Analysis and Design of the Switched-beam Antenna Array for Automotive Radar Applications

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Abstract— More and more vehicles equip with millimeter-wave radar systems to improve the driving safety. Usually, multiple antenna arrays are used to cover different horizontal field of view (FOV) for most models. Integration is one way to make the automotive radar system more compact and more affordable. A three-mode antenna array is designed to cover narrow ($-8°$ to $+8°$), wide ($-45°$ to $+45°$), and two-direction ($-75°$ to $-45°$ and from $+45°$ to $+75°$) FOV scenarios. The horizontal FOVs of a typical long-range radar (LRR) and short-range radar (SRR) cover from $-8°$ to $+8°$, and from $-45°$ to $+45°$, respectively. For the front-end blind side detection, the two-direction FOV covers from $-75°$ to $-45°$ and from $+45°$ to $+75°$, which are often blocked by the vehicle front pillars. Thus, this system can provide a total 150° FOV coverage. Based on these FOV requirements, a switch-beam antenna array is proposed, which is based on the minimum variance distortion less response (MVDR) beamforming algorithm. The simulation demonstrates this antenna array can operate not only over the narrow, wide, and two-direction FOV scenarios, but also wide bandwidth (76 to 81 GHz).

1. INTRODUCTION

In recent years, more and more high-end or safety-oriented automobiles equip with the millimeter-wave (mm-wave) automotive radar systems as a standard safety feature. The automotive radar systems can provide various active and passive safety features, such as adaptive cruise control (ACC), blind side detection, and pre-crash sensing and so on [1–3]. These automotive radar systems can alert and assist drivers to avoid possible impacts and stay away from the potential dangers, and some systems even response automatically to dangerous situations in a short time. If all cars equipped with automotive radar systems, this could reduce traffic accidents, which are due to drivers' errors, misjudgments, and bad driving behaviors. This will not only enhance drivers' and passengers' safety, but also improve road safety for all road users. However, the price of the automotive is still not affordable for every model and everyone. If a car buyer wants to enjoy all possible safety benefits as mentioned in [1–3], he will need multiple automotive radar modules to have a 360° radar protection, as shown in Fig. 1. This will cost the vehicle consumer even more.

To make the automotive radar modules affordable, one way is to use less separated modules, and do more integrations. This paper will analyze the automotive radar system first to understand the limitations, and discuss the possible strategies to integrate more modes. Finally, a three-mode switched-beam antenna array will be proposed to cover the narrow, wide, and two-direction field-of-view (FOV) objectives, and also 77/79 GHz automotive radar bands.

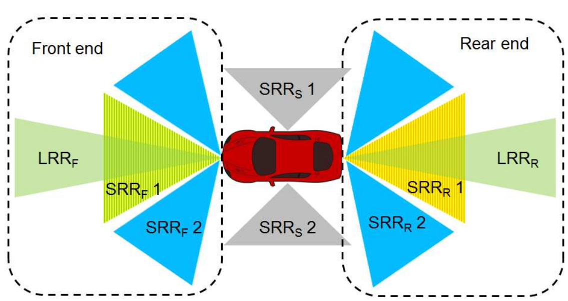

Figure 1: A 360° radar protection with LRRs and SRRs.

2. SYSTEM ANALYSIS

A typical FMCW (frequency-modulation continuous wave) automotive radar system is shown in Fig. 2. The advantages of FMCW radars in comparison to pulse radars are the low measurement time and low peak-to-average power ratio. Note that low measurement time is the key to integrate more radar modes together and this will be discussed later. The system usually consists of 1-transmitter and N-receivers [3–5]. Note that N is the number of the radar receiver chains. The N-receivers make the target angle detection possible through the spatial signal processing. The baseband signal processor controls the PLL/synthesizer and VCO to generator desired FMCW waveforms, and the signals will be amplified by PA and transmitted through the antenna.

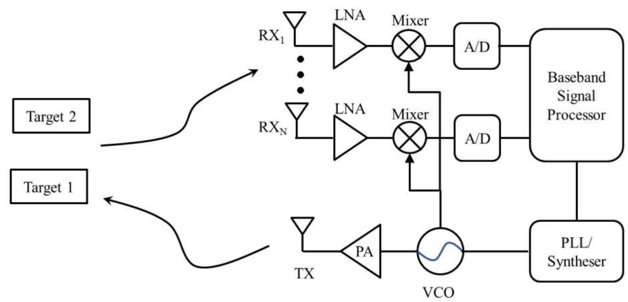

Figure 2: A typical FMCW automotive radar system.

The proposed 360° radar protection with LRRs (long-range radars) and SRRs (short-range radars) is shown in Fig. 1. There are one LRR (LRR_F) and two SRR (SRR_F1 and SRR_F2) for front-end detections, and these can also be applied for the rear-end detections. Moreover, there could be some (SRRS1 and SRRS2) for side detections. The LRR operates at 76–77 GHz and detects the range up to 200 $\sim$ 250 meters. A SRR operates at 77–81 GHz. A SRR provides wider coverage and higher range resolution than a LRR [1–3]. Many papers and products have talked about integration of LRR_F and SRR_F1. This paper focuses on a three-mode (LRR_F, SRR_F1 and SRR_F2) automotive radar system for a total 150o front-end protection. SRR_F2 is very important for the front-end blind side detections, which are often blocked by the vehicle front pillars. This is extremely helpful for the driving situations like leaving the perpendicular parking spots, exiting the narrow streets, and driving in the winding mountain roads, etc.

For RF circuits (LNAs, VCO, PAs, mixers, etc.), many researchers make the RF circuits feasible to work well over the operation band (76–81 GHz) [3–5]. For antenna designs, the challenges are not only to cover the wide operation frequency, but also the different horizontal FOV requirements, as shown in Fig. 1. In compared to a wide operation frequency, it is more challenge to design multiple FOV modes. Thus, there are usually two specific antennas for LRR and SRR applications, respectively. Some are even applied a lens antenna to achieve a narrow FOV requirement for a LRR [3, 6]. However, the temperature variations could have a big impact on the lens antenna characteristics. If one array is able to generate multiple FOVs, it will not only avoid extra packages, such as dielectric lens, but also reduce the module size. This will make the automotive radar more affordable.

Assume that a FMCW radar system is applied. Because LRR and SRR share the same RF circuits (Fig. 2), each possible radar operation mode should run in sequence. Thus, the total observation and processing time of all radar operation modes should be much less than the human's potential brake response time (PBRT) [10]. According to [7, 8], the transmitted FMCW signal $S_T(t)$ can be modeled as

$$S_T(t) = A_T \cos\left(2\pi f_c t + 2\pi \int_0^t f_T(\tau) d\tau\right). \tag{1}$$

where $f_T(\tau) = \frac{B}{T} \cdot \tau$ is the transmit frequency as a function of time, f_c is the carrier frequency, B is the bandwidth, A_T represents the transmitted signal amplitude, and T is the time duration. From [8] and [9], the bandwidth B is related to the given range resolution ΔR and can be formulated as

$$B = \frac{c}{2\Delta R}. \tag{2}$$

Similarly, the observation time T is related to the velocity resolution Δv and can be expressed as

$$T = \frac{c}{2 f_c \Delta v}. \tag{3}$$

From Equation (3) and [9], the total period of operation modes will be tradeoffs among a velocity resolution, a radar waveform design, the capability of a baseband processor, the number of possible operation modes, etc. As mentioned earlier, in compared to pulse radar, the low measurement time of FMCW radar could accommodate more radar modes in the same period. Since the number of radar operation modes, which run in sequence, is limited, one possible solution is to divide modes for different driving situations. For example, if cars are running in the high way, the $\mathrm{LRR_F}$ and $\mathrm{SRR_F1}$ modes will be activated; if cars are running in the community, mountain road or parking lot, the $\mathrm{SRR_F1}$ and $\mathrm{SRR_F2}$ modes will be activated. This will allow more integration in a system.

3. BEAMFORMING ALGORITHM AND SIMULATION RESULTS

Here, the minimum variance distortionless response (MVDR) beamforming algorithm [10] is applied. For this automotive radar system, the horizontal FOV of $\mathrm{LRR_F}$ is $-8°$ to $+8°$, the horizontal FOV of $\mathrm{SRR_F1}$ is $-45°$ to $+45°$, the two-direction FOV of $\mathrm{SRR_F2}$ is $-75°$ to $-45°$ and $+45°$ to $+75°$, respectively. The several characteristics of MVDR will be utilized to obtain the array weights for different scenarios. Assume that a six-element uniform linear array (ULA) is applied. Six-element array matches to the receiver chain design in [4]. The separation of each element is $\lambda/2$ at 79 GHz and this will make the 77–81 GHz design easier. The radiation pattern of each array element is assumed as $|\cos(\theta)|$, which is close to a typical patch antenna [11]. When the radar system switches modes, the number of array elements will be selected, and the pre-derived beamforming weights will be employed. The broadside is 0o, and the endfire is $\pm 90°$.

MVDR is well-known that it can suppress the uncorrelated interference well [10]. This will be applied to narrow the mainlobe to meet the small FOV requirement of LRR. Assume that the desired signal is at 0° and two interferences are at $-15°$ and $+15°$, respectively. Fig. 3 is shown the normalized pattern at 76 and 77 GHz, respectively. The 3-dB mainlobe is well confined between $\pm 8°$, and the sidelobes are less than -13 dB.

MVDR is also well-known that it cannot suppress the correlated interference [10]. Thus, assume that the desired signal and the correlated signal are at $-15°$ and $+15°$, respectively. The angles can be tuned around to meet the wideband operation. Fig. 4 shows the normalized pattern of $\mathrm{SRR_F1}$

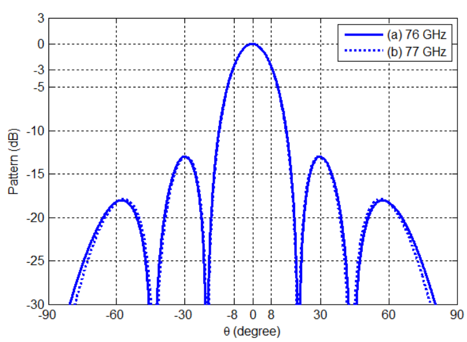

Figure 3: Horizontal pattern for the LRR application.

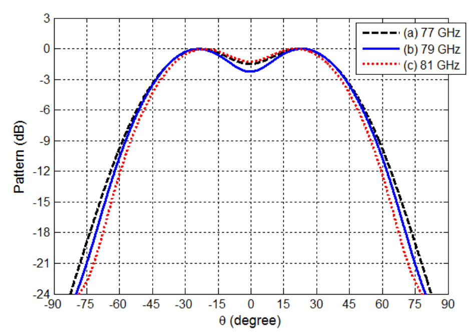

Figure 4: Horizontal pattern for the $\mathrm{SRR_F1}$ application.

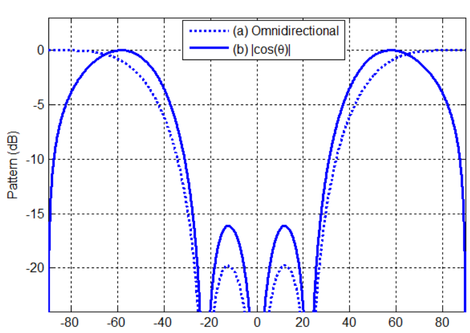

Figure 5: Horizontal pattern for the $\mathrm{SRR_F2}$ application with omnidirectional and $|\cos(\theta)|$ element patterns.

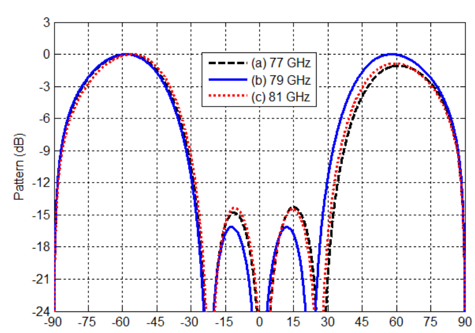

Figure 6: Horizontal pattern for the $\mathrm{SRR_F2}$ application.

application at 77, 79 and 81 GHz, respectively. The 3-dB beamwidths are all between ±45°. Here, the number of array elements is three to have a wider beamwidth by utilizing less array elements.

While the beam is steered to around the endfire, the beam broadening effect will be seen [11]. If the omnidirectional pattern of each array element is applied, the pattern will be like the dash line in Fig. 5. Because the pattern of each array element is assumed as $|\cos(\theta)|$, the overall beam pattern [11] will be shaped as the solid line in Fig. 5. This makes it possible to generate two mainbeams close to endfire. Assume that the desired signal are at +90°. To suppress the sidelobes, two interferences are set at −20° and + − 20°. Fig. 6 shows the normalized pattern of $\mathrm{SRR_F}2$ application at 77, 79 and 81 GHz, respectively. The 3-dB patterns are all between about −75° to −45° and +45° to +75°, and all sidelobes are less than −15 dB. Here, the number of array elements is four.

4. CONCLUSIONS

The proposed three-mode automotive radar system is intent to cover narrow (−8° to +8°), wide (−45° to +45°), and two-direction (−75° to −45° and from +45° to +75°) FOV scenarios. Instead of applying complex multi-beam beamforming algorithms, several properties of MVDR beamforming are utilized to narrow the mainlobe beamwidth, broaden the mainlobe beamwidth, and even create two mainlobes. The simulation results demonstrate that the three-mode automotive radar system is able to cover the desired FOVs and 77/79-GHz radar bands. Only one set of antenna array and one set of RF circuits are needed for this system. This highly integrated system will not only lower the cost, but also provide more added value for auto customers.

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