Antenna Placement Optimization for Vehicle-To-Vehicle Communications

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***Abstract*—Vehicle-to-vehicle (V2V) technology has the potential to significantly enhance driver safety. The type, placement, and orientation of V2V antennas all affect the performance of the communication system. Simulation software for high frequency electromagnetics can be used to analyze the far-field effects of various vehicle antenna configurations without the need to perform physical testing. We present a simulation-based method for optimizing the placement and orientation of a monopole antenna on a vehicle using a Global Response Surface Method (GRSM). The resulting antenna configuration emits a stronger and more uniform far-field pattern while insuring a minimal reflection coefficient. A full-wave method, namely, the Multi-Level Fast Multipole Method (MLFMM), is used to perform the analysis of the antenna mounted atop a vehicle. This process has the potential to improve the performance and reduce the cost and design time of V2V antenna systems.**

Keywords—automotive; antenna; vehicle-to-vehicle; V2V; antenna placement; simulation; optimization; HyperStudy; FEKO

I. Introduction

Potential for significant improvements in automotive vehicle safety has led to increased interest in V2V communication over the last few years. The National Highway Traffic Safety Administration has recently issued notice of proposed rulemaking FMVSS-150 which would require all manufacturers to install dedicated short-range communication radios in new vehicles [1]. Several design decisions affect V2V system performance, including antenna type, placement, and orientation. In the presence of a large, electrically-conducting structure such as a car body, an antenna's far-field pattern will become distorted. These distortions are highly dependent on antenna mounting location, orientation, and vehicle geometry.

The placement of vehicle-mounted antennas has been successfully studied with FEKO [2]. Notable works also exist in the field of antenna placement optimization. [3] demonstrated how optimization can be used to select from discrete antenna locations on the MBCOTM Stryker military vehicle. [4] used a genetic algorithm to identify optimal antenna locations aboard an aircraft. Work has also been done on optimizing vehicle antenna placement for V2V communications with ray-casting techniques [5]. In each of these works, optimization took place over a few predesignated mounting locations, or in the case of [4], along a straight line or flat plane. The method presented in this paper allows for antenna placement optimization over a broader design space, and is general enough to be used on any vehicle geometry.

II. Antenna simulation

The ideal numerical method for antenna simulation depends on the scale of the problem. At 5.9 GHz a vehicle is considered an electrically large structure. Altair FEKO's Multi-Level Fast Multipole Method (MLFMM) was selected as it is a memory-efficient, full-wave solution ideal for electrically large structures [6]. The selected model is a compact sedan similar to the Volkswagen Polo. Only the outer body was considered in the analysis as it is the largest conducting component on a vehicle and thus has the greatest impact on antenna performance. The body was assumed to be a perfect electrical conductor. The antenna was modeled as a monopole with a length of 12.8 mm ($\lambda/4$ at 5.9 GHz).

The nominal mounting location was selected to be the current location of the Volkswagen Polo's radio antenna. The antenna pointed rearwards at an angle of 45° above the horizontal. The simulation concluded after six minutes on two cores. A "dead zone" was observed in the front of the vehicle where directivity levels are at or below -5 dB (Fig. 1.A). This would result in a lower bit error rate in the front of the vehicle, requiring signal amplification. If allowed for by the design, alternative antenna mounting locations can be considered.

III. Optimization Method

Optimization can result in better solutions than a "guess-and-check" method, and often does so in less time. The optimization process was driven by Altair's HyperStudy [7], which ran FEKO, analyzed results, and proposed new antenna locations automatically. A Global Response Surface Method (GRSM) was selected as the optimization algorithm. GRSM combines a response surface based optimization with a global search: a method that is efficient and robust in highly nonlinear optimization problems [8].

A. Design Variables

The following method was developed to map two, continuous design variables to an arbitrary search area on the vehicle's surface:

1. Two independent design variables (u, v) are assigned some value from a continuous range.
2. The design variables (u, v) are mapped to spherical coordinates (θ, φ) with equations 1 and 2.
3. The intersection of the meshed body and the vector (θ, φ) is calculated. Note that the origin lies inside the vehicle. If no intersection exists, return to step 1.

4. The location of the nearest node to the intersection point is considered for the next antenna position.

$$\theta = 2\pi u \tag{1}$$

$$\varphi = \cos^{-1}(2v - 1) \tag{2}$$

Equations 1 and 2 prevent point clustering for very small values of θ [9]. Proposed antenna locations are restricted to a user-defined search area to account for design constraints such as windows and panels. The search area used in this study covered half of the vehicle's roof; however, any arbitrary search area could be used, including one that encompasses the entire vehicle.

B. *Objective and Constraints*

According to [1], the far-field pattern should be most uniform in the azimuth direction at elevation angles between 80° and 96°. In this paper, we optimized only on the azimuth plane at a 90° elevation (parallel to the road). Under ideal circumstances, the far-field pattern would be a perfect circle; therefore, the average deviation from the mean directivity was selected as the objective function. This value should be minimized for improved performance. An antenna configuration with a large reflection coefficient will perform poorly, even if the resulting far-field pattern is favorable. To prevent this scenario, the reflection coefficient was constrained to be less than -6 dB.

IV. Optimization Results

The optimal antenna location was determined after 3.5 hours, requiring 20 iterations of GRSM. The optimal location is closer to the front bumper than the nominal location and lies roughly in the center of the vehicle (Fig. 1.B). The resulting average deviation from the mean directivity was reduced by 85% while maintaining a reflection coefficient below -6 dB. The average directivity in the azimuth plane was increased by 140%. The optimization was repeated with a more restrictive search area that leaves room for a sunroof. The new optimal location is off-center and shifted back towards the rear bumper. The average deviation from mean directivity is 64% lower than the nominal position but greater than that of the first optimization (Fig. 1.C). The tradeoff in antenna performance resulting from an added sunroof can therefore be quantified.

By designating the angle between the antenna and the horizontal as a design variable (α), the antenna's orientation can be included in the optimization process. The original optimization was repeated with the freedom to vary α between 30° and 90°. The optimized antenna design employed an angle of 59°, and was positioned roughly 27 mm in front of the optimal location from the first optimization (Fig. 1.D). The difference in optimal location between the two optimizations suggests that some interaction exists between antenna placement and orientation. The resulting average deviation from mean directivity was 86% lower than nominal – a marginal improvement over the fixed angle design. The reflection coefficient remained below -6 dB.

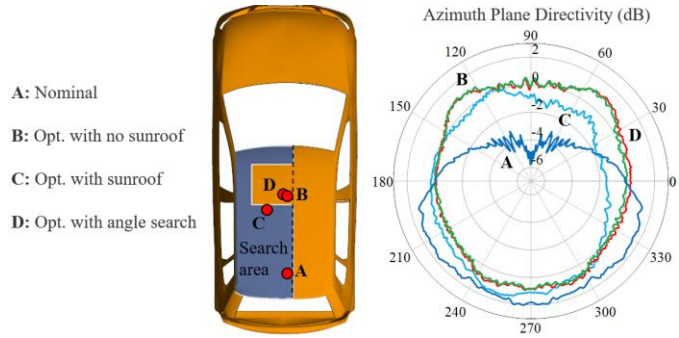

Fig. 1. The optimimal mounting location of a monopole antenna, originally mounted at (A), is shown for the following circumstances: without sunroof (B), with sunroof (C), without sunroof including antenna angle in optimization (D). The optimized far-field patterns are more uniformly distributed than the nominal, resulting in improved V2V system performance.

TABLE I. ANTENNA PERFORMANCE COMPARISON

Run	Reflection Co. (dB)	Avg. Deviation from Mean Directivity (dB)	Pct. Change in Objective
A	-12.8	2.21	-
B	-10.8	0.34	-85%
C	-11.4	0.79	-64%
D	-6.03	0.32	-86%

V. Summary

The placement and orientation of an antenna mounted atop a vehicle have a significant impact on the performance of the communication system. High frequency electromagnetic simulation is an effective way to predict the performance of V2V systems early in the design cycle. Response surface based optimization algorithms can be used to optimize the antenna's placement and orientation, resulting in improved far-field patterns. Though presented for V2V systems, this method could be applied to other applications.

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