Novel Compensation Method for Direction of Arrival (DOA) Estimation

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Abstract: In this paper, we propose a novel compensation method improving direction of arrival (DOA) and preventing target split tracking. Amplitude and phase mismatching and mutual coupling between radar arrays cause an inaccuracy problem in DOA estimation. By quantifying amplitude and phase distortions for angles, we compensate the distortion. Applying the proposed method to Bartlett, Capon and multiple signal classification (MUSIC) algorithms, we experimentally demonstrate the performance improvement using experimental data from the chamber and real data obtained in actual road.

Keywords— **Antenna array, Array signal processing, Array beamforming, DOA estimation, Array compensation**

1. Introduction

The most important aspect of recent automobile technologies is safe driving. Safe driving aims to prevent accidents due to weather conditions, drivers' carelessness or unexpected situations while driving. Because radar is robust to bad weather and poor road conditions, automotive radar is rapidly and increasingly being installed. Thus the needs for autonomous radar sensors will grow for autonomous emergency braking or autonomous driving for safety [1, 2]. Existing radar sensors used only information about the distance and speed of objects. However, as the demand for safety-related technologies increases, high-resolution digital beamforming has been combined, so much attention has been paid to the importance of direction of arrival (DOA) estimation algorithms. Digital beamforming is performed by using array antennas at the receiving end and array antenna signal processing techniques can be divided into spectral and parametric algorithms according to the approaching methods used [3]. Spectral algorithms can be divided into beamforming and subspace algorithms. Typical methods are Bartlett, Capon [4] and multiple signal classification (MUSIC) algorithms [5].

However, there is an inaccuracy problem when estimating DOA using real data. This problem occurs due to amplitude and phase mismatching between channels, sensor position errors, signal pointing errors and mutual coupling between antennas, which causes misrecognition of objects. Many studies have been conducted to solve these problems. To solve the amplitude and phase mismatch between channels, methods of measuring amplitude and phase responses to received signals to correct the received signals have been proposed [6]. Another method has been proposed to correct direction vectors using solutions obtained through the null characteristic of the MUSIC spectrum and the first Taylor series expansion [7] and a study on the correction of sensor position errors and signal pointing errors using the abovementioned method has been conducted [8]. To solve the mutual coupling problem, a method of using a mutual coupling coefficient can be used [9].

This paper aims to solve the inaccuracy problem of DOA estimation using the responses of amplitude and phase. Existing methods only solved the amplitude and phase mismatch between channels. Through signal processing using reference data that quantifies distortion of amplitude and phase between angles, a method proposed in this paper not only solves amplitude and phase mismatching between channels but also sensor position errors, signal pointing errors and mutual coupling problems simultaneously. To verify the performance of our method, we used real radar signals including three experimental data from the chamber and one driving data in actual road conditions. Performance of the proposed antenna array compensation technique was verified in terms of the improvement of the accuracy of DOA estimation by applying to Bartlett, Capon and MUSIC algorithms.

2. Conventional DOA estimation algorithms

Spectral-based DOA estimation algorithms can be divided into beamforming and sub-space algorithms [3] according to the methods of searching for the maximum point and defining the spectrum.

A beamforming algorithm is one of the most basic DOA estimation methods, in which an angle that has the maximum of the average output power in an array antenna is found. With respect to a received signal $\boldsymbol{x}(t)$, the output $y(t)$ of an array antenna and the average output power $P(\boldsymbol{w})$ of an array antenna are as follows [3]:

$$y(t) = \boldsymbol{w}^H \boldsymbol{x}(t) \tag{1}$$

$$P(\boldsymbol{w}) = E\left[|y(t)|^2\right] = \boldsymbol{w}^H E\left[\boldsymbol{x}(t)\boldsymbol{x}^H(t)\right]\boldsymbol{w} = \boldsymbol{w}^H \boldsymbol{R}\boldsymbol{w} \tag{2}$$

According to a method that determines weight vector $\boldsymbol{w}$, it is divided into Bartlett or Capon algorithms.

A Bartlett algorithm is a method of making the maximum signal output by giving a large weight to incident signals from specific directions [4]. For this algorithm, a weight vector $\boldsymbol{w}_B$ and the space spectrum $P_B(\theta)$ are as follows:

$$\boldsymbol{w}_B = \frac{\boldsymbol{a}(\theta)}{\sqrt{\boldsymbol{a}^H(\theta)\boldsymbol{a}(\theta)}} \tag{3}$$

$$P_B(\theta) = \frac{\boldsymbol{a}^H(\theta)\boldsymbol{R}\boldsymbol{a}(\theta)}{\boldsymbol{a}^H(\theta)\boldsymbol{a}(\theta)} \tag{4}$$

where $\boldsymbol{a}(\theta)$ is a direction vector of an array antenna response to a specific direction θ.

A Capon algorithm is a method of giving a relatively small weight to interference or noise while maintaining a gain of incident signals from a specific direction [4]. For this algorithm, a weight vector $\boldsymbol{w}_C$ and the space spectrum $P_C(\theta)$ are as follows:

$$\boldsymbol{w}_C = \frac{\boldsymbol{R}^{-1}\boldsymbol{a}(\theta)}{\boldsymbol{a}^H(\theta)\boldsymbol{R}^{-1}\boldsymbol{a}(\theta)} \tag{5}$$

$$P_C(\theta) = \frac{1}{\boldsymbol{a}^H(\theta)\boldsymbol{R}^{-1}\boldsymbol{a}(\theta)} \tag{6}$$

A MUSIC algorithm is a subspace-based algorithm, which takes advantage of the characteristics that all direction vectors corresponding to incident signals are orthogonal with the noise sub-space [5]. The algorithm employs the eigen-decomposition in the received signal covariance matrix, which can be represented as follows:

$$\boldsymbol{R} = \boldsymbol{U}_S\boldsymbol{\Lambda}_S\boldsymbol{U}_S^H + \sigma^2\boldsymbol{U}_N\boldsymbol{U}_N^H \tag{7}$$

where $\boldsymbol{U}_S$ is the signal sub-space and $\boldsymbol{U}_N$ is the noise sub-space. $\boldsymbol{\Lambda}_S$ refers to a diagonal matrix consisting of signal eigenvalues and σ^2 is the thermal noise power. The spectrum $P_M(\theta)$ of MUSIC is calculated as

$$P_M(\theta) = \frac{1}{\boldsymbol{a}^H\boldsymbol{U}_N\boldsymbol{U}_N^H\boldsymbol{a}(\theta)}. \tag{8}$$

3. Proposed array antenna compensation

Fig. 1 shows the schematic diagram of the proposed array antenna compensation. Reference data is obtained by quantifying the distortion degree per angle in the specially manufactured test chamber. Then, compensation is performed using the reference data to estimate an angle.

The acquired reference data is expressed as $G_m(\theta)$ $(m = 1, \cdots, M)$, where M is the number of elements in the array antenna. Based on $G_m(\theta)$, the array antenna compensation is performed as

$$C_m(\theta) = \frac{G_m(\theta)}{|G_m(\theta)|e^{j2\pi\frac{d_m}{\lambda}\sin(\theta)}}. \tag{9}$$

$C_m(\theta)$ is a phase value for compensation, λ is a wavelength and d_m is the distance from the reference element to each of the other elements. Then the array antenna compensation value is calculated as

$$\boldsymbol{M}(\theta) = diag\left\{\frac{1}{C_1(\theta)}, \frac{1}{C_2(\theta)}, \cdots, \frac{1}{C_M(\theta)}\right\} \tag{10}$$

where $diag\{\}$ represents the matrix diagonalization. The obtained $\boldsymbol{M}(\theta)$ is used to calculate the compensated direction vector $\boldsymbol{S}(\theta)$.

$$\boldsymbol{S}^H(\theta) = \boldsymbol{a}^H(\theta)\boldsymbol{M}(\theta) \tag{11}$$

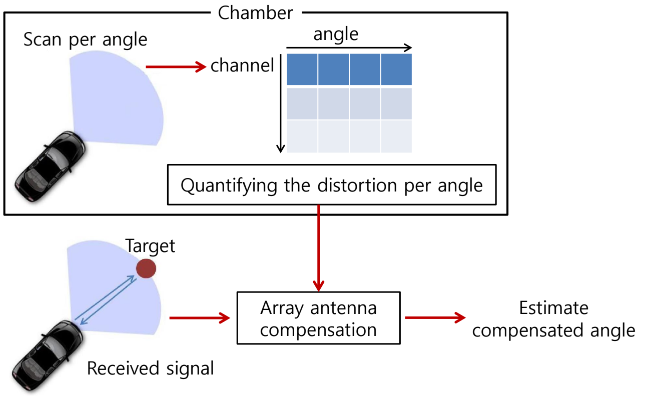

Figure 1. Schematic diagram of the proposed array antenna compensation

where $\boldsymbol{a}(\theta)$ refers to the existing direction vector and the following compensated spectrum can be obtained by applying $\boldsymbol{S}(\theta)$ to (4), (6) and (8) as follows:

$$P_B(\theta) = \frac{\boldsymbol{S}^H(\theta)\boldsymbol{R}\boldsymbol{S}(\theta)}{\boldsymbol{S}^H(\theta)\boldsymbol{S}(\theta)} \tag{12}$$

$$P_C(\theta) = \frac{1}{\boldsymbol{S}^H(\theta)\boldsymbol{R}^{-1}\boldsymbol{S}(\theta)} \tag{13}$$

$$P_M(\theta) = \frac{1}{\boldsymbol{S}^H\boldsymbol{U}_N\boldsymbol{U}_N^H\boldsymbol{S}(\theta)} \tag{14}$$

4. Experimental results

77 GHz frequency modulated continuous wave (FMCW) was used. There were three experimental data from the chamber and one driving data in actual road conditions. In the case of three experimental data, DOA was set from -11° to 0° by 1° increments for Long Range Radar (LRR) data, from -40° to -20° by 1° increments for Short Range Radar (SRR) data and from -47° to 47° by 0.5° increments for SRR data which had eight to twelve scans per each angle. With the driving data, we present the tracking performance of forward vehicle before compensation and after compensation. In this case, the reference data which was used to compensate DOA estimation was pre-acquired in the chamber.

The experiments were conducted with all DOAs. In the case of LRR, an element gap was 1.6λ and the number of elements in the array antenna was eight. In the case of SRR, an element gap was 0.6λ and the number of elements in the array antenna was four.

The conventional DOA estimation prior to compensation for three chamber experimental data was done by incrementing a directional vector by 0.5° through (4), (6) and (8). The DOA estimation after compensation was done by incrementing a directional vector by 1° for LRR data from -11° to 0° and SRR data from -40° to -20° and incrementing a directional vector by 0.5° for SRR data from -47° to 47° using (12), (13) and (14). In terms of the estimation error of each DOA, we quantified the performance.

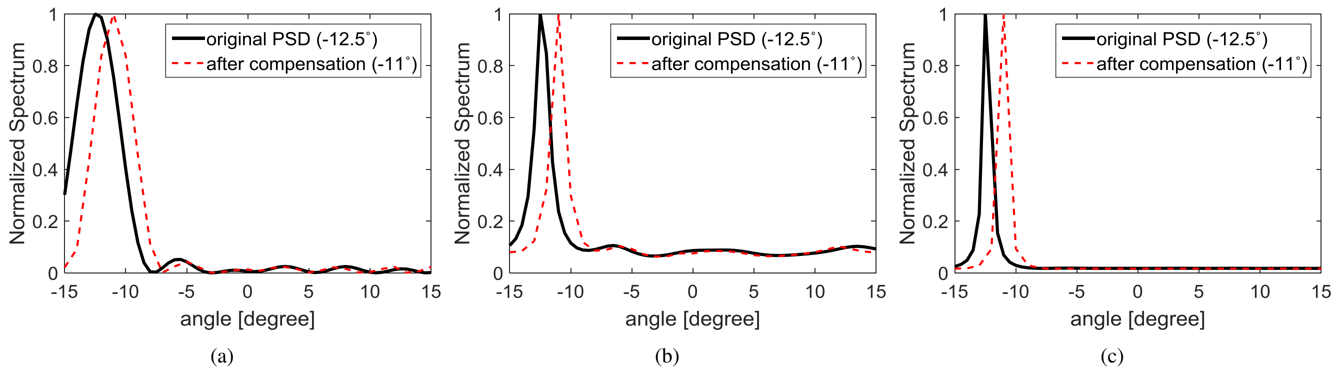

Figure 2. Improvement of DOA estimation using the proposed compensation (actual DOA: -11°). (a) Bartlett, (b) Capon and (c) MUSIC algorithms.

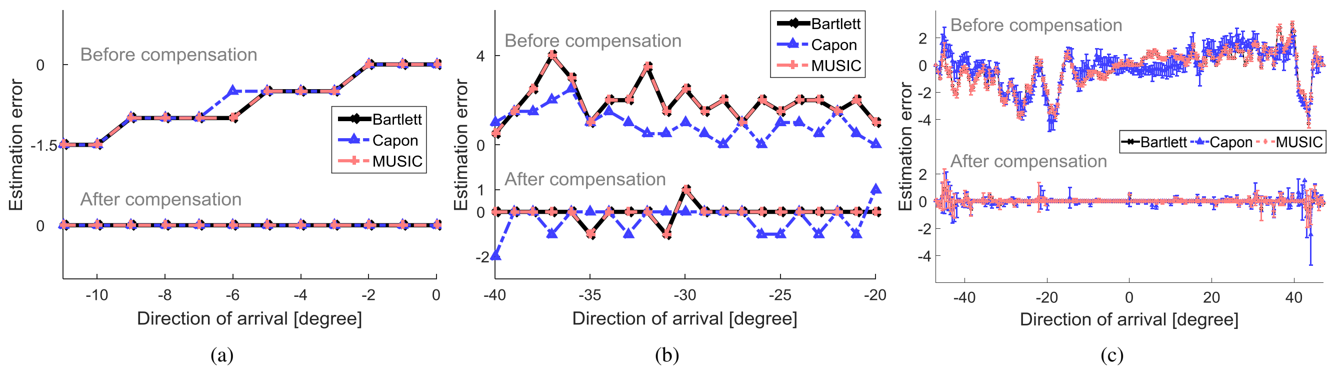

Figure 3. DOA estimation results of LRR and SRR data. (a) LRR data from -11° to 0°, (b) SRR data from -40° to -20° and (c) SRR data from -47° to 47°.

Fig. 2(a), (b) and (c) show the estimation results of Bartlett, Capon and MUSIC algorithms with respect to actual DOA of -11°. The original PSD is the result without compensation which has a peak at -12.5°. The proposed compensation result shows a peak at -11° which is the same as the actual DOA.

Fig. 3(a) shows the results of LRR data from -11° to 0°. The results before compensation cause errors from -1.5° to 0° for three conventional algorithms. However, after compensation, the results are the same as the actual DOA. Fig. 3(b) shows the results of SRR data from -40° to -20°. The DOA results before compensation are different with actual DOA. However, after compensation, the differences between estimated DOA and actual DOA are almost zero. Fig. 3(c) shows the results of SRR data from -47° to 47°. This data had eight to twelve scans per each angle and therefore each plots are displayed with the mean and the standard deviation of the errors. Before compensation, there were some differences between estimated DOA and actual DOA. However, after compensation, the average error is close to zero. Table 1 summarizes the mean and the standard deviation of the DOA estimation errors for Fig. 3(a), (b) and (c). In Table 1, after compensation, the mean and the standard deviation of the errors were decreased for all three algorithms.

Fig. 4 shows the tracking results of forward vehicle with the real driving data before and after compensation. The images in Fig. 4(a) is the sampled snap shots of road environments from scan #1200 to scan #1207. Fig. 4(b) and (c) illustrate the tracking results from the $1199th$ to the $1208th$ scan data. Before compensation, the target split phenomenon which is the misrecognition as two split objects for one target occurred as shown in Fig. 4(b). However, this phenomenon was overcome by applying the proposed compensation method to DOA estimation. Fig. 4(d) showed the DOA results of each scans before and after compensation.

Table 1. DOA estimation error before and after compensation (mean ± std)

		Error before compensation	Error after compepnsation
LRR Data	Bartlett	-0.71 ± 0.52	0
(-11° ∼ 0°)	Capon	-0.67 ± 0.51	0
	MUSIC	-0.71 ± 0.52	0
SRR Data	Bartlett	1.93 ± 0.82	-0.05 ± 0.38
(-40° ∼-20°)	Capon	0.95 ± 0.63	-0.33 ± 0.64
	MUSIC	1.93 ± 0.82	-0.05 ± 0.38
SRR Data	Bartlett	-0.27 ± 1.36	0.00 ± 0.35
(-47° ∼ 47°)	Capon	-0.17 ± 1.44	-0.01 ± 0.50
	MUSIC	-0.27 ± 1.36	0.00 ± 0.35

5. Conclusion

In this paper, the new compensation method to improve the DOA estimation was proposed by quantifying the distortion

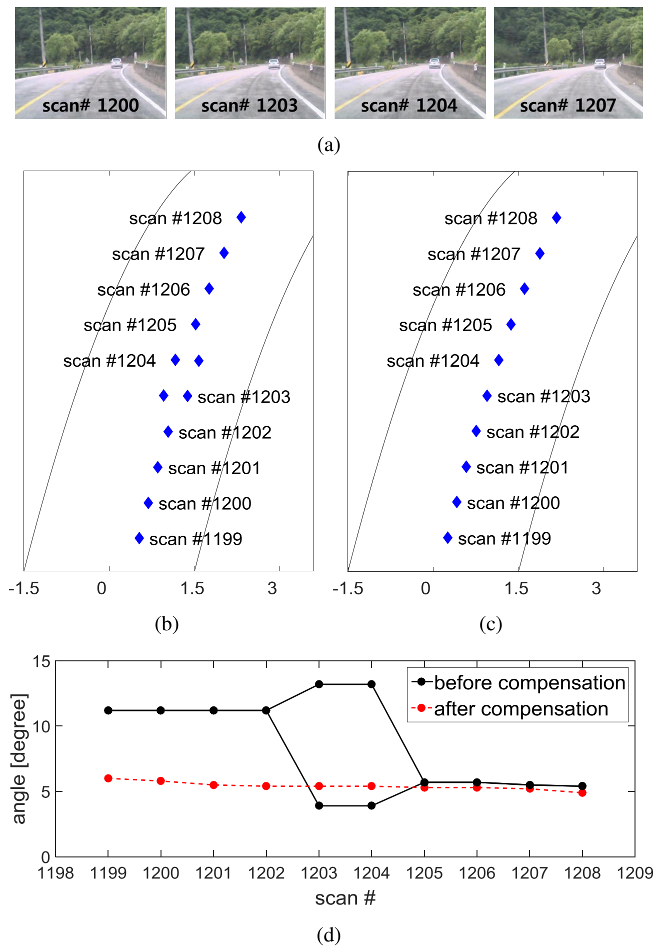

Figure 4. Comparison of the vehicle tracking results before and after compensation for real driving data. (a) Sampled snap shots of road environments, (b) vehicle tracking before compensation, (c) vehicle tracking after compensation and (d) DOA estimation results before and after compensation

per angle and overcame the inaccuracy problem of angle estimation. As for the convention DOA estimation algorithms, Bartlett, Capon and MUSIC algorithms were used and the results were compared before and after compensation. 77 GHz FMCW LRR, SRR and the driving data were used for experimental verification. Using the proposed compensation method, the results showed better DOA estimation results close to actual DOAs and the target split phenomenon was overcome.

Acknowledgment

This work was supported by the Technology Innovation Program (10051134, Middle Range Radar (150m) Development for Euro NCAP AEB) funded by the Ministry of Trade, industry & Energy (MI, Korea).

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