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Modeling of Shadow Fading Correlation in Urban Environments Using the Uniform Theory of Diffraction

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Mots-clefs *(en français et en anglais)* : shadow fading, correlation model, double exponential decay function, uniform theory of diffraction

Abstract
Shadow fading is a well known problem in wireless sensor networks (WSN) and ad hoc networks since the communicating devices often are at street-level where the surrounding buildings often obstruct incoming radio waves. Therefore, accurately modeling shadow fading is an important requirement for the optimal design of such networks. Because the height of building is the most important parameter to calculate diffraction loss, the correlation of building heights on two close paths may influence the correlation of shadow-fading. In this paper, we first assume that the building heights follow an exponentially correlated Gaussian distribution, and then investigate shadow-fading correlation through the uniform theory of diffraction (UTD). The result shows that the correlation of shadow-fading stems from multiple exponential decay functions. Considering that the buildings near RX and TX are dominant contributors to shadow fading, a multiple (double in particular) exponential decay function is expected to better model the correlation than a single exponential.

Introduction
Shadow fading is a well known problem in wireless sensor networks (WSN) and ad hoc networks since the communicating devices often are at street-level where the surrounding buildings often obstruct incoming radio waves. Therefore, accurately modeling shadow fading is an important requirement for the optimal design of such networks. The radio paths between a transmitter (TX) and a receiver (RX) rarely match the condition of line of sight (LOS), implying severe shadowing effect, which indirectly provides an advantage for the frequency reuse that can be exploited in cognitive radio (CR) systems as well as other in distributed wireless peer-to-peer systems (e.g. ad hoc networks, wireless local area networks), leading to the enhancement of spectrum efficiency. Given this context, the purpose of the present work is to develop simple and suitably accurate models of shadow fading in urban environments.

In early studies, for the sake of simplicity, the statistical distribution of shadow-fading was approximated as a lognormal distribution (Gaussian in dB), spatially correlated in an ad hoc manner, typically with a distance dependent exponential decay (Gudmundson model [1]). Recent works showed that correlated shadow-fading has a detrimental influence on the performance of wireless systems. In [2][3], the performance of collaborative spectrum sensing for opportunistic access in correlated shadow-fading environment degrades as the decorrelation distance increases. Another author asserts that highly correlated shadow-fading results in a large positioning error when applying a localization algorithm such as the weighted centroid localization algorithm in a WSN [4].

In order to obtain 2-dimensional results, several algorithms to generate 2-dimentional correlated shadow fading have been derived by expanding Gudmundson's 1-dimensional model [5][6]. Other researchers report that a high correlation has been observed within a certain angular separation between the directions going from the mobile stations to the base station [7]. Even though the exponential decay model or other angular correlation models are well-known and proved by a large amount of measurements, there is no elaborated impact on physical layer aspects of such model and the decorrelation distance.

In this paper, we first investigate shadow-fading correlation through the uniform theory of diffraction (UTD), which is a technique of reference to treat the diffraction by building edges in simulation tools of the propagation by deterministic methods. In urban areas, shadow-fading is indeed mainly caused by obstruction from buildings. In ray-tracing, when the TX and RX are far enough from each other (implying more than 3 reflections and 1 diffraction), the rays along streets are drastically attenuated and the rays over roof-tops dominate the received power. Since the height of building is the most important parameter to calculate diffraction loss, it is reasonable to consider that, if the building heights on two close paths are highly correlated, the shadow-fading may highly correlated too.

The paper is organized as follows: Section II describes the scenario setup and parameters; Section III presents analytical solution of correlation function for the proposed scenario; Section IV illustrates the simulated results by MATLAB and results from ray-tracing tool by exploiting real urban geometrical maps; finally, Section V draws a brief conclusion.

1. Simulation Scenario

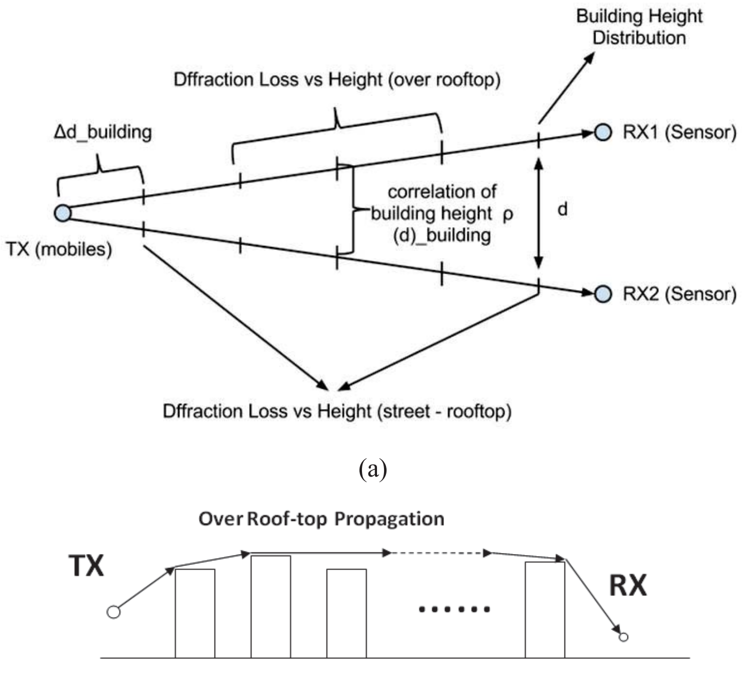
The simulation scenario is shown in Figure 1. The rays represent over-rooftop propagation from TX to RXs, experiencing several diffractions caused by buildings which have an average distance interval – $\Delta d_{building}$. We assume that the building heights follow an exponentially correlated Gaussian distribution with a decorrelation distance equal to the average dimension of building blocks, here taken as 20.1 meters. The correlation of heights of two building apart at a certain distance is shown in (1).

$$\rho\langle H_1, H_2\rangle\; d \;= e^{-\frac{In2\cdot d}{D}} \qquad (1)$$

where D donates decorrelation distance. The justification of this approach is that very high towers neighboring small houses are highly unlikely, owing to urban regulations. We use buildings data extracted from satellite geometrical maps covering the 1st to 4th districts in Paris, provided by the French company SIRADEL® and from literatures in civil engineering [8].

UTD [9] is applied to calculate diffraction loss caused by building edges, depending on the incidence and diffraction angles. Since the position of RX or sensors in WSN is below roof-top, the height for RX has been set to 2.5 m and 8 m as two representative cases. For the purpose of comparison, another height, typical of a base station in cellular network, has also been investigated. The TX such as mobile-phone is assumed to be located about 1.5 m above ground and moving along a street. The displacement of the RX is set from 1 m to 50 m with 0.1m interval. Besides, the radio frequency is chose to be 1.9 GHz.

We carried out Monte-Carlo simulations of the path loss, with 10000 realizations for each RX displacement. In each realization, the correlated Gaussian random heights are assigned to each building to calculate the path loss of each path. The shadow fading component has been extracted from the calculated path loss and has been found to match the Gaussian distribution reasonably well, with a standard deviation of 4-6 dB. As a contrast, we launched a series of simulation by a commercial ray-tracing tool within the same urban area where the building parameters are extracted (shown in fig x).



(a)

(b)

Figure 1 Mathematical simulation scenario (a) horizontal plane; (b) vertical plane

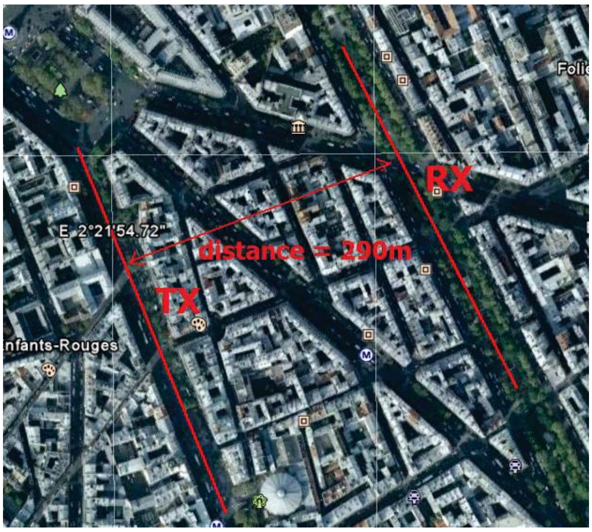
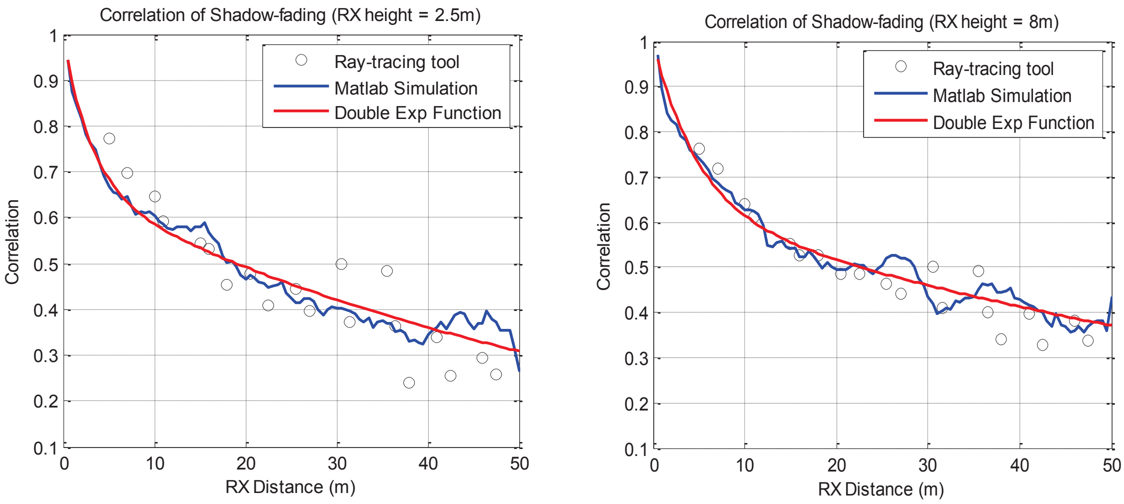


Figure 2 Location of TX and RXs in ray-tracing simulation tool Volcano® [10]

2. Results and Analysis

Figure 3(a) and 3(b) illustrate the correlations of shadow-fading versus RX distance when RX height is set to 2.5m and 8m respectively. A high correlation has been observed when the RX moves over a distance smaller than building block dimensions. For the RXs at street-level, the proposed simulation model provides a good agreement with the result from the ray-tracing tool, meanwhile, a double exponential decay function has been observed to better fit the simulated correlations. When the RX's position elevates, the correlation of shadow-fading will also increase slightly, implying an adjustment of this correlation can be achieved by changing RX's height. The parameters of the fitted double exponential function are shown in Table 1.



(a) (b)

Figure 3 Correlation of shadow-fading for the cases: (a) RX height = 2.5m; (b) RX height = 8m.

Table 1 Parameters of Fitted Double Exponential Function

	Double Exponential Function: $\rho(x) = a \cdot e^{-b \cdot x} + c \cdot e^{-d \cdot x}$			
	a	b	c	d
RX height = 2.5m	0.6704	0.0155	0.3296	0.3278
RX height = 8m	0.633	0.01068	0.367	0.2089
RX height = 22m	1	0.04388	N/A	N/A

In contrast, for the case of a RX placed over roof-tops (shown in fig. 4), the distance dependent correlation properly obeys the Gudmudson's single exponential model, with a decorrelation distance of 33.25m close to the size of building block. However, the proposed simulation model seems to diverge from the fitted exponential decay. A possible explanation for this overestimation of correlation is that the proposed simulation model ignores the reflected and diffusing rays which are probably less correlated than the direct over-rooftop rays.

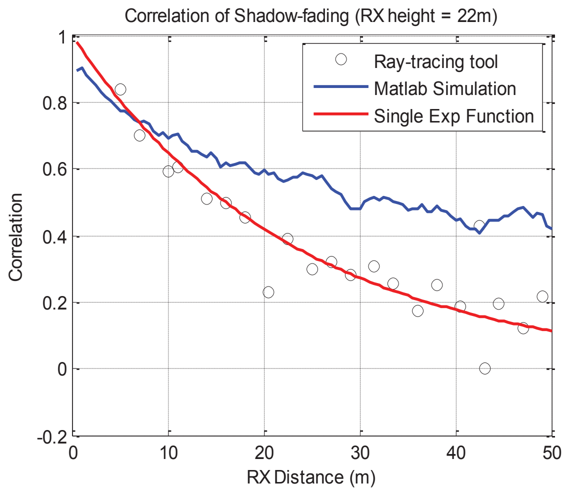


Figure 4 Correlation of shadow-fading for the case RX height = 22m

3. Conclusion

We proposed a simulation model based on the characteristics of urban structures in order to predict the correlation of shadow-fading in the context of distributed wireless peer-to-peer systems. The RX height is set to 2.5m, 8m and 22m to represent three typical heights for deploying a wireless sensor. It is concluded that since the obstruction formed by a single building block covers an area proportional to the distance from RX, the RX shall be multi-shadowed after propagating over multiple rows of buildings. In other words, the correlation of shadow fading stems from multiple exponential decay functions. Considering that the buildings near RX and TX are dominant contributors to shadow fading, a multiple (double in particular) exponential decay function is expected to better model the correlation than a single exponential.

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