Design of Decoupling Network for Monopole Four Square Array Antenna for Multi-Beam Applications

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***Abstract*— Multi-beam antennas can be used for sectorization of 360^o azimuthal coverage or diversity and MIMO concepts. One of the suitable realizations, where four monopoles antennas are placed at the corner of a square, is known as monopole four square array antenna to scan the beam in azimuth. In this paper a decoupling and matching network is presented to compensate for mutual coupling between array elements. The decoupling network design is based on the eigenmodes of the array admittance matrix and it is realized using microstrip lines.**

Keywords—antenna array; mutual coupling; decoupling network; matching network; port isolation.

I. INTRODUCTION

In multiport antennas for antenna diversity and MIMO, the design goal is to realize radiation patterns. For such goal to be achieved, element spacing of more than half-wavelength is required to inhibit the effects of mutual coupling. In applications where a space less than half-wavelength is available, strong mutual coupling will distort the beam patterns [1]. A decoupling network of reactive elements connecting neighbouring array's elements to compensate for mutual coupling was presented in [2] for two-element and three-element arrays based on the characteristic circuits for the eigenmodes [3]. This technique is only applicable where off-diagonal elements of the admittance matrix of the original array are all purely imaginary [4]. In this paper a decoupling network of reactive elements for the monopole four square array antenna with arbitrary complex mutual admittances is presented. In this method, the azimuth port pattern is modeled as a linear combination of mutually orthogonal azimuth eigenmodes patterns.

II. PROPERTIES OF MONOPOLE FOUR SQUARE ARRAY ANTENNA

The array structure of the Monopole Four Square Array Antenna (MFSAA) comprised of four monopole antenna elements is shown in Fig .1. The port currents $[I]$relates to the port voltages $[V]$according to

$$[I]=[Y][V] \tag{1}$$

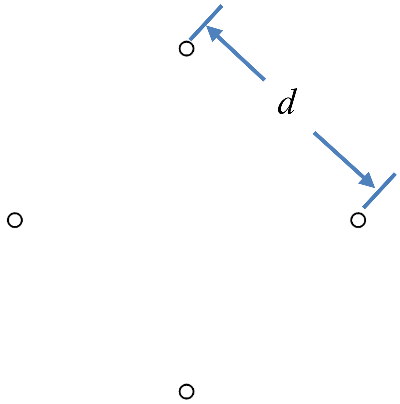

Fig. 1. Monopole four square array antenna (MFSAA) with monopole elements (length $l=0.25\lambda$, radius $r=0.01\lambda$) and element spacing $d=0.35\lambda$.

The array admittance matrix $[Y]$is given by

$$Y_{array}=\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{12} \\ Y_{12} & Y_{11} & Y_{12} & Y_{13} \\ Y_{13} & Y_{12} & Y_{11} & Y_{12} \\ Y_{12} & Y_{13} & Y_{12} & Y_{11} \end{bmatrix} \tag{2}$$

The eigenvalues of the MFSAA admittance matrix are given by $Y_{\text{mode1}}=Y_{11}+2Y_{12}+Y_{13}$, $Y_{\text{mode2}}=Y_{11}-Y_{13}=Y_{\text{mode3}}$,
$Y_{\text{mode4}}=Y_{11}-2Y_{12}+Y_{13}$,
while the corresponding orthonormal eigenvectors matrix is given by

$$U=\frac{1}{2}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix} \tag{3}$$

Numerical simulation for frequency dependent mode admittances and corresponding radiation patterns of the MFSAA structure in Fig. 1, were carried out with Empire XCcel. Fig. 2, and Fig. 3, show MFSAA modes admittances and corresponding normalized eigenmodes radiation patterns respectively. The eigenmodes patterns are created; so that antennas are excited based on the corresponding eigenvectors matrix in (3).

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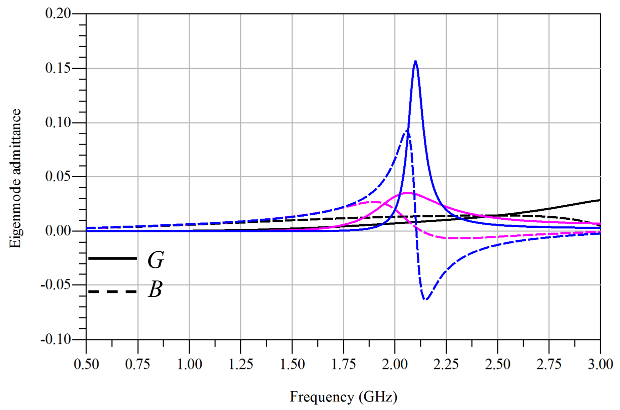


Fig. 2. Frequency dependent MFSAA eigenmodes admittances Y_{mode1} (black), $Y_{\text{mode2,3}}$ (pink), and Y_{mode4} (blue).

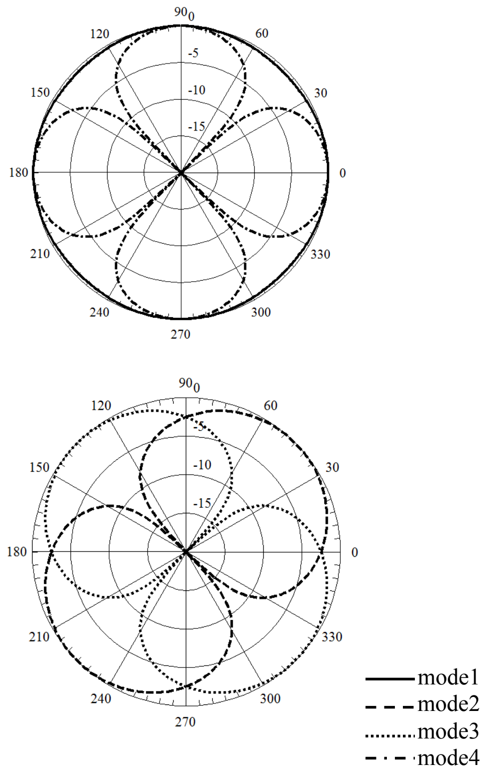


Fig. 3. Normalized azimuth radiation patterns of the MFSAA eigenmodes.

III. EFFECT OF MUTUAL COUPLING

The azimuth radiation pattern for port n $(n=1,2,..,4)$, is represented as a linear combination of the mutually orthogonal azimuth eigenmodes radiation patterns $C_m(\pi/2,\phi)$ $(m=1,2,..,4)$, of the array

$$C_n(\pi/2,\phi)=\sum_{m=1}^{4}u_{nm}\Lambda_m\rho_m C_m(\pi/2,\phi) \qquad (4)$$

where, Λ_m ,**is** the complex mismatch factor of eigenmode m , $(m=1,2,..,4)$, defined as [4]:

$$\Lambda_m=\frac{2\sqrt{G_m G_{in}}}{Y_m+Y_{in}} \qquad (5)$$

G_m, G_{in} are $\text{Re}\{Y_m\}$and $\text{Re}\{Y_{in}\}$respectively.

Due to coupling between array elements, the eigenmodes radiation patterns are now correlated. To model such effect, a frequency dependent complex factor ρ_m , is introduced in (4). The value of ρ_m is optimized so that good agreement between EM and (4) is achieved. $C_m(\pi/2,\phi)$, $(m=1,2,..,4)$, are mutually orthogonal eigenmodes radiation patterns, and u_{nm} **r**epresents corresponding elements in the unitary matrix U . As a test to model port pattern as linear combination of mutually orthogonal eigenmodes radiation patterns, Fig. 4 shows good agreement between EM numerical simulation and (4), when port 1 is excited and the other three ports are terminated in matched loads.

IV. DECOUPLING OF ANTENNA PORTS

Decoupling the MFSAA ports requires matching all eigenmodes admittances. In [5], an N – element array with k distinct eigenvalues required a decoupling network (DN) in $k-1$ stages where each stage consists of $2(k-1)$ series reactive elements X and $2(k-1)$ shunt reactive elements B . For the MFSAA, two stages of DN are required; in the 1st stage modes (1, 4) admittances are matched, while in the 2nd stage modes (1, 4) and modes (2, 3) are decoupled. Fig. 5 shows the MFSAA two-stage DN. The modal admittances as seen from the input ports $(1',2',3',4')$ and $(1'',2'',3'',4'')$ are obtained

$$Y'_{\text{mode1}}=(Z_{\text{mode1}}+jX_1)^{-1}+jn'_1B_1$$

$$Y'_{\text{mode2}}=(Z_{\text{mode2}}+jX_1)^{-1}+jn'_2B_1=Y'_{\text{mode3}}$$

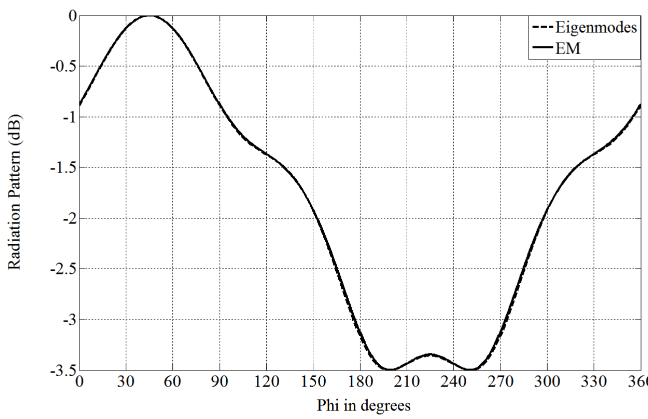


Fig. 4. Port radiation pattern $C_1(\pi/2,\phi)$, simulated in Empire XCcel (solid) and derived from (4), (dashed).

$$Y'_{\text{mode}4} = (Z_{\text{mode}4} + jX_1)^{-1} + jn'_4 B_1$$

$$Y''_{\text{mode}1} = (Z'_{\text{mode}1} + jX_2)^{-1} + jn''_1 B_2$$

$$Y''_{\text{mode}2} = (Z'_{\text{mode}2} + jX_2)^{-1} + jn''_2 B_2 = Y''_{\text{mode}3} \quad (6)$$

$$Y''_{\text{mode}4} = (Z'_{\text{mode}4} + jX_2)^{-1} + jn''_4 B_2$$

where n_i ,($i = 1,2,..,4$), are parameters depending on the topology and the eigenmodes under consideration. Closed-form design equations for calculating the values of reactive elements X and B are taken from [2]. Impedance parameters and reactive elements values for MFSAA are given in Table I.

$$X = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (7)$$

$$B = \frac{1}{n}\left(\frac{X_{\text{mode}2} + X}{R^2_{\text{mode}2} + (X_{\text{mode}2} + X)^2} - \frac{X_{\text{mode}1} + X}{R^2_{\text{mode}1} + (X_{\text{mode}1} + X)^2}\right)$$

where, $c = R_{\text{mode}1}(R^2_{\text{mode}2} + X^2_{\text{mod}e2}) - R_{\text{mode}2}(R^2_{\text{mode}1} + X^2_{\text{mode}1})$, $b = 2(R_{\text{mode}1} X_{\text{mode}2} - R_{\text{mode}2} X_{\text{mode}1})$,and $a = R_{\text{mode}1} - R_{\text{mode}2}$.

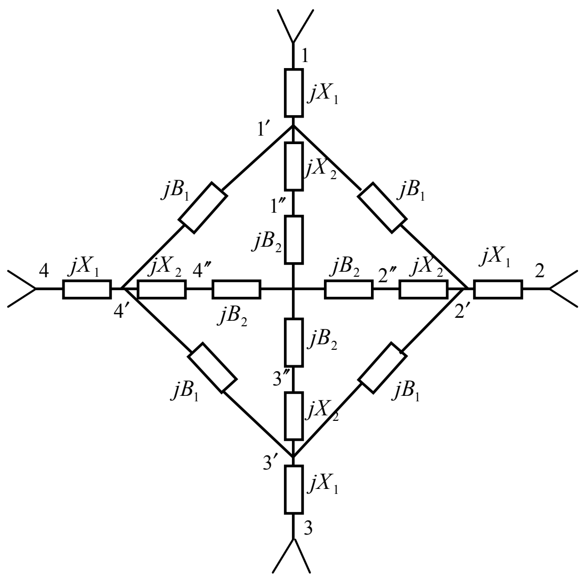


Fig. 5. Decoupling network series and shunt reactive elements of the MFSAA.

TABLE I. MFSAA IMPEDACE PARAMETERS AND ITS DMN REACTIVE ELEMENT VALUES.

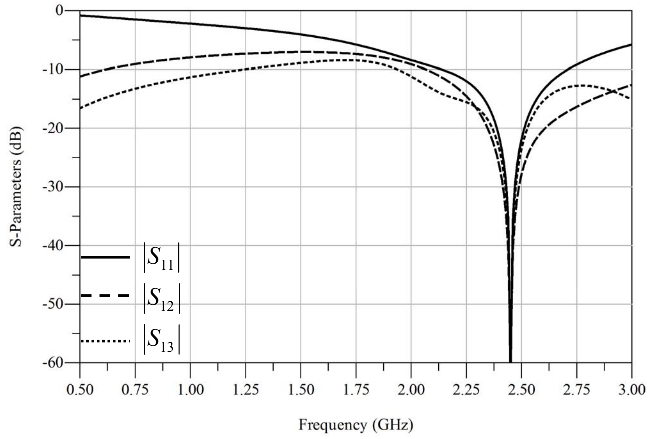
Array input impedance parameters at matching frequency 2.45 *GHz*	$Z_{11} = 46.867 + j18.502$ $Z_{12} = 2.603 - j23.268$ $Z_{13} = -17.268 - j9.061$
Decoupling network 1st stage	$X = -11.9409$ $B = 0.0077$
Decoupling network 2ndstage	$X = 17.7438$ $B = 0.0143$
Matching network	$X = 51.1909$ $B = 0.0211$

Admittance matrices for 1st and 2nd stage are obtained to be

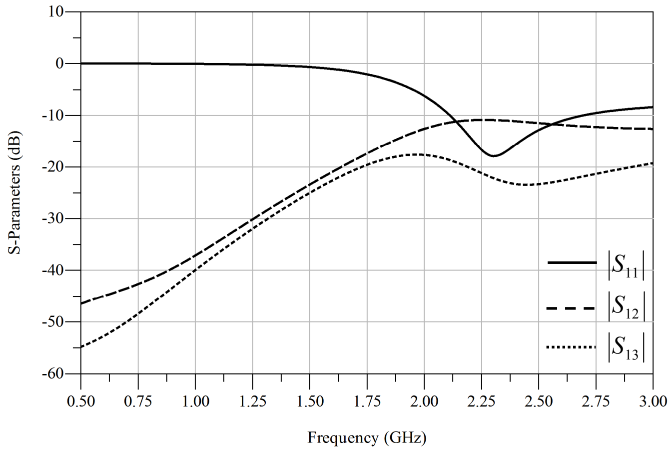
$$Y'_{DN} = \begin{bmatrix} j2B_1 & -jB_1 & 0 & -jB_1 \\ -jB_1 & j2B_1 & -jB_1 & 0 \\ 0 & -jB_1 & j2B & -jB_1 \\ -jB_1 & 0 & -jB_1 & j2B \end{bmatrix} \quad (8)$$

$$Y''_{DN} = \begin{bmatrix} j\frac{3}{4}B_2 & -j\frac{1}{4}B_2 & -j\frac{1}{4}B_2 & -j\frac{1}{4}B_2 \\ -j\frac{1}{4}B_2 & j\frac{3}{4}B_2 & -j\frac{1}{4}B_2 & -j\frac{1}{4}B_2 \\ -j\frac{1}{4}B_2 & -j\frac{1}{4}B_2 & j\frac{3}{4}B_2 & -j\frac{1}{4}B_2 \\ -j\frac{1}{4}B_2 & -j\frac{1}{4}B_2 & -j\frac{1}{4}B_2 & j\frac{3}{4}B_2 \end{bmatrix}$$

The coupling admittances in (2), are not purely imaginary, the DN was optimized using ADS gradient optimizer to realize minimum coupling between array elements. The ports are matched to the system impedance Z_0 using L -section impedance matching networks [6]. Good port isolation and return loss obtained after the DN and matching network are both realized as shown in Fig. 6a, compared to the scattering parameters for MFSAA without decoupling and matching network (DMN) as Fig. 6b, shows.



(*a*)



(*b*)

Fig. 6. Scattering parameters of (a) MFSAA with and (b) without DMN.

V. REALIZATION OF DECOUPLING MATCHING NETWORK

The decoupling and matching network designed above was based on lossless concentrated capacitors and inductors. This network of ideal lumped elements has to be converted to a realizable form. One convenient way of realization uses microstrip lines (MSL) for connecting ports and realizing reactive elements by replacing the capacitors and inductors with open and short circuit stubs calculated so that

$$\theta_{sc} = \tan^{-1}\left(\frac{\omega L}{Z_0}\right)$$
$$\theta_{oc} = \tan^{-1}(\omega C Z_0) \quad (9)$$

A microstrip line DMN was designed and optimized so that good isolation between ports was achieved. Fig. 7 shows the scattering parameters of the DMN.

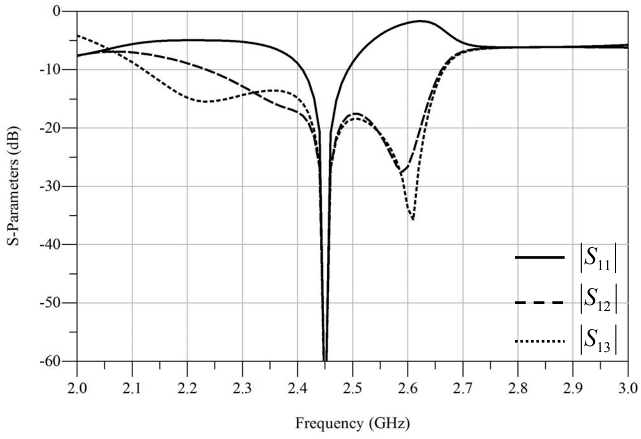


Fig. 7. Scattering parameters of microstrip line DMN.

The layout of the MSL DMN is shown in Fig. 8. Presently, the designed MFSAA with DMN is under production in order to be investigated experimentally. Measurement results will be presented at the conference.

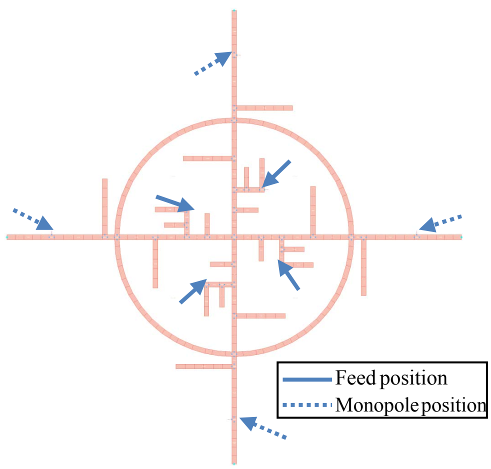


Fig. 8. Layout of the microstrip line decoupling matching network for the MFSAA.

VI. CONCLUSION

A decoupling matching network for the MFSAA was described. The first approach was illustrated using lossless concentrated capacitors and inductors, while in the second approach; the DMN was realized using MSL. Single frequency decoupling networks are usually characterized by narrow bandwidths. Bandwidth enhancement can be achieved by replacing each reactive element in the single frequency decoupling network with either a series or parallel combination of an inductor and a capacitor. For matching network, two or more stages of L-section network can possibly also enhance the bandwidth.

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