The Effective Ray-Tracing Algorithm for Analysis of mm-Wave V2V Propagation Channels

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***Abstract*—The author presents the numerical and empirical analysis of the recently introduced by the author and now improved fast ray-tracing algorithm for calculation of stochastic electromagnetic fields in mm-wave vehicle-to-vehicle propagation channel having random geometrical parameters. The support Ω_c of these random variables is electrically very large for the mm-wave band what enforces very long computation times of random electromagnetic fields when ordinary Mone-Carlo (MC) or Polynomial Chaos Expansion (PCE) methods are implemented. The author's algorithm takes advantage of the arbitrary Polynomial Chaos (aPC) to derive the PCE meta-models having random parameters whose support has the size which is a small fraction of the support Ω_c. The large decrease in the size of the random variables support enables to obtain the percentiles (e.g. median) of an attenuation of the mm-wave propagation channel in a relatively very short time. The numerical accuracy of the improved algorithm is verified using the reference Monte-Carlo method. The lamp posts, tree trunks are included in the ray-tracing simulation what was not done in the previous work. The simulation results are compared with the measurement results taken from the literature.**

Keywords—ray-tracing, stochastic simulation, arbitrary polynomial chaos.

I. INTRODUCTION

The paper deals with the stochastic simulation of real mm-wave vehicular-to-vehicular (V2V) propagation channels having random geometrical parameters as obstacles positions and sizes as well as transmitting/receiving antennas positions. The author uses the ray-tracing method which is commonly used for computation of EM fields in wireless propagation channels for high and large frequencies, especially for the mm-wave band, e.g. [1]. Consequently, information about the geometry as well as the material parameters (permittivity, conductivity, roughness) of the propagation channel components is required. In the simulations, the consecutive snapshots of the V2V propagation scenario are analyzed as in [2, 3].

The results presented in this paper are the continuation of the work presented in [4]. In this work, the author presented the novel ray-tracing algorithm for stochastic simulation of V2V propagation channels having random geometrical parameters. When the uncertainty in the geometry of the V2V propagation channel is considered, a rapid variation of an electric field amplitude is expected. Consequently, it is very important to predict the stochastic behavior of the attenuation of the electric field in such a V2V wireless propagation channel.

Stochastic simulation of EM fields is an important subject in the literature dealing with the antennas and propagation area, e.g. [5-7]. In recent years two approaches have been used for simulation of computation of the mean, standard deviation, and percentiles of random distributions of stochastic EM fields. The first of them, the reference method, is the Monte-Carlo (MC) method which requires the drawing of many realizations of random variables according to a given joint probability density. In this method, the required number of simulation repetitions is likely to be much more than 10^6 for the mm-wave band. The alternative, and nowadays more popular method, is the Polynomial Chaos Expansion (PCE) [8, 9] in which the stochastic EM fields are expanded in the support of joint probability density of the random variables. It requires much fewer repetitions of a simulation to obtain accurate simulation results than for the case of the MC method. However, this is not the case for the mm-wave band for which the required expansions are very slowly convergent when the commonly used computation algorithms [10] are implemented. The reason for this is the fact that support of random variables is electrically very large for the mm-wave band.

As the solution to this drawback, the author introduced in [4] the novel algorithm which implements transformation of random geometrical variables as well as the arbitrary Polynomial Chaos (aPC) [11]. The presented in [4] transformations of the random geometrical variables enable to decrease the support of the new random variables by a factor of the phase constant. Consequently, the reduction of this support is the stronger the higher frequency of the analyzed EM field is and is especially very effective for the mm-wave band.

The basic result of the application of the presented in [4] algorithm is the PCE meta-model of an electric field according to which the percentiles of an electric field amplitude are computed [12]. In this paper, the new scheme for these computations is presented and verified. The application of this new scheme enables to decrease the computation times by a significant factor when compared to results presented in [4].

A variety of the measurement campaigns devoted to V2V 5G propagation channels, were presented in the literature e.g. [1-3, 13]. The author verifies the processed simulation results with the measurement results taken from [3].

The paper is organized as follows. In Section 2 the author presents the improved author's algorithm for computations of random EM fields for mm-wave band V2V propagation channels. Section 3 gives the numerical example analysis in which the results of an electric field amplitude obtained using the author's algorithm are compared with the reference MC results and with the measurement results taken from [3]. Buildings, tree trunks, and lamp posts are included in the simulation example. In Section 4 the conclusions are provided.

II. THE IMROVED ALGORITHM FOR COMPUTATIONS OF MM-WAVE STOCHASTIC EM FIELDS

The original algorithm for fast calculation of PCE meta-models of ray transfer functions was presented by the author in [4]. The algorithm takes advantage of the fact of the periodicity of the phase function of each ray. When the random length of the ray no. n depends on random geometrical variables vector $\boldsymbol{\xi g}_n$ and is denoted by ξ_{Ln} while its support is in the range $<a_n, b_n>$, then the phase function of the ray transfer function can be written as follows [4].

$$e^{-j\cdot\beta\cdot\xi_{Ln}} = e^{-j\cdot\beta\cdot a_n} \cdot e^{-j\cdot\beta\cdot\xi s_n} \tag{1}$$

When the random geometrical variables $\boldsymbol{\xi g}_n$ have uniform distribution then ξ_{Ln} and ξs_n have a triangular probability density function (PDF) while the support of ξs_n is in the range $<0, b_n - a_n>$ [4]. This support is electrically too large for the mm-wave band to efficiently compute the PCE coefficients of the ray transfer function. As a solution, the author introduced in [4] the transformation of the random length of the ray into the following random variable:

$$\xi m_n = \mathrm{mod}(\xi s_n, \Delta) \tag{2}$$

where:

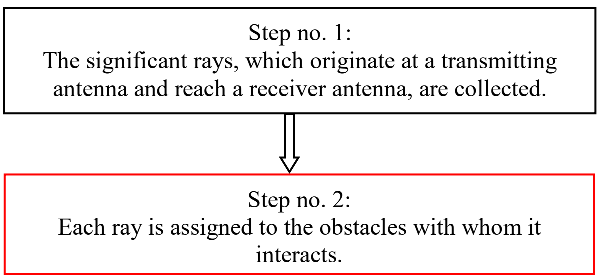
$$\Delta = \frac{2\pi}{\beta} \tag{3}$$

where β is the phase constant. Consequently, the following substitution is made:

$$e^{-j\cdot\beta\cdot\xi s_n} = e^{-j\cdot\beta\cdot\xi m_n} \tag{4}$$

The rest of the details for calculations of the overall PCE meta-model of a random electric field are given in [4].

In this paper, the author's algorithm from [4] is improved and its diagram is shown in Fig. 1. The improved algorithm enables a computation speedup in the range 3-5, depending on the platform used when compared to the algorithm from [4]. The new steps of the improved algorithm are indicated by red-color frames.



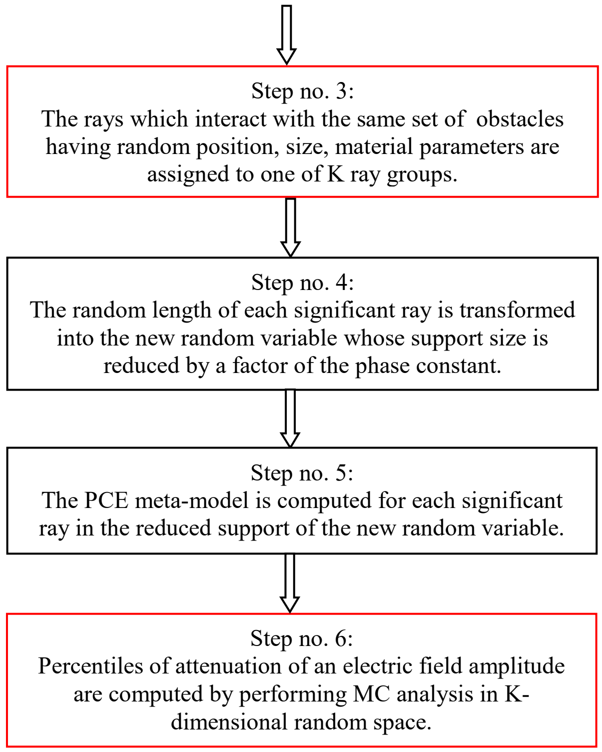


Fig. 1. The block diagram of the updated algorithm for simulations of the random attenuation of an electric field amplitude in the mm-wave V2V propagation channel having random geometrical and material parameters.

In the algorithm from [4], the median value of an attenuation of an electric field amplitude was found by taking advantage of the maximum entropy principle MEP as in [12]. In the improved author's algorithm, the percentiles of an electric field amplitude are computed using the MC approach in K-dimensional random space of transformed by using (2) random variables, where K is the number of different ray groups originating from the point of a transmitting antenna and reaching the point of a receiving antenna. As a result, the minimum required order of PCE meta-model of each ray is decreased twice, from 4 to 2.

The idea of assigning a given ray into the specific ray group is illustrated for the simple 2-dimensional V2V propagation scenario in Fig. 2.

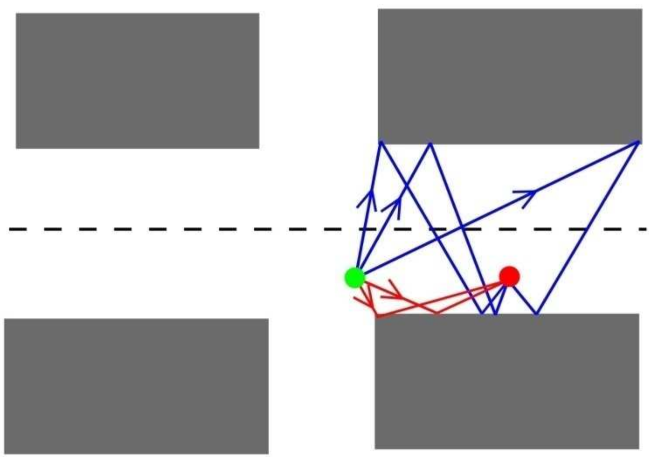


Fig. 2. The illustration of assigning rays, which originate at the position of a transmitting antenna (green circle) and reach the point of a receiving antenna (red circle), to the separate ray groups (red and blue rays).

The procedure of the new MC approach for the computation of percentiles of an electric field attenuation includes the following operations:

1. Selection of one ray from each ray group (K rays are selected as a result)
2. The drawing of consecutive realizations of the vector of K transformed by using (2) random variables.
3. Computation of realizations of transformed random variables for the remaining rays in each group of rays using the results drawn in the previous step as well as the information about the ray lengths calculated for the nominal values of vector $\boldsymbol{\xi g}_{n}$.
4. Calculation of the attenuation of an electric field amplitude for the realizations of random variables computed in the previous two steps using the PCE-meta-model derived as in [4].
5. Computation of the histogram and desired percentiles of attenuation of an electric field amplitude.

III. Simulation Example

The author presented in [4] two simulation examples that are used to verify the original author's algorithm for computation of stochastic mm-wave band EM fields in a V2V propagation channel. In those simulations, reflections from the road and walls of buildings as well as diffraction from buildings edges are considered. In this paper, a more complex propagation scenario is considered. The propagation channel includes tree trunks and lamp posts. The 3D-view of the considered scenario is shown in Fig. 3.

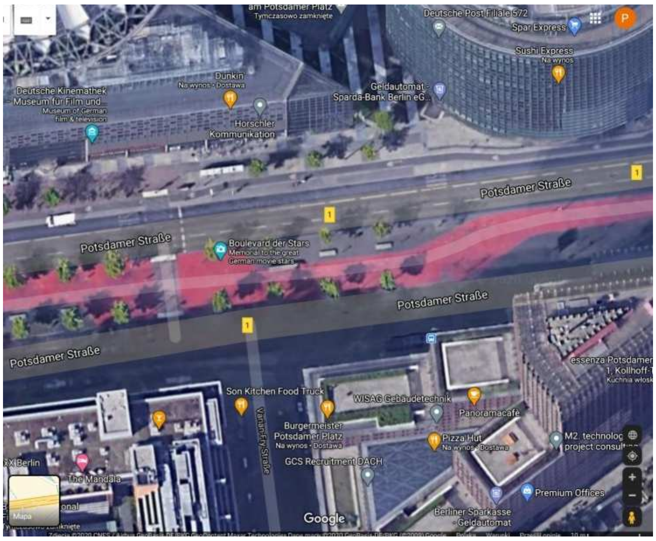


Fig. 3. The scenario for stochastic simulation analysis.

The simulation analysis is performed for frequency 60GHz along the center of the median strip between the lanes of the Potsdamer Straße in Berlin [3]. The top-view of the simulation scenario is shown in Fig. 4 [3]. In the measurements, the antennas were separated by a 25m distance for which 10cm uncertainty was assumed.

In this paper, the author assumes 40cm uncertainty of the geometrical data from the 3D-CAD model of the scenario and 10% of relative uncertainty to the given in [3] values of material parameters of the obstacles. As in [3], two omnidirectional vertically-polarized antennas are considered. The nominal height of the transmitting and receiving antennas are 3.5m and 1.5m, respectively. A 5cm uncertainty is assumed in these heights. The uncertainty of antenna positions in vertical domains is assumed to be 20cm. The nominal phase characteristics of antennas are assumed to be 0°. To relative uncertainties of phase and magnitude characteristics are equal to 10%. They are implemented in the simulation, as in [14]. The rays, that are included in the simulation, are reflected rays, diffracted from the edges and creeping rays. Up to 6-order reflections are allowed for the reflected rays. One diffraction is allowed for a single ray. The diffraction can be combined with two reflections. From the author's experience, such rays should be included in the simulation to make the results converge.

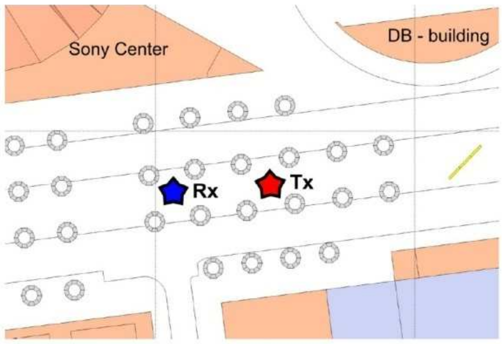


Fig. 4. The top-view of the propagation scenario with antennas separated by 25m distance [3].

The results of the measurements and the simulation results of the median power delay profile (PDP) for the considered scenario are shown in Fig. 5.

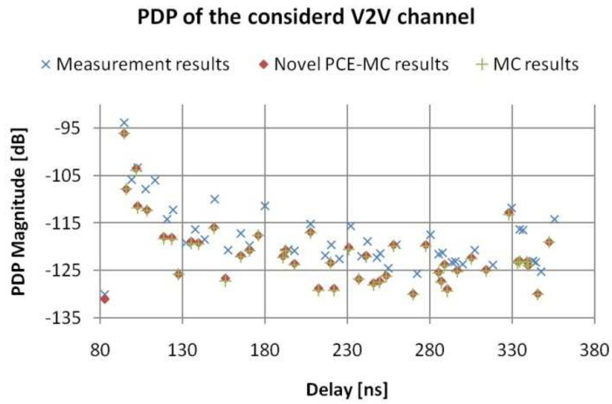


Fig. 5. Comparison of the measurement results and simulation results calculated using the author's apporach and the MC apporach.

When the simulation results are taken into consideration, it can be seen that an excellent agreement between the author's approach results and MC results is obtained. The author's results required 8.54min while the corresponding simulations for the MC approach were completed in about 928min. A 4-core Intel platform was used for the computations. It can be seen also that the stochastic simulation results (median PDP) are in relative agreement with the measurement results.

IV. Conclusions

The author introduces in the paper the improved fast and accurate PCE-MC algorithm for computation of random EM fields for mm-wave V2V propagation channels. The author's algorithm provides a great speedup of computations when compared to the original MC approach. The main reason for this is the large reduction of the electric size of the support of random variables of the propagation scenario. Consequently, the resulting PCE meta-models of the ray transfer function include no more than 20 coefficients. The large decrease of the support of random variables enables a large reduction of required realizations of the PCE meta-model for the MC computation of the percentiles of an electric field attenuation. The author's algorithm is tested using the relatively complex propagation scenario. Its accuracy is successfully verified by comparing it with the reference MC approach. The comparison of the simulation and experimental results can indicate that the author's algorithm can provide stochastic results that are in good agreement with the real results. It can be achieved by consideration of sufficient uncertainties in the propagation scenario and higher-order rays in the simulation as in the analyzed in the previous section example.

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