Bistatic Scattering Center Models for the Simulation of Wave Propagation in Automotive Radar Systems

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***Abstract*—Deterministic radio channel simulations for large and complex environments at very high frequencies are a challenging task. In this paper an approach is presented in which the computational complexity is significantly reduced by using scattering center models for the most complex objects. The scattering centers are described in form of directional, bistatic scattering intensities and can be computed for the isolated complex object in advance without considering the complete environment. Thus, the simulation performance benefit is due to a significant reduction of the complexity of the geometrical representation of the scene. The parameterization of the scattering centers itself is based on an efficient high frequency asymptotic field prediction tool incorporating Geometrical Optics and other techniques. The models are designed to study deterministically the wave propagation for vehicle based radar systems operating near 80 GHz. An example for a bistatic three-dimensional parameterization is given. Furthermore, a fast Inverse Synthetic Aperture Radar (ISAR) imaging technique is applied that can be used to find the most relevant scattering center positions on the objects.**

I. INTRODUCTION

Wave propagation modeling is a key issue in the design and development of communication or remote sensing systems. In the past, many empirical models have been developed and deterministic approaches have been implemented to enable engineers to get a better understanding of the characteristics of the radio channel at different frequencies and for different applications. For example, in the automotive industry there is a strong interest in developing radio based communication and sensor applications to increase road safety and passenger comfort. While empirical or stochastic channel models are quite satisfactory for many development and design purposes, some critical applications require deterministic channel knowledge.

In our case the development process of long range automotive radar sensors is to be supported by a comprehensive simulation chain. With such a modular tool, different phases in the development cycle of the hardware, as well as the algorithms and signal processing can be optimized and accelerated by virtual prototyping. Especially, a reduced need for drive tests and measurement campaigns is expected to improve the cost efficient development of new mass market radar sensors, which is one of the objectives of the *RoCC* project [1].

II. SYSTEM SIMULATION CONCEPT

To design and validate signal processing algorithms in specific situations deterministic channel knowledge is essential. For example if the sensor behavior in different well defined driving maneuvers is of interest (lane change, approaching other objects, etc.). Figure 1 depicts the detailed geometrical representation of a car used within the following investigations and Figure 2 depicts a typical highway scenario of interest with a radar system carried on a passenger car. Besides the reflecting contributions from other vehicles, many other scattering sources can be identified as well: the road surface, guard rails, traffic signs, bridges and even buildings and vegetation besides the road.

For deterministic investigations, ray-optical simulation approaches have been applied in the past to study communication systems (see for example [3]). A similar approach has been selected for the present problem. Even though in the asymptotic approach the requirements regarding the size of the geometrical elements are not directly related to the wavelength, as it is in the method of moments for example, the computational complexity increases also in this case. This is related to the geometrical approximation of the objects, in particular if irregular and complex shaped geometries are to be considered. Moreover, to study the channel characteristics in time-variant scenarios many snapshot simulations are required,

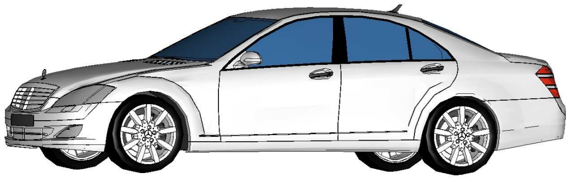


Fig. 1. CAD model of a passenger car used for the scattering center simulations. The model is built up of appr. 100 000 triangles [2].

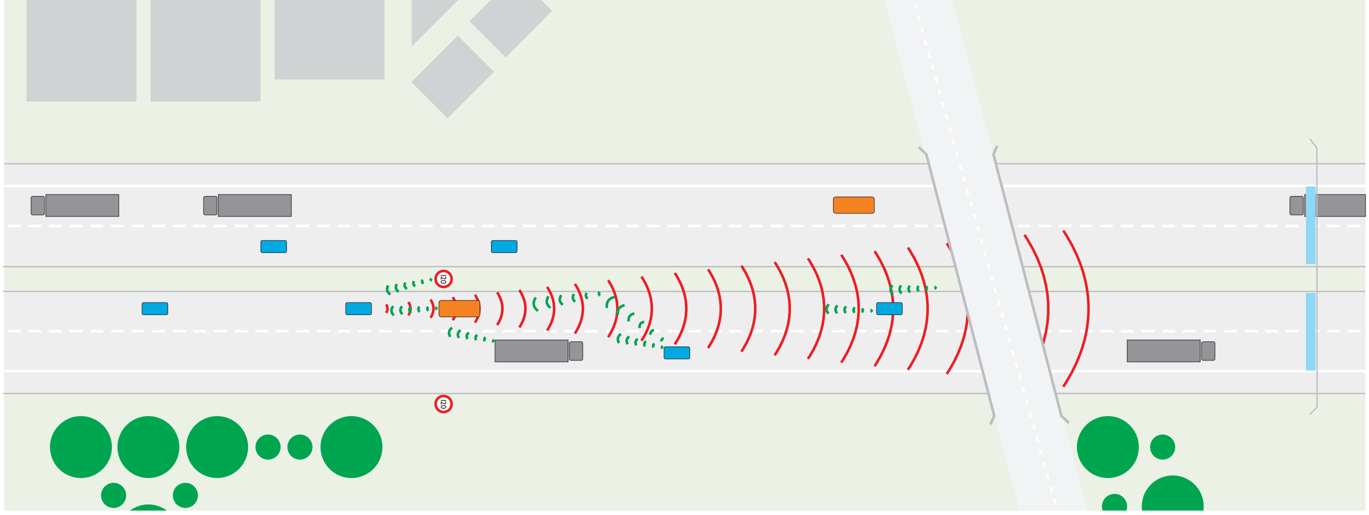


Fig. 2. Example for a complex system scenario. A large variety of different scattering mechanisms can be observed.

which strictly limits the computation time for a single simulation run. This clearly illustrates the need for a significant reduction of the overall simulation complexity compared to a brute-force ray-tracing approach.

The presented approach is based on a scattering center representation of the complex shaped objects within the system simulation. The original geometrical representation of the vehicles, which can easily reach a complexity in the order of a hundred thousand facets (see Fig. 1 for the example presented in this paper), is replaced by the pre-computed scattering center information as described in Section III.

For the simplification it is beneficial that in most cases the requirements regarding the accuracy of the characterization of the scattering properties are quite moderate. Often it is desired to model the properties of a typical example for a certain class of objects (passenger car, van, truck, ...), rather than exactly a particular object.

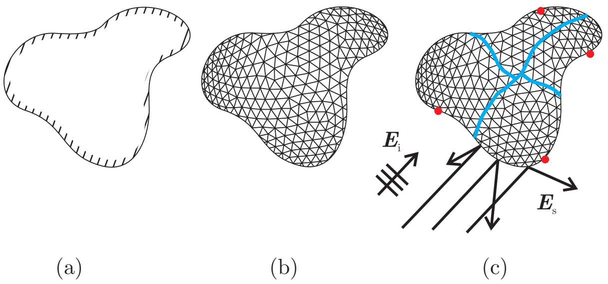
III. SCATTERING CENTER MODEL

An important observation regarding the scattering of high frequency electromagnetic waves is, that it is usually dominated by well localized effects. Hence, the idea of concentrating scattering information of a spatially limited source area has been successfully applied in different contexts of radar target identification or Radar Cross Section (RCS) simulation with data compression (see for example [4]–[6]). Usually, ideal omni-directional point sources are distributed for a given angle of incidence and observation direction.

In contrast to this, our approach is based on a predefined distribution of fixed bistatic scatterers. The fixed set of scattering centers allows a straight-forward integration into the system simulation, whereas on the other hand the bistatic parameterization is required to consider system level multipath effects. This means that in the presented approach the information is put into some kind of directivity of the scattering centers instead of using different distributions of point scatterers.

Far-field scattering of arbitrarily complex objects is usually characterized in terms of the Radar Cross Section [7]–[9]. With the far-field distance typically given by $d_{\mathrm{FF}} = 2D^2/\lambda_0$, where D denotes the maximum object dimension, it is evident that these conditions can be reached only in approximately $10\,\mathrm{km}$ distance for our considered applications. Fortunately, due to the use of several scattering centers, each with a limited spatial extent, the effective volume and extension that is represented by an individual center is significantly reduced. In consequence, also the far-field distance approaches the object and the RCS parameterization of the scattering centers can be applied also for nearby interactions. On the other hand, the use of multiple scattering centers is also important to preserve the geometrical extension of the simplified objects.

As these scattering properties shall be used as pre-computed data in a look-up-table fashion, an appropriate discretization for the angles of incidence and scattering is required. To keep the amount of data on a reasonable level, a one or five degree discretization is proposed. This was found to be sufficient from a system level point of view for a typical representation of the properties of a class of objects. Finally, the scattering center can be stored in form of a four-dimensional RCS matrix: the amplitude depends on the two solid angles of the direction of



(a) (b) (c)

Fig. 3. Arbitrarily shaped object (a), geometrical representation by plane facets (b), and scattering center parameterization (c).

incidence and the scattering direction.

On system level the interactions of individual rays with the complex objects are modeled in form of secondary sources weighted with the directional scattering amplitude of the relevant scattering center. In this way the RCS matrix of a scattering center can be considered very much like an antenna pattern.

IV. PARAMETERIZATION APPROACH

The object to be parameterized is considered under free space conditions in a turn-table-like scenario. Currently, the parameterization is based on a Geometrical Optics (GO) algorithm. Each ray launched from a far-field transmitter that hits the objects surface is traced with possibly multiple interactions until it exits the scenario. For the last interaction point the closest scattering center is selected. With the given angle of incidence, which is determined by the position of the current transmitter, and the angle of reflection the ray amplitude is accumulated incoherently. For the SC parameterization this means that, for a given direction of incidence, the field contributions of all rays are numerically integrated for all scattering directions of interest, e.g. in one or five degree discretization steps. Fig. 3 depicts an arbitrary object, its geometrical approximation and four scattering centers subdividing the surface.

For objects like passenger cars the symmetry can be advantageously utilized to reduce the simulation effort by a factor of two. In addition to the mentioned GO fields other contributions could be considered as well, for example Physical Optics (PO) as described in [7] and also [9]–[11]. It is far out of the scope of this paper to go into details about this.

In the presented algorithm the Shooting and Bouncing Rays principle (see [12]) can be applied very efficiently as the bistatic scattering characteristics are of interest. Nevertheless, the handling of large and complex shaped objects makes it worthwhile to apply advanced techniques regarding the handling of the geometrical elements. The algorithm is based upon a volume partitioning approach to speed up the ray-tracing process [13], so that the computation time for a typical parameterization as shown in Section VI takes about one hour on a standard office PC.

The examples presented within this paper are based on vertical co-polarized calculations. The extension to consider different polarizations is straight forward. For each combination of transmit and receive polarization one independent set of RCS matrices is to be used. Considering both co- and cross-polarizations the amount of data is quadrupled.

V. LOCALIZATION OF SCATTERING

The presented approach is based on a fixed set of scattering centers. This means that the number and positions of the scattering centers are, for example, independent of the direction of the incoming waves. In order to discover the most important scattering parts of the objects surface ISAR imaging techniques can be a useful tool [14]. Typically, ISAR imaging is based on multi-dimensional Fourier processing, which requires costly data acquisition in multiple dimensions (e.g. frequency and aspect). In our case we have to study bistatic scattering phenomena for many different illumination directions and for reasons of computational cost this way is therefore not very attractive. Instead, we use a fast simulation approach which requires only a single aspect simulation run (at only one center frequency) to produce comparable images.

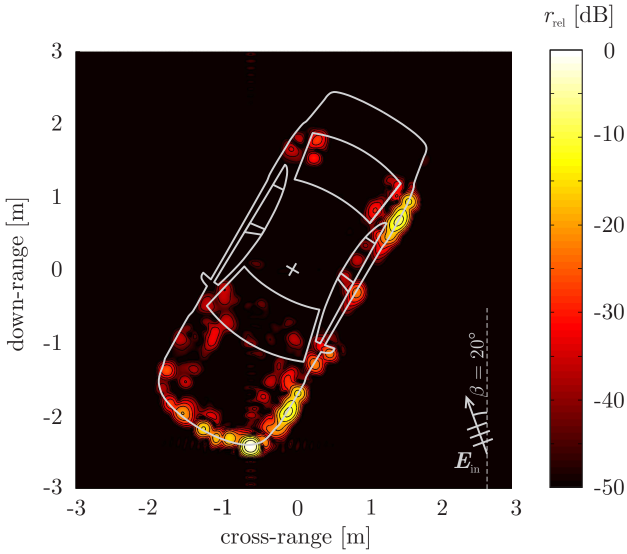


Fig. 4. Horizontal plane ISAR image of a passenger car with bistatic illumination ($\beta = 20°$).

Fig. 4 shows an example fast ISAR image with bistatic illumination. Isolated scattering centers can be identified for this configuration mainly at the vehicle front and near the wheels. The reflectivity is normalized to the maximum.

The single aspect imaging algorithm is based on the Shooting and Bouncing Rays technique and directly exploits the ray path interactions, inherently known by the ray-tracer. Assuming far-field conditions and considering a narrowband system with only a small aspect range, the ISAR image contribution of individual rays can be determined analytically. A simple surface currents based formulation has been derived to use this approach in our hybrid GO/PO simulations.

VI. EXAMPLE RESULTS

Twenty scattering centers have been distributed across the surface of the passenger car as illustrated in Fig. 5. Additionally the coarse polygon model used in the system level simulations is shown as an overlay. Some of the most important parameters of the simulation example, which are indeed quite typical for our applications, are listed in Table I. Fig. 6 shows the parameterization result for the scattering center located at the front of the vehicle. For visualization purposes, only the horizontal plane representation has been selected, i.e. the scattering amplitude is depicted depending on the azimuth of the direction of incidence ϕ_{in} and depending on the azimuth of the scattering direction ϕ_{out}. It should be noted that wave propagation in the horizontal plane is expected to

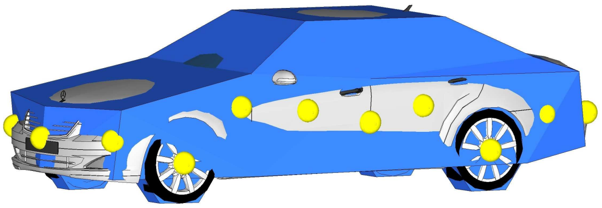


Fig. 5. Coarse polygon model and scattering center locations overlaid on the original CAD data. The coarse model is reduced to appr. 80 triangles

TABLE I
TYPICAL SIMULATION PARAMETERS

Parameter		Value
Frequency	f_0	76 GHz
Number of rays	N	$1 \cdot 10^6$
Max. Interactions		5
Number of SC	N_{SC}	20
Polarization		vv
Angular Discretization	$\Delta\phi$	1°
Symmetry		xz-plane

cause the dominating signal contributions, but nevertheless in some scenarios strong multipath effects may occur and a full 3D modeling is necessary.

A one degree angular discretization has been applied and the obtained RCS matrices have been normalized to an overall broadside RCS of $30\,\mathrm{dBm}^2$. Interestingly, the dominating specular contributions (parallel to the falling diagonal) split into two maxima. This can be attributed to a slight v-shape of the vehicles front. Also, considerable monostatic contributions can be observed in parallel to the main diagonal, although much weaker and much more diffuse compared with the specular components.

VII. CONCLUSION

The presented approach leads to a significant reduction of the ray-tracing complexity in terms of geometric details to be considered. This is achieved by a suitable isolation of individual scattering centers on the complex shaped vehicles. Each scattering center is characterized in a kind of pre-calculation and can therefore be handled at runtime by look-up tables. By this, the number of geometrical elements to be handled by the ray-tracer can be easily reduced by a factor of 100 or even 1000, while, at the same time, a detailed description of the electromagnetic interactions can be preserved. For the radio channel simulation on system level only a very coarse geometrical description of the object is required in order to determine the shadow boundary and to select the appropriate scattering center according to the local interaction point. A number of scattering centers distributed at appropriate locations over the vehicles surface assures a proper representation of the object dimensions as well as the far-field condition for individual centers.

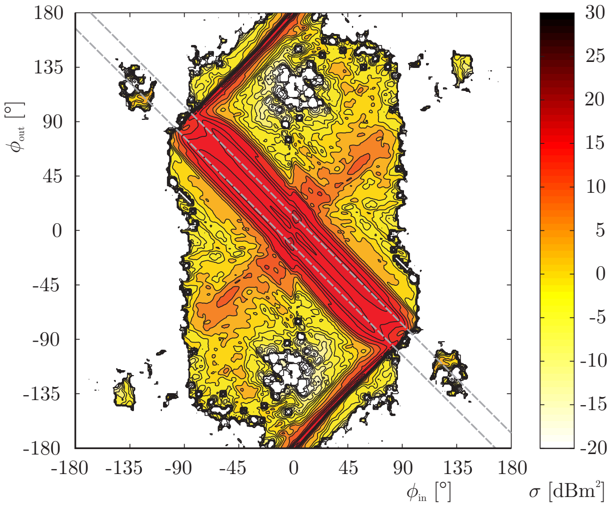


Fig. 6. Example scattering center parameterization for the front part of the vehicle. This graph depicts the scattering intensity in the horizontal plane, i.e. depending on the angle of incidence ϕ_{in} and on the scattering angle ϕ_{out}

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