A TIME-DOMAIN TECHNIQUE FOR FADING DEPTH CHARACTERISATION IN WIDEBAND MOBILE COMMUNICATIONS SYSTEMS

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ABSTRACT

A time-domain technique for fading depth characterisation in wideband Rayleigh and Ricean environments is proposed. New expressions for the probability functions of the received power, which apply to both Line-of-Sight and Non-Line-of-Sight cases, are derived. The fading depth for continuous and discrete channel models is evaluated as a function of the Rice factor, and the product between the system bandwidth and the *rms* delay spread of the propagation channel. Application examples for UMTS working in different environments are shown, and the results are discussed, giving a general insight into the fading depth behaviour. The fading depth observed by UMTS within different environments ranges from less than 4.3 to 12.5 dB, which is significantly lower than the ones for GSM, thus, different fading margins must be considered. Moreover, UMTS is less sensitive to the existence of Line-of-Sight than GSM.

INTRODUCTION

The propagation channel in mobile communications systems exhibits properties of a multipath fading channel, since waves arrive at the receiver from several reflected and/or diffracted paths. If there is Non-Line-of-Sight (NLoS) between the transmitter and the receiver, the short-term fading behaviour of the amplitude of the received signal is usually well modelled by a Rayleigh distribution. Otherwise, if there is a LoS component, the signal amplitude usually follows a Ricean one. Until nowadays much of the research was based on the assumption of analysing narrowband signals, whose bandwidth is much narrower compared to the coherence bandwidth of the propagation channel. Under these conditions, the signal at the receiver is said to be in a frequency flat fading environment, and varies with the Rayleigh or Ricean distributions, as referred above. However, when one considers wideband signals, whose bandwidth is greater than the coherence bandwidth, the signal at the receiver is distorted, but the fading depth is smaller than the one obtained from the Rayleigh or Ricean distributions. Since existing systems, e.g., UMTS and HIPERLAN, and others to appear in the future, e.g., Mobile Broadband Systems (MBS), are wideband ones, operating many times in LoS conditions, for the former, or intended to work mainly under LoS, for the latter, new approaches are needed, both in the frequency and time domains, for the development of existing systems, as well as for the design, assessment and implementation of future ones.

A frequency-domain theoretical model for the study of wideband signal transmission is presented in [1]. An analytical expression for the evaluation of fading depth, accounting for the maximum difference in propagation path length and having the Rice factor as a parameter, derived from fitting simulated data from the model in [1] is proposed in [2]. A time-domain level variation analysis technique of wideband signals in Rayleigh fading environments is proposed in [3], the approach being based on the eigenvalue decomposition technique. In this paper a time-domain technique for fading depth characterisation in wideband Rayleigh and Ricean environments is proposed. Following a similar approach as the one in [3], new expressions for the Probability Density Function (PDF) and Cumulative Distribution Function (CDF) of the received power, which apply to both LoS and NLoS, are derived. Moreover, the fading depth observed by UMTS, working in different environments, as proposed by standard-setting bodies, are shown.

The paper is organised as follows. The time-domain technique for fading depth characterisation in wideband Rayleigh and Ricean environments is presented and new expressions for the probability functions of the received power, are derived. A brief comparison between the results obtained with continuous and discrete Power Delay Profiles (PDPs) is made. Results on the fading depth observed by UMTS in different environments, namely Indoor, Pedestrian, Vehicular, Rural Area, Typical Urban and Hilly Terrain, are presented and discussed. Finally, conclusions are drawn.

PROPOSED APPROACH

Assuming that the PDP of the propagation channel is expressed as a function of the time delay, τ, by $p_d(\tau)$, the correlation function between the f_i and f_k frequency components is obtained as:

$$\rho(f_i - f_k) = \int_0^{\infty} p_d(\tau) \cdot e^{-j2\pi(f_i - f_k)\tau} d\tau \tag{1}$$

The i–th frequency component, f_i, is given by [3]:

$$f_i = \delta f\left(i - \frac{(M'+1)}{2}\right) \quad , \quad i = 1, 2, ..., M' \quad ; \quad \delta f = \frac{B}{M'} \tag{2}$$

where B is the signal bandwidth, and M' a number defining the value of the incremental bandwidth, δf. The covariance matrix is then obtained by generating a matrix, $\mathbf{\Gamma}$, whose element in the i-th row and k-th column is given by:

$$\Gamma_{ik} = \rho(f_i - f_k)\, H^*(f_i)\, H(f_k)\, \delta f \tag{3}$$

where $H(f)$ is the frequency response of the pulse–shaping filter used in the transmitting equipment. Performing the eigenvalue decomposition of $\mathbf{\Gamma}$, the obtained eigenvalues, λ_m (m = 1, 2, …, $M \le M'$), correspond to the decomposition of the M signals, which fade incoherently. The decomposed signals and their powers correspond to the eigenvectors and eigenvalues respectively. The total received power corresponds to the sum of the respective decomposed signal powers, i.e., the obtained eigenvalues [3].

Under LoS, the amplitude of the first arriving wave usually follows a Ricean distribution. Scattered waves are assumed to be Rayleigh distributed. Hence, the PDF of the received power, s, is obtained from the convolution of the PDF of the LoS component with M – 1 scattered ones [4]:

$$p_{\mathrm{LoS}}(s) = p_{\mathrm{LoS}_1}(s) * p_{\mathrm{NLoS}_2}(s) * \cdots * p_{\mathrm{NLoS}_M}(s) = \left[\frac{2K}{a_d^2} e^{-\frac{K(2s+1)}{a_d^2}} I_0\left(\frac{2K\sqrt{2s}}{a_d}\right)\right] * \left[\frac{1}{\sigma_2^2} e^{-\frac{s}{\sigma_2^2}}\right] * \cdots * \left[\frac{1}{\sigma_M^2} e^{-\frac{s}{\sigma_M^2}}\right] \tag{4}$$

where σ_i^2 is the mean received power of the i-th arriving wave, a_d is the amplitude of the LoS component, and K is the Rice factor, defined as the ratio between the power of the LoS component and the scattered ones. I_0 is the modified zero-th order Bessel function of the first kind. Thus, $p_{LoS}(s)$ can be represented as a function of the obtained eigenvalues, λ_m:

$$p_{\mathrm{LoS}}(s) = \int_{-\infty}^{+\infty} \frac{2K}{a_d^2} e^{-\frac{K(2x+1)}{a_d^2}} I_0\left(\frac{2K\sqrt{2x}}{a_d}\right) \cdot \sum_{m=2}^{M} \frac{(\lambda_m)^{M-3} e^{-\frac{s-x}{\lambda_m}}}{\prod_{\substack{k=2 \\ k \ne m}}^{M} (\lambda_m - \lambda_k)} \cdot dx \quad ; \quad a_d = \sqrt{\lambda_1 \frac{2K}{K+1}} \tag{5}$$

There is no closed–form expression for (5); hence, the evaluation of the CDF of the received power has to be performed by numerical integration. When the amplitude of the first arriving wave is modelled as Rayleigh, (5) reduces to the NLoS case, with PDF and CDF given by:

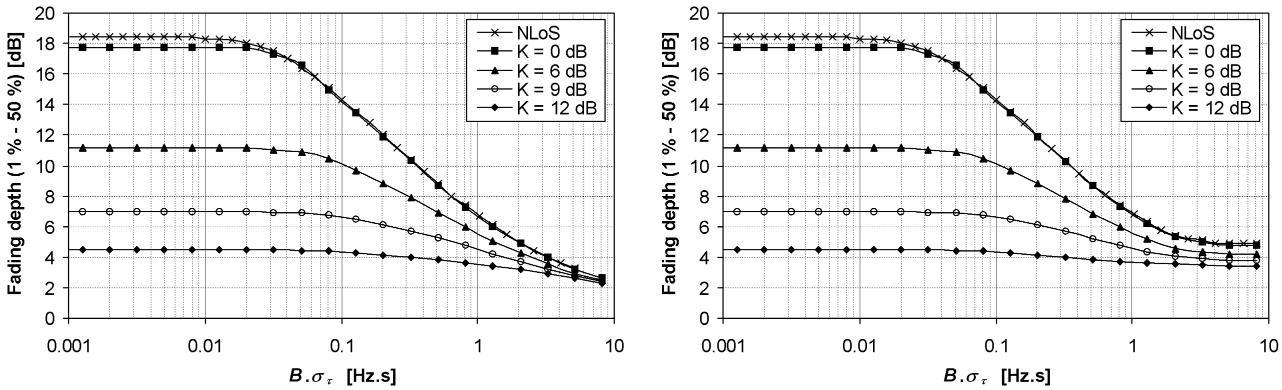
$$p_{\mathrm{NLoS}}(s) = \sum_{m=1}^{M} \frac{\lambda_m^{M-2} e^{-\frac{s}{\lambda_m}}}{\prod_{\substack{k=1 \\ k \ne m}}^{M} (\lambda_m - \lambda_k)} \quad \text{and} \quad \mathrm{Prob}_{\mathrm{NLoS}}(s \le s') = 1 - \sum_{m=1}^{M} \frac{(\lambda_m)^{M-1} e^{-\frac{s'}{\lambda_m}}}{\prod_{\substack{k=1 \\ k \ne m}}^{M} (\lambda_m - \lambda_k)} \tag{6}$$

The process for the evaluation of the CDF of the received power can then be summarised in the following steps: (i) derive the frequency correlation function, $\rho(f_i - f_k)$; (ii) generate the covariance matrix, $\mathbf{\Gamma}$; (iii) find the eigenvalues of $\mathbf{\Gamma}$; and (iv) obtain the CDF of the received power.

Note that the value of the incremental bandwidth, $\delta(f)$, must be carefully determined, since the smaller the value of $\delta(f)$ the larger the number of eigenvalues, and consequently the larger the size of $\mathbf{\Gamma}$. On the other hand, if the value of $\delta(f)$ is not small enough the eigenvalues corresponding to higher signal bandwidths, will oscillate. Typical values of M' for UMTS environments are usually between 100 and 500, depending on the type of PDP.

FADING DEPTH EVALUATION

There are several types of PDPs that have been used for modelling the propagation channel. Real PDPs are continuous functions of the delay. However, since most of the channel simulators are usually based on a tapped–delay line structure, discrete PDPs (usually derived from continuous ones) are commonly recommended by standard-setting bodies for simulating the propagation channel [5]. This type of PDPs is defined by a set of taps with specified relative arrival delays and average relative powers. Using the proposed approach, one obtains the CDF of the received power for different channel models described by its PDPs. The fading depth is then evaluated as the difference in power corresponding to 1 and 50 % of the CDF (other percentage intervals can be taken), and represented as a function of K and the product between the system bandwidth and the *rms* delay spread of the propagation, $B \cdot \sigma_\tau$. Besides the dependence on the type of PDP, the results in Figure 1 illustrate the differences among considering continuous or discrete PDPs. The results for the continuous case are representative of a large set of continuous exponential channels models that are usually recommended for system evaluation purposes. Different values of K are considered 0, 6, 9 and 12 dB, respectively. The continuous model is described by an exponential decaying function with decay rate equal to the inverse of the *rms* delay spread of the propagation channel. The results are independent on the decay rate, since the fading depth is represented as a function of $B \cdot \sigma_\tau$. The discrete PDP is obtained from the equivalent continuous one being composed of 10 distinct taps with different average relative powers and relative arriving delays.



(a) continuous (b) discrete

Figure 1 – Fading depth obtained from continuous and discrete PDPs.

As one can observe, for each value of K, the fading depth remains practically constant for $B \cdot \sigma_\tau < 0.02$ Hz·s. This corresponds to a situation where the system bandwidth is below the coherence bandwidth of the propagation channel; thus, signals are in a frequency flat environment. One also observes that, when considering a discrete PDP, the fading depth curves are coincident with the ones for the continuous case until a given value of $B \cdot \sigma_\tau$ is reached, roughly $B \cdot \sigma_\tau = 1$ Hz·s, and then start to differ from the ones for the continuous case until it keeps constant and independent on the value of $B \cdot \sigma_\tau$. This is due from considering a discrete PDP; hence, the fading depth remains constant for a system bandwidth above the one that is larger enough in order to discriminate all arriving waves. This value depends on the number, average relative power and relative delay of arriving waves. One must remember that discrete PDPs are simple realisations of real PDPs; therefore, this behaviour is an approximation error, rather than an inherent characteristic of the propagation channel. In practice, when considering continuous PDPs, the fading depth approaches zero as $B \cdot \sigma_\tau$ tends to infinity.

UMTS PROPAGATION MODELS

Using the discrete channel models for UMTS, as proposed by the European Telecommunications Standards Institute (ETSI) [6] and Third Generation Partnership Project (3GPP) [7], one compares the observed fading depth within different environments, namely Indoor–A and B (IA and IB), Pedestrian–A and B (PA and PB), Vehicular–A and B (VA and VB), Rural Area (RA), Typical Urban (TU) and Hilly Terrain (HT), Table 1. For VA, VB, PB and TU environments, the fading depth is overestimated due to the error introduced by using a discrete PDP, since the product $B \cdot \sigma_\tau$ is above the one from which the fading depth curves start to differ from the ones corresponding to the continuous case. For VB environments, only the results for NLoS are presented, since this model is not intended to be used if LoS is assumed.

Table 1 – Fading depth observed in UMTS environments.

Fading depth [dB]	**Environment ($B\cdot\sigma_\tau$ [Hz·s])**								
	IA (0.16)	PA (0.23)	VA (1.85)	IB (0.50)	PB (3.75)	VB (20.00)	RA (0.50)	TU (2.50)	HT (15.00)
NLoS	12.5	12.3	< 7.4	9.0	< 6.3	< 7.7	8.7	< 5.1	6.1
K = 6 dB	9.1	9.1	< 5.9	7.0	< 5.2	–	6.9	< 4.3	5.1

The fading depth observed by UMTS, under NLoS, ranges from less than 5.1 dB in TU environments to 12.5 dB in IA ones. Under LoS, and K = 6 dB, the fading depth observed by UMTS is between less than 4.3 dB verified in TU environments and 9.1 dB verified in IA and PA ones. The difference in fading depth between NLoS and LoS is usually below 3.4 dB. When not considering the influence of the system bandwidth, i.e., assuming that UMTS is as a narrowband system, which corresponds to consider that $B\cdot\sigma_\tau < 0.02$ Hz·s, a fading depth of 18.2 and 11.2 dB is observed for NLoS and LoS, respectively. In this case, the difference in fading depth between NLoS and LoS is 7 dB. Thus, in practice, the fading depth experienced by UMTS is usually between 5.7 to 13.1 dB and 2.1 to 6.9 dB below the ones for the narrowband case, for the NLoS and LoS cases, respectively. Therefore, using the proposed approach, i.e., accounting for the influence of the system bandwidth, one concludes that the short-term fading margin for UMTS can be considerably reduced when compared to the one obtained from considering the narrowband case. Moreover, from the difference in fading depth observed between the LoS and NLoS situations, one also concludes that UMTS is less sensitive to the existence of LoS than existing narrowband systems.

CONCLUSIONS

A time-domain analysis technique of wideband signals, in Rayleigh and Ricean fading environments, is used to derive the PDF and CDF of the received power for various fading channels whose PDPs are expressed as continuous or discrete functions of the delay. The fading depth is evaluated as a function of the Rice factor, K, and the product between the system bandwidth and the *rms* delay spread of the propagation channel, $B\cdot\sigma_\tau$. It is observed that the results obtained with discrete propagation models are similar to the ones for the continuous models. However, one must be aware that this is valid only below a value of $B\cdot\sigma_\tau$ that depends on the minimum system resolution needed in order to resolve all paths. Hence, some of the discrete proposed models are not appropriate for fading depth evaluation purposes, since its validity domain is below the one needed when accounting for the system bandwidth. Regarding the fading depth observed by UMTS within different environments, one concludes that it ranges from less than 4.3 to 12.5 dB, which is significantly lower than the ones for narrowband systems such as GSM, thus, different fading margins must be considered. Moreover, UMTS is less sensitive to the existence of LoS than GSM.

As a final conclusion, one can state that the proposed approach is of interest for properly identifying the fading margins within different environments, while accounting for the influence of the system bandwidth. Since this is a key issue for development of existing systems, as well as for the design, assessment and implementation of future ones, an accurate study is needed in order to properly identifying the fading margins in different environments.

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