CALIBRATION-FREE DOA-ESTIMATION BY THE DIFFERENTIAL ARRAY ANTENNA

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Abstract

To estimate DOA, we need to calibrate the mutual coupling and phase and amplitude differences between channels. However it is required for the calibration to prepare several signals from known sources. Installing these sources make the system complex, especially in the real propagation environment. Therefore, a calibration-free DOA system is very attractive in practical application. In this paper, we propose a new type of array antenna, "Differential Array Antenna estimating DOA without calibration. We present this new antenna array by simulation and experiment in anechoic chamber.

1. Introduction

To improve the propagation environment of mobile communication system or radar application, there are a lot of research in Direction-of-Arrival (DOA) Estimation[1]. When we estimate DOA, we must consider the influences of mutual coupling and phase and amplitude differences between channels which reduces the accuracy of the estimation results. Therefore, we should calibrate these factors to obtain high accuracy in DOA estimation. Many calibration techniques such as using measured data of array antenna parameters and the reference signals from known sources. The former is the technique using mutual impedance matrix derived from S parameter measured by network analyzer, and it is difficult to apply to the real time calibration[2]-[3]. The latter technique is useful for real time calibration, however, this calibration needs many reference signals more than the number of antenna elements. In an ideal environment such as anechoic chamber, we easily obtain the reference signals and calibrate the system accurately. In a real environment, it is difficult because of the existence of the interference waves, and installing the reference signals makes the system complex. The proposed method in this paper is made by 2 antenna arrays. The ratio of 2 received signals makes a new received signal virtually when the incident wave is single and Signal to Noise Ratio (SNR) is enough large. The proposed method is useful when the SNR is large and calibration is difficult, such as DOA system using stratopheric platforms.

This paper consists of 4 sections. We explain the calibration technique using the reference signals and proposal technique in section 2. We present the results of simulation and experiment in section 3, and section 4 is conclusion. We applied MUSIC(MUltiple SIgnal Classification) algorithm in simulation and experiment.

2. Definition of the Differential Array Antenna

In this section, we explain the differential array antenna. The differential array antenna may apply to all type of antenna array. We explain using linear array antenna to simplify the equation. The received signal of array antenna in which number of element is n and the antenna spacing is d is described follows,

$$X(t) \;=\; A(\theta)S(t) + N(t) \tag{1}$$

$$A(\theta) \;=\; \begin{bmatrix} a(\theta_1) & a(\theta_2) & \dots & a(\theta_\ell) \end{bmatrix}$$

$$a(\theta) \;=\; exp[-j\frac{2\pi}{\lambda}d(k-1)sin\theta] \tag{2}$$

where S, N, and A denote signal component, noise component, and mode vector, respectively. When we consider mutual coupling and phase and amplitude differences between channels, we rewrite equation (1) as follows,

$$X(t) \;=\; C\Gamma A(\theta)S(t) + N(t) \tag{3}$$

$$C = \begin{bmatrix} C_{11} & C_{12} & \dots & C_{1n} \\ C_{21} & C_{22} & \dots & C_{2n} \\ \vdots & & & \vdots \\ C_{n1} & C_{n2} & \dots & C_{33} \end{bmatrix}$$

$$\Gamma = \begin{bmatrix} \gamma_1 & 0 & \dots & 0 \\ 0 & \gamma_2 & \dots & 0 \\ \vdots & & & \vdots \\ 0 & \dots & & \gamma_n \end{bmatrix}$$

$$C\Gamma = \begin{bmatrix} \gamma_1 C_{11} & \gamma_2 C_{12} & \dots & \gamma_3 C_{1n} \\ \gamma_1 C_{21} & \gamma_2 C_{22} & \dots & \gamma_3 C_{2n} \\ \vdots & & & \vdots \\ \gamma_1 C_{n1} & \gamma_2 C_{n2} & \dots & \gamma_3 C_{nn} \end{bmatrix} \tag{4}$$

C and Γ are the mutual coupling and the phase and amplitude differences between channels. C and Γ are often given as their product, then there are n^2-1 unknowns for $\gamma_1 C_{11} = 1$as a reference. Noise eigenvalue of received signal e_k^m and mode

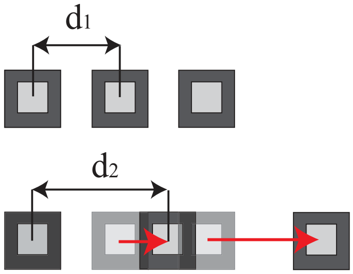

Fig. 1: Antenna model

vector $A(\theta)$ have the following relation and n-1 equations are obtaind by a single reference signal, therefore, we need at least n+1 reference signals for calibration.

$$e_j^m C \Gamma a(\theta) = 0 \tag{5}$$

The mutual coupling C is calculated by S parameters of each antenna element. We obtain S parameters by simulation or measurement by network analyzer. S parameter is replaced to Z parameters, then the coupling coefficient is given as follows,

$$Z = (I+S)(I+S)^{-1}$$

$$= \begin{bmatrix} Z_{11} & Z_{12} & \dots & Z_{1n} \\ Z_{21} & Z_{22} & \dots & Z_{2n} \\ \vdots & & & \vdots \\ Z_{n1} & Z_{n2} \dots & Z_{nn} & \end{bmatrix}$$

$$C = \frac{1}{Z_0} \begin{bmatrix} 1+Z_{11} & Z_{12} & \dots & Z_{1n} \\ Z_{21} & 1+Z_{22} & \dots & Z_{2n} \\ \vdots & \vdots & & \vdots \\ Z_{n1} & Z_{n2} & \dots & 1+Z_{nn} \end{bmatrix}^{-1}$$

where Z_0 is the reference impedance of the measurement system.

The mutual coupling C heavily depend on the spacing of antenna elements. We may neglect the coupling components when antenna spacing is large. However large antenna spacing causes another problem such as grating robe. The proposed array antenna is made by changing the antenna spacing from d_1 to d_2 as shown in Fig.1. The ratio of 2 received signals is described as follow,

$$X_{def} = \frac{X_2(t)}{X_1(t)} = \frac{C_2\Gamma_2 A_2(\theta)S_2(t) + N_2(t)}{C_1\Gamma_1 A_1(\theta)S_1(t) + N(t)} \tag{6}$$

When we set the antenna spacing enough large, we may neglect the mutual coupling as $C_1 = C_2 \cong I$,where I is a unit matrix. Provided we use the same elements and the data is received almost the same time, we may approximate $\Gamma_1 \cong \Gamma_2$.Then eq.(6) is given as

$$X_{def}(t) = \frac{\Gamma_1 A_2(\theta)S_2(t) + N_2(t)}{\Gamma_1 A_1(\theta)S_1(t) + N_1(t)} \tag{7}$$

When the SNR is enough large, we approximate eq.(7) in the following,

$$X_{def}(t) \cong \frac{A_2(\theta)S_2(t)}{A_1(\theta)S_1(t)} \tag{8}$$

Assuming a single incident wave, eq.(7) is described as follow.

$$x_{def,k}(t) = exp[-j\frac{2\pi}{\lambda}(d_2-d_1)sin\theta]\frac{S_2(t)}{S_1(t)}$$

$$= A_{def,k}(\theta)S_{def}(t) \tag{9}$$

The eq.(9) is very close to eq.(1). The virtual antenna spacing is $d_2 - d_1$, and the virtual signal component is S_2/S_1.

3. Simulation

In this section, we show the result of simulation and experiment with linear array antenna of 3 elements. We set the first array spacing, $d_1 = 1.862\lambda$ and second array spacing,$d_2 = 2.394\lambda$. The virtual antenna spacing of differential array antenna is 0.532λ. We can neglect mutual coupling in this array spacing and we give random value of Γ. We use the sinusoidal signal and we assume the DOA of the incident angle is 0 ând ± 30 ˆ,respectively. Simulation result is shown in Figs. ˆ2, ˆ3,and ˆ4. The SNR is 20dB, and the snapshot is 2000. Figure 2 and 3 shows the MUSIC spectrum of the second linear array antenna with/without Γ. Figure 2 shows sharp peaks, but it contains grating robes. The phase and amplitude differences between channels decrease the dynamic range of the spectrum as shown in Fig 3. The MUSIC spectrum of proposed differential array antenna is shown in Fig.4. The dynamic range is enough large and there is no grating robe. Therefore this result shows that the proposed antenna surpresses the influence of Γ and make a new antenna spacing virtually. The differential array antenna is useful for DOA estimation without calibration. Figure 5 shows RMSE(Real Mean Square Error) characteristics by changing the SNR and snapshot. We changed SNR and the number of snapshot, respectively. The number of snapshot improved the accuracy of the estimation result. SNR is a dominant factor in the accuracy of the estimation result. The SNR more than 20 dB is necessary to keep the RMSE less than 0.25 ˆ

4. Experiment

In this section, we show the experimental results in anechoic chamber shown in Fig. 6. The SNR is assumed more than 20dB.We used patch antenna for array because patch antenna has low mutual coupling.

The parameters of the experiment are shown in Table 1. We calculated the S parameters of each antenna element by a simulaor. Figure 7 shows S_{11} and S_{12}. We calculated C_1 and C_2 with these S parameters, respectively.

$$C_1 = \begin{bmatrix} \text{0.806+0.057j} & \text{0.005-0.008j} & \text{0.003-0.002j} \\ \text{0.005-0.008j} & \text{0.806+0.056j} & \text{0.005-0.008j} \\ \text{0.001-0.002j} & \text{0.005-0.008j} & \text{0.806+0.057j} \end{bmatrix}$$

$$C_2 = \begin{bmatrix} \text{0.806+0.057j} & \text{0.008-0.000j} & \text{0.001-0.000j} \\ \text{0.008-0.000j} & \text{0.806+0.057j} & \text{-0.008-0.000j} \\ \text{0.001-0.000j} & \text{-0.008-0.000j} & \text{0.806+0.057j} \end{bmatrix}$$

Simulation result with/without calculated mutual coupling is shown in Fig. 8, which shows that the mutual coupling is not as large as to influence on the accuracy of the estimation results.

Figure 9 and 10 show the experiment results in anechoic chamber. Figure 9 is very close to Fig. 3. Figure 10 shows that the proposed array antenna could estimate DOA without calibration. However, the estimation result is not as accurate as simulation result. Figure 11 shows the estimation error. More than 3 ˆerror is shown in Fig.11, and the RMSE is 1.13 .ˆWe assume the estimation error was caused by mutual coupling between elements and cables, and the measurement error.

Table 1: Parameters

d_1	1.862λ	element number	3
d_2	2.394λ	RF	5.32GHz
d_{def}	0.532λ	IF	10MHz
Modulation	Sinusoidal	Fs	40MHz
DOA	0 ,ˆ±30 ˆ	Power of transmitter	-15dBm

5. Conclusion

In this paper, we proposed the new array antenna system using the ratio of received signals of array antenna consists of large element spacing. Differential array antenna can estimate DOA without calibration in the situation of one incident wave and very weak mutual coupling. The result of experiment verified the proposed method. However, we could not obtain the results such as large dynamic range and high accuracy as the simulation.

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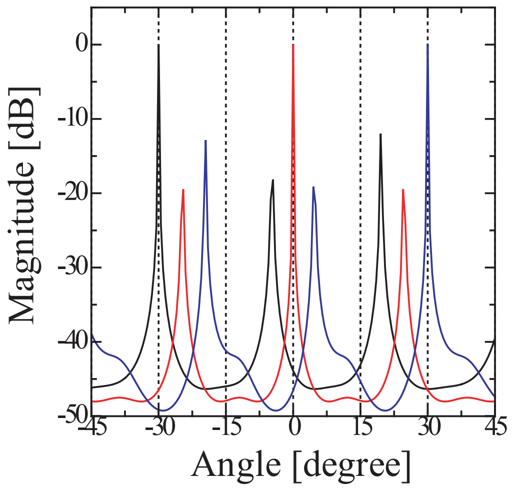

Fig. 2: MUSIC spectrum of linear array antenna

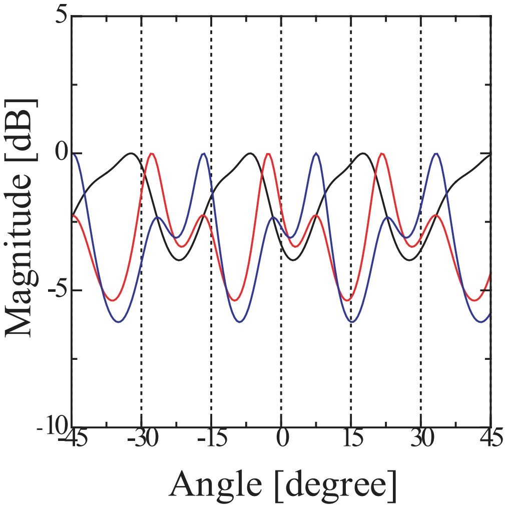

Fig. 3: MUSIC spectrum of linear array antenna contains Γ

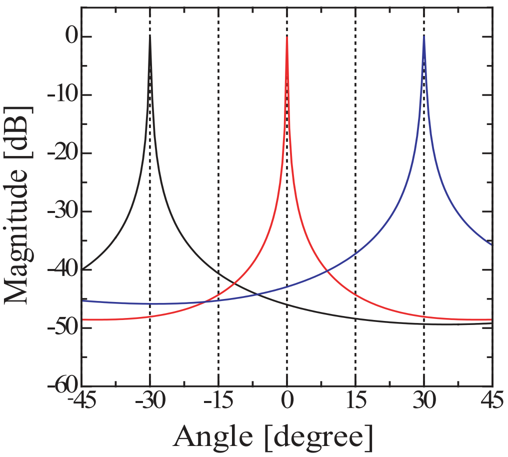

Fig. 4: Smulation of differential array antenna

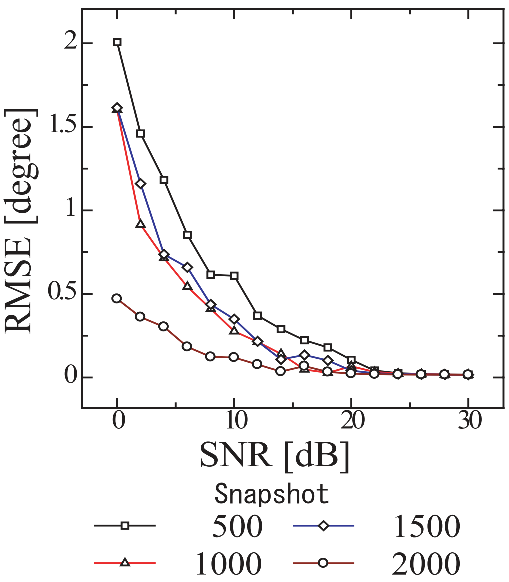

Fig. 5: RMSE charactristics

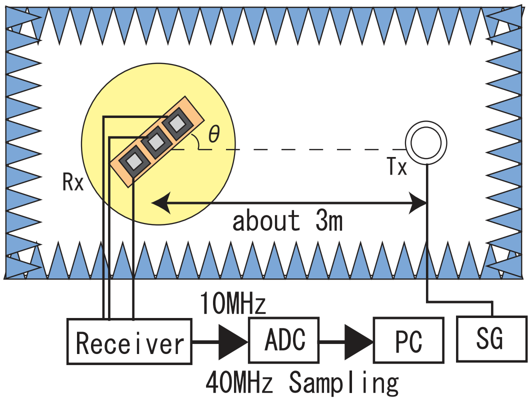

Fig. 6: Experimental situation

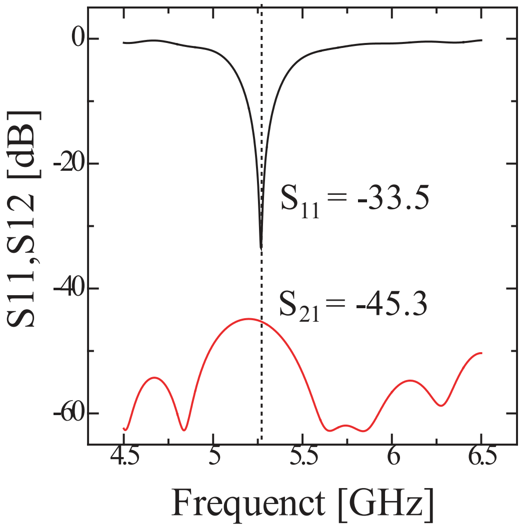

Fig. 7: S parameters

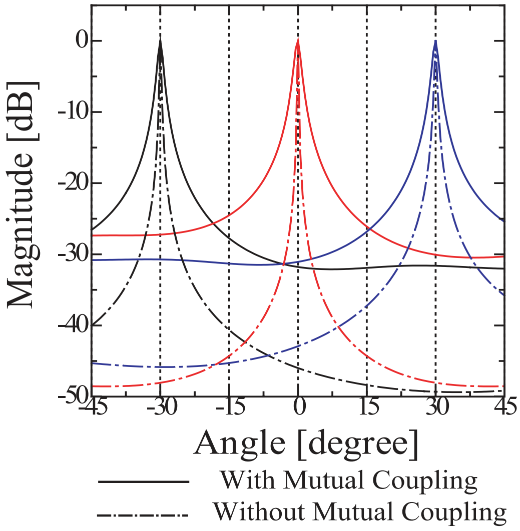

Fig. 8: Spectrum with Calculated C

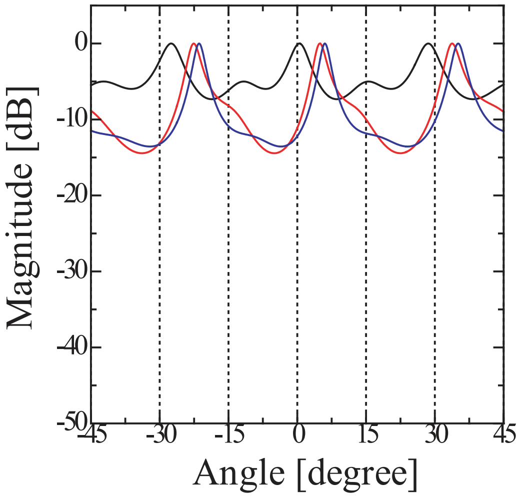

Fig. 9: Expriment results of linear array

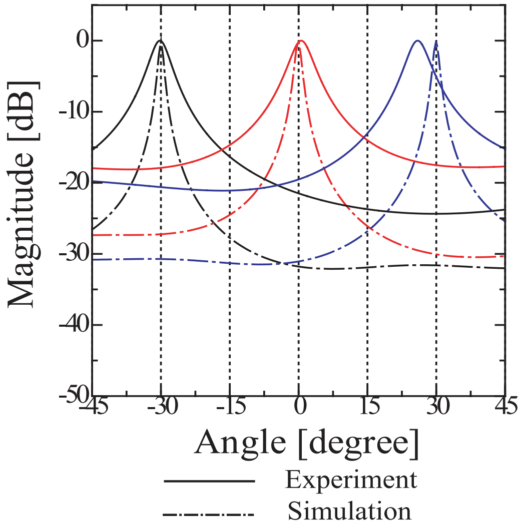

Fig. 10: Experiment results of proposal array

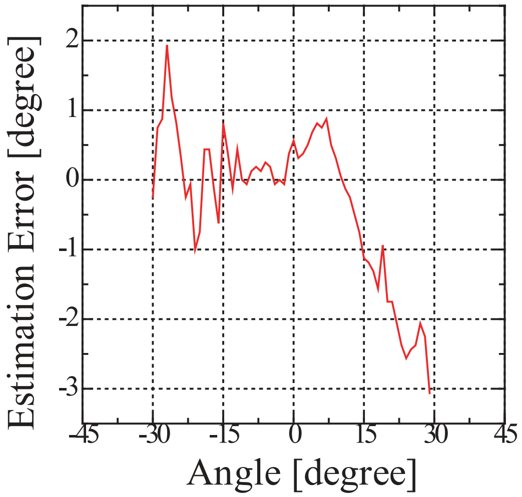

Fig. 11: Estimation error of experiment