mm-Wave Antenna Array Modeling for Autonomous Vehicle Radar Applications

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Abstract— The emergence of the Internet of Things technology is driving the development of several large cities around the world. In line with these incentives is the increasing demand to study the advent of autonomous vehicles that will drive the need for multiple sensors, spanning microwave and millimeter wave radars, as well as visible and infra-red spectra. In this work, the design and optimization of mm-wave printed antenna array for autonomous vehicle radar application at 77GHz is demonstrated. The simulated subarray bandwidth is more than 5GHz with half-beamwdith of 5 degrees (Vertical) and 60 degrees (Horizontal). In addition, modeling the installation effects of the radar sensor including the defocusing effect of bumpers, fascia and grills is also illustrated. Finally, the radar system performance is tested in terms of a series of range-Doppler maps for a realistic street intersection scenario with typical road objects, like cars, and well identified through their differences in distance from the radar and their velocities relative to the radar.

***Index Terms*—Internet of Things, Smart Cities, Street Intersection, mm-Wave Antenna Array, Radar, Autonomous Vehicles, ADAS, Range-Doppler maps.**

I. Introduction

Large cities around the world are now considered as innovation hubs and are developing quickly into what so called the connected smart cities. The number of smart cities is expected to grow exponentially over the next few years and by 2050, 70% of the world's population will be living in smart cities. Not only the city street's infrastructure will have an impact on the future of smart cities but the idea of using transportation infrastructure to help monitoring, analyzing and optimizing the backbone of the smart city and deliver tangible benefits in understanding the surrounding environment.

Hence Vehicle to Vehicle communications technology was introduced to enable sharing data via wireless networks including speed, location, direction of travel, braking and loss of stability [1]. The goal is to estimate the maximum range across which the vehicles can reliably communicate using the Dedicated Short-Range Communications (DSRC) protocol operating at 5.9GHz. DSRC Antennas are designed to cover a range up to 300 meters or 1000 feet. Ceramic patch antennas are usually used for emerging V2V & V2X applications [2].

Exploring the bigger picture of intelligent road transportation will also include the vehicle to infrastructure communication [3]. With that, all vehicles and street infrastructure systems will start interacting with each other and passing along messages regarding road conditions and traffic flow. This connectivity will help building precise knowledge of traffic situation across the entire network that helps reducing traffic congestion, cut accident numbers and that will influence positively the level of automotive safety.

Establishing a complete dynamic traffic information system can improve the overall city traffic coverage and performance while reducing the number of accidents and consequently the number of people injured at roads. Many roads and driving assistance systems such as navigation systems have been around for long time and have already proven to result in improved driving experience as well as better overall road safety but that still didn't stop car accidents from happening especially in harsh weather circumstances like heavy rain or during snowstorms [4].

The advent of autonomous vehicles will drive the need for multiple sensors, spanning microwave and millimeter wave radar, as well as visible and infra-red spectra. ADAS and Autonomous vehicle systems are likely to require at least 6 radar systems to monitor traffic and to perform safety functions to ensure the safety of the passengers. These safety systems will be effective and efficient, giving autonomous and human-drive vehicles instantaneous reflexes to react to sudden and unanticipated dangers and to take evasive action [5]. In addition, radar sensors are likely to have a significantly higher degree of functionality, with ability to image the road scene, detect and track objects and obstructions, and to locate safe paths through unfolding hazards. In addition, these radars will be able to monitor road conditions—even locating and reporting potholes and debris on the road [6].

The represented work will demonstrate the design flow of a 77GHz antenna array system for Autonomous Vehicle Radar Applications. Section II will illustrate the antenna array design and optimizations. In Section III, authors will explore some engineering design challenges using ANSYS for modeling radar sensors in a realistic road scene. Finally, Section IV will summarize the presented work and apply the scope on future work.

II. MM-WAVE ANTENNA ARRAY MODELING FOR AUTONOMOUS VEHICLE RADAR APPLICATIONS

Recently, the development of automotive radar sensors is mainly focusing on allocating frequency bands of 76–77 GHz for long-range radar (LRR) [7] and 77–81 GHz for short-range radar (SRR) [8]. Antenna design and modeling is usually the key component for this type of applications since it can influence the overall radar system performance in terms of detection resolution and range as well as cost and size. It is crucial to design a compact antenna array that can be attached to the vehicle's bumper without the need of any manufacturing design changes.

A. Single Element Patch Antenna Design

Both printed patch and lens antennas were reported to be used for this type of applications for their compact size advantages. Several series fed microstrip patch antenna arrays were utilized and designed to work with Rotman lens and MEMS RF switches to change the angular coverage of the radiation pattern [9-11]. In this work, a new approach of parallel fed multi-layered edge probe fed patch antenna array design is implemented. The design of the single element patch antenna is shown in Fig. 1. A rectangular patch antenna is designed to operate at 77GHz with a bandwidth of 5GHz. A CPW line was used to feed this antenna since it enhances the overall antenna radiation performance compared to microstrip feeding for mm-wave frequency range.

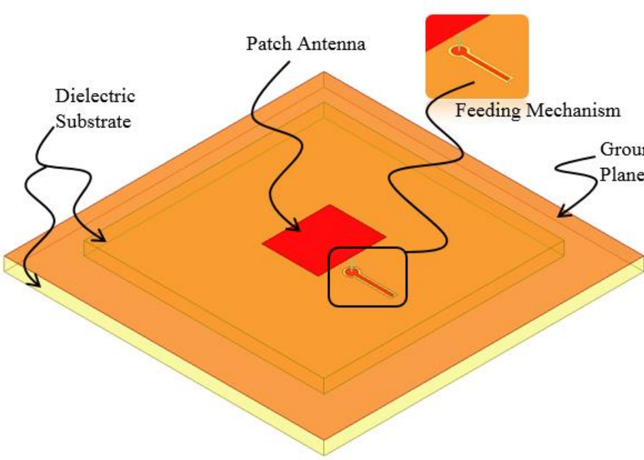
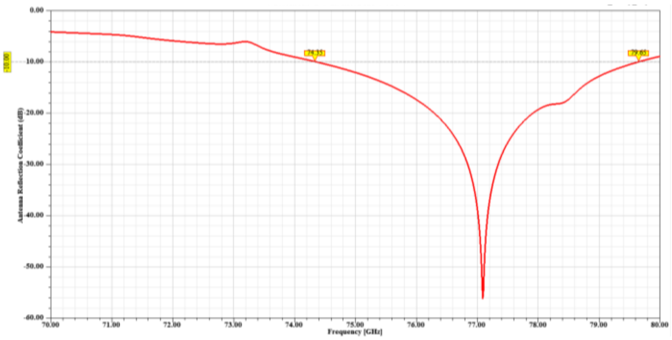


Fig. 1. Proposed Probe-CPW Fed Patch Antenna simulated geometry.

Both simulated antenna reflection coefficient and far field gain patterns are show in Fig. 2 using ANSYS HFSS [12].



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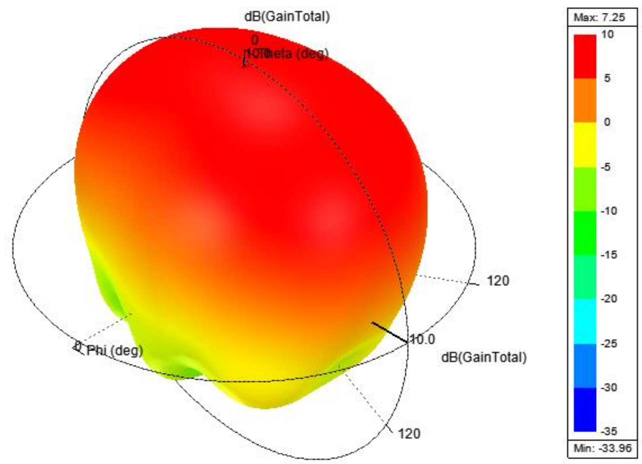


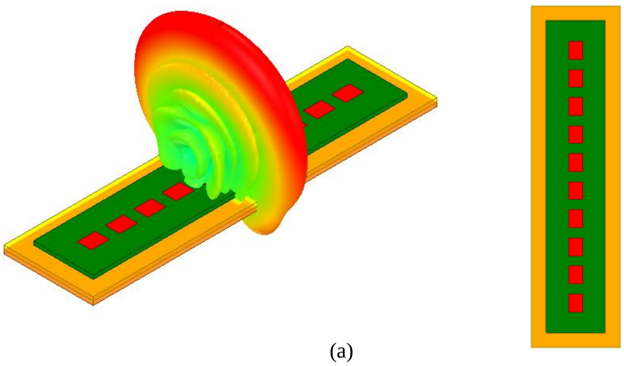
(b)

Fig. 2. (a) Proposed patch antenna reflection coefficiet, (b) far field 3D polar gain plot.

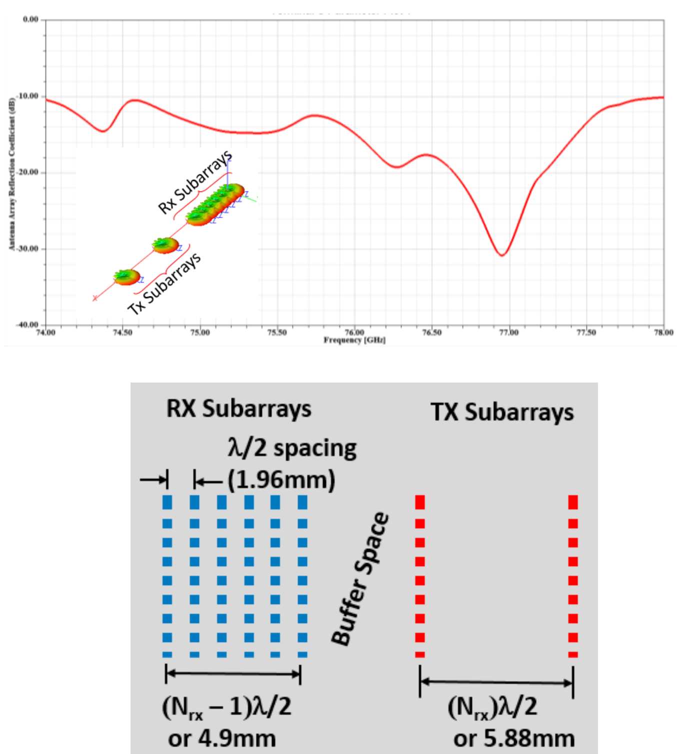
B. Antenna Sub-Array Design for Autonomous Radar Applications

A good radar system design begins with the antenna array which must tightly control the distribution of radiation energy, focusing it on the areas of the road under observation and minimizing energy broadcast to locations that are not of interest to the sensor. Thus, it is very important to accurately build a very well synthesized and optimized radar arrays then evaluated their performance in a virtual prototyping environment that is highly precise. The proposed radar antenna array is composed of both TX and RX subarrays. Each subarray is made of 10 antenna elements as shown in Fig. 3(a). The goal is to implement a radar antenna array design for a front-mounted medium-range 77 GHz radar system, capable of monitoring forward traffic and objects within a distance of 50m, with object location accuracy of 0.1m and object velocity measurement precision of 0.2 m/s.

Fig. 3(b) illustrates the patterns of the Tx/Rx Subarrays with their specifications. The subarray was optimized to achieve 5De vertical beam-width and 60 Deg horizontal beam-width as show in Fig. 3c. The achieved sub-array matching bandwidth is around 4GHz which covers the frequency range of interest.



(a)



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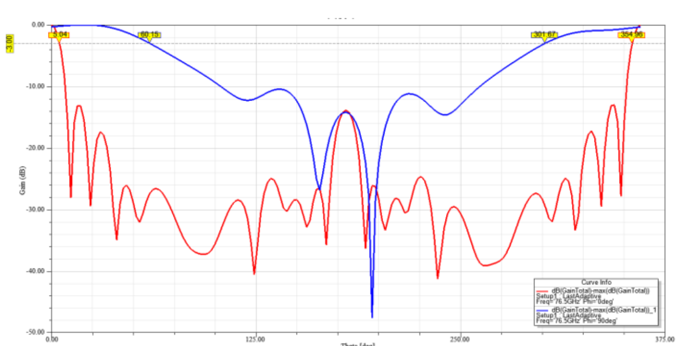

(c)

Fig. 3. (a) Sub-array modeled geometry with ANSYS HFSS [12] and simulated 3D polar total gain, (b) Sub-array antenna reflection coefficient and TX/RX subarrays configurations, (c) Far field gain pattern with vertical and horizontal beam-width at 76.5GHz.

III. Engineering Challenges for Modeling Autonomous Vehicle Radar Sensors

Once a sensor design has been done, it can then be placed on a virtual vehicle, in a virtual world and evaluated as a complete radar system. The ANSYS HFSS SBR+ [12] provides an advanced shooting-and-bouncing ray analysis technique that evaluates the performance of a radar in the presence of an extended road containing vehicles, stationary objects, and other structures found on a road scene to test the signals and target indications that would be returned by a sensor design. This is a powerful technique for evaluating radar performance in a complete simulation loop involving the radar sensor, detection algorithms, advanced safety systems, vehicular control systems and vehicle dynamics. ANSYS HFSS [12] can be used to model the installation effects of the radar sensor, including the defocusing effect of bumpers, fascia and grills as shown in Fig.4.

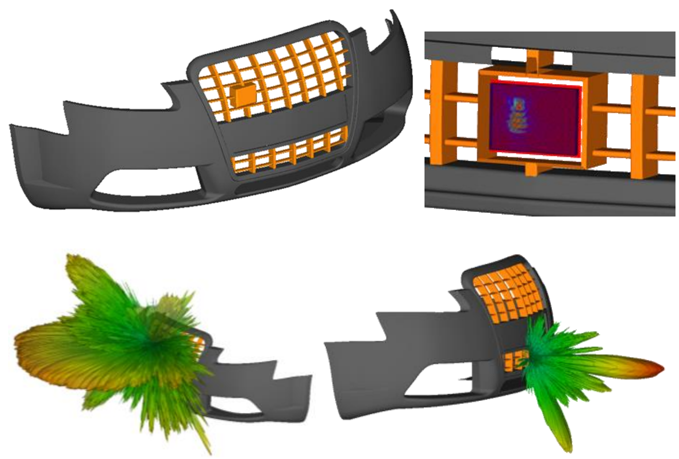

Fig. 4. Implemented radar array installation on front car bumper. Far field TX/RX subarray patterns installed performance.

Analysis of the radar module and its installation location can affect the radar's ability to detect the direction of an object, as well as to reduce the radar's sensitivity to objects that are more difficult to detect. Factors such as bumper material composition, paint and lacquer layers, and weather effects like rain, ice, dust and mud can be evaluated for their impact on the radar's performance. Fig. 5 demonstrates the use of ANSYS HFSS SBR+ in modeling complex and realistic road scenes with unmatched efficiency. In this simulation, each radar pulse can be simulated in a few minutes on a typical laptop computer.

A single pulse in the simulated radar can be used to identify the presence of targets as a function of distance from the radar as shown in Fig. 5. This result was produced in under 2 minutes using a laptop computer for a long-range radar design evaluation. Strong radar returns are shown from the back of a car that is 27m in front of the radar, and the plots show that physical radar returns are extended in nature—occupying several range cells in the radar range profile.

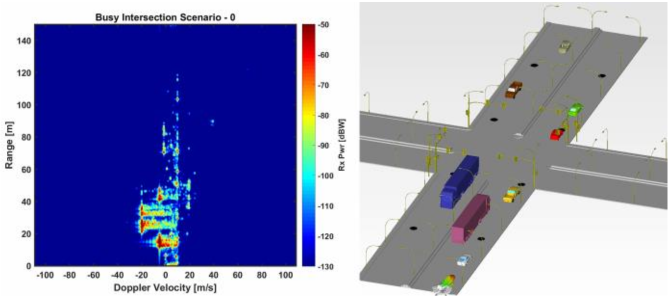

Fig. 5. Complex street intersection implementation with ANSYS [12].

Longer vehicles create returns which are longer in the range axis, occupying more of the radar's range bins as illustrated in Fig. 6. Most vehicles are longer than the radar's range accuracy, and it is useful in active safety situations to know the length of given vehicle in the road. ANSYS HFSS SBR+ provides highly realistic radar signatures of objects observed by the radar. Access to such modeling provides the radar systems and sensor systems engineer with insight into the radar's full capability, and to consider tradeoffs to the radar signal processing, target tracking and vehicle control systems.

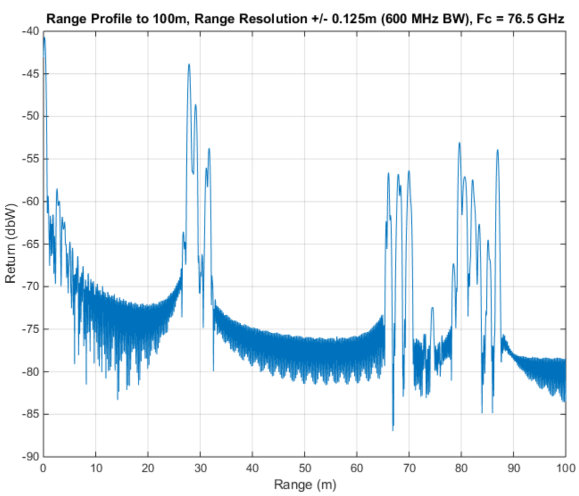

Fig. 6. Radar Range profile and scattering centers.

IV. Conclusion

Probe-CPW fed patch antenna at 77GHz was demonstrated in this paper for automotive radar applications. Modeled TX/RX radar arrays were designed and simulated using ANSYS. The obtained radar system array showed sufficient radiation characteristics as well as wide impedance matching bandwidth of 5GHz. Moreover, the array was installed on a realistic front car bumper and in a complex road scene scenario. Radar signatures were studied and radar range profile and doppler maps were obtained for further virtual prototyping tests.

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