Experimental Study of DOA System with Synthesized Virtual Planar Array Using Eigenvectors

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ABSTRACT

In this paper, we propose a method of direction of arrival (DOA) estimation with synthesized virtual planar array with eigenvectors and report evaluation of the performance of the proposed method by simulations and experiments in an anechoic chamber. This method estimates DOA through synthesis of data received by a virtual planar array using eigenvectors. First, we describe the method to synthesize the data received by the virtual planar array using eigenvectors. Then, we present the simulation results, which confirmed that the estimation based on the virtual planar array was as accurate as that based on a real planar array. Finally, we demonstrated the effectiveness of the proposed system through experiments in an anechoic chamber.

INTRODUCTION

The quality of mobile communication should be improved, however it is difficult to maintain the quality of mobile communication at certain locations because of multipath fading. In order to cope with these problems, transmitters of the interference waves are estimated and it is desirable to improve the area design. Thus, the system based on the multiple signal classification (MUSIC) method [1] and the estimation of signal parameters via rotational invariance techniques (ESPRIT) [2] with a planar array for DOA estimations is useful as a measurement system. However, this method requires many elements and results in a high expenditure on receivers. As a solution to these problems, there is a method in which a linear array of antenna elements is moved to sweep an area, such that it can obtain a performance equivalent to that of a planar array occupying an area of a similar size [3][4][5]. However, it had not been possible to estimate DOA correctly when arrival waves are arbitrary signals.

In this paper, we propose a method of DOA estimation with synthesized virtual planar array using eigenvectors of correlation matrixes that are calculated from data received by a T-shaped array at each position. And we demonstrate the proposed method by simulations and experiments in an anechoic chamber. An advantage of the proposed method is a low cost because of a reduction of receivers and analog to digital converters (ADC). It is also possible to apply to arrival waves that are random signals. The proposed method can estimate DOA when arrival waves are correlated waves, which are random.

THEORY OF DOA ESTIMATION WITH A VIRTUAL PLANAR ARRAY USING PILOT SIGNALS

In this study, it is assumed that arrival waves are random and correlated waves. The proposed method adopts a novel approach to solve the problem of data acquisition. This approach uses a T-shaped array antenna shifted in parallel, instead of a conventional planar array antenna to estimate DOA. Synthesizing data received by a planar array antenna implies that a T-shaped array antenna is used to receive arrival waves, and the received data are used to realize the same data as those received by the conventional planar array antenna by synthesizing the received data. To provide a brief in this section, it is assumed that the number of arrival waves is only one and N is odd. We describe the method of synthesizing data received by the virtual planar array and realized by shifting the (N+1) T-shaped arrays as shown in Fig. 1.

The data X_1 received by a T-shaped array antenna at its first position are given by

$$\mathbf{X}_1(t) = \left[x_{11}(t), x_{12}(t), \cdots, x_{1(N+1)}(t) \right]^T$$
$$= \mathbf{A}_1(\theta) F(t) + \mathbf{N}_1(t)$$

where the superscript ^{T} denotes a transposition, t is time, θ is DOA, F(t) is a random signal of a base point, and $\mathbf{A}_1(\theta)$ and $\mathbf{N}_1(t)$ can be expanded as

$$\mathbf{A}_1(\theta) = [e^{j\phi_{11}(\theta)}, e^{j\phi_{12}(\theta)}, \cdots, e^{j\phi_{1N+1}(\theta)}]^T$$
$$\mathbf{N}_1(t) = [n_{11}(t), n_{12}(t), \cdots, n_{1N+1}(t)]^T$$

where $\phi_{1n}(\theta)(n = 1, 2, \cdots, N+1)$ is a phase difference introduced by θ to a base element, and $n_{1n}(t)$ is thermal noises. A correlation matrix $\mathbf{R}_1$ of $\mathbf{X}_1(t)$ is calculated by

$$\mathbf{R}_1 = E[\mathbf{X}_1(t)\mathbf{X}_1^H(t)]$$

where the superscripts $E[\bullet]$ and ^{H} denotes an ensemble average and a conjugate transposition, respectively. Eigenvalues λ_{1n} of $\mathbf{R}_1$ and the eigenvectors $\mathbf{e}_{1n}$ to the eigenvalues can be calculated, respectively. When the number of arrival waves is one, relationships between eigenvalues is given by

$\lambda_{11} > \lambda_{12} = \cdots = \lambda_{1N+1}$

and a eigenvector of $\mathbf{e}_{11}$ is expressed by

$$\mathbf{e}_{11} = \alpha_1 \mathbf{A}_1(\theta) = \left[\alpha_1 e^{j\phi_{11}(\theta)}, \alpha_1 e^{j\phi_{12}(\theta)}, \cdots, \alpha_1 e^{j\phi_{1,N+1}(\theta)} \right]^T \quad \textbf{(1)}$$

where α_1 is a constant [1].

The T-shaped array antenna is shifted parallel by the distance of only an element interval (see Fig. 1), and an eigenvector $\mathbf{e}_{21}$ can be obtained by data at the position as well as above procedures.

$$\mathbf{e}_{21} = \alpha_2 \mathbf{A}_2(\theta) = \left[\alpha_2 e^{j\phi_{21}(\theta)}, \alpha_2 e^{j\phi_{22}(\theta)}, \cdots, \alpha_2 e^{j\phi_{2,N+1}(\theta)} \right]^T \quad (2)$$

The elements of the eigenvectors $e^{j\phi_{1,(N+1)/2}}$ and $e^{j\phi_{2,N+1}}$ are same data, because the elements of $e^{j\phi_{1,(N+1)/2}}$ and $e^{j\phi_{2,N+1}}$ are located at the same position at two different times before and after the shifting of the T-shaped antenna, respectively. Hence, by comparing $\alpha_1 e^{j\phi_{1,(N+1)/2}}$ with $\alpha_2 e^{j\phi_{2,N+1}}$, it is possible to obtain the different phases ψ_{12} between first and second positions as follow.

$$\psi_{12} = \frac{\alpha_1 e^{j\phi_{1,(N+1)/2}}}{\alpha_2 e^{j\phi_{2,N+1}}} = \frac{\alpha_1}{\alpha_2}$$

Therefore, we can calibrate the different phases between first and second positions and synthesize data of 2 × N virtual planar array as follow.

$$\begin{aligned}
\mathbf{Y}_{2\times N} &= \left[\hat{\mathbf{e}}_{11}, \psi_{12}\hat{\mathbf{e}}_{21} \right] \\
&= [\alpha_1 e^{j\phi_{11}(\theta)}, \alpha_1 e^{j\phi_{12}(\theta)}, \cdots, \alpha_1 e^{j\phi_{1N}(\theta)}, \psi_{12}\alpha_2 e^{j\phi_{21}(\theta)}, \cdots, \psi_{12}\alpha_2 e^{j\phi_{2N}(\theta)}]^T \\
&= \alpha_1 [e^{j\phi_{11}(\theta)}, e^{j\phi_{12}(\theta)}, \cdots, e^{j\phi_{1N}(\theta)}, e^{j\phi_{21}(\theta)}, \cdots, e^{j\phi_{2N}(\theta)}]^T \qquad (3) \\
\hat{\mathbf{e}}_{11} &= [\alpha_1 e^{j\phi_{11}(\theta)}, \cdots, \alpha_1 e^{j\phi_{1N}(\theta)}]^T \\
\hat{\mathbf{e}}_{21} &= [\alpha_2 e^{j\phi_{21}(\theta)}, \cdots, \alpha_2 e^{j\phi_{2N}(\theta)}]^T
\end{aligned}$$

By repeating the above procedures (M-1) times, we can synthesize virtual data $\mathbf{Y}_{M\times N}$ received by an M × N planar array antenna by a parallel shift of the T-shaped antenna. Using $\mathbf{Y}_{M\times N}$ as an input vector, we can perform an analysis of DOA estimation by the MUSIC and ESPRIT methods.

In fact, there are several correlated waves transmitted from a base station, thus, the eigenvectors at each position get in degeneracy. However, data at each position can be synthesized as well as (3), the proposed method can estimate DOA

using F/B spatial smoothing. An array shifting speed is arbitrary, if DOA do not change, because the phase difference due to an error of sampling points caused by the shifting time can be calibrated by comparing (1) and (2).

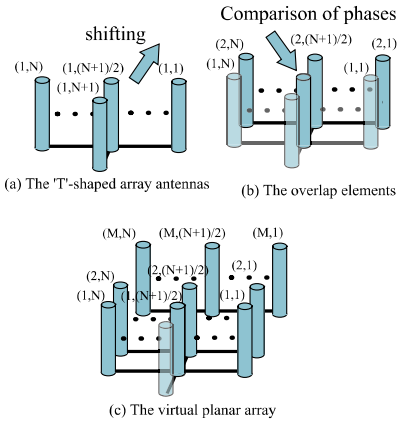

Fig. 1 Synthesis of the virtual planar array

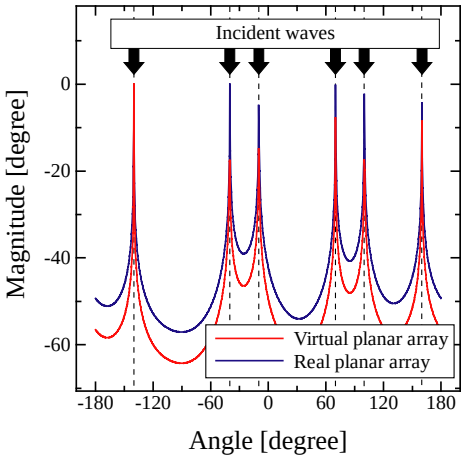

Fig. 2 Simulation results

SIMULATION

The performance of the proposed system in DOA estimation is evaluated through a comparison of the conventional method using the planar array. There are 6 arrival waves and all these arrival waves have the same power level. All arrival waves are correlation waves. There are 28 (7 × 4) elements included in the virtual planar array, and sub-arrays are 3 × 3 planar arrays for spatial smoothing. The interval between the elements is 0.4 wavelength. The number of sampling times is 2000. We use the MUSIC method as the DOA estimation algorithm. Figure 2 shows the results for the real and virtual planar arrays. Averages of estimation errors of planar array and virtual planar array are 0 degree, respectively. Based on the results of these simulations, it is evident that the virtual planar array of the proposed system can estimate the DOA with almost the same accuracy as the real planar array.

EXPERIMENT IN AN ANECHOIC CHAMBER

The performance of the proposed system in DOA estimation is evaluated through an experiment. We conduct the experiments in an anechoic chamber as shown in Fig. 3. In this experiment, a transmitting antenna is shifted to decrease estimation errors caused by the influence of cable twist. The area swept out by shifting a T-shaped receiving antenna is equivalent to the size of 5 × 4 elements planar antenna, which is the size of the virtual planar array. The moved distance $\Delta\hat{x}$ is defined by (2) such that it becomes equivalent to the theory.

$$\Delta\hat{x} = \Delta x \times \cos\theta$$

where Δx is the interval between elements. The sub-array for spatial smoothing is a 3 × 3 planar array. The radio frequency is 900 MHz band, a transmitted signal is the random that is modulated with QPSK method, the sampling frequency of ADC is 5 MHz, the number of sampling times is 2000, and the method used for DOA estimation is MUSIC. The estimation errors are summarized in Fig. 4. An average of estimation errors is about 0.5°. Based on these results, we can say that the performance of the proposed method in DOA estimation was confirmed experimentally.

We conducted experiments in the case of 2 waves in an anechoic chamber as shown in Fig. 5. The specifications for the experiment are the same as the case of 1 arrival wave. Figure 6 shows the MUSIC spectrum. As shown in Fig. 6, the directions of arrival waves were estimated accurately. This result confirmed that the proposed method was effective for DOA estimation.

CONCLUSION

In this paper, we proposed a method of DOA estimation using eigenvectors and evaluated the proposed method by performing simulations and experiments in an anechoic chamber. DOA was estimated correctly in these simulations, and the effectiveness of the proposed method was confirmed. We evaluated the average of estimation errors to be about 0.5° in the anechoic chamber. These results confirmed that the proposed method provides an effective DOA estimation.

Further studies are attempting to apply the proposed method to uncorrelated waves and estimate DOA from certain base stations through experiments.

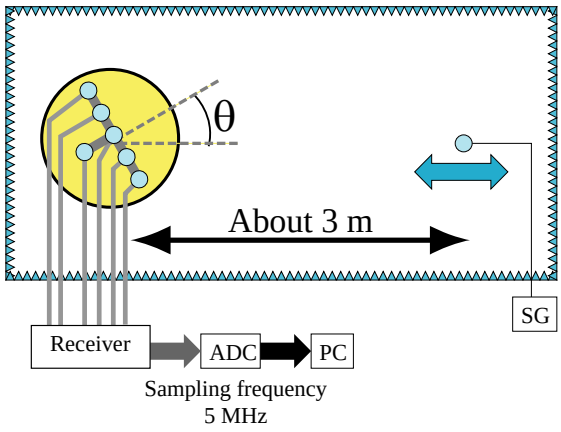

Fig. 3 Schematic view of experiment (1 arrival wave)

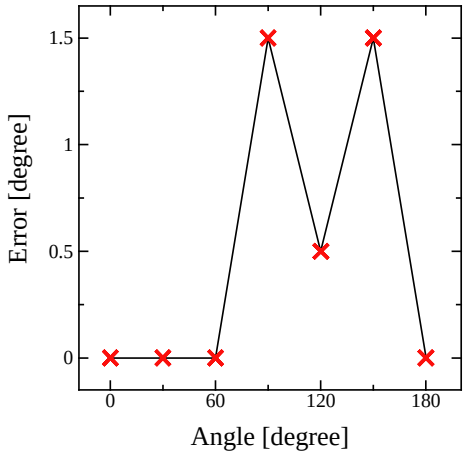

Fig. 4 Experiment results (1 arrival wave)

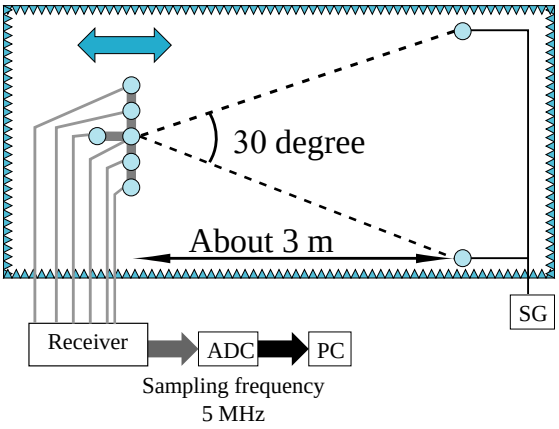

Fig. 5 Schematic view of experiment (2 arrival waves)

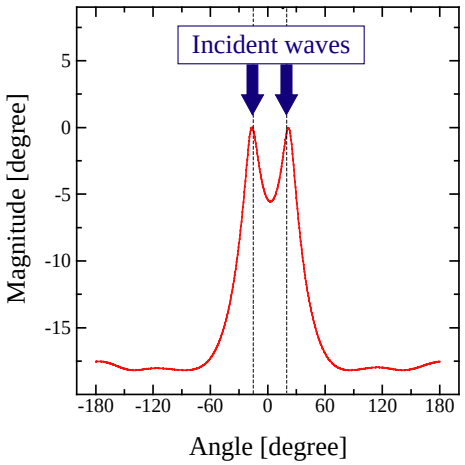

Fig. 6 Experiment result (2 arrival waves)

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