Proceedings of ISAP'04, Sendai, JAPAN

MUTUAL COUPLING MATRIX ESTIMATION AND NULL FORMING METHODS FOR MBF ANTENNA

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1 Introduction

Antenna pattern control techniques for mobile terminals such as adaptive array antenna are expected to improve the characteristic of high-speed radio communications. The drawbacks of adaptive antenna based on DBF (Digital Beam Forming) are the requirement of the same number of RF receivers and A/D (analog-to-digital) converters as the number of array elements, since digital signal processing have to be performed in the baseband. The adaptive antenna also requires high speed signal processing, which is difficult to apply for mobile terminals, since mobile terminals need to be fabricated with low cost and be miniaturized [1]. In addition, mutual coupling effect can not be neglected when array elements are mounted in small space to miniaturize mobile terminals, and no ideal directivity patterns are obtained.

This paper focuses on the MBF (Microwave Beam Forming) antenna, consisting of array antenna, phase shifters, and power combiner. Antenna pattern control is presented for mobile terminals, and mutual coupling matrix estimation and null forming methods are also presented in this antenna. We propose the estimation method of coupling matrix. Conventional methods require all of the signals on the antenna element [2], but proposed method does not need each signal and use combined signal of all the input signals. Secondly, we discuss about null forming by phase control including mutual coupling effect. In conventional methods, effect of mutual coupling is compensated by multiply the inverse of coupling matrix to the antenna weight, using both phase and amplitude. It is difficult to apply conventional methods to the MBF antenna and we extend the method by Takanashi *et al.* [3] to include coupling matrix. Proposed methods can be applied for any shape of array antenna, and a rectangular array of 4 elements of $\lambda/4$ spacing is demonstrated in anechoic chamber.

2 Configuration of the MBF antenna

The MBF antenna uses only microwave analog phase shifters for antenna weight control, for the low cost design as shown in Fig. 1. RF signals received by array antennas are adjusted by phase shifters and summed up by power combiner. These processes are performed in RF. Summed signal is down converted to IF level, and digitized by A/D converter for digital signal processing. Consequently we need only a single RF receiver and A/D converter. To miniaturize the system, we assume distance between antenna elements is short enough, thus we have to consider mutual coupling. When we assume that the K elements of MBF antenna with weight $\boldsymbol{W_m}$ receives a signal from the angle of θ_n in the horizontal plane, normalized output of the power combiner y_{mn} is expressed as

$$y_{mn} = \boldsymbol{W_m}^T \boldsymbol{V_n} \tag{1}$$

$$\boldsymbol{W_m} = [\, w_{m1} \quad \ldots \quad w_{mk} \quad \ldots \quad w_{mK} \,]^T, \quad \boldsymbol{V_n} = [\, v_{n1} \quad \ldots \quad v_{nk} \quad \ldots \quad v_{nK} \,]^T$$

ISBN: 4-88552-207-2 C3055©IEICE

where T, $\boldsymbol{W_m}$, $\boldsymbol{V_n}$, denote transpose, K-dimensional weight vector, K-dimensional array response vector, respectively. The effect of mutual coupling can be expressed in coupling matrix C, and we rewrite (1) with C as

$$y_{mn} = \boldsymbol{W_m}^T C \boldsymbol{V_n} \tag{2}$$

$$C = \begin{bmatrix} c_{11} & \dots & c_{1K} \\ \vdots & \ddots & \vdots \\ c_{K1} & \dots & c_{KK} \end{bmatrix}.$$

The coupling matrix C is required to consider the effect of mutual coupling. We explain the estimation method of coupling matrix, which only requires output signals from the microwave power combiner. The matrix C has K^2 elements when the number of array elements is K, thus we need K^2 linear independent equations to evaluate the C. Consequently, we change the weight $\boldsymbol{W_m}$ K times(m=1,2,$\cdots$,K) and measure y_{mn} about K directions(n=1,2,$\cdots$,K) at each weight in (2). We can express these equations in matrix as

$$Y = W^T C V \tag{3}$$

$$\begin{aligned} Y &= \begin{bmatrix} y_{11} & \dots & y_{1K} \\ \vdots & \ddots & \vdots \\ y_{K1} & \dots & y_{KK} \end{bmatrix} \\ W &= [\boldsymbol{W_1} \quad \boldsymbol{W_2} \quad \dots \quad \boldsymbol{W_m} \quad \dots \quad \boldsymbol{W_K}] \\ V &= [\boldsymbol{V_1} \quad \boldsymbol{V_2} \quad \dots \quad \boldsymbol{V_n} \quad \dots \quad \boldsymbol{V_K}]. \end{aligned}$$

Therefore we can estimate the C from (4).

$$C = \left(W^T\right)^{-1} Y V^{-1} \tag{4}$$

The above equation does not contain each signal on the antenna element, thus we can apply this method to the MBF antenna.

3 Null Forming Method

We explain the null forming method including mutual coupling effect. Under the mutual coupling effect, a initial condition weight $\boldsymbol{W_1}$ is perturbed by a small amount $\boldsymbol{\Phi}$ and form a null in direction θ_n, we can rewrite (2) as

$$\begin{aligned} y'_{1n} &= \{\mathrm{diag}\,(\boldsymbol{W_1})\,\boldsymbol{\Phi}\}^T C \boldsymbol{V_n} = 0 \\ \boldsymbol{\Phi} &= [e^{j\phi_1} \dots e^{j\phi_k} \dots e^{j\phi_K}]^T \end{aligned} \tag{5}$$

where, diag $(\cdot)$ is diagonal matrix derived from the elements of the vector in a bracket. We form a null with the smallest perturbation, since the amount of analog phase shift is limited. Thus we redefine the problem to minimize the sum of ϕ_k^2 for the equation (5). The problem can be expressed as (6), when the number of nulls is N.

$$\begin{gathered} \boldsymbol{\phi}^T \boldsymbol{\phi} \rightarrow \min \\ \textit{subject to} \quad \boldsymbol{L} = 0, \quad \boldsymbol{L}^* = 0 \end{gathered} \tag{6}$$

$$\boldsymbol{\phi} = [\phi_1 \dots \phi_k \dots \phi_K]^T, \quad \boldsymbol{L} = [y'_{11} \dots y'_{1n} \dots y'_{1N}]^T$$

where, $\boldsymbol{\phi}$ is K-dimensional perturbation vector, $\boldsymbol{L}$ is N-dimensional constraint vector, $*$ denote complex conjugation, respectively. To solve this problem, we adopt an approximation of $e^{j\phi_k} \cong$

$1 + j\phi_k$ based on Taylor expansions for ϕ_k being assumed small enough. Lagrange multipliers is used for solving this class of problems, and then we can derive the amount of perturbation $\boldsymbol{\phi}$, that form nulls in desired direction θ_n (n=1,2,$\cdots$,N) as

$$\boldsymbol{\phi} \;=\; -j\frac{1}{2}\left(P\boldsymbol{\Lambda} - P^*\boldsymbol{\Lambda}^*\right) \tag{7}$$

where, P is defined as $\mathrm{diag}\left(\boldsymbol{W_1}\right)CV$, $\boldsymbol{\Lambda}$ is N-dimensional undetermined coefficient vector, respectively. Substituting (7) into constraint, $\boldsymbol{\Lambda}$ is derived as

$$\begin{bmatrix} \boldsymbol{\Lambda} \\ \boldsymbol{\Lambda}^* \end{bmatrix} = 2\begin{bmatrix} -P^TP & P^TP^* \\ P^HP & -P^HP^* \end{bmatrix}^{-1}\begin{bmatrix} P^T\boldsymbol{I} \\ P^H\boldsymbol{I} \end{bmatrix} \tag{8}$$

where, $\boldsymbol{I}$ is K-dimensional unit vector. Using eqns. (7) and (8), we derive the optimum perturbations. The optimum weight is derived as

$$\boldsymbol{W_{opt}} = \mathrm{diag}\left(\boldsymbol{W_1}\right)\boldsymbol{\Phi}. \tag{9}$$

If nulls are not formed or null-level is not enough, we use the perturbed weight (9) as a initial condition weight $\boldsymbol{W_1}$ and calculate eqns. (7) and (8) again until it forms nulls in desired directions.

4 Experimental Results

For an experiment in anechoic chamber, we used $\lambda/4$ spaced 4 elements rectangular MBF antenna at 2 GHz. The MBF antenna has sleeve antenna elements and analog phase shifters with phase shift range of 117 degrees for weight control. To achieve high-precision estimation based on least-square method, we used 16 weights and $-180\leq \theta \leq 180$ degrees output signals at each weight. Hence, "pseudo inverse" is used for matrix inverse calculation. For a null forming, we defined N=1 for simplicity. Fig. 2 shows the comparison of measured and calculated patterns for θ_1= 135, −120, 90, 60 degrees, respectively. As seen from these patterns, estimation of coupling matrix and null forming are well obtained, and MBF antenna can form a null in any direction.

5 Conclusion

In this paper we focused on the MBF antenna as an antenna pattern control suitable for mobile terminals, and demonstrated mutual coupling matrix estimation and null forming methods for this antenna. We showed that mutual coupling matrix could be estimated from output signals about K directions at each K weight and null forming could be done by perturb the phase considering the estimated coupling matrix. Experimental results showed that MBF antenna could form a null in any direction including mutual coupling effect.

References

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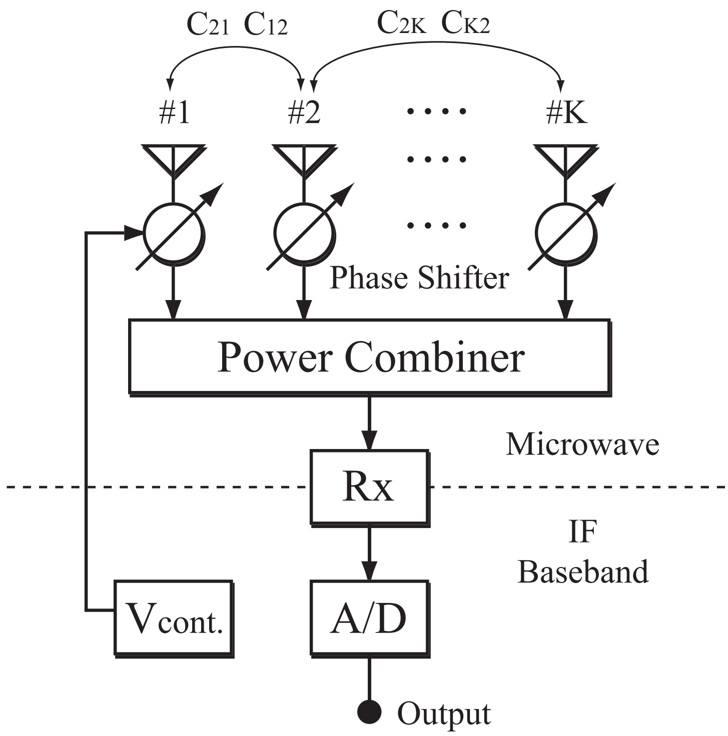

Figure 1: MBF antenna. The phase of each element is controlled by DC voltage.

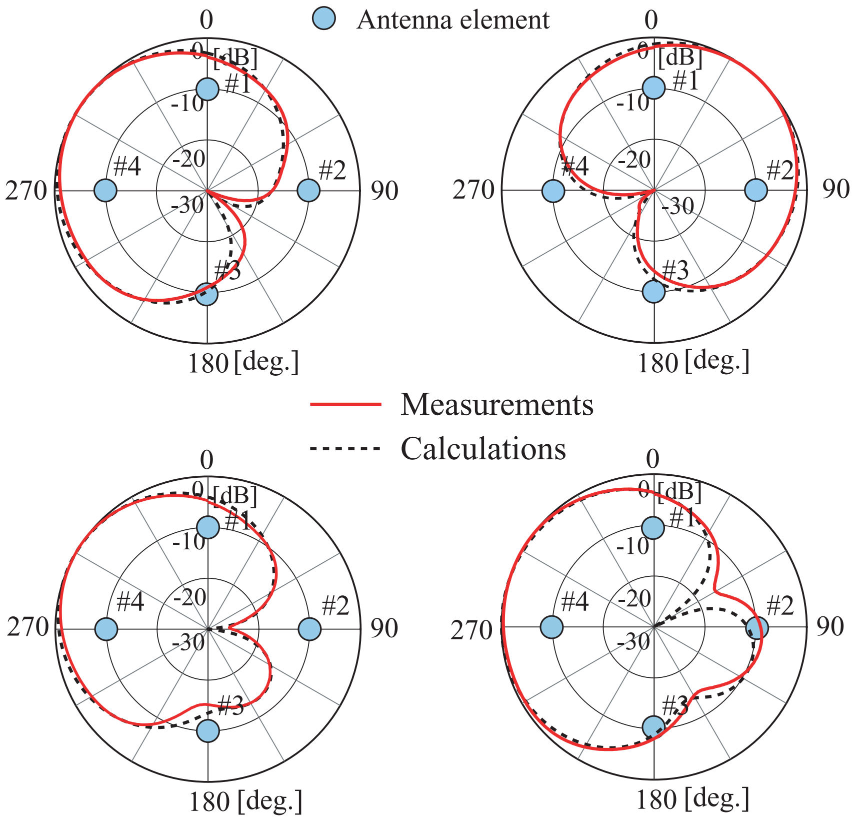

Figure 2: Experimental nulling performance of the MBF antenna.