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Mobile Networks

Geometry-based directional model for mobile radio channels—principles and implementation†

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SUMMARY

Adaptive antennas are used in mobile radio systems for improving coverage and increasing capacity. For realistic system design and simulation, channel models are required in order to assess the performance of such systems. We propose the so-called 'geometry-based stochastic channel model' (GSCM), which is easy to implement and has a low complexity even when the directional dimension of the channel is taken into account. In this model, we prescribe the probability density function (PDF) of the location of the scatterers. From this, the angularly resolved impulse response can be computed by a simple ray tracing. We then present various extensions of the model in urban environments, namely for diffraction losses and wave guiding by street canyons. We also discuss methods for efficiently implementing GSCM. Copyright © 2003 AEI.

1. INTRODUCTION

In the last few years, adaptive antennas have emerged as a leading candidate for increasing the capacity of mobile radio networks [1]. One interpretation of their basic idea is to adjust the antenna pattern at the base station always in such a way that the energy is focussed towards the desired user, while no energy is transmitted in the direction of other users. This can be exploited in several ways: (i) increase of coverage (if the transmit power stays the same, more power arrives at the receiver), (ii) spatial filtering for interference reduction (SFIR): the directivity of the antennas reduces the co-channel interference and (iii) space division multiple access (SDMA): within one cell, several users in different directions can be served on the same traffic channel. For the design and simulation of any of these systems, we need channel models that allow to predict performance in a wide range of realistic environments.

Channel models for these applications have to include the directional information. However, most existing channel models, like the famous COST 207 wideband models, give only the power delay profile (PDP) and the Doppler spectrum (note that the Doppler spectrum is *not* uniquely associated with a directional distribution of arriving waves). For efficiency reasons, it is desirable to have channel models with various levels of complexity, where all levels are self-consistent and compatible in both upwards and downwards direction.

The purpose of this paper is to present a channel model that fulfils the requirements for adaptive antenna

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simulations. We call it the 'geometry-based stochastic channel model (GSCM)', and we will show that it has important advantages compared to other modelling approaches. In the current paper, we concentrate on the philosophy and the implementation of the GSCM. The actual configuration, i.e. the choice of parameters to fit specific environments, is relegated to future work. Section 2 discusses the basic requirements for a good spatial model. In Section 3, we will explain the basic philosophy of the GSCM, we analyse various ways of implementing the GSCM efficiently and discuss how those implementations are interrelated. Section 4 presents several extensions of the channel model, like the inclusion of shadowing, diffraction, wave guiding along street canyons, etc. A summary concludes this paper.

The version of the paper that was reviewed and accepted was submitted in 1998 and accepted in 2000. Not wanting to make significant changes to the approved version, the literature citations in this paper do not cover papers after that time. Further references can be found in many of the recent papers on MIMO channel modelling.

Most of the extensive system simulations (e.g. for UMTS—IMT2000) in the literature have utilized a two level simulation approach, dividing considerations roughly into link (transmission) and system-level simulations [4]. The 'interface' between those two simulations is usually a look-up table that has, e.g. the signal to noise and interference (SNIR) as input and the bit error probability (BEP) as output. However, we can put the interface at different 'positions', in other words, we can include certain effects either in the link-level or the system-level simulations. The look-up tables contain only 'condensed' information about the channel, and thus entail a loss of information. The best accuracy would be achieved by a simulation that is only done on the link level, obviating the need for information condensation. However, such an approach is currently impossible because of the extremely high computer time requirements. In other words, the more effects are included in the link-level simulations, the higher is the accuracy, and the lower is the simulation speed. A good channel model should thus allow efficient 'interfacing' at various positions.

2. REQUIREMENTS

The most important requirements for channel models are: (i) reproduction of measured joint angular delay power spectrum (ADPS). In other words, the system shall behave as if it were operating in a real operational environment. Unrealistic models for the ADPS can lead to wrong conclusions when different transmission schemes are compared; (ii) compatibility with previously used stochastic wideband channel models [2, 3], in order to facilitate comparisons with previous simulation results; (iii) the model should reflect physical propagation mechanisms. This makes the model easy to understand and enables realistic parameter selection by means of straightforward geometrical and environmental considerations.

A further, practically important requirement is (iv) *simplicity*, which should allow extensive simulations in short time. Unfortunately, this is usually in contradiction to requirement (i), i.e. faithful modelling of the physical radiowave propagation between the transmitter and receiver. Furthermore, for different applications, the balance between those two requirements may have to shift. This leads to a new model requirement, namely (v) *adaptivity*, i.e. the model should allow the user to define which functionalities are included in the current simulation. This flexibility is especially important because future systems might have somewhat different requirements for the channel models.

3. SEMI-STOCHASTIC CHANNEL MODELS

3.1. Philosophy

There are two basic philosophies for channel models: (i) deterministic models: in these models, the environment (position of the base station, mobile station, location of scatterers,[§] reflection coefficients etc.) is prescribed and Maxwell's equations (or some approximation to it) are solved. Alternatively, the angular impulse response can be measured once and stored for repeated use; (ii) stochastic channel models: in these models, the average PDP, angular power spectrum (APS) etc. and their statistical distributions are specified by the model, following measurements. For the simulation, instantaneous ADPSs are then selected, where the probability of selecting a specific value is determined by the statistical distributions.

While both approaches have been successfully used in the past for wideband simulations, they have drawbacks when we try to include the spatial components. The deterministic approach relies too much on the specific simulation environment. In order to get a good overview over different channel situations, enormous databases would have to be established. The purely stochastic approach,

[§]Note that we are using the expression 'scattering' irrespective of the fact whether 'diffuse scattering' or 'specular reflection' occurs.

on the other hand, requires a large number of statistical distributions, which are usually correlated with each other (e.g. the distributions of the times of arrival and the directions of arrival are correlated). This makes long-term simulations especially difficult.

Yet another approach to channel modelling is the GSCM. In this approach, the *statistical distribution* of the scatterers (and not their exact location, as in the deterministic approach) is prescribed by the model. For the actual simulation, a specific realization of scatterers is selected according to their statistical distribution, and the angularly resolved impulse response is computed by a simple ray tracing algorithm. Of course, the scatterer distributions have to be chosen in such a way that the resulting PDPs, APSs, etc. agree reasonably well with typical measured values.

Compared to the purely stochastic approach, the GSCM has several advantages: (i) its relation to the physical reality is immediately visible; the important parameters, like location of the scatterers, can often be determined from simple geometrical considerations; (ii) all necessary information is inherent in the distribution of the scatterers; therefore, possible correlations between PDP and APS do not lead to a complication of the model; (iii) the movement of mobile station and scatterers can be included in a straightforward way. Furthermore, also the shadowing, and the appearance and disappearance of transmission paths (e.g. because of blocking by obstacles) can be easily implemented—this allows to include long-term correlation (memory) of the channel in a straightforward way.

Compared to the purely deterministic model, the GSCM has the advantage that only a few PDFs of scatterer distributions have to be specified—in contrast to the complete geometry specifications required in the deterministic model.

3.2. Standard implementation

The basic form of the GSCM is also known as 'local scatterer model' and was originally suggested in References [5, 6], which in turn relies on a paper from the early 1970s [7]; see also Reference [17]. In this model, all relevant scatterers are positioned around the mobile station (MS); the PDF is often assumed to be uniform in a disk around the MS. Alternatively, Gaussian and Rayleigh PDFs have been suggested.

As an extension, some of us suggested the inclusion of so-called 'far scatterers' [8], which represent e.g. high-rise buildings, mountains; they are far away from both the MS and the base station BS (Figure 1). While the local

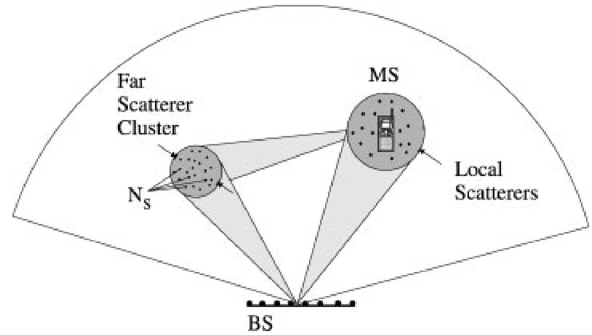

Figure 1. Principle of the GSCM.

scatterers are always centred around the MS (and thus change when the MS changes its position), the position of the far scatterers are fixed at an absolute position in space, which corresponds to physical reality. Finally, there can also be scatterers in the vicinity of the BS; these are mainly relevant for micro- and pico-cells, i.e. if the BS antenna is below the rooftops. Reference [8] proposed various configurations (number and distribution of local and far scatterers, Rice factor, etc.) for macro-, micro- and pico-cells that were either extracted from measurements or derived from physical plausibility considerations.

The choice of the configuration is the first step in any practical implementation. Next, we have to fix the actual positions of the scatterers (remember that in the first step, we had only determined the PDFs). The procedure of selecting random variables according to a given PDF is well known in the literature [9]. Once that the position of the scatterers is known, we compute the angle-resolved impulse response by a simple ray-tracing, i.e. we sum up the incident rays from all the scatterers, assuming that only single scattering occurs (this assumption will be discussed in Section 3.5). Channel characteristics simulated by GSCM agree well with recent angular-resolved measurements [10].

3.3. Nonuniform-scattering-cross-section (NSCS) implementation

In the standard implementation of the GSCM, the location of the scatterers is chosen according to a certain PDF, and the scattering cross section is the same for all scatterers. An alternative implementation, which we call NSCS, is to choose the location of the scatterers from a uniform distribution in the whole relevant area, and then to weigh the scattering cross sections. As an example, we weigh the scattering cross section by a Gaussian function centred at the position of the mobile—in the standard implementation,

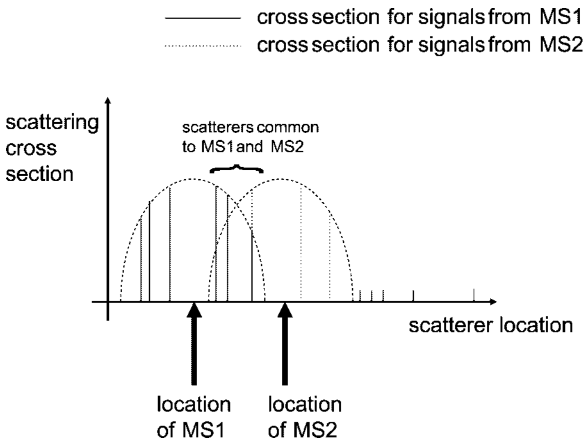

Figure 2. Nonuniform scattering cross section implementation of the GSCM. Some scatterers are relevant for both MSs, but with different cross sections.

we would have chosen a Gaussian PDF of the scatterer location. The NSCS implementation also corresponds well to physical reality. If we take, e.g. an urban environment, then the scatterers (e.g. houses) are distributed throughout the town. Due to the propagation mechanisms and the shadowing, the scatterers close to the MS have more influence than those far away. This is exactly what we model.

The NSCS implementation also facilitates the simulation of the temporal evolution of the channel. The location of the scatterers is determined at the beginning of a simulation, and then remains constant, even when we move the MS.[¶] The physical propagation mechanism is described by the fact that the scatterer cross section becomes smaller as the distance between scatterer and MS increases (Figure 2). The correlations between the movement of the MS and the changes of the DOAs are correctly included in the model (note that this would be very difficult in a purely stochastic model).

Another important point of the NSCS implementation is that the physical location of the scatterers is identical for different MSs, while their relative importance is different. Also this corresponds to the physical reality: a house or a car acts as a scatterer for an MS that is very close to it, as well as for another MS that is far away, only the cross section is different. The correlation between the rays of different users scattered, e.g. by a moving car, is given correctly by the NSCS model.

[¶]This description is valid if the MS moves, while the physical location of the scatterers (e.g. houses) stay constant. A movement of physical scatterers (cars, people) can also be simulated easily.

While there is little difference to the standard method in the limit of an infinite number of scatterers, the NSCS implementation has several important advantages for the practically important case of a finite number of scatterers:

(i) it simplifies implementation of MS movements. As we have seen above, MS or scatterer movement can be easily implemented. In the standard method, on the other hand, scatterers have to 'appear' and 'vanish' in order to adjust the PDF to the new scatterer location. The transitions between the scatterer realizations are then not continuous anymore.
(ii) It is numerically advantageous. Take the example of a Gaussian distribution of scatterers in the standard implementation. In the 'tails' of the Gaussian curve, i.e. at large distances from the MS, we still need a large number of scatterers in order to get good statistical performance—this implies that the density of scatterers near the MS must be huge. This is avoided in the NSCS method.

The disadvantage of the NSCS implementation lies in the fact that, at the beginning of the simulation, we have to create and store the location of the scatterers for the whole area of interest.

The NSCS implementation can also be viewed as an intermediate step between deterministic simulations and stochastic models: in deterministic models, both the location of the scatterers and the weighing of the rays is deterministic; in the NSCS implementation, the location is stochastic and the weighing is deterministic. We also note that we can generate the impulse responses in advance and use those stored responses during the simulation. This could be considered as an intermediate step to the 'stored measurement' version of the deterministic modelling approach, which was mentioned in Section 3.1.

3.4. Averaging

Let us next discuss the question of averaging in the model, which is strongly related to the topic of 'interfacing' between link-level and system-level simulations (Section 2). It is common to derive 'typical' ADPSs by averaging the instantaneous angular impulse responses over a certain area, and then perform the simulations with the averaged ADPS.

The ADPS measured at one time instant (or at a single location) is called 'instantaneous ADPS'. When we average over MS positions that are within a range of about 10 λ, we call this the 'small-scale-averaged ADPS'. Since the statistics of the small-scale averaged ADPS are usually known (Rayleigh or Rician fading), small-scale averaging entails no serious loss of information. In the averaging area, the delays of the various echoes and the directions of arrival stay the same; only amplitude and phase change due to the small-scale fading. In the GSCM, it is straightforward to compute the averaged ADPS, namely by summing up the powers the rays arriving at the receiver; the instantaneous ADPS can of course be produced by summing up the rays coherently, i.e. with their correct phases.

When we average the ADPSs over much larger areas (e.g. even over MS positions that cover the whole cell), we average over different delays and DOAs of the echoes. Furthermore, it is not easy to predict the amplitude statistics. Such a 'large-scale averaging' thus entails a significant loss of information. One example is the PDP of the 'typical urban' environment of the COST 207 model [2]. In GSCM, we simulated this environment by assuming local *and* far scatterers, using realistic parameters (far scatterer cluster, Gaussian distribution of scatterers with 1/e widths of 75 m for local scatterers and 50 m for far scatterers, 20 dB diffraction attenuation for contribution from local scatterers, see Section 4.3). The small-scale averaged PDP in such environments usually has a shape with several distinct peaks. However, when averaging over a large number of different MS and scattering area positions, we get a monotonously decaying PDP that has an exponential shape (see Figure 3), which agrees very well with the COST model. We note however, that the COST model could also be reproduced by assuming a single scatterer disk with a disk diameter on the order of 1 km. It is thus not possible to judge whether far scatterers are involved or not from the large-scale averaged PDP alone.

3.5. Single and multiple scattering

One important question for GSCM is whether multiple scatterings play a role, or whether consideration of single scatterings is sufficient from a physical point of view. An analysis of the importance of multiple scatterings from measurements is possible if the ADPS at both the transmitter and the receiver is available [11]. First results indicate that the single-scattering assumption is often correct in macrocells, but breaks down in micro- and picocells. Waves guided in a street canyon, for example, suffer multiple reflections, as waves in indoor environments, where multiple reflections from walls, floors and ceilings are common. However, a correct implementation of the multiple scattering leads to a significant increase in computational complexity and is thus undesirable.

The question of single-scattering can also be considered from a slightly different point of view. Under the assumption of single-scattering, the ADPS and the scatterer location are related by a bijective mathematical transformation. Thus, for a given ADPS (e.g. from a measurement), we can assign a scatterer distribution that is not necessarily the true physical distribution, but allows to

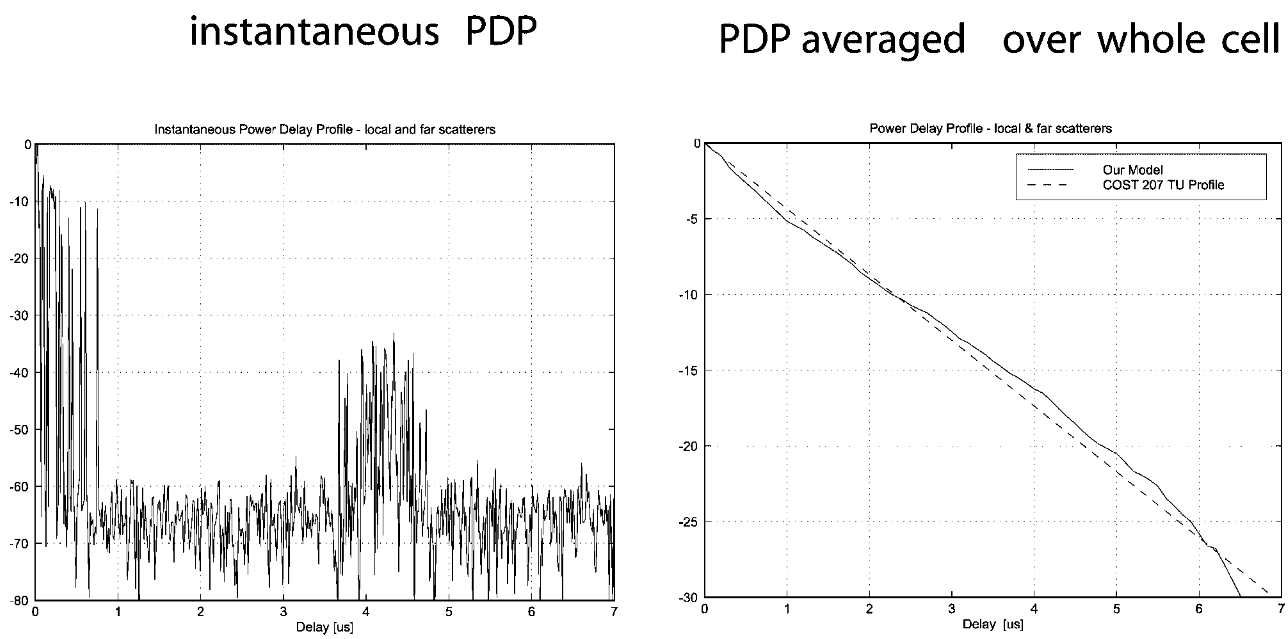

Figure 3. Single realization (a) and large-scale-averaged PDP (b) for a 'typical urban' COST 207 model.

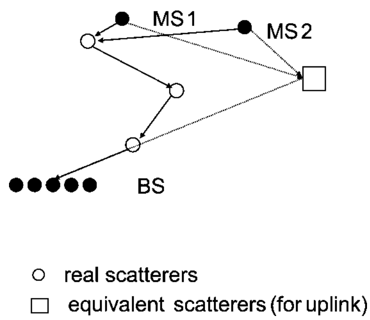

Figure 4. Effect of multiple scattering.

reproduce the correct ADPS by ray-tracing under the assumption of single-scattering [12, 13]. While this is in contradiction to requirement (iii), modelling of the physical propagation mechanism, it fulfils the more important requirement (i) in Section 2 (i.e. we can reproduce the ADPS at one location correctly). Furthermore, inclusion of the multiple scattering would be in contradiction to requirement (iv), i.e. simplicity.

Now a computation of a scatterer distribution just for the sake of reproducing a single ADPS (which formed the basis of the scatterer distribution anyway) would not be useful in practice. More interesting is the question whether the scatterer distribution produced that way can, e.g. extrapolate the ADPS correctly when the MS is moved. We see from Figure 4 that this is not strictly true: when we move from MS 1 to MS 2, the runtime in the true model must increase, while the runtime from the MS via the effective scatterer to the BS decreases. The error gets the worse the larger the distance between the first and the last real scatterer is, and the larger the covered distance by the MS is. Furthermore, if the scatterers are placed for a good reproduction of the ADPS at the BS, then the ADPS at the MS is not correctly reproduced. Still, it is a good approximation for many simulation purposes.

Finally, we can compare GSCM with the model of Heddergott *et al.* [14], which they call stochastic radio channel model (SRCM). In their approach, they prescribe the directions, amplitudes and phases of incident planar waves, according to a given PDF. In our language, we can call this a zero-scattering approach, i.e. we have virtual signal sources in the direction of the DOAs, and at a distance prescribed by the delay of the waves. When *multiple-scattering* occurs in physical reality, GSCM is not accurate in predicting downlink and long-term behaviour; and SRCM has those problems even when *single-scattering* occurs (which always is the case).

4. EXTENSIONS OF THE GSCM

4.1. Shadowing

In a mobile radio scenario, not only small-scale fading effects due to multipath propagation, but also large-scale fading due to shadowing effects has to be taken into account for many investigations. In this section, we ignore (average out) the small-scale fading.[‖] This implies that the shadowing for all the elements in a scatterer cluster is identical, while it is considered uncorrelated between the different clusters—a physically reasonable assumption.

The large-scale fading is modeled as a statistical lognormally distributed variable \xi with zero mean and standard deviation σ (typically 6–8 dB). The total path loss g_m for the m-th cluster is thus

$$g_m = \frac{1}{\xi_m \rho_m^{\alpha}} \tag{1}$$

where ρ is the distance between BS and MS and α is the pathloss exponent. From the mechanism of shadowing, it follows that the total path loss for *each* cluster should be lognormally distributed. Note that in this case, the path loss for the *sum* of all paths (e.g. measured with an omni-directional antenna) is *not* strictly lognormal. However, for a small number of clusters, the deviation is small.

If a scenario is simulated in which the MSs move in a cellular environment, the slow fading is correlated for small distances between two terrain points and uncorrelated for larger distances between two terrain points. To model this effect, we first generate statistically independent values of the lognormal distribution, which model the shadowing on 'grid points' that are spaced at a considerable distance (typically 100 wavelengths), see Figure 5. For locations between those grid points, an interpolation (two-dimensional filter function) gives the local values of the shadowing; this automatically introduces a correlation between closely-spaced points. One possibility for a filter function would be an ideal low pass filter. A better choice is a Gaussian filter [15] because it requires less computational effort.

4.2. Street dominated propagation

The evaluation of channel sounder measurements conducted in dense urban environment [16] indicates that streets canyons and street crossings (canyon effect) dominate the propagation, but scatterers all around the MS also

[‖]It can be included in the same way as described in Section 3.

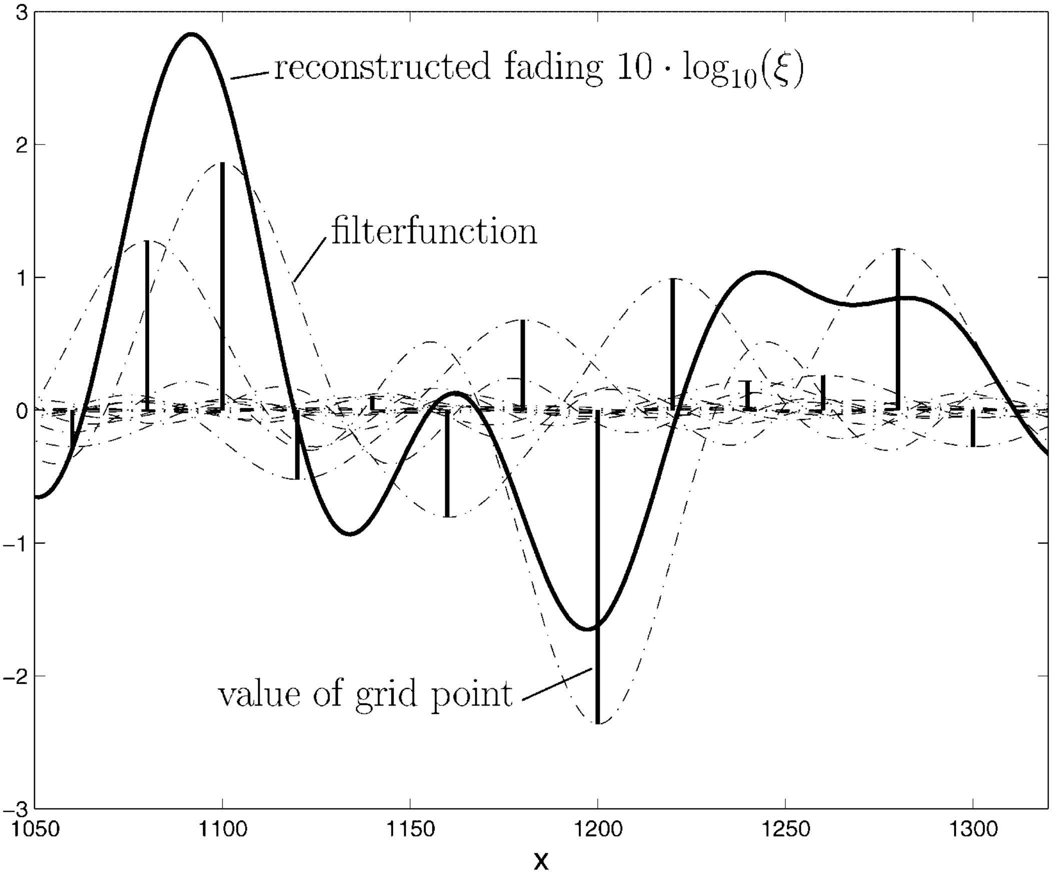

Figure 5. Correlation of the shadowing at different MS positions.

contribute to the PDP. In these measurements, the receive antenna was below the rooftops, while the transmit antenna was above the rooftops—in other words, the ADPS at the MS was analysed. We stress that this does not allow direct conclusions about the ADPS at the BS. This situation is thus especially interesting when also the mobile terminals employ antenna arrays; however, the propagation effects are expected to be similar in micro-cells, where the BS is also below the rooftops.

We found that one important effect is the guiding of waves along the street in which the MS is situated. To implement this behaviour into the GSCM, we suggest:**

(i) to use for the scatterer distribution a line, a rectangular or a bivariate Gaussian distribution. In case of the line distribution, we assume that the local scatterers are buildings along a street. The rectangular distribution locates the scatterers uniformly over the cross section of the street. Another alternative is a bivariate Gaussian distribution, which is mathematically convenient, but which leads to local scatterers that are spread beyond the housewalls bounding the street (Figure 6).

(ii) to use a far scatterer disk located in the direction of the street. Again from measurements we found that far scatterers are often positioned in the direction of the street. We explain this from the fact that far echoes with relative large power in general have a (quasi-) LOS to the MS. In some measurement locations, we found that far scatterers are present in both directions of the street as seen from the MS. We therefore may place two far scatterer disks that are connected with the straight line corresponding to the direction of the street.

Another important effect is the guiding of waves along the streets that are orthogonal to the one in which the MS is situated. This effect is especially important if the receiver

**We explain here the standard implementation. Naturally, an NSCS implementation is also possible.

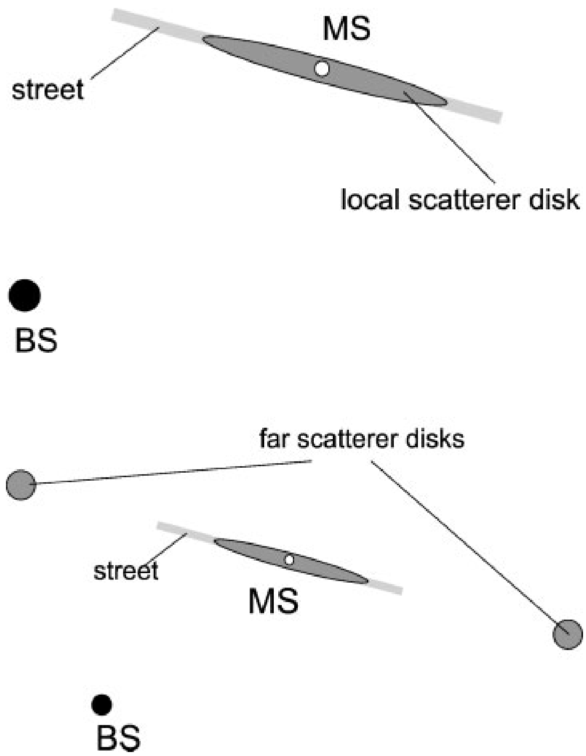

Figure 6. Scatterer location for modelling wave guiding along streets in which MS (receiver) is located.

is on a plaza (as in Figure 7) or near a street crossing. Multiple reflections significantly influence the ADPS [16]. As explained in Section 3.5, we want to place 'equivalent' scatterers that give the correct delays and DOAs under assumption of single scattering. From the receiver point of view, a multiple reflection leads to larger excess delay of the incident waves. The directions from where the waves arrive are defined by the location of the last reflection/scatterer. We therefore place scattering regions in the directions of the street aperture, from where most of the signal energy is expected to reach the receiver (Figure 7). Note that the scatterer disks are not aligned in parallel to streets, but more in the direction from the receiver to the street aperture. Of course we can additionally still apply the local scatterer disk around the transmitter that corresponds to propagation over the rooftops.

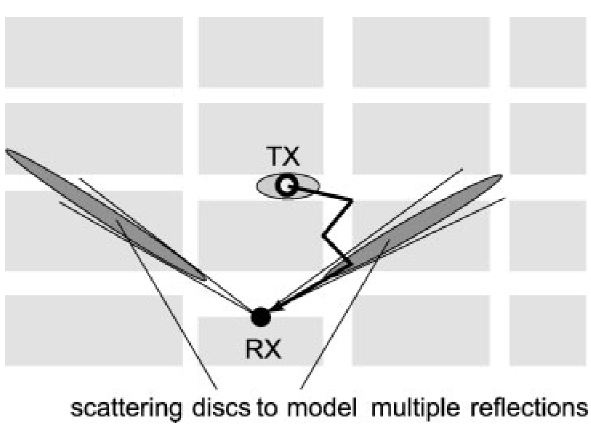

Figure 7. Scatterer location for modelling wave guiding in streets orthogonal to the street in which the receiver is located.

Such a model will give small angular spreads and considerable delay spread for each of the major paths corresponding to a multiple reflection situation, and thus give better agreement with measured ADPSs.

4.3. Diffraction losses

If far scatterers are present and we assume only free space attenuation, the far echoes have significantly smaller power than any waves reflected at local scatterers. This will also lead to relatively small values for the delay spread even when the maximum excess delay due to far scatterers is large. However, the MS typically operates in NLOS conditions and the geometrically direct propagation component between the local scatterers and the BS suffers a diffraction over the edge of the rooftop. Thus we introduce an additional attenuation factor for the paths coming via local scatterers, which means that the local scatterer power does not dominate the whole channel situation. This was also confirmed by the measurements of Reference [16], where we found large elevation angles at the MS of the paths arriving along the LOS direction of the BS. This implies that these waves are diffracted by rooftops close to the MS.

5. SUMMARY

In this paper, we have described the geometry-based stockastic channel model (GSCM) which we suggested for testing mobile radio systems with smart antennas. In the model, the statistical distribution of the position of the scatterers and the scattering cross section are prescribed. The angularly resolved impulse response is then computed by a simple ray tracing, using the assumption of single scattering. We described two different implementations: the standard implementation, where all scatterers have the same cross section, and the PDF of the location determines the amount of energy coming from a certain area, and the nonuniform scatterer cross section (NSCS) implementation, where the scatterers are uniformly distributed, but the cross section is different for each scatterer.

The GSCM can be used at different levels of complexity, including both small-scale and large-scale fading and also accurately describing the temporal evolution of the channel. Furthermore, it can be extended to cover scenarios that are common in urban environments, namely waveguiding along the streets, and diffraction losses of over-the-rooftop propagation. It is thus well suited for all situations where simulations have to be performed quickly yet accurately.

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