Backward Compatibility of the COST259 Directional Channel Model

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Abstract— **We consider the relation of the COST259 Directional Channel Model (DCM) with other existing channel models. The COST259 DCM is a general model for the mobile radio channel that includes narrowband power (field strength), power delay profiles, and directions of arrival. For comparison purposes, it is desirable that the channel models forming the basis of earlier simulations are contained as special cases in the COST259 DCM. We show how a mixed stochastic/deterministic approach allows to keep the GSM wideband models as special cases of COST259 DCM while still including new measurement results. The mean received powers agree with the Hata model when proper averaging over stochastic variables is done. Finally, the shadowing distribution of the narrowband power is shown to agree with Gudmundson's model.**

I. INTRODUCTION

In the last few years, smart antennas have emerged as a key technology for increasing capacity, enhancing the transmission quality, and improving estimates for the location of the mobile station (MS) [1], [2]. For the design and testing of smart antenna algorithms, directional channel models, i.e. models that include the directions-of-arrival, are required. The COST259 Directional Channel Model (DCM) [3] has emerged recently as a standard model for these applications. The model has been developed by subgroup 2.1 of the COST259 European Research Initiative, and adopted by its general assembly, which included the major European equipment manufacturers, network operators, and universities. Even more importantly, it has been introduced to 3GPP, the standardization body for third-generation cellular systems, and is being used by various research groups for the simulation of cellular systems.

In the past, channel models have been mainly designed to reflect the statistics of the narrowband power or the time dispersion. Important examples of such models are the Okumura-Hata and COST231 Hata models for the large-scale-averaged narrowband power , Gudmundson's model for the shadowing variations of the narrowband power [4], and the GSM models for the power delay profile [5]. Those models have, however, serious restrictions:

- they do not include directions-of-arrival at the base station (BS)
- they do not give the interrelation between narrowband power and power delay profile,
- nor do they include large-scale variations or their correlation properties.

This clearly shows the need for a more general model, as provided by the COST259 DCM. However, a huge number of simulations exist that are based on the old models. It is thus highly desirable that those models are included as special cases in the COST259 DCM, as this allows comparisons with earlier simulations, e.g. in order to demonstrate the performance improvement of a GSM system by the use of smart antennas.

In the remainder of this paper, we will describe how the authors (who participated in the development of the COST259 DCM) have solved this compatibility problem. Section 2 sets out the basic philosophy of the COST259 DCM for macrocells, and gives the most important parameter settings. In Section 3, the large-scale averaged narrowband-power model, and its relation to the Hata model, will be explained. Next, the power delay profile and the number of scatterer clusters (compared to the GSM model) are discussed. Section 5 will analyze the shadowing, and show how the shadowing statistics of separate scatterer clusters can be related to the shadowing of the narrowband power as given by Gudmundson's model. A summary concludes this paper.

II. THE COST259 DCM

In this section, we briefly describe the basic modeling philosophy of the COST259 DCM for macrocells (the micro- and picocell approach is somewhat different, and beyond the purview of this paper), see [3], [6], [7], [8]. The model is based on a joint probability density function of narrowband power, temporal and angular dispersion. It defines four different radio environments: GTU, GRA, GBU, and GHT (Generalized Typical Urban, Rural Area, Bad Urban, and Hilly Terrain), which is the same morphologic categorization as in the GSM wideband models.

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For each radio environment, there is a set of *external parameters*, which are constant throughout the simulation (e.g. BS height, carrier frequency). The directionally resolved impulse response for this set of external parameters is then given by probability density functions for the arriving multipath components (MPCs); the parameters describing those pdfs are called *global parameters*. All MPCs are grouped in clusters; the mean number of clusters is one global parameter. The MPC clusters can also be interpreted as clusters of scatterers that reflect (scatter) waves on their way from the transmitter to the receiver. The center of the first (always present) scatterer cluster is at the position of the MS; the centers of the additional clusters are distributed according to a certain pdf. Within each cluster, the (small-scale averaged) power of the MPCs is distributed exponentially in delay, and Laplacian in azimuth around the connecting line BS - cluster center. Delay spread and angular spread are global parameters, depending on the considered radio environment. The relative powers of the clusters are random variables whose distribution will be discussed in more detail in Sec. 3. The first cluster (i.e. MPCs scattered in the vicinity of the MS) might include a line-of-sight component; the probability for the occurrence of LOS, as well as the pdf of the Rice factor, is a global parameter, and depends (via the excess pathloss) on the distance between BS and MS. The power of each cluster depends not only on the distance, but also undergoes shadowing.

Due to the considerable number of stochastic parameters, a large number of realizations has to be taken in order to achieve good statistical averaging. This is no problem for testing a specified system, e.g. for type approvals, but might not be desirable in the design phase of a system - for this, a small number of typical channel realizations would be preferable. This could be accomplished by specifying one deterministic value for most global parameters, which is then used instead of the realization according to the prescribed pdf.

The original version of the COST259 DCM is described in [3]; this reference contains a very brief description of all the relevant processes and parameters. A more extensive description can be found in [6], [7], [8]. These references contain also several modifications of the COST259 model that have been introduced by the subworking group after the publication of [3], in order to make the model more self-consistent and improve agreement with measured results. In the following, we will refer to these two version as the original and the updated version of the model, respectively.

III. NARROWBAND POWER

The most popular models for the narrowband power (field strength) are the model of Okumura-Hata [9], [10], and the Walfish-Ikegami model. They have been extended recently [11] to cover a larger range of frequencies and MS-BS distances. In the following, we will denote all those models just as "Hata" model. The Hata model predicts the narrow-band power; apart from some external parameters (height of BS, MS, buildings, carrier frequency, radio environment), it depends only on d, the distance between BS and MS. The COST259 model, on the other hand, gives the statistical distribution of the powers for each scatterer cluster, and also treats the occurrence of multiple clusters and LOS as stochastic process. If we want to ensure compatibility of COST259 with the Hata model, we thus have to guarantee that for a given distance, the sum of the instantaneous cluster powers (i.e. instantaneous narrowband powers), averaged over all global parameters, is equal to the narrowband power as computed by Hata. In this section, we will show how this can be achieved.

In the original COST259 DCM, the power of the clusters are lognormal variables with a mean (in dB)

$$\begin{aligned} P[dB] = -L[dB] = -(L_1 + L_{extra}) = \\ -(L_1 + U(0..20dB) + 1dB \cdot \tau_{excess}[\mu s]) \end{aligned} \qquad (1)$$

where L is the attenuation in dB, τ_{excess} is the excess delay in microseconds, U is a uniformly distributed random variable, and L_1 a parameter that has yet to be determined. The variance of the shadowing is 6 or $9dB$, depending on the radio environment.

In order to determine the pdf of the extra attenuation L_{extra}, we have to determine the pdf of the excess delay of the clusters. The distribution of the clusters is specified to be uniform within a circle of radius $d_{\max}$ (3 or 5km, depending on the radio environment). By performing a variable transformation with the Jacobian determinant [12], we obtain

$$\begin{aligned} pdf_{\tau_{excess}}(\tau) = \frac{4c}{d_{\max}^2 \pi \sqrt{\tau c}} \int_{c\tau/2}^{\min(d_{\max}, d+c\tau/2)} & dw \qquad (2) \\ w(\tau c + d - w) \left[-w^2(8d + 4\tau c) \right. & \\ \left. + w(8d^2 + 12 d\tau c + 4\tau^2 c^2) \right. & \\ \left. -(4\tau c d^2 + 4\tau^2 c^2 d + \tau^3 c^3) \right]^{-1/2} & \end{aligned}$$

This integral can be evaluated analytically, but the resulting equation has too many terms to be printed here. The pdf of L_{extra} for delayed clusters is then obtained by convoluting $pdf_{\tau_{excess}}(\tau)$ with $U(0..20dB)$. An example is shown in Fig. 1. This pdf could be approximated quite well by a triangular distribution.

In addition to averaging over the shadowing and the extra attenuation, we also have to average over the Rice factor (which is modeled as a lognormal variable), the probability that a LOS component occurs, and the number of clusters. Figure 2 summarizes the various levels of averaging, and the sequence in which this has to be done. The

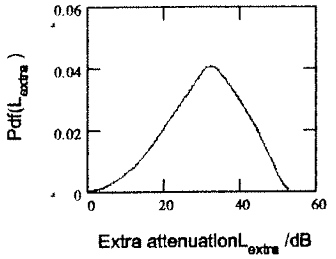

Fig. 1. Probability density function of extra attenuation L_{extra} for additional clusters in HT cell; $d = 500m$.

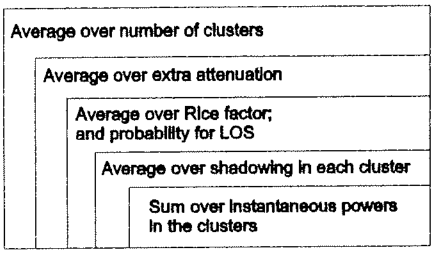

Fig. 2. Averaging procedure for computing narrowband power.

total power computed that way still includes the unknown factor L_1. L_1 is then chosen in such a way that the total power is identical to the power predicted by the Hata model.

Basically, we have two possibilities to do the averaging processes: numerically or analytically. For the analytical averaging, several simplifications have to be used: most importantly, we have to assume that the sum of lognormal variables is again a lognormal variable (see also Sec. 5). Furthermore, we have to approximate the pdf of L_{extra} as triangular pdf. Great care has also to be taken that we sum really the ***powers on a linear scale***, and not the attenuations, nor the logarithmic powers. Due to the involved approximations, the theoretical result can deviate up to about $3dB$ (in those cases that we considered) from the exact result. The alternative is to compute the powers numerically for a range of possible values of L_1; since for given L_1 all parameters of all pdfs are known, the averaging can be done numerically and thus exact. By interpolating between the discrete values, we thus get a curve $f(L_1)$, and by setting this equal to P_{Hata}, can compute L_1.

For the updated version of the COST259 DCM, the probability density function of the distance between BS and far scatterers as an exponential distribution for the radial distance r_c of the cluster from the base station, and uniform in azimuth

$$f(r_c, \varphi_c) = \begin{cases} 0 & r_c < r_{\min} \\ \frac{1}{2\pi\sigma_r}\exp\left(-\frac{r_c - r_{\min}}{\sigma_r}\right) & r_c \geq r_{\min} \end{cases} \quad (3)$$

The parameters $r_{\min}$, σ_r are given in Table 1.

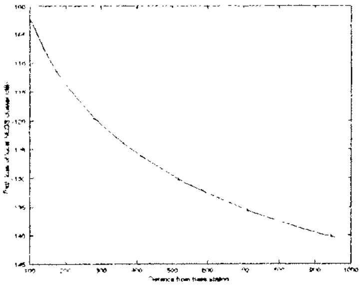

Fig. 3. Attenuation of the local cluster, L_1, as a function of BS-MS distance for GBU environment.

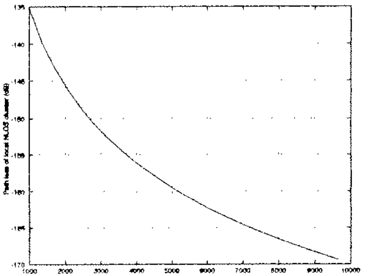

Fig. 4. Attenuation of the local cluster, L_1, as a function of BS-MS distance for GHT environment.

	GTU/GBU	GRA/GHT
$r_{\min}$ $[m]$	1000	1000
σ_r $[m]$	1500	5000

Table 1 Cluster position parameters

The cluster power model can thus be formulated as

$$L_{extra}[dB] = k_c \min(\tau_{excess}, \tau_B), \quad (4)$$

Figures 3 and 4 show L_1 of the updated COST259 DCM model as a function of distance between BS and MS for the Generalized Bad Urban and the Generalized Hilly Terrain model.

IV. POWER DELAY PROFILES

The temporal (and also angular) dispersion is critically influenced by the number of scatterer clusters. The GSM model, which is the classical model for the power delay profiles (PDP), prescribes deterministically either one (for TU, RA) or two (for BU, HT) clusters; the decay time of the clusters and the delay between the clusters is also fixed. A number of recent measurements (see, e.g., [3], [7] and references therein) has shown that the actual number of clusters can be larger; up to five clusters have been identified in urban environments. Furthermore, it has become clear that the number of clusters varies as the MS moves in the cell. For a physically correct model, it is thus necessary to describe the number of clusters by random variables, as is foreseen in the standard COST259 implementation. However, the "typical" realizations are chosen in such a way that they agree with the GSM models. Also, the delays of the clusters are simply fixed at the values prescribed by the GSM model.

The GSM models also specify an exponential PDP for each cluster, with a deterministic (fixed) cluster delay spread $S_{\tau,GSM}$. No statement is made there about the angular dispersion. In COST259, on the other hand, the cluster delay spreads and angular spreads are modeled as correlated lognormally-distributed random variables with correlation coefficient $\rho = 0.5$.[1] The PDPs for each cluster are also assumed to be exponential; the angular power spectra are Laplacian. The S_τ, i.e. the cluster delay spreads in COST259, can deviate quite significantly from M_{S_τ}, i.e. the mean values of S_τ, but are still within the range covered by the pdf. As mentioned above, the GSM model makes no statement about the angular spread. Since in COST259 the cluster angular spread and delay spread are correlated, we recommend that for "typical, GSM-like" realizations, the mean value of S_ϕ under the condition that $S_\tau = S_{\tau,GSM}$ is taken as deterministic value. Performing the appropriate mathematical manipulations, this results in

$$S_\phi = M_\phi \exp\left[\rho \ln\left(\frac{S_{\tau,GSM}}{M_{S_\tau}}\right)\right] \tag{5}$$

Table 2 shows the resulting angular spreads for all four environments in the original COST259 DCM.

	TU	BU	RA	HT
1st cluster	15.8	15.8	5.24	8.5
2nd cluster	n.a.	15.8	n.a.	15.8

Table 2 Angular Spreads for quasi-GSM models. Delay spreads identical to GSM models.

Again, the updated COST259 DCM shows some slight modifications. There the cluster delay spread exhibits a distance dependence, according to

$$S_\tau(d) = S_\tau(1\text{km})(d/\text{km})^{0.5} \tag{6}$$

Consequently, also S_ϕ becomes dependent on the considered distance between BS and MS.

Finally, it is also necessary to explore the general relation between a directional channel model and a non-directional wideband model. The general relationship between PDP and Azimuth-Delay Power Spectrum (ADPS[2]) is

$$PDP(\tau) = E_t\{|h(t,\tau)|^2\} \tag{7}$$

$$= \int_{-\pi}^{\pi} ADPS(\tau,\varphi)|g(\varphi)|^2 d\varphi$$

$$+ \int_{-\pi}^{\pi}\int_{-\pi}^{\pi} g(\varphi)g^*(\varphi')\tilde{P}_h(\tau:\varphi,\varphi')d\varphi d\varphi'. \tag{8}$$

where E_t means averaging over the small-scale fading and g is the antenna pattern. In Eq. (5), the delay-cross-azimuth power spectral density $P_h(\tau;\varphi,\varphi')$ was decomposed into one part that reflects angular uncorrelated scattering viewed from the BS site and one part containing the remaining correlations,

$$P_h(\tau;\varphi,\varphi') = \delta(\varphi-\varphi')ADPS(\tau,\varphi) + \tilde{P}(\tau;\varphi,\varphi'). \tag{9}$$

In the case that the multipath components not only at different delays but also those at different DOAs are uncorrelated (*extended uncorrelated scattering (US))*,[3] the correlation terms all vanish. In principle consistency of the ADPS with the PDP can be achieved also if US is not valid. However, several additional parameters are needed which partly have not been evaluated from measurement results yet. Thus, for the COST259 DCM, we demand validity of extended US.

V. SHADOWING

For taking into account the shadowing in a wideband model, it is required that the shadowing mean and variance *of each cluster* is specified. Existing models based on measurements, e.g. in Gudmundson's model [4], evaluate only the shadowing variance of the narrowband signal. In order to make conclusions about the variance for each cluster, and still stay compatible with the narrowband approach, we need some simplifying assumptions:[4]

- The shadowing of each cluster is independent. This is not exactly true; clusters that are close in space will show higher correlation than clusters that are widely separated. Analysis has been made of the correlation coefficient as a function of the angular separation (in degrees) and the distance (in km), see e.g. [13] and references therein. However, in the interest of simplicity, and because the correlation coefficient is usually quite small, the COST259 DCM assumes statistical independence of the shadowing of all clusters.

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[1] Note that there is also a correlation between the angular spreads and the shadowing.

[2] Exactly, the ADPS is the azimuth-delay power spectral density.

[3] US in this context means that different delays and different azimuthal DOAs exhibit uncorrelated waves.

[4] Note that the first two are assumptions of the COST259 DCM, while the last one is an assumption we make here in order to allow anaytical tractability

- the shadowing of all clusters has the same variance. This is a standard assumption that is also supported by the statement in Ref. [14] that the (narrowband) shadowing variance is approximately independent of the distance.
- the sum of log-normal variables is approximated as log-normally distributed. This is not exact, and a discussion of the various approximation methods and their resulting errors can be found e.g. in [15]. For simplicity, we chose the Fenton-Wilkinson method.

Under these assumptions, the relation between the (natural) logarithmic mean and variance of the components μ_i, σ_{comp} and the mean and variance of the sum signal μ_{sum}, σ_{sum} is

$$\mu_{sum} = \frac{\sigma^2_{comp} - \sigma^2_{sum}}{2} + \ln\left(\Sigma_i \exp(\mu_i)\right), \qquad (10)$$

$$\sigma^2_{sum} = \ln\left([\exp(\sigma^2_{comp}) - 1] \frac{\Sigma \exp(2\mu_i)}{(\Sigma \exp(\mu_i))^2} + 1 \right). \qquad (11)$$

The desired variance of the shadowing for each cluster σ^2_{comp} can be found from the above equations. Note that the above equations are for mean and variance in $natural$ logarithmic terms, which are related to those in decadic logarithmic terms as $\mu = \frac{\ln(10)}{10}\mu[dB]$, $\sigma = \frac{\ln(10)}{10}\sigma[dB]$. Since the variance of the narrowband shadowing is prescribed as $6dB$ and $9dB$, the variance per cluster can be determined for a given number of clusters and cluster powers.

VI. SUMMARY AND CONCLUSIONS

The COST259 DCM is a general approach to modeling the mobile radio channel. All relevant parameters are treated as random variables, whose pdfs are given for different radio environments. For comparison purposes, a smaller number of "typical" scenarios is defined by prescribing a single deterministic value for some parameters instead of treating them as random variables. For small-scale simulations, those deterministic values are chosen in such a way that the COST259 DCM reduces to the GSM models, however *with* DOA-information. This is especially important for analyzing the benefits of smart antennas in GSM systems.

The narrowband power as computed by the COST259 DCM agrees with the well-known Hata model. The traditional Hata model computes the narrowband power as a function of the distance only. Thus the COST259 DCM must be averaged over LOS/NLOS situations, shadowing, and different numbers of scatterer clusters to be comparable. The averaging can be done either analytically or numerically.

Finally, the shadowing in each scatterer cluster is chosen in such a way that the shadowing of the narrowband power agrees with Gudmundson's model. Again, analytical equations allow the prescription of the variance of each cluster.

The described measures ensure the compatibility of the COST259 DCM with existing channel models, and thus will allow the comparison of previous simulation results with new, direction-resolved transmission schemes.

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