Low-Complexity Geometry-Based Modeling of Diffuse Scattering

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***Abstract*—Modelling diffuse components in geometry-based radio channel models is computationally very complex. It usually requires to add a large number of complex exponentials, which is very time consuming.**

To overcome this complexity constraint, we propose to use the simulation method from Kaltenberger et al. [1]. With this approach, the simulation time becomes independent of the number of multipath components in the channel.

We demonstrate the low-complexity approach by modelling the diffuse components of the vehicular radio channel. Our new implementation reduces simulation time by a factor of 30.

I. Introduction

Recently, the identification of diffuse components in the radio channel has received great attention. It was found that the diffuse part of the channel carries significant power, particularly in non-line-of-sight channels. This leads to a strong impact on channel capacity [2].

To identify diffuse scattering, the authors of [3] developed a high-resolution parameter estimation algorithm which inherently estimates the parameters of diffuse multipath. However, the authors concentrated only on the spatial and frequency properties of diffuse multipath. Recently, the Doppler-delay spectrum of the diffuse part of the vehicular radio channel was investigated in more detail in [4]. In [5], the authors identified the diffuse channel contribution from vehicular radio channel measurements as the remainder of the impulse response after removing deterministic propagation paths. A completely parametrized radio channel model for vehicle-to-infrastructure and vehicle-to-vehicle communications is presented in their work.

However, no efficient way to model diffuse scattering was proposed, yet. Conventionally, diffuse scattering can be modeled geometrically by a large number of planar-wave components. This leads to a tremendous increase in the simulation time. To overcome this problem, we propose to use the concepts presented in [1]. As a result, the simulation time *does not increase with the number of modeled components*.

We demonstrate this concept for diffuse scattering in vehicular channels [5]. Note that the method can be implemented in any kind of geometry-based channel model, as long as the response of the diffuse components can be assumed to be band-limited — an assumption that is usually fulfilled.

The rest of the paper is organized as follows: Section II provides a short survey of the vehicular channel model. In Section III, we discuss the method to significantly reduce the complexity of channel simulation. Section IV presents the simulation results and the performance of the low-complexity model. Finally, Section V concludes this paper.

II. Geometry-based vehicular communications model

We demonstrate the modeling of the diffuse components by the example of a geometry-based stochastic channel model for vehicle-to-vehicle communications [5]. In this section, we review the features of this model. The major components of the model are shown in Figure 1.

The model distinguishes between four major types of contributions: (i) the line-of-sight (LOS) between the cars, (ii) scattering/reflections from stationary discrete scatterers (SD), e.g. road signs, (iii) scattering/reflections from moving discrete scatterers (MD), e.g. other cars, and (iv) diffuse scatterers (D) (e.g. scattering from trees on the road side).

The time-variant frequency response of the channel is thus calculated as

$$\begin{aligned} H(f,t) =& \gamma^{(\mathrm{LOS})}(t)\exp[-j2\pi f\tau^{(\mathrm{LOS})}(t)]+ \\ & \sum_{k=1}^{N_{\mathrm{SD}}}\gamma_k^{(\mathrm{SD})}(t)\exp[-j2\pi f\tau_k^{(\mathrm{SD})}(t)]+ \\ & \sum_{k=1}^{N_{\mathrm{MD}}}\gamma_k^{(\mathrm{MD})}(t)\exp[-j2\pi f\tau_k^{(\mathrm{MD})}(t)]+ \\ & \underbrace{\sum_{k=1}^{N_{\mathrm{D}}}\gamma_k^{(\mathrm{D})}(t)\exp[-j2\pi f\tau_k^{(\mathrm{D})}(t)]}_{H^{(\mathrm{D})}(f,t)}, \end{aligned} \tag{1}$$

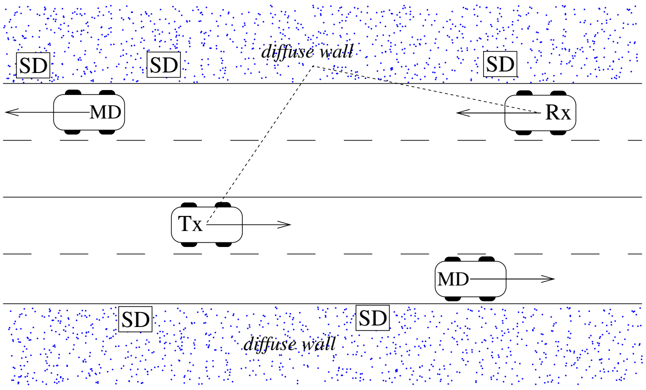

Fig. 1. Geometry-based stochastic channel model. We model the diffuse scattering by a large number of scatterers (blue dots).

where $\gamma_k^{(\cdot)}$ denote the complex-valued attenuation coefficient of the different paths, which include the effects of path loss, antenna patterns, and large-scale fading, $\tau_k^{(\cdot)}$ denote the delays of the paths, and $N_{(\cdot)}$ denote the numbers of SD, MD and D scatterers, respectively. Note that the path weights and delays are time variant, and are updated for every time instant. Path loss, antenna gain and delays are calculated geometrically, while large-scale fading is modeled as stochastic process.

In the rest of the paper, we will only focus on modeling the diffuse components, $H^{(\mathrm{D})}(t,f)$, of the channel.

A. Modeling the diffuse scattering

Diffuse scattering is modeled by a multitude of single-bounce scatterers, which are uniformly distributed in two rectangles along the road side as shown in Figure 1. Each diffuse scatterer is modeled by its complex-valued attenuation coefficient, $\gamma_k^{(\mathrm{D})}$, and its delay $\tau_k^{(\mathrm{D})}$ as shown in (1).

The attenuation coefficient $\gamma_k^{(\mathrm{D})}$ is given by

$$\gamma_k^{(\mathrm{D})}(t) = g_k \sqrt{G_{\mathrm{D}}/N_{\mathrm{D}}} \cdot \sqrt{a_{\mathrm{Tx}}[\phi_k(t)] \cdot a_{\mathrm{Rx}}[\varphi_k(t)]} \cdot d_k(t)^{-n/2}, \tag{2}$$

where g_k is a random number with complex Gaussian distribution, i.e. $g_k \sim \mathcal{CN}(0,1)$, $\sqrt{G_{\mathrm{D}}/N_{\mathrm{D}}}$ is an initial gain, a_{Tx} and a_{Rx} are the antenna gains of the transmitter and receiver, respectively, ϕ_k and φ_k denote the angle of departure and arrival of the kth diffuse path, respectively, d_k denotes the path length of the kth path, and n is the attenuation exponent. The values for n and G_0 were estimated from measurements in [5] as $G_{\mathrm{D}} = 104\,\mathrm{dB}$, and $n = 5.4$ for highway environments.

The path delay is simply given by $\tau_k^{(\mathrm{D})}(t) = d_k(t)/c_0$, where c_0 denotes the speed of light.

III. Reducing complexity

In (1), the channel is represented as a sum of the contributions of all paths. The calculation of the complex exponentials has a significant impact on the complexity of the model. Since the number of diffuse scatterers is chosen to be very large (in the order of $1000 - -5000$) to correctly represent the diffuse part of the channel, the complexity becomes prohibitive. In the following, we will focus on modeling the paths from the diffuse scatterers with low complexity.

For a first reduction in complexity, we assume that the channel is wide-sense stationary in the simulated time interval (e.g. the period of a single transmission frame) and in the simulated frequency range (e.g. the occupied bandwidth of the signal). In a second stage, we assume that the channel is bandlimited in time and delay. We then exploit this bandlimitation by a reduced sub-space approach such that the calculation time does not any more depend on the number of paths.

A. Conventional sum-of-complex-exponentials (SoCE) channel model

The assumption of the channel being wide-sense stationary in the time interval $t \in [0,T]$ and the frequency interval $f \in [f_c - B/2, f_c + B/2]$ implies that (i) the complex-valued path weights and the directions of the paths are not (significantly) changing during this interval, (ii) the path delays are changing linearly and can thus be modeled by a Doppler shift.

The time-variant frequency response of the diffuse channel can then be expressed as

$$H^{(\mathrm{D})}(f,t) = \sum_{k=1}^{N_{\mathrm{D}}} \tilde{\gamma}_k^{(\mathrm{D})} \exp[-j2\pi\Delta f \tau_k^{(\mathrm{D})}] \exp[j2\pi t \nu_k^{(\mathrm{D})}], \tag{3}$$

where the frequency $f = f_c + \Delta f$ is composed of the carrier frequency f_c and the frequency offset Δf. The delay $\tau_k^{(\mathrm{D})} = \tau_k^{(\mathrm{D})}(t=0)$ is defined as the delay at the start of the simulation period. The path weight needs to be updated as $\tilde{\gamma}_k^{(\mathrm{D})} = \gamma_k^{(\mathrm{D})}(t=0) \cdot \exp[-j2\pi f_c \tau_k^{(\mathrm{D})}]$. Finally, the Doppler shift of the path at the center frequency is calculated given the geometry by

$$\nu_k^{(\mathrm{D})} = \frac{f_c}{c_0}\left[v_{\mathrm{Tx}} \cos(\phi_k(t=0)) + v_{\mathrm{Rx}} \cos(\varphi_k(t=0))\right], \tag{4}$$

where v_{Tx} and v_{Rx} denote the velocities of the transmitter and receiver, respectively.

Using this implementation, the path weights and delays no longer need geometric calculations for every realization. Only for the initialization, geometric calculations are necessary. This already brings performance improvements by a factor of 3. However, the computation time still depends on the number of simulated scatterers.

B. Discrete prolate spheroidal sequences channel model

In a second stage, we reduce complexity much further by making use of the low-complexity channel simulation method of [1]. The algorithm uses the multidimensional discrete prolate spheroidal sequences (DPSS) as basis functions to approximate the sum of complex exponentials (3).

The basis expansion is based on the following two facts: Firstly the channel (3) only needs to be computed for a certain number of samples and frequency bins (we will call these index-limited snapshots). Secondly, the channel (3) is bandlimited in time and frequency by the maximum Doppler shift and the maximum delay respetively. Such index-limited snapshots of a bandlimited process span a subspace of small dimension which is optimally represented by the multidimensional DPSS [1], [6]. The advantage of this representation is that it is that the subspace dimension is much smaller than the number of multipath components, thus reducing the complexity of the model.

In the following we will use t and f as discrete time and frequency. Let $v_d(t, f)$ denote the two-dimensional DPSS for the index set $(t, f) \in \{0, \ldots, T\} \times \{f_0, \ldots, f_Q\}$ and the bandlimiting region $(\tau_k^{(D)}, \nu_k^{(D)}) \in [0, \tau_{\max}^{(D)}] \times [-\nu_{\max}^{(D)}, \nu_{\max}^{(D)}]$. The basis representation of (3) is then given by

$$H^{(\mathrm{D})}(f, t) \approx \sum_{d=0}^{D-1} \alpha_d v_d(t, f),$$

where α_d are the basis coefficients.

It is shown in [1] that the basis coefficients α_d can be calculated approximately but very efficiently in $\mathcal{O}(1)$ operations from the multipath parameters given by the model. More precisely we can write

$$\alpha_d = \sum_{k=1}^{N_D} \tilde{\gamma}^{(D)} \lambda_d(\tau_k^{(D)}, \nu_k^{(D)}),$$

where $\lambda_d(\tau_k^{(D)}, \nu_k^{(D)})$ is the projection of a complex exponential function on the DPSS basis. This projection can be efficiently calculated by making use of the aproximate DPS wave functions (see [1] for details).

The number of basis functions typically required for accurate channel simulation is much smaller than the number of paths and thus a lot of complexity can be saved.

IV. Simulating diffuse scattering

In this section, we compare our low-complexity implementation of diffuse scattering with the conventional channel model.

A. Simulation parameters

We simulated a vehicle-to-infrastructure environment on a highway using the channel model presented in [5]. The transmitter (Tx) was moving at a speed of 100 km/h, while the receiver (Rx) was placed at a fixed position in the middle of the highway. The initial position of the Tx was at a distance of 100 m to the Rx, such that during a simulation time of 7.2 s the Tx was moving over a distance of 200 m. A number of 5 mobile discrete scatterers and 6 stationary discrete scatterers were randomly placed by the model.

To model the diffuse scattering, two scattering walls were placed along a highway, where each wall contained 2000 paths uniformly distributed in a rectangle of 500 m×5 m. The parameters of the paths were geometrically calculated as shown in (2). To further reduce complexity, we dropped all diffuse paths whose powers were 50 dB below the strongest diffuse path.

For simulation, we used the parameters of the IEEE 802.11p standard, i.e. a bandwidth of $B = 10$ MHz at a carrier frequency of $f_c = 5.9$ GHz, a frame length of $T = 296\,\mu$s, and a number of $M = 64$ subcarriers. All delays are normalized to the delay of the line-of-sight (LOS) path, thus assuming that the receiver can perfectly synchronize to the LOS.

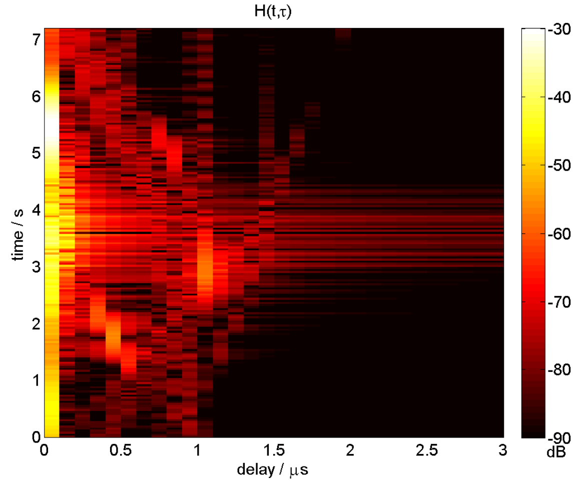

Fig. 2. Time-variant impulse response of a simulated vehicle-to-infrastructure radio channel. Simulation time was reduced by a factor of 30.

For the implementation of the reduced-complexity model, we assumed the channel to be stationary for the transmission of a frame period, which is a reasonable assumption as discussed in [7]. As accuracy for the reduced-complexity approach we chose an error 2^{-15}, being below the resolution of commonly used digital-to-analog converters.

B. Simulation results

First of all we note that the simulation time for the low-complexity approach is *reduced by a factor of 30*! This significant reduction is due to the strong bandlimitation of the channel in delay and Doppler.

First, we discuss the evolution of the channel over the whole simulation period. Figure 2 depicts the time-variant impulse response of the simulated channels. The LOS path is subject to large-scale shading (shadowing). Other stronger paths from stationary discrete and moving discrete scatterers are visible as well, e.g. at a time of 3 s and a delay of $1.1\,\mu$s.

The contribution of the diffuse scattering is seen best between the time of 3 s and 4 s (where the Tx is passing the Rx). The contribution of the diffuse scattering is clearly visible up to $1\,\mu$s after the LOS path.

On small scale, the diffuse scattering is time variant due to its specific Doppler profile [4]. Figure 3 shows the time-variant transfer function of the diffuse channel $H^{(\mathrm{D})}(f, t)$ at the starting time $t = 2.88\,s$ (right before the crossing of Tx and Rx), over a time period of $296\,\mu$s.

The approximation error $|H^{(\mathrm{D})}(f, t) - \tilde{H}^{(\mathrm{D})}(f, t)|^2$ of the low-complexity implementation is seen in Figure 4. It is noteworthy that the maximum error is more than 30 dB below the power of the simulated channels.

V. Conclusions

We implemented a reduced-complexity approach for simulating diffuse scattering along a highway. The complexity

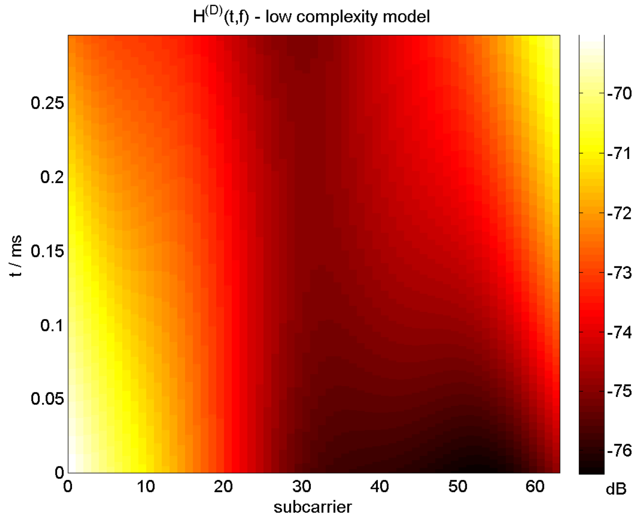

Fig. 3. Time-variant frequency response of the diffuse contribution of the channel.

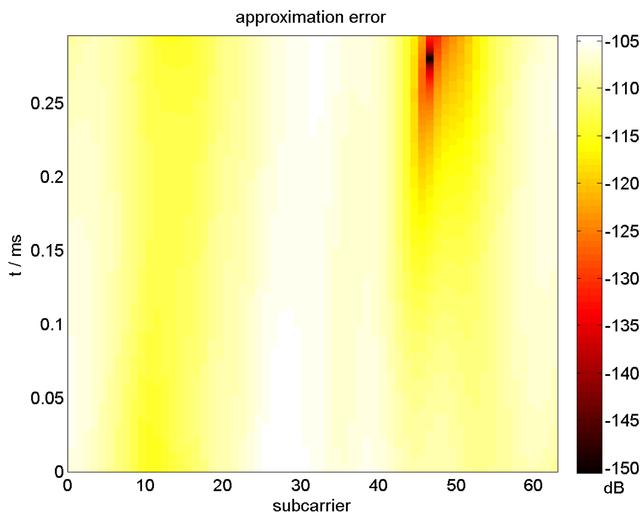

Fig. 4. Approximation error of low-complexity model. The maximum error is more than 30 dB below the power of the simulated channels.

reduction can be used whenever the simulated channels are bandlimited in Doppler and/or delay domain. Using the system parameters of the IEEE 802.11p standard for vehicular environments, our approach could reduce the simulation time by a factor of 30 as compared to the geometry-based modelling approach, at negligible approximation errors.

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REFERENCES

[1] F. Kaltenberger, T. Zemen, and C. W. Überhuber, "Low-complexity geometry-based MIMO channel simulation," *EURASIP Journal in Advances in Signal Processing*, vol. 2007, 2007.

[2] A. Richter, J. Salmi, and V. Koivunen, "Distributed scattering in radio channels and its contribution to MIMO channel capacity," in *EUCAP 2006*, Nice, France, 2006.

[3] J. Salmi, A. Richter, and V. Koivunen, "Detection and tracking of MIMO propagation path parameters using state-space approach," *IEEE Transactions on Signal Processing*, vol. 57, no. 4, pp. 1538–1550, April 2009.

[4] Y. Zhou, X. Yin, N. Czink, T. Zemen, A. Guo, , and F. Liu, "Evaluation of doppler-delay properties of diffuse components in vehicular propagation channels," in *2nd IEEE International Conference on Wireless Access in Vehicular Environments*, Shanghai, China, December 21-22 2009.

[5] J. Karedal, F. Tufvesson, N. Czink, A. Paier, C. Dumard, T. Zemen, C. Mecklenbräuker, and A. Molisch, "A geometry-based stochastic MIMO model for vehicle-to-vehicle communication," *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, pp. 3646–3657, July 2009.

[6] D. Slepian, "Prolate spheroidal wave functions, fourier analysis, and uncertainty—V: the discrete case," *The Bell System Technical Journal*, vol. 57, no. 5, pp. 1371–1430, 1978.

[7] L. Bernado, T. Zemen, A. Paier, G. Matz, J. Karedal, N. Czink, C. Dumard, F. Tufvesson, M. Hagenauer, A. F. Molisch, and C. F. Mecklenbräuker, "Non-WSSUS vehicular channel characterization at 5.2 GHz - spectral divergence and time-variant coherence parameters," in *Assembly of the International Union of Radio Science (URSI)*, Chicago, Illinois, August 7-16 2008.