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Statistical Mobile Radio Channel Simulator for Multiple-Antenna Reception

Utz Martin

Deutsche Telekom AG, Technology Center
Box 100003, D-64276 Darmstadt, Germany
Fax: +49-6151-83 4638, E-mail: martin@fz.telekom.de

A directional channel simulation model for investigations of multiple antenna reception is introduced which is an extension to GWSSUS. Due to its relatively low structural complexity, this directional Gaussian scattering (DGS) concept is applicable not only to soft- but also to hardware fading simulators. The most important advantage of the DGS simulator is that it can easily be configured to match the properties of real-world propagation scenarios.

1 Introduction

To achieve improved capacity of cellular mobile radio systems, a lot of investigations currently stress new base station concepts which allow to make better use of the directional anisotropy of the reverse link wavefronts by means of adaptive multiple antenna receivers. Appropriate simulation models for the directional mobile radio channel are the prerequisite for such investigations.

The design and optimization of new receiver structures for mobile communication systems require the evaluation of the link quality and the capacity of the entire radio interface by means of simulations. To achieve reliable results, the real-world properties of the radio channel have to be taken into account by means of fading simulators. Today most available soft- and hardware simulators are based on the Gaussian (wide sense) stationary uncorrelated scattering (GWSSUS) model for the propagation properties of the radio channel in its wide-band formulation [Par82]. Unfortunately, this simulation model is not able to treat any spatial information besides path correlation. Thus, it may be applied only to single antenna and space diversity but not to multiple antenna reception in its general formulation.

The first simulation model which is able to take into account the full spatial information about the propagation mechanism was recently introduced [Bla95]. Although it is, in principle, valuable for investigations of all path diversity schemes, its application seems to be problematic from two practical considerations concerning its configuration and its complexity. Firstly, the model requires a detailed a priori knowledge about the spatial scatterer distribution which cannot be easily acquired by means of propagation measurements. Thus, the realistic model configuration is problematic. Secondly, the propagation phenomena are modeled by a deterministic quasi-optical ray approach. A lot of rays are required to achieve a sufficient modeling quality. Thus, the structural complexity required is very high and prevents hardware implementation. In software simulations the computation time required for the quality assessment of a certain transmission scheme will be very large.

The directional Gaussian scattering (DGS) simulation concept was constructed to achieve both hardware implementation and reduced software simulation time by means of relatively moderate complexity. It is an extension of the conventional GWSSUS simulation approach. To match the popagation properties of a certain scenario, the model can easily be configured directly from the results of channel sounding [Schw93] by application of the echo estimation method introduced in [Mar94, Mar95].

The outline of the paper is as follows. In section 2 the DGS model for directional channel simulation is motivated by a short summary of the physical background of GWSSUS. Section 3 deals with the implementation of the DGS model. Its real-world like configuration based on the results of sounding experiments is demonstrated in section 4. Section 5 gives a short summary.

2 Physical Background

The mobile radio channel may be modeled as a stable linear system. Thus, its properties are fully described by its time-variant impulse response. For simulation purposes, this system functions can be interpreted as random processes to describe the channel behavior in an expectational mean sense. The advantage of stochastic modeling compared to e.g. the deterministic ray tracing approach is that exact knowledge of the scatterer positions and their electromagnetic properties is not required. Thus, most frequently the stochastic GWSSUS model is applied for channel simulation. GWSSUS is a special case of the WSSUS systems treated in [Bel63] from a system theoretical viewpoint. The validity of GWSSUS for narrowband radio transmission was shown in [Cla68] based on some physical properties of electromagnetic wave propagation. The corresponding wide-band formulation can be found in [Par82].

Unfortunately, the GWSSUS model in its original one-input one-output formulation cannot handle directional anisotropy of wave propagation. It may not be applied to investigations dealing with multiple-antenna receiver concepts. However, by rescanning the physical background GWSSUS can easily be extended to the directional Gaussian scattering model (DGS) which is appropriate for the simulation of multiple-output radio channels.

In mobile radio we have to deal with links between elements of the base station (BS) antenna array and the mobile station (MS) antenna. We will start with an investigation of the link between a virtual omnidirectional antenna at the geometrical base station center and the MS antenna.

Due to scattering, the transmitted electromagnetic waves propagate to the receiver antenna not only along the direct line of sight, but also over a variety of other paths. This multipath propagation is characterized by path delays t_ν, by angles α_ν between the vector of the velocity v of the MS and the propagation direction of the partial wavefronts at the MS according to Fig. 1, and by coefficients $\tilde{A}_\nu$ which contain information about complex scattering coefficients and the propagation loss. Although delays, angles and coefficients depend on the instant t of observation, they can be treated as approximately constant if two conditions are fulfilled:

- The bandwidth of the transmitted signal has to be much smaller than the carrier frequency ω_0. In array processing this condition is known as the narrowband assump-

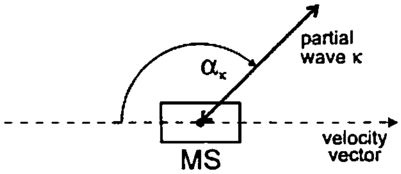

Fig. 1: The angle α_κ of the partial wave κ at the MS.

tion. Obviously, in the case of radio systems it is not a strong requirement.

- The observation time interval is sufficiently short, i.e. the mobile station covers a distance not longer than some tens of the wavelength of the carrier frequency wave [Par82]. This condition is required to allow the simple modeling of the radio channel properties by means of stationary random processes. It restricts the validity of the resulting simulation models to the short term range.

Under these assumptions a modified version of the complex base-band impulse response $h_e(t,\tau)$ is given by

$$h(t,\tilde{t}) = h_o(t, t-\tilde{t}) = \sum_\kappa \underbrace{\tilde{A}_\kappa e^{-j\omega_o t_\kappa}}_{A_\kappa} e^{j\omega_{d\kappa} t}\, \delta_o(\tilde{t} - t_\kappa) \ , \quad (1)$$

where the $\omega_{d\kappa} = -\omega_o (v/c)\cos\alpha_\kappa$ are the Doppler frequency shifts of the partial waves and c is the velocity of light.

The contributions in (1) can be grouped, assuming that in each of p groups the individual ones differ by small delay differences only. This grouping is motivated by a physical interpretation (Fig. 2): There is a finite number p of significant scattering areas far from both the base and the mobile station. Additionally, there occurs a variety of scattering effects in the local surroundings of the MS. All partial waves propagating between the BS and the MS over the same far scattering area arrive at or leave the local scattering area around the MS at approximately the same angle α_ν measured from the mobile's velocity vector. Their delays $t_\kappa = t_\nu + \Delta t_{\nu\kappa}$ are approximately equal t_ν, $\forall\kappa$. Due to local scattering around the MS as well as within the far scattering area, negligible delay differences $\Delta t_{\nu\kappa}$ occur. Negligible means here that these delay differences are not resolved within the transmission bandwidth. By grouping we obtain

$$h(t,\tilde{t}) = \sum_{\nu=1}^{p} [\underbrace{A_\nu e^{j\omega_{d\nu} t} + a_\nu^{(s)}(t)}_{a_\nu(t)}] \cdot \delta_o(\tilde{t} - t_\nu) \ , \quad (2)$$

$$\text{where} \qquad a_\nu^{(s)}(t) = \sum_\kappa \tilde{A}_{\nu\kappa} e^{j(\omega_{d\nu\kappa} t + \phi_{\nu\kappa})}$$

$$\text{and} \qquad \phi_{\nu\kappa} = [-\omega_o \overbrace{(t_\nu + \Delta t_{\nu\kappa})}^{t_\kappa}]_{\mathrm{mod}\, 2\pi} \ .$$

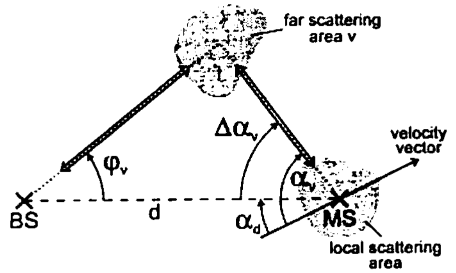

Fig. 2: Group ν of partial waves propagating over the far scattering area ν.

Within each of the p groups a power-dominant component of Doppler shift $\omega_{d\nu} = -\omega_o (v/c)\cos\alpha_\nu$ may be present which describes a partial wave propagating from the receiver over a strong reflector in the far scattering area directly to the receiver without further local scattering. These pure Doppler components may be interpreted as deterministic time-variant mean values of the complex scattering processes $a_\nu(t)$. They change the power distributions of the scattering processes from the Rayleigh to the Ricean type.

The key step of statistical modeling is the stochastic interpretation of the phases $\phi_{\nu\kappa}$ which are effected by the variety of local scatterers. The phases are assumed to be realizations of statistically independent random variables which are uniformly distributed in the interval $[0, 2\pi[$. Using the central limit theorem, it is now easy to show that the stochastic parts $a_\nu^{(s)}(t)$ of the scattering processes are complex Gaussian distributed with mean zero. More than that, they are stationary and mutually uncorrelated due to the assumptions regarding the statistical properties of the $\phi_{\nu\kappa}$. The properties of the stochastic scattering processes make them easy to generate. Together with the tapped delay line structure inherent in (2), this forms the base of GWSSUS channel simulation. The redundant WS for wide sense (stationary) is kept in the acronym GWSSUS to denote that the the simulation model is a special case of Bello's WSSUS channels [Bel63].

For the extension of the GWSSUS simulation concept to the multiple antenna BS type, we have to take into account the antenna configuration (Fig. 3) and three additional assumptions:

- There is no local scattering around the BS.
- The far scattering areas are so far from the BS that the plane wave assumption is realistic at the BS.
- The geometrical size of the antenna configuration is so small that the angles φ_ν of the wavefronts are the same at the different antenna elements.

The modified version $h_i(t,\tilde{t})$ of the complex base-band impulse response for transmission from the MS antenna to the element i of the BS antenna array or for the forward direction, respectively, can be derived in the same manner as $h(t,\tilde{t})$ for transmission between MS and the BS center. The only difference is that small element-dependent delay differences

$$\Delta t_\nu^{(i)} = -\frac{r_i}{c}\cos(\varphi_\nu + \theta_{MS} - \theta_i) \quad (3)$$

occur due to differences in the propagation path lengths within the BS array. However, due to the limited size of the array these delay differences are not resolved within the limited transmission bandwidth. Thus, they only result in element-dependent phase variations of the scattering processes $a_\nu(t)$. Additionally, the antenna pattern $g_i(\varphi)$ in azimuth of the element i can be taken into account. The

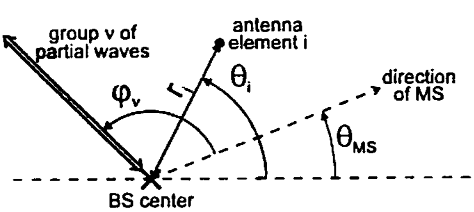

Fig. 3: The BS antenna configuration and the angle φ_ν of the group ν of partial waves at the BS.

mobile antenna is assumed to be omnidirectional. In total, as a generalization of (2) we obtain

$$h_i(t,\tilde{\tau}) = \sum_{v=1}^{p} \underbrace{g_i(\varphi_v + \theta_{\mathrm{MS}})\cdot e^{-j\omega_{dv}\Delta t_v^{(i)}}}_{w_{iv}} \cdot a_v(t)\cdot\delta_0(\tilde{\tau} - t_v)\ . \quad (4)$$

3 Implementation

The GWSSUS and the DGS fading simulators may be realized digitally because both the transmitted signals and the scattering functions are bandlimited. As a consequence of (2), the structure of a GWSSUS simulator is a tapped delay line, where the different delayed signal components are weighted by the time-variant scattering functions $a_v(t)$ and added to form the equivalent base-band antenna signal observed by the receiver. Internally the digital fading simulator runs at a clock frequency f_s. Due to the sampling theorem, f_s has to be at least as large as the bandwidth of the radio system under investigation.

As can be seen from (4), the simulator for the general forward link, i.e. for multiple-antenna transmission and single antenna reception, has the GWSSUS structure. The missing influence of the channel's directional anisotropy on the forward link's transmission properties is a consequence of both the assumed small geometrical size of the BS antenna configuration and the omnidirectional MS antenna.

However, the directional anisotropy strongly affects the reverse link. Eq. (4) yields the simulator structure shown in Fig. 4 for multiple-antenna reception. Compared to the GWSSUS simulator type the difference is that the output adder is replaced by a matrix combiner. The I output antenna signals $y_T^{(i)}(k)$ are generated as linear combinations

$$y_T^{(i)}(k) = \sum_{v=1}^{p} w_{iv}\cdot y_v(k)\ , \qquad \forall k\ ,\ i = 1(1)I \qquad (5)$$

of the component sequences $y_v(k)$. The complex time-invariant weights w_{iv} have already been defined in (4).

At moderate mobile velocities, the scattering sequences $a_v(k)$ are relatively narrowband. Thus, they may be generated at a rate which is much smaller than the simulation clock rate f_s. The stationary, mutually uncorrelated, complex Gaussian scattering components are generated at this low rate (Fig. 5). To reduce the computational complexity by avoiding non-linear transformations, a binary noise source, e.g. a linear feedback shift register structure, may be used instead of a Gaussian type. The binary noise is then demultiplexed to obtain the real and imaginary parts of p white, mutually uncorrelated sequences $n_v(k_{1/r})$ of mean zero. Then linear filters shape Doppler power spectral densities (DPSD) of the stochastic components. If these filters are properly designed to have long and slowly decaying impulse responses, the output sequences are approximately Gaussian distributed due to the central limit theorem. After power adaptation the complex Doppler exponentials are added and the interpolation to the simulation clock rate is performed.

The ideal band-limited interpolator can be approximated with sufficient accuracy by a low complexity linear one if a certain minimum oversampling factor is chosen at the low rate part of the scattering sequence generator. For a low-rate oversampling factor of 10, a sufficiently small relative DPSD error of about −50 dB is achieved.

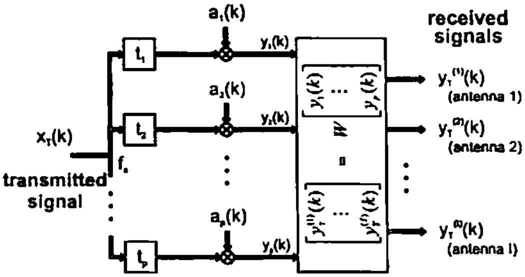

Fig. 4: Structure of the DGS simulator.

4 Configuration

An important problem of channel simulation is the real-world-like configuration of the fading simulator, i.e. the realistic selection of the simulation parameters like the path number p, the delays t_v, the amplitudes A_v, and Doppler frequencies ω_{dv} of the deterministic scattering components and the DPSDs of the stochastic scattering components $a_v^{(s)}(t)$. A set of empirically determined real-world-like configurations was specified in [CEC89]. Recently a method was introduced which estimates complete GWSSUS configurations directly from the results of wide-band sounding experiments [Mar94, Mar95].

To configure DGS simulators the original echo estimation procedure has to be extended by a method for determination of the BS angles φ_v. These BS angles establish the path combiner weights w_{iv}. They can be calculated from the Doppler frequencies ω_{dv} available from echo estimation. Obviously, measurement results from reverse link sounding experiments carried out with some type of moving measurement receiver at the BS position are required for this purpose. If reverse link sounding results for double antenna reception are available the Doppler based method may be supplemented or even replaced by a rudimentary DOA estimation step.

Although at the Deutsche Telekom AG reverse link sounding experiments are in preparation, only results from forward link sounding are available at the moment. Thus, as a preliminary expedient to our configuration problem the required BS angles can be determined as follows. First, the MS angles α_v are calculated from the Doppler information. The velocity v, the distance d between BS and MS and the angle α_d (see Fig. 2) are known from the sounding experiment. Assuming that each group of partial waves is scattered in the local surroundings of the MS and in only one far scattering area, simple triangular geometry (see Fig. 2) offers a non-linear relationship between the MS angles α_v and the BS angles φ_v we are interested in:

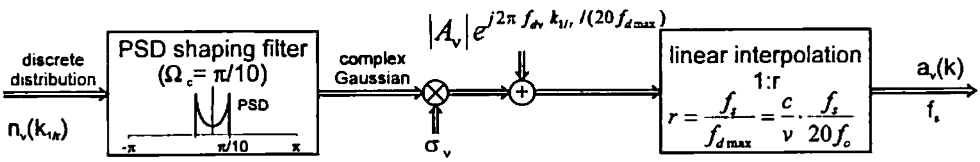

Fig. 5: Generation of the complex scattering sequences.

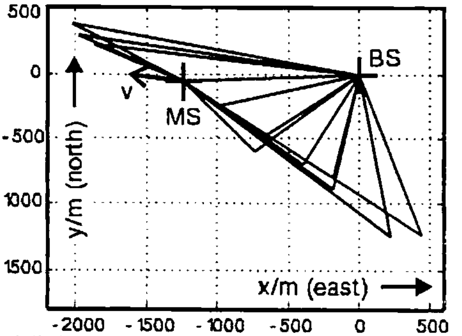

Fig. 6: Estimated geometrical configuration of the propagation paths.

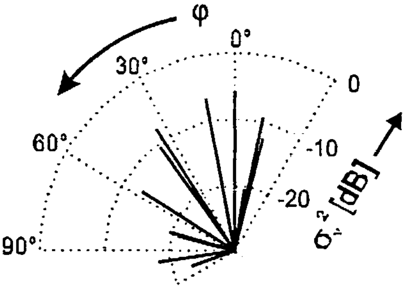

Fig. 7: Angular power distribution at the BS (MS at $\varphi = 0$).

$$\frac{c\cdot t_\nu}{d} = \frac{\sin\varphi_\nu + \sin(\Delta\alpha_\nu)}{\sin(\varphi_\nu + \Delta\alpha_\nu)}, \quad 0 < \varphi_\nu + \Delta\alpha_\nu < \pi \qquad (6)$$

$$\text{where } \Delta\alpha_\nu = \alpha_\nu - \alpha_d$$

An exemplary real-world-like configuration for the DGS simulator was determined in this preliminary manner. The basic sounding experiment was performed with the measurement device RUSK X (Schw93) in a typical urban macro-cell scenario within the city of Frankfurt. The estimated geometrical configuration of the $p = 12$ groups of propagation paths is shown in Fig. 6. The angular distribution of the mean powers of the scattering processes is shown in Fig. 7. Both the standard deviations of the stochastic and the amplitudes of the deterministic scattering components were normalized to achieve a unit mean power transfer factor of the fading simulator. The numerical results required for DGS configuration can be found in Tab. 1.

t / µs	$\sigma_{s,\nu}$	$\lvert A_d \rvert$	$f_{d,\nu}\,c$ / v	φ_ν /°
4.1	0.470	0.176	-0.95	0
4.4	0.469	0	-0.92	11
5.2	0.401	0.078	-0.92	33
5.5	0.304	0	-0.84	36
6.2	0.217	0	-0.92	58
7.0	0.105	0	-0.93	74
7.4	0.092	0	-0.91	75
8.7	0.056	0.075	0.98	350
9.5	0.127	0.316	0.98	349
9.8	0.186	0.151	0.97	347
10.4	0.119	0.034	-0.90	97
11.2	0.068	0.018	-0.94	107

Tab. 1: Parameters of DGS configuration.

$z_{o\mu}$	0.950304± j 0.311324	0.923639± j 0.383263	0.839874± j 0.542782	0.292378± j 0.956303
$z_{\infty\mu}$	0.922501± j 0.237365	0.892028± j 0.095580	0.943887± j 0.296578	0.950733± j 0.308025

Tab. 2: Zeros and poles of the 8-state Jakes-type IIR filter.

Although echo estimation outputs the coefficients of autoregressive, IIR-type DPSD shaping filters, for simplicity reasons we suggest to adopt an 8-state IIR-type filter for all simulator taps which approximates a standard Jakes-type DPSD. The filter zeros $z_{o\mu}$ and poles $z_{\infty\mu}$ given in Tab. 2 were determined from the reference filter of [Bre86] by means of an appropriate frequency transformation. The nominator scaling coefficient for achieving a unit power transfer factor of the filter is $b_s = 0.00418$.

5 Summary

A statistical simulation model for the directional mobile radio channel was introduced. This DGS concept is an extension of GWSSUS. It is appropriate for investigations on all types of multiple antenna reception schemes in mobile radio. Due to its moderate complexity the DGS simulator offers relatively short software simulation time and may be implemented in hardware with reasonable expenditure. To match the properties of real-world propagation scenarios the DGS simulator can be configured directly from the results of wide-band sounding experiments by application of the echo estimation method. Reverse link sounding experiments are required to achieve reliable BS angle information.

Acknowledgment

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