing between transmitter and receiver in a specific position is correlated with the shadowing experienced between the same transmitter and the same or other receiver in a neighbor location. Gudmundson [2] suggested a one-dimensional model of its autocorrelation function, following the user-specific trajectory.

The relevance of second-order statistical properties of shadowing is widely accepted and Gudmundson's model has been extensively used in test beds and simulation studies of wireless communications. However, this model is limited in the sense that it independently considers the shadowing for each mobile unit, thus resulting in uncorrelated shadowing even for receiver units that are in close vicinity to each other and their surrounding obstacles are identical. As observed in different measurement campaigns (e.g. [3],[4]) such lack of correlation does not happen in real networks.

Neglecting the shadowing correlation can become an important flaw when evaluating the performance of techniques that strongly depend on the radio link quality conditions (e.g. soft handover, macro-diversity and link adaptation). To overcome this limitation, different studies (see e.g. [4]) have proposed a bi-dimensional shadowing model that results in a unique shadowing map for each transmitter. The shadowing maps relate each geographical point to a particular shadowing value and, consequently, their use allows generating correlated shadowing values for neighboring mobile units.

Another aspect of shadowing modeling is Shadowing Cross-Correlation (SCC), which considers the relation between the shadowing components experienced by a receiver from two different transmitters at a given position. Several experimental results (e.g. [3][5]) have confirmed the existence of such cross-correlation and, in spite of suggesting different values for it depending on the terrain morphology, all studies agree in the fact that this SCC has a decisive effect on the final system performance. It is generally understood that the more two radio links share a common propagation path, the higher the correlation coefficient is. Therefore, SCC has been modeled as a function of two variables [6]: the Angle-of-Arrival Difference (AAD) and, optionally, the relative distance difference. From the measurements campaign carried out by Graziano, Saunders proposed a model considering jointly both variables [1]. For its simplicity and accuracy this model is in common use.

In this context, [4] presents a bi-dimensional shadowing model capable of representing both spatial correlation and a constant site-to-site cross-correlation. This paper steps forward and proposes a model which allows for a full characterization of shadowing including more complex SCC models, such as Saunders'.

III. COMPLETE SHADOWING MODEL

The complete shadowing model presented here provides two-dimensional shadowing maps for each base station included in the cellular layout; each map covering the entire simulation area. It deals with SCC in the first place and, next, it introduces the spatial autocorrelation. Given that the major contribution of this paper is the specific inclusion of SCC modeling, this aspect of modeling will be addressed more fully in this section.

A. *Shadowing Cross-Correlation*

The shadowing experienced by signals transmitted from a set of N base stations to a specific point *(x,y)* can be calculated as a realization of a set of N Gaussian random variables $S_i\left(i=1,2,\ldots,N\right)$. It is assumed that these variables have the same mean and standard deviation σ_{SH}, since all propagation paths occur within the same type of environment. The value of the correlation coefficient, ρ_{ij}, of each pair of variables, $\left\{S_i, S_j\right\}$, is specified by the selected SCC model.

$$\rho_{ij} = R_{ij}\left(0\right) = \frac{E\left[S_i\left(n\right)\cdot S_j\left(n\right)\right]}{\sqrt{E\left[S_i\left(n\right)^2\right]\cdot E\left[S_j\left(n\right)^2\right]}} \quad (1)$$

Specifically, Saunders [1] modeled the SSC coefficient as:

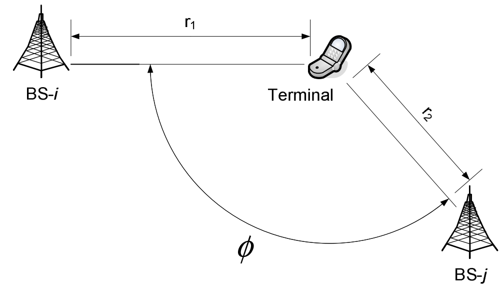

Figure 1. Parameters of Saunders' SCC model

$$\rho_{ij} = \begin{cases} \sqrt{\dfrac{r_2}{r_1}} & ,0 \le \phi < \phi_T \\ \left(\dfrac{\phi_T}{\phi}\right)^{\gamma}\sqrt{\dfrac{r_2}{r_1}} & ,\phi_T \le \phi < \pi \end{cases} \quad (2)$$

Where r_2 is the smallest path length between base stations and the mobile terminal and r_1 is the other one. The AAD is denoted by ϕ and all three parameters are graphically represented in Fig.1. ϕ_T represents a threshold angle and is related to the decorrelation distance [2] r_{dec} in this way:

$$\phi_T = \frac{2}{\sin\left(\dfrac{r_{dec}}{2r_2}\right)} \quad (3)$$

Finally, the parameter γ takes into account the particular structure of both terrain and buildings and varies in practice depending on the heights of terrain and base stations. Based on measurements realized by Graziano [3] this parameter was adjusted to be equal to 0.3.

The problem of generating adequate samples for all S_i can be mathematically solved by means of the Cholesky factorisation (see e.g. [6]) as follows. If the matrix containing the correlation coefficients for every pair of transmitters received at a certain location (the correlation matrix, hereon), $\mathbf{R}_{NxN} = \left\{\rho_{ij}\right\}$, is symmetric, what is always true, and positive definite then its Cholesky factorisation results in $\mathbf{R} = \mathbf{C}\mathbf{C}^{\mathrm{T}}$, where $\mathbf{C}$ is a lower triangular matrix and the superscript T means transposition. The matrix $\mathbf{C}$ can be utilised to transform a vector $\mathbf{r}$ containing N statistically independent random variables with the same distribution into, another vector $\mathbf{s}$ of N equally distributed random values (shadowing values, in fact) satisfying all correlation conditions between links as follows:

$$\mathbf{s} = \mathbf{C}\mathbf{r} \quad (4)$$

The main limitation of this model is that $\mathbf{R}$ must be positive definite. In case matrix $\mathbf{R}$ is actually not satisfying this positiveness, what happens often for scenarios with a large number of transmitters that result in high-order correlation matrices, one solution is to find the nearest diagonalizable correlation matrix through the alternating projection method [7].

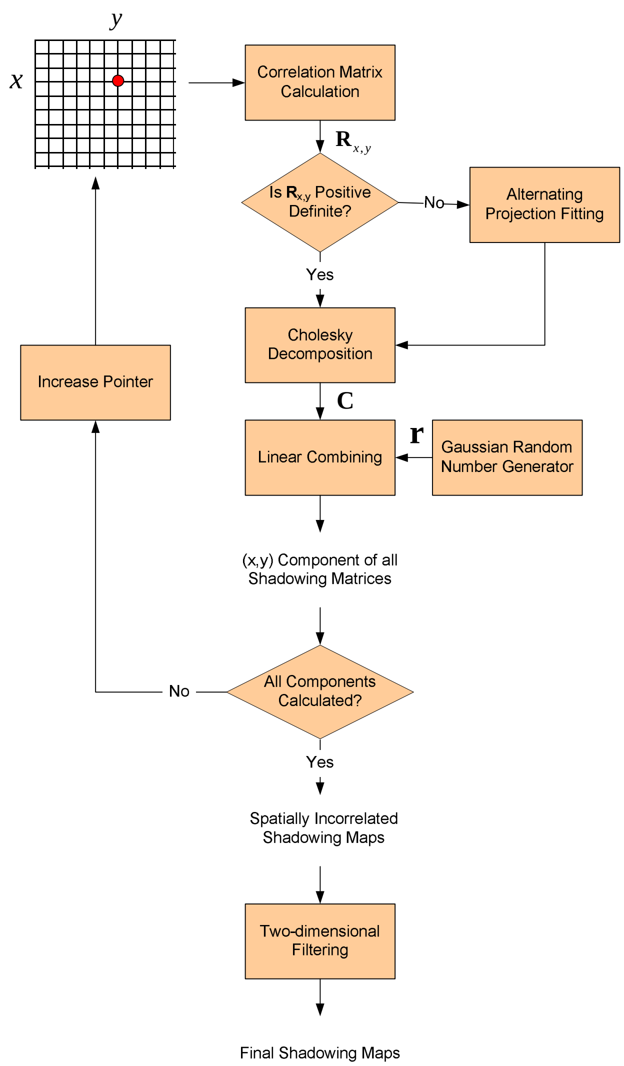

Figure 2. Map generation process of complete shadowing model

The procedure is repeated for each geographical point. Finally all the shadowing maps are obtained, one for each base station, satisfying the desired SCC.

B. *Spatial Autocorrelation*

In order to introduce also the spatial autocorrelation, each shadowing map corresponding to one transmitter is passed through a two-dimensional filter, thus providing the desired autocorrelation function. Detailed information on the design and characteristics of this filtering method can be found in [4]. In Fig.2 the whole the process followed to create the two-dimensional shadowing maps with both cross-correlation and spatial autocorrelation is summarized.

IV. SYSTEM PERFORMANCE

A. *Simulation Scenario*

As explained before, performance evaluation of the complete shadowing model has been carried out by means of a downlink UMTS simulation platform. In these simulations only web browsing service has been considered, using the model described in [8] with a non-strict deadline of 30s.

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). The path loss for the i-th user is calculated using the model described in [9].

Users are on the move with a constant speed of 50 km/h. The thermal noise power level is -102 dBm. The orthogonality factor ρ 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. Users are multiplexed over a common Downlink Shared Channel (DSCH) and, therefore, within the code tree one branch of spreading factor 256 is reserved per user for signalling. Finally, five additional branches, also having a spreading factor equal to 256, are reserved for common and broadcast channels. The rest of available branches determine the total maximum bit rate, bearing in mind that one code of spreading factor equal to 8 entails a bit rate of 256 kb/s. The set of possible bit rates considered is {256 kb/s, 128 kb/s, 64 kb/s, 32 kb/s, 16 kb/s, 0 kb/s}. The corresponding required E_b/N_0 ratios are {5.6 dB, 4.4 dB, 4.62 dB, 4.55 dB, 4.55 dB, $-\infty$ dB}, as proposed for web service in [10].

B. *Reference Shadowing Models*

Four modeling techniques with an increasing level of complexity and accuracy have been investigated:

- *Model 1 - One-dimensional with spatial correlation*. This model fits with the proposal of Gundmundson [2] and is widely used by the research community. Each user is characterized by means of a specific one-dimensional shadowing model with spatial autocorrelation. The user trajectory has not any influence on the model but the distance run by the user.
- *Model 2 - Two-dimensional with spatial correlation*. 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. The SCC is not considered.
- *Model 3 - Two-dimensional with constant cross-correlation*. This model was proposed in [4] and is similar to the previous model excepting that a fixed cross-correlation coefficient equal to 0.5 is assumed among all transmitters.
- *Model 4 - Complete shadowing model* proposed in this paper and previously described in Section III.

Fig. 2. Main Paramenters of the Shadowing Maps

Number of Nodes-B	7
x size	1000 m
y size	1000 m
Number of points per map	200 x 200
Sampling distance	5 m
Decorrelation distance	20 m

TABLE I. AVERAGE RESULTS

	M1	M2	M3	M4
Outage probability (%)	1.75	1.12	0.421	0.346
Total power (W)	12.85	12.83	11.53	11.42
Number of active users	14.11	13.95	10.63	10.38
Effective throughput (kbps)	1026.4	1028.4	1083.4	1090.2
Throughput per user (kbps)	77.58	78.39	103.66	106.38
Object delay (s)	1.21	1.22	0.875	0.851
Web page delay (s)	7.12	7.17	5.15	5.02

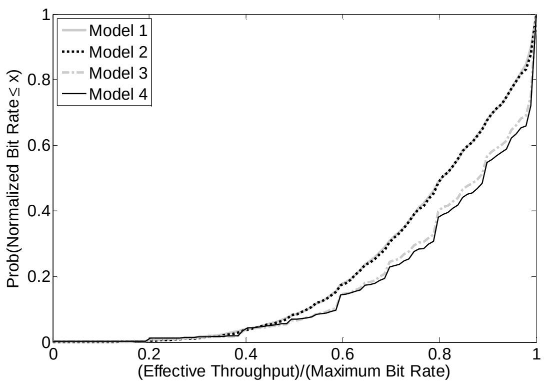

Figure 3. CDF of the normalized throughput

For those models based on shadowing maps, namely 2, 3 and 4, Table I summarizes the main parameters considered in their generation.

C. *Numerical Results*

For each of the considered shadowing models, 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. A fixed number of 70 web users have been introduced in the system. It is worth noting that although 70 users are in the system they are not active at the same time due to the bursty traffic pattern of web service.

Table II shows a set of system performance metrics obtained with the four shadowing models. From among all the analyzed parameters, the outage probability 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 the lower the outage probability since an increasing correlation favors channel stability and therefore power control is able to follow changes in the signal to noise plus interference ratio.

In agreement with the previous reasoning, the lowest outage probability is achieved by the complete shadowing model, which is two-dimensional and with a more detailed SCC modeling. Recall that in this model all interferers and the useful signal are correlated in accordance with Saunders' model. In models where SCC is not included (M1 and M2) the outage probability is highly increased. Besides, between models which only implement the spatial correlation, again models 1 and 2, the two-dimensional approach significantly reduces the outage probability.

Concerning the average power, it can be observed that the usage of the classical Gudmundson's model entails an overestimation of the consumed power of about 12.5%, as compared with the most accurate shadowing model (M4).

Table II also shows that the reduction of the outage probability comes with an important 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. According to these results, models considering cross-correlation produce performance indicators significantly different from those models only including spatial correlation.

Fig. 3 depicts the experimental distribution, specifically, the cumulative distribution function (CDF), of the effective throughput allocated in the central cell normalized with respect to the maximum data rate achievable in the system. Again, results demonstrate that cross-correlation effect must be included in the shadowing modeling since it is decisive to assess accurately system performance. Models not including cross-correlation tend to make a pessimist analysis of the system capacity. Regarding models 3 and 4, although the more realistic and accurate complete shadowing model (M4) provides the best results, the little difference in comparison with the two-dimensional model with constant cross-correlation (M3) questions the necessity of including with so much precision SCC.

Last, Fig. 4 represents the service response time, i.e. the period elapsed since the instant of the data request until the complete message reception, as a function of the web page size. Again, the complete shadowing model presented in this paper, which represents more accurately the real behavior of shadowing samples, exhibits more optimistic results.

D. *Analysis and Discussion*

Intuitively, effect of shadowing model on simulation results should vary significantly depending on the considered Radio Access Technology (RAT). If the RAT is based on link adaptation techniques, as for instance GPRS or HSDPA, little variations of channel quality have an important effect on the success of the transmission and, therefore, on the effective throughput and quality of service. Shadowing modeling is of paramount importance in these cases [4].

Moreover, in systems implementing handover algorithms, the decision on handover to a new base station is made on the basis of the relative power level of the current and the candidate base stations and depends highly on the variability of channel quality. Once more, a proper shadowing modeling will have a significant effect on the handover probability and therefore on the macro-diversity process related to it [1].

In contrast, within this paper a downlink UMTS system has been taken into account. UMTS is not based on link adaptation and, besides, in this case no macro-diversity occurs since handover is not modeled. Nevertheless, results have demonstrated that the choice of the shadowing model affects the outcomes of the system analysis, even when the systems are not based on link adaptation. In order to explain this, the following aspects must be taken into account:

- The scheduler has to maximize the resource utilization, i.e. power and number of codes in UMTS. Once a certain resource allocation has been decided, this is kept fixed until the next run of the scheduler. During the time passed between consecutive allocations, channel conditions or interferences can vary due to user mobility or load fluctuations. The lower the shadowing correlation the higher the channel quality variability and consequently more mistakes will be made by the system.
- UMTS executes a fast power control mechanism (1500 times per second). This technique allows following slow channel variations provided that these changes are not abrupt. However, if either channel conditions change too quickly or the system becomes congested, power control is not able to follow the channel and, therefore, the required signal to interference ratio is not fulfilled. In these cases users do not experience the adequate quality of service and are in a situation of outage, in which packets are not properly received. If packets are not delivered then the amount of data pending for transmission in the buffers increases hence augmenting the packet delay too.
- Variability of signal to interference ratio does not only depend on the autocorrelation of the received signal but also on the behavior of the interferences. If interference signals coming from neighbor cells are more correlated then signal to interference ratio will remain more stable and the system performance will improve.

V. Conclusions

This paper has presented a novel two-dimensional shadowing model that is able to consider not only the spatial correlation characteristic of the slow fading phenomena but also the non-negligible cross-correlation between signals transmitted from different base stations. As this complete model is based on previous works already contrasted with real measurements, the validity and accuracy of the model is guaranteed.

After formulating the model, its effect has been assessed with the results of the evaluation of a UMTS system. It has been demonstrated that a high accuracy model, like the one proposed in this paper, gives more optimistic results than other simpler approaches. However, as compared with other models that also consider both correlation effects, the difference is not very significant.

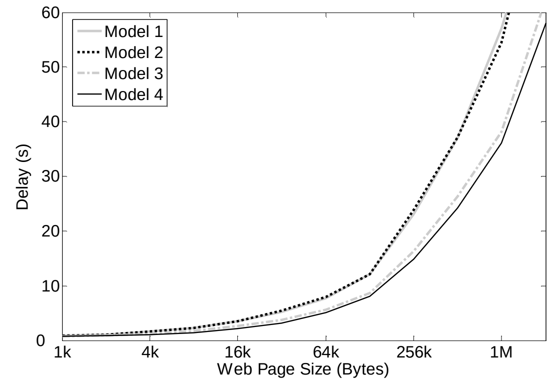

Figure 4. Average delay per web page as a function of its size

Finally, it is worth noting that, since base station positions are fixed during all the simulation, the generation of the shadowing maps is always an off-line process. Therefore, the burden cost added in the simulation by the usage of the complete shadowing model is null. In consequence, and given that the complete model is the most accurate one, its usage seems the most adequate option among the others herein analyzed.

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