

Design of a 5.9 GHz High Directivity Planar Antenna Using Topology Optimization for V2V Applications

Aseim Elfrgani and C. J. Reddy
 Altair Engineering

ABSTRACT

A low profile high directivity antenna is designed to operate at 5.9 GHz for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications to ensure connectivity in different propagation channels. Patch antennas are still an ongoing topic of interest due to their advantages: low profile, low cost, and ease of fabrication. One disadvantage of the patch antenna is low directivity which results in low range performance. In this paper, we introduce an efficient and novel way to improve the directivity of patch antenna using topology optimization and design of experiments (DoE). Numerical simulations are done using Method of Moments (MoM) technique in the commercially available tool, FEKO. We use global response surface method (GRSM) for double objectives topology optimization. Numerical results show a promising use of topology optimization and DoE techniques for the systematic design of high directivity of low profile single element patch antennas. The optimized directivity is 10.4 dBi, which is 3 dB higher than the directivity of the original patch antenna.

CITATION: Elfrgani, A. and Reddy, C., "Design of a 5.9 GHz High Directivity Planar Antenna Using Topology Optimization for V2V Applications," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 10(1):2017, doi:10.4271/2017-01-1691.

INTRODUCTION

The road toward autonomous vehicle implementation has been closer than ever before. A simple low profile antenna for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications is needed; however, the necessity of high directivity antenna should be considered to ensure connectivity in different propagation channels. Although patch antennas have been introduced long time ago, they are still an ongoing topic of interest due to their advantages: low profile, low cost, and ease of fabrication. One of the disadvantages of the patch antenna is low directivity which results in low range performance. The directivity of conventional single element microstrip patch antenna is around (6-7dBi). The radiation pattern of the resonant single patch antenna is directed in the broadside.

One way to increase the directivity is to design an array of microstrip patch elements; however, designing an array of elements require feeding network which might complicate the design and occupy more design space. There are several techniques are appearing to improve the directivity of the patch antennas. These techniques can be classified in: 1) use of stacked patch [1-2], 2) use of fractal boundary [3-4], 3) incorporate of metamaterials in the substrate [5-6], and 4) optimize the shape of the patch [7]. In this paper, we introduce an efficient way to improve the directivity of patch antenna using topology optimization and design of experiments (DoE). Although the term "Topology optimization" has been used recently in the electromagnetic field, it has become very popular in structural analysis and design field. Topology optimization is a mathematical approach that optimizes material layout within a given design space, for a given set of constraints such that the resulting layout meets a

prescribed set of performance goals. The common way of carrying out topology optimization is through the material distribution approach, in which the design domain is divided into small elements, which together represent an image of the device. A design variable is assigned to each element to indicate presence or absence of a material. Using topology optimization, engineers can find the best concept design that meets the design requirements. Topology optimization can also be defined as the process of determining the connectivity, shape, and location of voids inside a given solid design domain and is often understood as determining the best material distribution [8]. This allows for greater design freedom when compared to the size and shape optimization, which deal with variables such as thicknesses or cross-sectional areas of structural members (sizing) and geometric features (shape) of predefined geometry. In electromagnetics, there has been an overlap in the usage of right term of the shape and topology optimization. However, still, there have been several publications of the use of topology optimization in antenna design [9, 10, 11]. In general, genetic algorithm (GA) has been widely used for the shape and topology optimization [12, 13, 14]. In this paper, we propose to use Global Response Surface Method (GRSM) which usually requires less time to obtain the optimized goal compared to GA. To apply topology optimization, the patch is divided into 12×12 square cells. To reduce the further optimization time, DoE is incorporated in the design process. To the best of our knowledge, this the first time GRSM and DoE have been applied to an electromagnetic problem. Designs are simulated in Hyperworks/FEKO 14.0 suite [15] in combination with Altair HyperStudy 14.0 [16] to perform the optimization on the binary design variables.

The rest of the paper is organized as follows: section on antenna structure and analysis; another section introduces topology optimization with a subsection about the optimization method; namely, global response surface method (GRSM), and design of experiments (DoE). Numerical results are discussed including the optimization using GRSM, GA, and DoE and GRSM. Finally, a discussion section is included to conclude the findings of this paper.

ANTENNA STRUCTURE AND ANALYSIS

A square patch antenna is designed such that the shape of the rectangular patch is modified in order to improve the directivity keeping the physical volume of the antenna constant. The patch area is fixed to be 3.39 cm X 3.39 cm. The substrate has a thickness of 1.34 mm and 2.2 relative permittivity and 0.004 loss tangent. The microstrip patch antenna (shown in [figure 1](#)) is analyzed using the commercial software FEKO 14.0 using MoM solver. [Figure 2](#) shows the antenna reflection coefficient over a wide frequency band. As it can be seen, the first resonance is at 2.9 GHz, and the first higher order mode is around 5.9 GHz. The radiation patterns of patch antenna at the first resonance and first higher order mode are shown in [figure 3](#). The directivity of the fundamental mode is around 7 dBi directed to the broadside; whereas the directivity is 5 dBi at the higher order mode directed far away from the broadside.

As stated in the introduction, the directivity can be increased using an array of elements, but that requires feeding network, which can add complexity to the design and require extra design space as well. In this work, the antenna is optimized at the first order higher mode to increase the directivity since the antenna supports higher directivity at the off-broadside directions and not at the broadside as required.

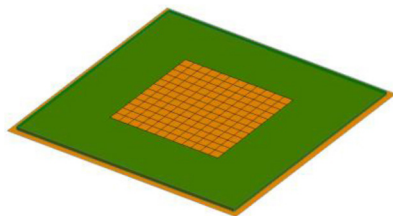


Figure 1. Low profile microstrip patch antenna discretized into 144 square elements.

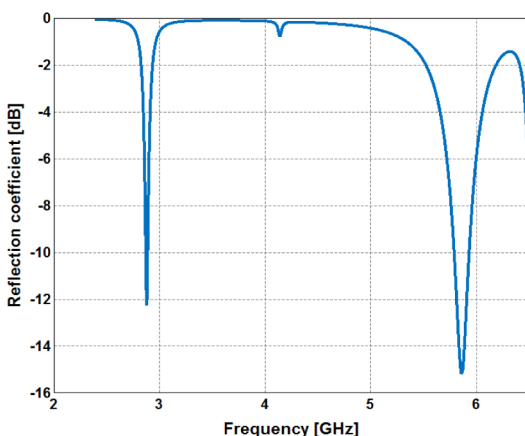


Figure 2. Reflection coefficient of the microstrip patch antenna shown in [Figure 1](#).

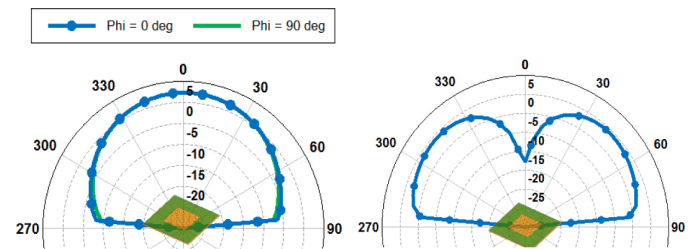


Figure 3. Antenna Radiation pattern (a) fundamental mode 2.9 GHz. (b) first higher order mode 5.9 GHz.

TOPOLOGY OPTIMIZATION

To apply topology optimization, the design space is divided into small elements. The design space can be any structure that needed to be optimized for certain pre-defined goal. Small elements can be a surface (e.g., rectangular, triangular, curved surface, or a combination of two or more element types) or solid (e.g., cuboid, cylinder, and so on). Here, the microstrip patch antenna ([Fig 1](#)) is pixelized into 144 (12×12) square elements. Each small element (e.g., square element) is set to be a design variable that can be either a logic 1 or 0 to indicate presence or absence of a material (e.g., metal in this particular case). The design variables are 146 including the position of the pin feed for the patch antenna. We applied two axes of symmetries reducing the design variables to 38. However, this can reduce the degree of freedom for the optimizer to achieve possible optimum outcomes. The optimization algorithm steps are then used to remove some of the metallic cells. Although maximizing the directivity is the main objective of this work, maintaining low reflection coefficient is also another necessary objective. Multi-objective optimization algorithm solves this problem by exploring the design space to locate the section of the design space that is Pareto optimal: the idea is that one objective cannot be made better without making another worse. The constraints are to keep the reflection coefficient small, and maintain constant relative dielectric and physical volume. The optimization method; namely, global response surface method (GRSM) is proposed to perform the optimization.

Global Response Surface Method

To perform a topology optimization, a suitable optimizer/algorithm needs to be used. In this paper, we proposed the use of the global response surface method (GRSM), since it requires less computation resources compared to the other methods. Response surface methodology is an approach to optimization that was developed in the 1950s [17]. Gary Wang *et al.* were the pioneer to publish the adaptive response surface method in their informative paper [18]. GRSM is a global adaptive response surface method that works by internally building response surfaces and adaptively updating them as new evaluations are available to have a better fit of the model. Additional evaluations are generated globally to ensure a good balance of local search capability and global search capability. The response surface built is higher order regression polynomials. It finds the optimum on this surface and validates it with the exact simulation. If the response values from the response surface and the exact simulation are not close; GRSM updates the surface with the new evaluation and finds the optimum in the updated surface. GRSM repeats this loop until it meets one of the convergence criteria; as in