An alternative approach to decoupling of arrays with reduced element spacing

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Abstract

An alternative method for port decoupling and matching of arrays with small inter-element spacing is proposed. The approach is based on the inherent decoupling effect obtained by feeding the eigenmodes of the array. For this purpose, a modal feed network is introduced. The decoupled external ports of the feed network may individually be matched using conventional matching circuits. Such a system may be used in digital beam forming applications with good signal-to-noise performance.

1. INTRODUCTION

Antenna arrays with digital beam forming can be used to adaptively form radiation patterns which maximize the gain in a pre-specified direction of incidence (beam forming) or to spatially reject interference (adaptive nulling). Mutual coupling between the antenna elements leads to system performance degradation. It causes a reduction in the signal-to-interference-plus-noise ratio [1, 2]. The presence of mutual coupling decreases the eigenvalues of the covariance matrix of the signal, which controls the response time of an adaptive array [1]. The effects of mutual coupling become more severe when the inter-element spacing is reduced beyond half a wavelength. In many applications, the available volume places a restriction on the physical size of the antennas. For maximum versatility, the number of elements in an adaptive array needs to be as large as possible. On the other hand, the increased mutual coupling associated with a decrease in element spacing limits the frequency bandwidth and increases the sensitivity to dissipative losses. The required bandwidth and radiation efficiency dictates the maximum number of array elements for a given platform size. It nevertheless remains vital that mutual coupling be taken into consideration during the design of arrays, especially in cases of reduced inter-element spacing.

In shaped beam antennas, modification of the excitation vector can compensate for the mutual coupling effect [3]. In digital beam forming antenna array, a matrix multiplication technique may be performed on the received signal vector to restore the signals at the isolated elements in the absence of coupling [4 – 7]. However, signal-to-noise maximization can only be achieved by employing a decoupling network (DN) [8, 9]. Decoupling networks have been implemented by connecting simple reactive elements between the input ports and antenna ports, but it is only applicable in special cases where the off-diagonal elements of the admittance matrix are all purely imaginary [8-10]. The design of decoupling networks for 3-element [11] and 4-element [12] arrays with arbitrary complex mutual admittances was described. The DNs described in [11, 12] are symmetrical networks. Network elements were obtained by either applying an eigenmode analysis or a complete network analysis of the DN/array combination.

In this paper, we propose an alternative approach to achieve port decoupling. It involves a modal feed network which makes use of the orthogonality of the eigenmodes of the array to achieve decoupling. The input ports to the feed network and array combination can then be matched independently. In digital beam forming applications, the required element weights are obtained as a linear combination of the orthogonal eigenmode vectors.

2. MODAL FEED NETWORK

Consider a $2N$-port modal feed network connected to an N-port array as shown in Fig. 1. The first N ports are the external ports and the remaining N ports are the internal ports, which are connected to the array. The modal feed network produces the nth eigenvector of the array at the internal ports in response to an input signal at external port n.

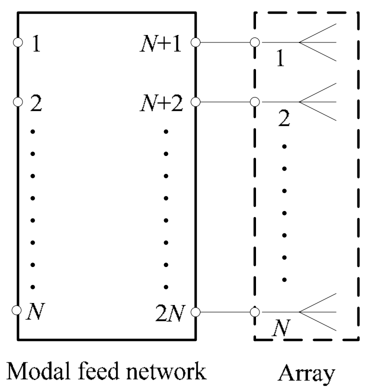

Fig. 1: $2N$-port modal feed network connected to an N-port array.

A. Ideal feed network

The S-parameters of an ideal modal feed network are given by

$$\mathbf{S} = \begin{pmatrix} \mathbf{S_{ee}} & \mathbf{S_{ei}} \\ \mathbf{S_{ie}} & \mathbf{S_{ii}} \end{pmatrix} \tag{1}$$

where

$$\mathbf{S_{ee}} = \mathbf{S_{ii}} = \mathbf{0}\,, \tag{2}$$

$$\mathbf{S_{ie}} = [\mathbf{e}_1 \;\; \mathbf{e}_2 \;\; \ldots \;\; \mathbf{e}_N]\,, \tag{3}$$

$$\mathbf{S_{ei}} = \mathbf{S_{ie}}^T = \mathbf{S_{ie}}^{-1}\,, \tag{4}$$

and column vector $\mathbf{e}_m$ is the mth orthonormal eigenvector of the array scattering parameter matrix $\mathbf{S^a}$. Note that $\mathbf{S_{ie}}$ is the orthogonal matrix which diagonalizes $\mathbf{S^a}$.

The S-parameters of the N-port network resulting from connecting the modal feed network to the array are then given by

$$\begin{aligned} \mathbf{S^d} &= \mathbf{S_{ee}} + \mathbf{S_{ei}}(\mathbf{S_a}^{-1} - \mathbf{S_{ii}})^{-1}\mathbf{S_{ie}} \\ &= \mathbf{0} + \mathbf{S_{ei}}(\mathbf{S_a}^{-1} - \mathbf{0})^{-1}\mathbf{S_{ie}} \\ &= \mathbf{S_{ie}}^{-1}\,\mathbf{S_a}\,\mathbf{S_{ie}} \\ &= \mathrm{diag}[\lambda_1, \lambda_2, \ldots \lambda_N]\,, \end{aligned} \tag{5}$$

where λ_m is the mth eigenvalue of $\mathbf{S^a}$. The input ports of the combined network are therefore decoupled ($\mathbf{S}^{\mathbf{d}}_{ij} = 0$, $i \neq j$) but mismatched ($\mathbf{S}^{\mathbf{d}}_{ii} \neq 0$). They can be matched individually by introducing appropriate matching networks.

For a desired element excitation $\mathbf{y} = [y_1, y_2, \ldots y_N]^T$, the signals required at the external ports of the modal feed network, $\mathbf{x} = [x_1, x_2, \ldots x_N]^T$, are obtained from

$$\mathbf{x} = \mathbf{S_{ie}}^{-1}\,\mathbf{y} = \mathbf{S_{ei}}\,\mathbf{y}\,. \tag{6}$$

B. Practical feed network

It is often more practical to implement a modal feed network which produces orthogonal output vectors, but with an additional phase shift ϕ_m associated with mode *m*. The scattering parameters of the feed network are still characterized by (1) and (2), but in this case

$$\mathbf{S_{ie}} = \mathbf{P}\,\mathbf{\Phi}\,, \tag{7}$$

$$\mathbf{S_{ei}} = \mathbf{S_{ie}}^T = \mathbf{\Phi}\,\mathbf{P}^{-1}, \tag{8}$$

where

$$\mathbf{\Phi} = \mathrm{diag}[\exp(j\phi_1), \exp(j\phi_2), \ldots \exp(j\phi_N)] \tag{9}$$

and

$$\mathbf{P} = [\mathbf{e}_1 \;\; \mathbf{e}_2 \;\; \ldots \;\; \mathbf{e}_N]\,. \tag{10}$$

The S-parameters of the N-port network resulting from connecting the modal feed network to the array are then given by

$$\begin{aligned} \mathbf{S^d} &= \mathbf{S_{ei}}\,\mathbf{S_a}\,\mathbf{S_{ie}} \\ &= \mathbf{\Phi}\,\mathbf{P}^{-1}\,\mathbf{S_a}\,\mathbf{P}\,\mathbf{\Phi} \\ &= \mathrm{diag}[\lambda_1 \exp(j2\phi_1), \lambda_2 \exp(j2\phi_2), \\ &\qquad \ldots \lambda_N \exp(j2\phi_N)]. \end{aligned} \tag{11}$$

The signals required at the external ports of the modal feed network are related to the desired element excitations via

$$\mathbf{x} = \mathbf{S_{ie}}^{-1}\,\mathbf{y} = \mathbf{\Phi}^*\,\mathbf{P}^T\,\mathbf{y}\,, \tag{12}$$

with $\mathbf{\Phi}^*$ the conjugate of matrix $\mathbf{\Phi}$.

3. Example

To illustrate the principle, consider a simple 2-element dipole array. The S-parameters of the array are given by

$$\mathbf{S^a} = \begin{pmatrix} S^a_{11} & S^a_{12} \\ S^a_{12} & S^a_{11} \end{pmatrix}. \tag{13}$$

The eigenvalues of $\mathbf{S^a}$ are $\lambda_1 = S^a_{11} + S^a_{12}$ and $\lambda_2 = S^a_{11} - S^a_{12}$, while the orthonormal eigenvectors are given by

$$\mathbf{e}_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}, \quad \mathbf{e}_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}. \tag{14}$$

The modal feed network may be implemented as a rat-race 180° hybrid. With port numbering as defined in Fig. 2, the S-parameters of the hybrid are given by

$$\mathbf{S} = \frac{-j}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{pmatrix}. \tag{15}$$

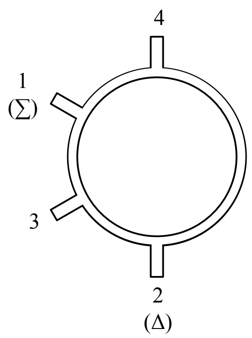

Fig. 2: Rat-race 180º hybrid acting as modal feed network.

In this case, we find that $\phi_1 = \phi_2 = -90°$. The S-parameters of the 2-port network resulting from connecting the hybrid to the array are obtained from (11) as

$$\mathbf{S^d} = \begin{pmatrix} -S^a_{11} - S^a_{12} & 0 \\ 0 & S^a_{12} - S^a_{11} \end{pmatrix}. \tag{16}$$

The combined network may then be matched by providing a suitable matching network at ports 1 and 2.

A prototype monopole array with an element spacing of 0.1λ was designed. The monopole length was chosen to provide an impedance match ($S_{11}^{a} \approx 0$) at a frequency of 2.6 GHz. The measured scattering parameters of the array are shown in Fig. 3. The reflection coefficient is small, but note that the mutual coupling is approximately −5 dB at 2.6 GHz.

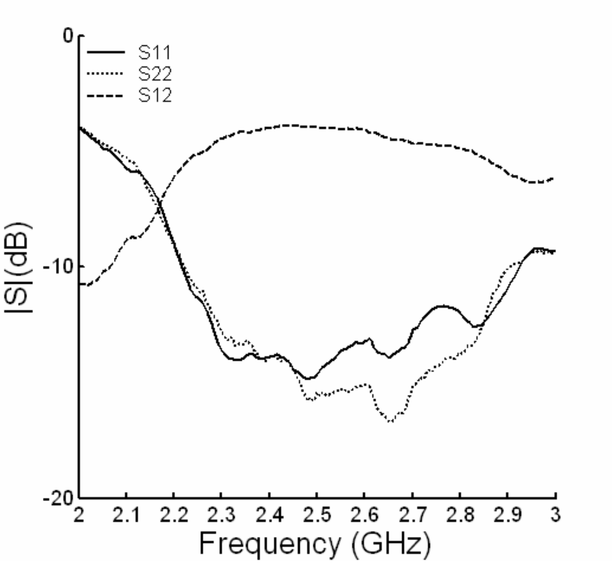

Fig. 3: Measured scattering parameters of the monopole array.

The 180º hybrid was connected to the array, and the scattering parameters were again measured. The results are shown in Fig. 4. The two ports are no longer matched, but according to (16), this is to be expected. However, note that the two ports are isolated, with the mutual coupling being less than −20 dB across the frequency band considered.

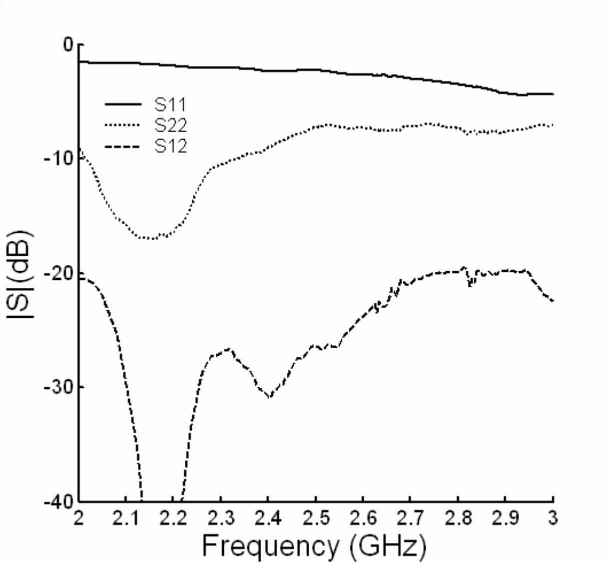

Fig. 4: Measured scattering parameters of the hybrid coupler connected to the monopole array.

Finally, the external ports were matched by introducing stubs at ports 1 and 2. The measured S-parameters are shown in Fig. 5. Decoupling and matching is achieved simultaneously, albeit over a narrow frequency band.

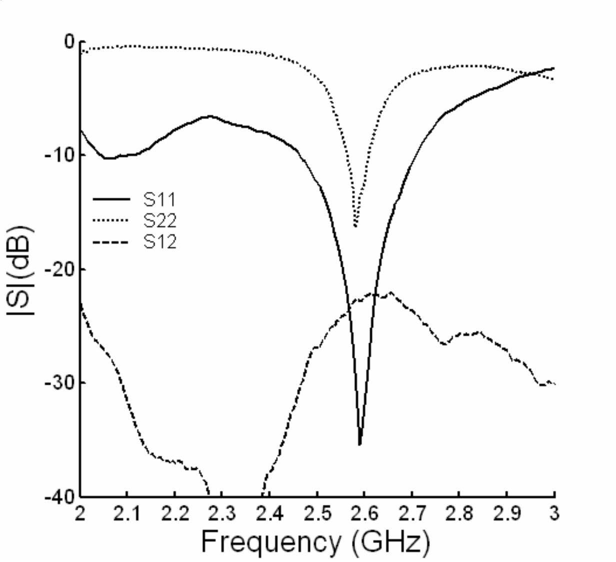

Fig. 5: Measured scattering parameters of the monopole array with matching networks at the external ports of the modal feed network.

4. CONCLUSION

The introduction of a modal feed network ensures isolation between the input ports of the system, which can then be matched independently. The frequency bandwidth of such a system is limited by the level of mutual coupling in the original array [8], but also depends on the extent of the impedance mismatch observed at the external ports of the modal feed network. In order to minimize the mismatch, it is desirable to start off with an array with matched elements, i.e. $\left|S_{11}^{a}\right|$ should be small. Theoretically, the alternative approach to port decoupling and matching presented in this paper is applicable to arrays with an arbitrary number of elements. However, the complexity in the implementation of the modal feed network may limit application of this method to smaller arrays.

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