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Estimation of Detection Performance for Vehicle FMCW Radars Using EM Simulations

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Abstract

This paper proposes a systematic method for estimating detection performances of a frequency-modulated continuous wave radar using electromagnetic simulations. The proposed systematic method includes a radar system simulator that can obtain range-Doppler images using the electromagnetic (EM) simulations in conjunction with a test setup employed for performance evaluation of multiple targets at different velocities in a traffic environment. This method is then applied for optimizing the half-power beamwidths of the antenna array using an evaluation metric defined to improve the detection strengths for the multiple targets. The optimized antenna has vertical and horizontal half-power beam widths of 10° and 60°, respectively. The results confirm that that the proposed systematic method is suitable to improve the radar detection performance with the enhanced radar-Doppler images.

Key Words: FMCW Radar, Radar Performance Estimation, Vehicle Antenna.

I. INTRODUCTION

Recent radars are frequently used in vehicles with other sensors to assist the driver in obtaining information about the driving environment, which includes pedestrians, traffic lanes, other vehicles, and traffic sign recognition [1, 2]. In particular, frequency-modulated continuous wave (FMCW) radar systems have often been used as main sensors in various automotive radar applications because of their low cost, simple implementation, and high reliability in harsh weather conditions [3]. The FMCW radar system usually consists of a radio frequency (RF) device, a signal-processing module, and an antenna array. Since the signal-to-noise ratio (SNR) significantly affects the detecting performance of the radar system, the properties of the antenna array for the radar system, such as the gain, radiation pattern, and half-power beamwidth (HPBW), should be carefully determined to maximize the strength of the signal transmitted and received through the antenna array. Thus, a systematic method for optimizing antenna characteristics of the FMCW radar is necessary to obtain the proper antenna performance in real traffic environments. However, most previous studies have focused on improving signal processing techniques and enhancing antenna gains, and in-depth studies of the radar estimation method for vehicle radars in a traffic environment have not been fully conducted yet [4, 5].

In this paper, we propose a novel systematic estimation method for the FMCW radar using electromagnetic (EM) simulations. The proposed systematic method is used to estimate detection performance based on the EM simulation in conjunction with a test setup employed for the evaluation of

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multiple targets with different velocities. In the test setup, the targets represent the surrounding objects in the real driving environment and are placed by considering the maximum detection range required for the FMCW radar. This radar system simulator is adopted to obtain range-Doppler images, which requires signal processing algorithms using data obtained from the EM simulations. In our EM simulation, the detailed antenna geometry and the targets are modeled as piece-wise mesh triangles, and the backscattered signals received by the antenna are accumulated for different frequencies. The range-Doppler images are completed by taking the two-step Fourier transform with the windowing, clipping, and filtering processes to improve the quality of the images. This systematic procedure is then applied to optimize the HPBW of the antenna array with an evaluation metric using an average and standard deviation of the detection strengths for the multiple targets. We also observe the variation of the images according to steering angles of the antenna array, and the results demonstrate that the proposed systematic method is suitable for use in estimating and optimizing the performance of FMCW radars in automotive applications.

II. PROPOSED SYSTEMATIC OPTIMIZATION PROCESS

Fig. 1 shows a flow chart of the proposed estimation method for evaluating the detection performance of an FMCW radar using the FEKO EM simulation software (Altair Engineering Inc., Troy, MI, USA). The procedure begins with modeling processes of radar targets and antennas to use in the radar system simulation, and their detailed design parameters are properly determined to improve the detection performance of the radar system. For example, if a horn antenna is used for the FMCW radar system, the width and the length of its aperture should be considered as the most important parameters for antenna characteristics, such as the gain, radiation pattern, and HPBW. In the EM simulation step, a test setup that includes targets, ground, and antenna is imported to obtain the transmitted and receive signal. The received signals for each chirp are used to calculate a range-Doppler map in the data processing step. This process is repeated to improving the detection performance of the antenna which has the optimal HPBW.

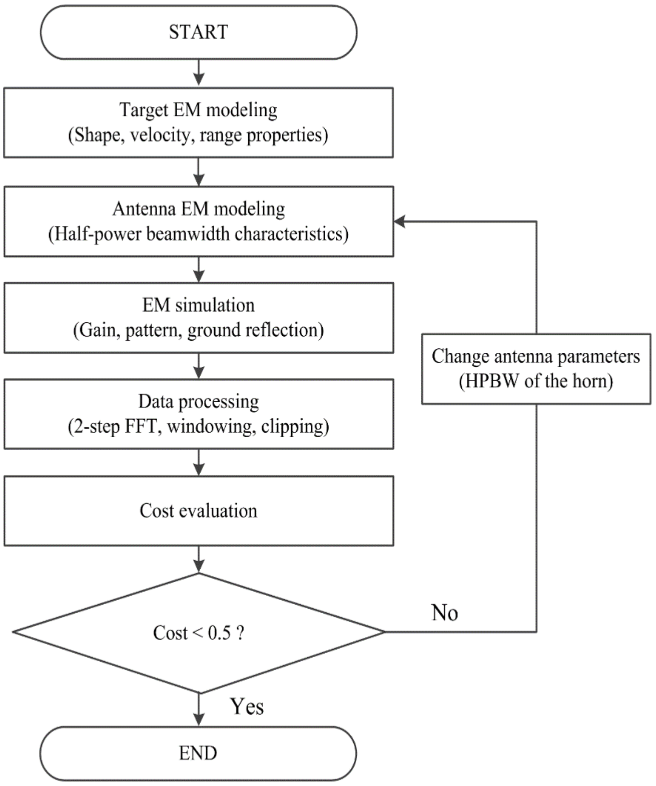
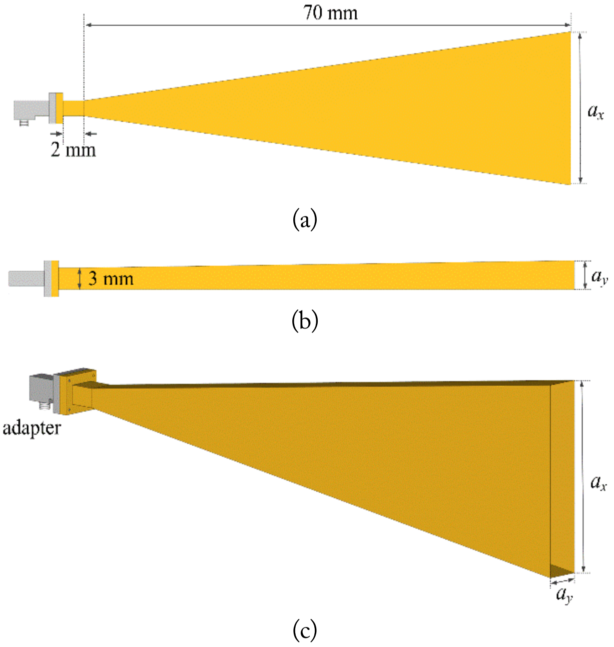


Fig. 1. Flow chart of the radar system simulator.

Fig. 2 presents the geometry of a horn antenna used in our approach. The antenna has a pyramidal shape, and the width and the height of the aperture are determined by a_x and a_y. The antenna is fed by a rectangular waveguide having a width of 3 mm and a height of 2 mm with a WR2810ADP adapter (Patentix Ltd., Ashkelon, Israel), and the total length of the antenna is about 74 mm [6]. The values of a_x and a_y are important to adjust the vertical and horizontal HPBWs as well as the boresight gain.

For example, if a_x varies from 19.2 mm to 4.1 mm, the vertical HPBW increases from 10° to 50°, and the horizontal HPBW becomes broader from 20° to 60°, when a_y is changed from 30 mm to 3.8 mm. The antenna and target models are then imported as piecewise mesh triangles, and the ground plane is assumed to be an infinite substrate with dielectric properties of $\varepsilon_r = 4.5$ and $\tan\delta = 0.97$. In the EM simulation process, the transmit antenna pattern is imported as a far-field source to



(a)

(b)

(c)

Fig. 2. Geometry of the basic pyramidal horn antenna. (a) Side view, (b) top view, and (c) perspective view.

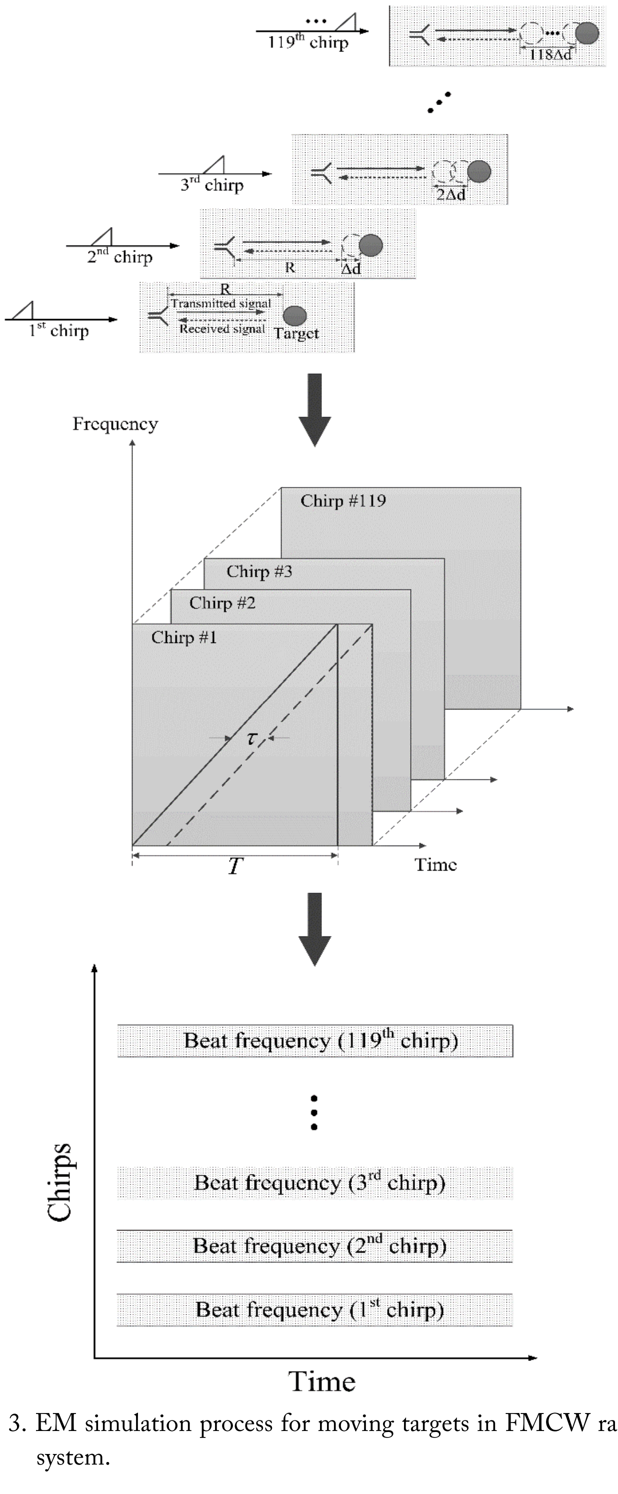


Fig. 3. EM simulation process for moving targets in FMCW radar system.

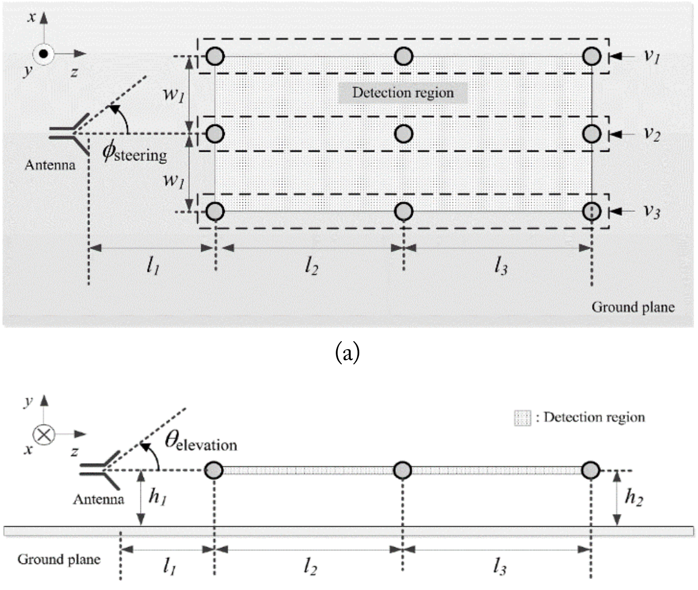
obtain the amplitude and phase information of the backscattered electromagnetic waves for every chirp duration [7], as illustrated in Fig. 3. The received signal contains the information of electromagnetic properties, such as gain of the transmitting antenna, reflectivity of targets, space losses due to target positions (R), and ground reflections. Then, the received signals are used to calculate the beat frequencies for the chirps, and these calculated data are stacked in sequence as a 2D matrix. Finally, the range-Doppler map is obtained using the matrix through the two-step fast Fourier transform (FFT), and the quality of the image can be further improved by applying the windowing, clipping, and filtering techniques [7]. It is assumed that the FMCW radar operates at a frequency of 77.5 GHz with a bandwidth of 200 MHz. The chirp duration of the transmitted signal is 33 μs, and 119 chirps are transmitted to plot range-Doppler images. At each chirp, the simulation based on the physical optic analysis is conducted at 165 frequency points, which implies a frequency interval of 5 MHz. In this case, the size of the 2D matrix with the beat frequency data becomes 165 × 119 for each range-Doppler image. Using the proposed systematic method, we optimize HPBWs of the antenna array using an evaluation metric that is defined to well visualize the multiple targets with a high average and a lower standard deviation of the target strengths as in (1).

$$Cost = c \cdot (\alpha \cdot \sigma - \beta \cdot \mu) + 1\,, \qquad (1)$$

$$\sigma = \sqrt{\frac{\sum_{k=1}^{N_{target}} (A_k - \mu)^2}{N_{target}}}, \quad \mu = \frac{\sum_{k=1}^{N_{target}} A_k}{N_{target}}\,, \qquad (2)$$

where σ is the standard deviation, and μ is the average value of the amplitude. k is an index of each target, and A_k shows the k-th amplitude of the A_k. We fixed α, β, and c as 0.02, 0.75, and 10 to obtain the positive value of the cost. The goal of 0.5 is empirically determined by the consideration of the detection performance to well visualize the multiple targets while the range and velocity property of all targets are clearly detected in the proposed system. When the cost value does not meet our goal of 0.5, we iterate this process by changing the values of the design parameters.

Fig. 4 shows the proposed test setup, which is composed of



(a)

(b)

Fig. 4. Geometry of the proposed test setup. (a) Top view and (b) side view.

Table 1. Parameters for the test setup in the detection region

Parameter	Value
v_1	10 m/s
v_2	0 m/s
v_3	–10 m/s
l_1	5 m
l_2	20 m
l_3	25 m
w_1	10 m
h_1	1 m
h_2	1 m
$\theta_{elevation}$	0°
$\phi_{steering}$	0°

one antenna and nine multiple targets. Each target has a spherical shape with a diameter of 50 mm, and the 3 × 3 targets are located in the detection region, which has a horizontal and vertical spacing of $w_1=10$ m, $l_2=20$ m, and $l_3=25$ m. The distance between the transmitting antenna and the first column targets is l_1, and a steering angle is ϕ_{steering}. The velocities of targets in the three rows, denoted as v_1, v_2, and v_3, are set differently to distinctly visualize all the targets on the range-Doppler image. The amplitudes at the target positions on the image represent the detection performance of a radar system. Note that this scenario is based on real driving environments as listed in Table 1, and thus the ground material is assumed as concrete with a relative dielectric constant of 7 and a conductivity of 0.08 S/m [8].

III. RESULTS AND ANALYSIS

To obtain the optimum HPBWs of the antenna with the improved the detection performances of the radar system, the vertical and horizontal HPBWs of the antenna are varied from 10° to 50° and from 20° to 60°, respectively. Fig. 5 presents the cost values of the radar images calculated at an interval of 10°, and the maximum value of the costs is 0.82 when the vertical and horizontal HPBWs of the antenna are 50° and 40°. The optimal vertical and horizontal HPBWs with minimum cost of 0.40 are 10° and 60°, respectively.

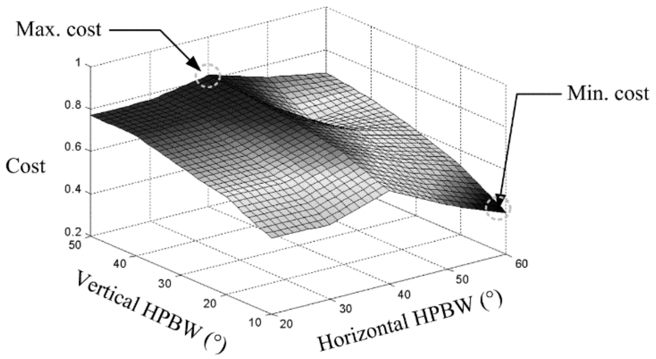


Fig. 5. 3D-plot of the costs with vertical and horizontal HPBWs.

Fig. 6 shows the comparison between the proposed antenna with minimum cost and the antenna with maximum cost. The proposed antenna, which has optimal vertical and horizontal HPBWs to improve the detection performances, is specified as the solid line with circle, and the solid line with triangle indicates the antenna with maximum cost. The bore-sight gain and HPBW of the proposed antenna are 17 dBi and 60° at 77 GHz, which are 12.4 dBi and 40° higher than greater than those of the maximum cost antenna, respectively. The comparison of the 3D radiation patterns is illustrated in Fig. 7(a) and (b). As ex-

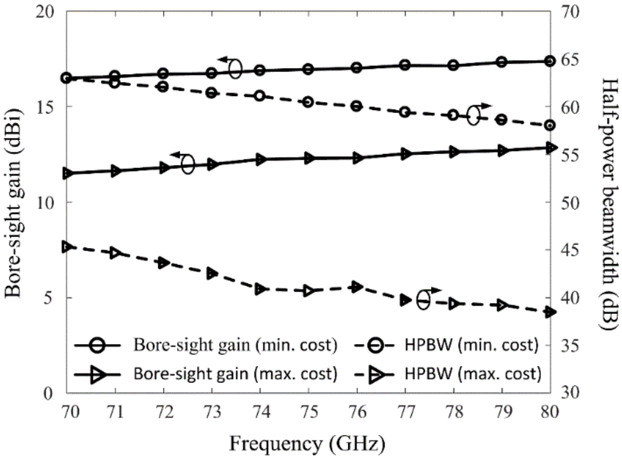
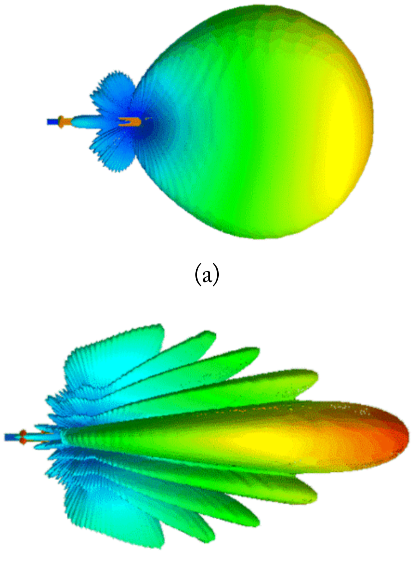


Fig. 6. Comparison of the antenna properties between minimum cost and maximum cost antennas.



(a)

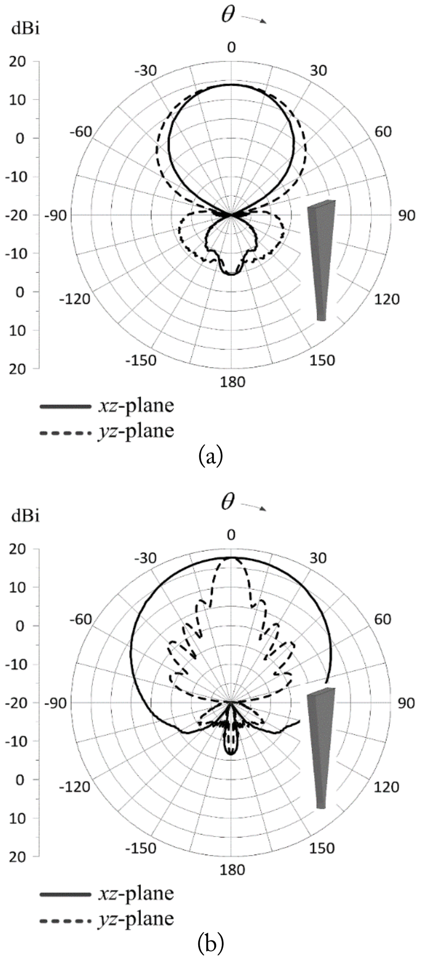
(b)

Fig. 7. Comparison of the 3D patterns of the antenna. (a) Vertical and horizontal HPBWs of 50° and 40° (max. cost antenna) and (b) vertical and horizontal HPBWs of 10° and 60° (min. cost antenna).

pected, the pattern of the proposed antenna has broader beamwidth and higher gain compared with the antenna with maximum cost in the horizontal direction (*xz*-plane).

Fig. 8(a) shows radiation patterns of the horn antenna with maximum cost, which has a bore-sight gain of 12.4 dBi and vertical and horizontal HPBWs of 50° and 40°. The HPBWs of the antenna with minimum cost are 10° and 60°, and the aperture size is 19.2 mm × 3.8 mm with the bore-sight gain of 17 dBi as presented in Fig. 8(b).

Fig. 9(a) and (b) represent the comparison range-Doppler image according to different antenna characteristics. Fig. 9(a) shows the range-Doppler image with vertical and horizontal HPBWs of 50° and 40°. The nine targets are detected separately according to their ranges and velocities, and the strengths of the targets with the velocity of 0 m/s are greater because they are placed in the main lobe direction of the transmitting antenna. On the other hand, other targets with non-zero velocities are detected with weaker strengths because the antenna gain of the side direction is lower than that of the bore-sight direction. Fig. 9(b) presents the range-Doppler image using an antenna with the optimum HPBWs. The minimum cost values result in the improvement of target strengths, especially for the boundary targets at the upper and lower rows, which is obvious when compared to the results provided in Fig. 9(a).



(a)

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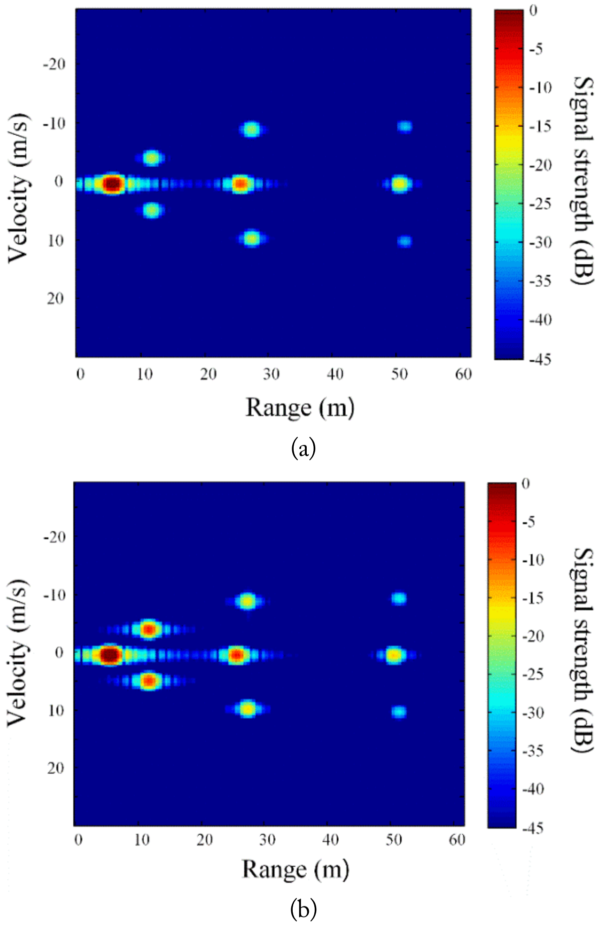
Fig. 8. Comparison of the 2D patterns. (a) Vertical and horizontal HPBWs of 50° and 40° (max. cost antenna) and (b) vertical and horizontal HPBWs of 10° and 60° (min. cost antenna).



(a)

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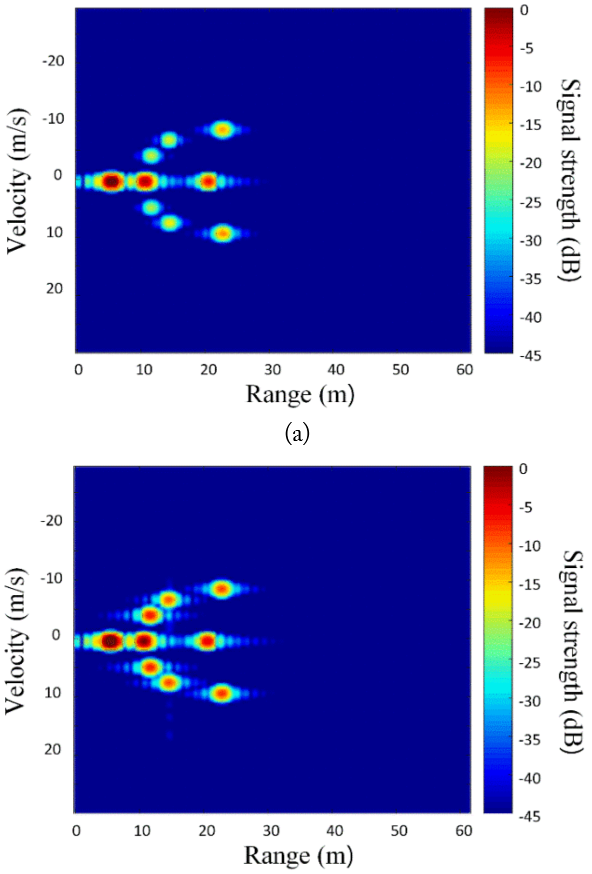
Fig. 9. Comparison range-Doppler images. (a) Range-Doppler image with vertical and horizontal HPBWs of 50° and 40° and (b) range-Doppler image with vertical and horizontal HPBWs of 10° and 60°.

To verify the applicability of the proposed systematic estimation scheme to other scenarios, we change the parameters of the test setup, such as distance between targets (l_2 and l_3) as shown in Fig. 10. The distance of l_2 is varied from 20 to 5 with l_3 of 10 to place the targets close together, and the nine targets are detected with greater strength using the optimal HPBW antenna with lower cost value compared to the antenna with the maximum cost. To observe the feasibility of the beam steering of the proposed radar system, we adopted a four-element array as shown in Fig. 11. The phase information of the individual elements is implemented to steer the beam direction of the array antenna, and the main-beam direction is varied from 0° to 15° without significant pattern degradation. The results indicate that the arrays are suitable to use with FMCW radar antennas to improve detection performance.



(a)

(b)

Fig. 10. Comparison range-Doppler image using another scenario. (a) Range-Doppler image with vertical and horizontal HPBWs of 50° and 40° and (b) range-Doppler image with vertical and horizontal HPBWs of 10° and 60°.

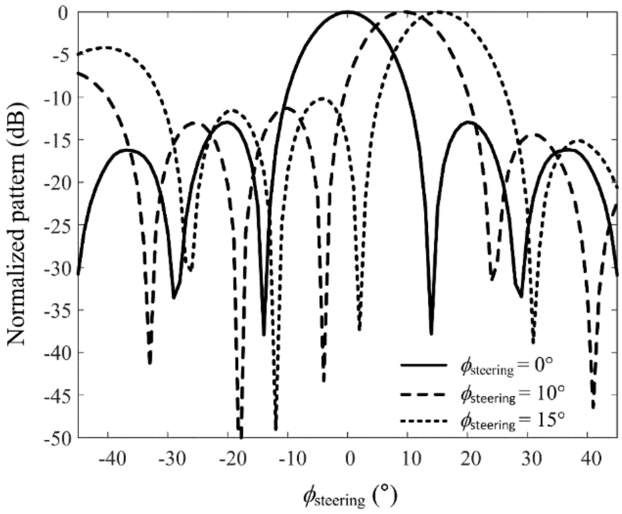


Fig. 11. Radiation patterns of the horn antenna array.

IV. CONCLUSION

We have investigated the systematic method for estimating detection performances of the FMCW radar using EM simulations. The proposed method was adopted to obtain range-Doppler images using signal processing algorithms and was also used to optimize the HPBW of the antenna array with the evaluation metric. The optimized antenna has vertical and horizontal HPBWs of 10° and 60° with the evaluation metric value of 0.4. To verify the variation of the images according to the steering angle of the antenna array, the steered array beam pattern was adopted to the test setup for obtaining the range-Doppler image. The results confirmed that the proposed systematic estimation method is suitable for use in estimating and optimizing the performance of FMCW radars.

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