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Hybrid Computer Simulation Of Automotive Radar Systems In High Multipath Environments

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Abstract—**The electromagnetic modeling of automotive radar in various traffic scenarios and in complex high multipath environments like highways and urban areas poses enormous computational challenges that cannot be addressed using conventional simulation approaches. In this paper, we describe a hybrid methodology that combines several full-wave and asymptotic numerical techniques within a unified framework that enables near-real-time dynamical simulation of an automotive radar system in a multipath physical channel, where the positions and orientations of the radar and target(s) can change dynamically as a function of time.**

Keywords—component automotive radar, target, radar cross section, ray tracing, physical optics.

I. INTRODUCTION

Automotive radar systems are critical elements of Advanced Driver Assistance Systems (ADAS). The 76-81 GHz frequency range has become the primary band of interest as it provides higher bandwidths (up to 4 GHz), enabling increased range resolutions of only a few centimeters. The development and testing of ADAS systems can be accelerated by using computer simulations of various traffic scenarios. Such simulations use mathematical models of the physical vehicle, of its ADAS and other control systems and of all relevant sensors. To simulate a large number of traffic scenarios, these radar models need to have the right balance of accuracy and computational speed, in some cases they are even required to run in real time. The physical modeling of traffic scenarios with a single radar target placed in a line of sight (LOS) and at a certain range from the radar antenna is quite straightforward using the well-known radar equation [1]. Unfortunately, automotive radar scenarios are much more complicated than the LOS case due to the presence of the road surface (ground) and other scatterers such as nearby vehicles and highway guard rails. As a result, a high multipath environment is created, whereby the radar signal may hit and bounce from the ground and/or other scatterers before reaching the actual target, or the echo signal may hit and bounce from the ground and/or other scatterers before returning to the radar antenna. The multitude of return signals arriving at the radar receiver with different time delays and different angles of arrival lead to detection ambiguity and increased probability of false alarms. The complexity of traffic scenarios requires a rigorous physics-based simulation of wave propagation that incorporates a high-fidelity geometric model and material composition of the primary target, an accurate model of the radar antenna and the physical details of the propagation channel. Physics-based electromagnetic modeling of automotive radar scenarios in the 76-81 GHz frequency range poses serious computational challenges as the free-space wavelength varies between 3.7mm and 4mm, while typical road objects have linear dimensions of several meters. The full-wave modeling of such propagation scenes typically involves millions to billions of unknowns.

This paper presents a hybrid approach that combines a number of innovative simulation techniques with a two-step process based on the shooting-and-bouncing-rays (SBR) method [2]. First, the polarimetric transfer function of the propagation channel is computed in the form of a global ray database. Then, in the context of a dynamic, mobile radar system simulation, the radiation pattern of the radar antenna and the polarimetric scattering matrix of the target(s) are combined with the channel transfer function matrix to compute the power of the received return signal(s) and the signal-to-noise ratio (SNR) at the radar receiver.

II. BACKGROUND TTHEORY

Fig. 1 shows a nominal radar propagation scene, which consists of the radar transmit/receive antenna, the primary road target, and other scatterers and clutter present in the scene. In a fully polarimetric field-based formulation, one can relate the electric field vector in the spherical coordinate system at different locations through 2×2 matrices representing the propagation channel's transfer function:

$$\begin{bmatrix} E_\theta^{inc} \\ E_\varphi^{inc} \end{bmatrix} = \begin{bmatrix} T_{\theta\theta} & T_{\theta\varphi} \\ T_{\varphi\theta} & T_{\varphi\varphi} \end{bmatrix} \begin{bmatrix} E_\theta^{Tx} \\ E_\varphi^{Tx} \end{bmatrix} \tag{1}$$

where [**T**] is the transfer function of the channel between the radar's transmit antenna and the target. The electric field scattered by the target is related to the electric field incident on the target through its polarimetric scattering matrix [**S**]:

$$\begin{bmatrix} E_\theta^{scat} \\ E_\varphi^{scat} \end{bmatrix} = \begin{bmatrix} S_{\theta\theta} & S_{\theta\varphi} \\ S_{\varphi\theta} & S_{\varphi\varphi} \end{bmatrix} \begin{bmatrix} E_\theta^{inc} \\ E_\varphi^{inc} \end{bmatrix} \tag{2}$$

Finally, the electric field received at the aperture of the radar's receive antenna are expressed in terms of the electric field scattered by the target:

$$\begin{bmatrix} E_\theta^{Rx} \\ E_\varphi^{Rx} \end{bmatrix} = \begin{bmatrix} T'_{\theta\theta} & T'_{\theta\varphi} \\ T'_{\varphi\theta} & T'_{\varphi\varphi} \end{bmatrix} \begin{bmatrix} E_\theta^{scat} \\ E_\varphi^{scat} \end{bmatrix} \tag{3}$$

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where [**T′**] is the transfer function of the channel between the target and the radar's receive antenna. In the course of a dynamic radar system simulation, all the received rays at the location of the radar's receive antenna are collected from the primary target and all the other road scatterers, reflectors and diffractors, and their electric fields are superposed coherently incorporating the polarimetric radiation pattern of the radar's transmit and/or receive antenna(s).

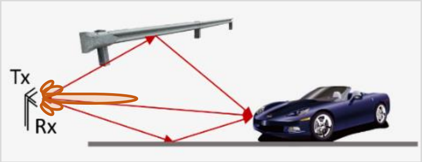

Fig. 1. A nominal automotive radar scenario comprising a radar antenna, a primary target, road surface and other scatterers such as highway guard rails.

In the case of the scattering characterization of road targets, it is important to consider a high-fidelity model of the entire target structure especially in the context of dynamic radar simulations whereby the mobile target may translate and rotate relative to the radar antenna. The target model is typically in the form of a high-resolution triangular surface mesh given by a stereolithography (STL) data file. The method of equivalent current approximation (MECA) [3] is utilized to extend the approach beyond PEC targets to objects with different material compositions. In order to model multiple scattering scenarios, e.g. on concave surfaces, an iterative physical optics (IPO) formulation [4] was combined with MECA.

III. SIMULATION RESULTS

As a typical road target, we considered a real-sized model of a Chevrolet Volt with the dimensions 4.6 m × 2.1 m × 1.7 m. The model involves a total of 1,730,719 triangular cells as shown in Fig. 2. This model's radar cross section (RCS) was calculated using both a commercial large-element PO solver and our IPO solver for the purpose of verification. The RCS simulation results are shown in Fig. 3. The parallelized and accelerated version of the IPO simulation takes only 2.5 seconds per azimuth angle on a single Intel Core i9 processor with 128 GB RAM.

The road targets analyzed previously and characterized by their polarimetric scattering matrices and the radar antenna characterized by its polarimetric installed radiation pattern are placed in a realistic automotive radar scene as shown in Fig. 4. The road surface is represented by a dielectric half space with $\varepsilon_r = 5$ and $\sigma = 0.005$ S/m. Two sets of double-bar metallic guard rails are placed at the two sides of the road with a spacing of 30 m. First, the 3D SBR channel analyzer computes the transfer function of the propagation channel. Then, the near-real-time "Polarimatrix" solver performs all the necessary matrix-vector multiplication operations to compute and collect all the multipath return signal arriving at the radar's receive antenna [9]. To keep the simulation manageable, the total number of consecutive reflections is limited to 5 bounces. Yet, a total of 463 rays arrive at the radar receiver as visualized in Fig. 4. The channel characterization and generation of the global ray database takes only 4 seconds on a single Intel Core i9 processor. The Polarimatrix simulation takes less than a second, thus making it suitable for running dynamic mobile simulations in almost real time. Fig. 4 also shows a bar chart plot of the power - delay profile of the multipath return signals received by the radar's antenna. These include the LOS echo signal as well as those reflected from the road surface and the two guard rails.

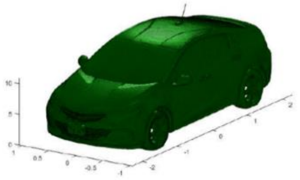

Fig. 2. The surface triangular mesh of the Chevrolet Volt model containing more than 1.73 million cells.

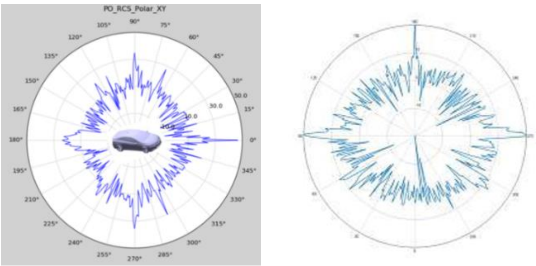

Fig. 3. The RCS of the Chevrolet Volt model of Fig. 2 computed at 78 GHz using (Left) hybrid IPO method of this paper, and (Right) commercial large-element PO simulator.

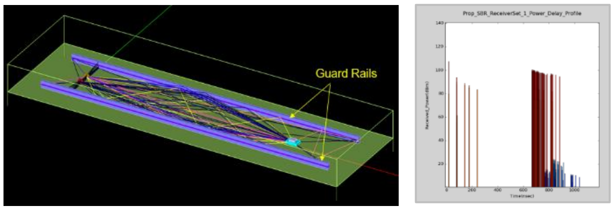

Fig. 4. (Left) Ray visualization of the multipath signals propagating between a radar antenna, a vehicle target, the road surface and highway guard rails in a 78 GHz automotive radar scene with a range of 100 m, and (Right) the computed power - delay profile of the multipath received return signals.

IV. CONCLUSIONS

A multi-pronged strategy has been developed for physics-based computer simulation of automotive radar systems in high multipath environments. To enable dynamic mobile simulation scenarios, a real-time approach to the 3D polarimetric SBR method has been developed. Full-wave and/or hybrid physical optics solvers are used to characterize the installed radar antenna and various road targets and other types of scatterers.

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