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Decoupling technique for n-element linear array antenna using transmission lines between neighboring elements

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Abstract: In this letter, a design method of a simple decoupling network (DN), which decouples adjacent antenna ports for n-element linear array antenna, is presented and evaluated based on simulation and measurements. In our technique, microstrip line (MSL) is used to configure DN. MSLs work as bridge susceptances and are connected between two adjacent antenna ports, and they decouple the antenna ports by means of cancelling the mutual admittance. From the experimental results, it is found that the mutual coupling less than -30 dB between adjacent antenna elements is achieved by using proposed design method.

Keywords: decoupling network, mutual coupling, transmission line, array antenna, MIMO

Classification: Antennas and Propagation

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1 Introduction

In order to enhance the performance of the wireless communication systems, multi-antenna systems, such as MIMO (Multiple-Input Multiple-Output), and so on, have been studied [1, 2]. However, the communication quality is deteriorated by the effect of mutual coupling in such multi-antenna systems [3]. Therefore, the mutual coupling reduction technique is needed in multi-antenna systems. To reduce the effect of the mutual coupling, decoupling network (DN) can be used. Studies about DN have been pursued [4, 5] and in [4], a deterministic design theory of decoupling and matching network (DMN) for n element array is denoted. However, this DMN has narrowband property and its complexity of circuit configuration dramatically increases as the number of antenna elements increases. In [5], the circuit design method by using transmission lines and lumped element is described. This method can be applied only for two elements antenna configuration, and the expansion of this method to n elements antenna configuration has not been studied. As explained above, simple DN which can be applicable to n elements array antenna is needed. When we focus on a n element linear array antenna, the mutual coupling between adjacent antenna elements is higher than that of other antenna combinations. This means suppression of the mutual coupling just among adjacent antenna elements will efficiently enhance the array antenna performance.

In this letter, a design method of a simple decoupling network suitable for n element linear array antenna is presented. In order to simplify the DN configuration, only adjacent antenna elements are decoupled in the proposed design. To achieve the decoupling network with simple and feasible configuration, it is configured by using only MSL. In the following section, the proposed circuit design theory is explained first. Next, the circuit characteristic is evaluated based on simulation and measurement.

2 Circuit design theory

Fig. 1 shows the sketch of the antennas and DN configuration [6]. In Fig. 1, $\boldsymbol{Y}_a$, $\boldsymbol{Y}_l$, $\boldsymbol{Y}_d$, $\boldsymbol{Y}$ are the admittance matrices of the array antenna, transmission line, DN and synthesized circuit observed at the reference plane 1, respectively. Since the antenna and DN are connected in parallel, the synthetic admittance matrix, $\boldsymbol{Y}'$, can be written as

$$\boldsymbol{Y}' = \boldsymbol{Y} + \boldsymbol{Y}_d. \quad (1)$$

Decoupling between two neighboring antenna ports is realized by forcing

$$Y_{d,k+1,k} = -Y_{k+1,k}, \quad (2)$$

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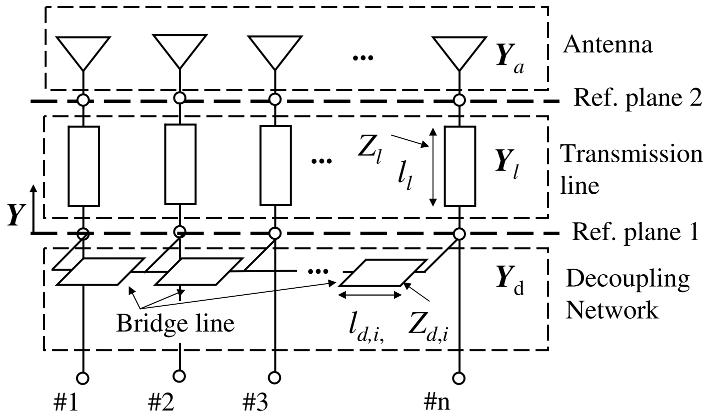

Fig. 1. Proposed DN configuration

where k is integer number, $1 \leq k \leq n-1$. The mutual coupling between two neighboring antenna elements can be cancelled by connecting a reactance element between these antenna ports if the mutual admittance is purely imaginary. However, the antenna mutual admittance has generally not only the imaginary value but also real value. To obtain the purely imaginary value of the mutual admittance, the serial transmission lines for phase rotation whose lengths are l_l are used. Assuming MSL is lossless transmission line, the admittance matrix elements of i-th $(1 \leq i \leq n)$ transmission line are expressed as

$$Y_{li,i} = Y_{ln+i,n+i} = \frac{1}{Z_l}\frac{\cos\beta_l l_l}{j\sin\beta_l l_l}, \tag{3}$$

$$Y_{ln+i,i} = Y_{li,n+i} = \frac{-1}{Z_l}\frac{1}{j\sin\beta_l l_l}, \tag{4}$$

where, Z_l and β_l are the characteristic impedance of the transmission line and the phase constant, respectively. These parameters are given identically for all of the serial lines. Therefore, $\boldsymbol{Y}_l$ is defined as $2n \times 2n$ matrix and can be partitioned into four matrices as

$$\boldsymbol{Y_l} = \begin{pmatrix} \boldsymbol{Y}_{l11} & \boldsymbol{Y}_{l12} \\ \boldsymbol{Y}_{l21} & \boldsymbol{Y}_{l22} \end{pmatrix}, \tag{5}$$

where, the size of each partitioned matrices are $n \times n$. Each of partitioned matrix is diagonal matrix defined by (3), (4). By using these partitioned matrices and $\boldsymbol{Y}_a$, the observed matrix,$\boldsymbol{Y}$, at the reference plane 1 is expressed as [6]

$$\boldsymbol{Y} = \boldsymbol{Y}_{l11} - \boldsymbol{Y}_{l12}(\boldsymbol{Y}_a + \boldsymbol{Y}_{l22})^{-1}\boldsymbol{Y}_{l21}. \tag{6}$$

By using (3), (4) and (6), the line length l_l which achieves purely imaginary mutual admittance can be determined. Therefore, the mutual coupling can be cancelled by connecting a reactance element. In our technique, the reactance element is configured by using a bridge MSL as a bridge susceptance. The bridge susceptance can be realized by using the bridge MSL if its length satisfies $\beta_d l_d = \pi/2 + m\pi$, $(m \geq 0)$. Where, β_d and l_d are the phase constant

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and length of the bridge MSL, respectively. Structurally, the length of bridge susceptance must be longer than the antenna space, d. Therefore,

$$l_d = \lambda_g/2(1/2 + m) \geq d \tag{7}$$

must be satisfied, where, λ_g is effective wavelength in the bridge susceptance. Similarly to (4), mutual admittance of the bridge susceptance can be expressed as

$$Y_{d,i+1,i} = Y_{d,i,i+1} = \frac{j}{Z_{d,i}}(-1)^m. \tag{8}$$

To satisfy (2), (7), m and characteristic impedance of the bridge MSL must be properly determined. The characteristic impedance of the bridge MSL is derived by considering the transformed mutual admittance of the antennas shown in (6). From the absolute value of the antenna's mutual susceptance, $Y_{i+1,i}$, the characteristic impedance of bridge line is derived as

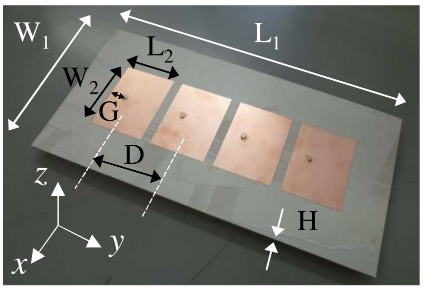
$$Z_{d,i} = \frac{j(-1)^m}{Y_{i+1,i}}. \tag{9}$$

Note that, m must be chosen to satisfy $Z_{d,i} > 0$.

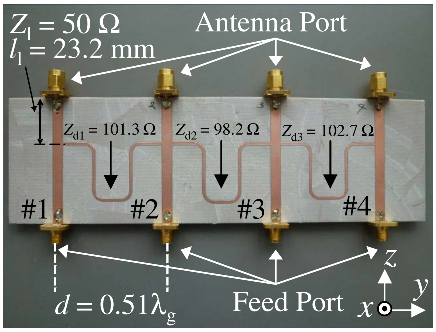
3 Measurement and simulation

3.1 Fabricated antenna and DN

Fig. 2 (a) shows the fabricated antenna. The antenna is 4-elements E-plane patch array. The operation frequency, f_0, is 2.085 GHz. The dimension of the antenna is described as follows; $W_1 = 140$ mm, $L_1 = 280$ mm, $W_2 = 65$ mm, $L_2 = 47.1$ mm, $G = 14.5$ mm, $D = 140$ mm and $H = 1.6$ mm. The antenna is configured on the Polytetrafluoroethylene (PTFE) substrate, and its relative permittivity is 2.2. Fig. 2 (b) shows the fabricated DN. The same substrate is used for the DN. The DN was designed by using the circuit design theory described in Section 2 and its design value was calculated based on measured antenna admittance matrix, that is, we assume this antenna admittance matrix as $\boldsymbol{Y}_a$. From calculation result, the length of serial transmission line,



(a) Fabricated antenna



(b) Fabricated DN

Fig. 2. Fabricated antenna and DN

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l_l, is 23.2 mm from (3), (4) and (6). The length of the bridge MSL is determined as $3\lambda_g/4$ ($\beta_d l_d = 3\pi/2$) from (7). The characteristic impedances of the bridge MSLs are calculated by using (9) and calculated values are as follows; $Z_{d1} = 101.3\,\Omega$, $Z_{d2} = 98.2\,\Omega$ and $Z_{d3} = 102.7\,\Omega$. By determining characteristic impedance of the bridge MSL, the width of the bridge line which achieves desired impedance is determined. It should be noted that l_l is determined by considering the phase delay of the connector.

3.2 Results

3.2.1 Simulation result

Fig. 3 (a) shows simulated S-parameter. The frequency characteristics of the DMN in [4], which decouples all the antenna elements are also indicated in Fig. 3 (a) for comparison. Here, the reflected characteristics of only $|S_{11}|$ and $|S_{22}|$ are shown since the antenna structure is symmetric. From Fig. 3 (a), it can be seen that the fractional bandwidth ($|S_{11}| \leq -10$ dB) with proposed DN and with [4] are 1.247% and 0.0959% respectively. $|S_{21}|$ and $|S_{32}|$ can be decreased to about 30 dB at resonant frequency by using proposed DN. It can be seen that the impact of the proposed DN on $|S_{31}|$, $|S_{41}|$ is negligible. This is because the proposed DN decouples only two adjacent antenna elements.

3.2.2 Measurement result

Fig. 3 (b) shows measured S-parameter. From Fig. 3 (b), it can be seen that the operation frequency with fabricated DN is slightly shifted. The reason of this is considered that self admittance of the fabricated bridge line was not zero, and it affects the self-admittance observed at the feed port. That is, the manufacturing error of bridge MSL length can affect the reflection coefficient. By using proposed DN, the mutual coupling between two adjacent antenna ports, $|S_{21}|$ and $|S_{32}|$, was decreased to less than -30 dB at the operation frequency. From Fig. 3 (b), the levels of $|S_{21}|$, $|S_{32}|$, $|S_{31}|$ and $|S_{41}|$ around $2.1 \sim 2.2$ GHz are higher than that of Fig. 3 (a). The reason of this is considered the bridge susceptances between antenna ports deteriorate the mutual coupling around this frequency band. Fig. 3 (c) shows measured E-plane radiation pattern. Since the antenna structure is symmetric, the radiation patterns of 1st and 2nd antenna are only shown. From Fig. 3 (c), radiation patterns with and without DN differ slightly, and radiation pattern distortion can be seen. It is considered this distortion is caused by change of antenna port current resulted from connecting DN.

4 Conclusion

In this letter, the design method of the simple DN, which decouples adjacent antenna ports in n-element linear array antenna has been presented. The design method of the DN using MSL is explained. Decoupling is realized by connecting MSLs between adjacent antenna ports as a bridge susceptance. From simulation results, the impact of proposed DN on bandwidth is negligible. From experimental results, by using proposed DN, the mutual coupling

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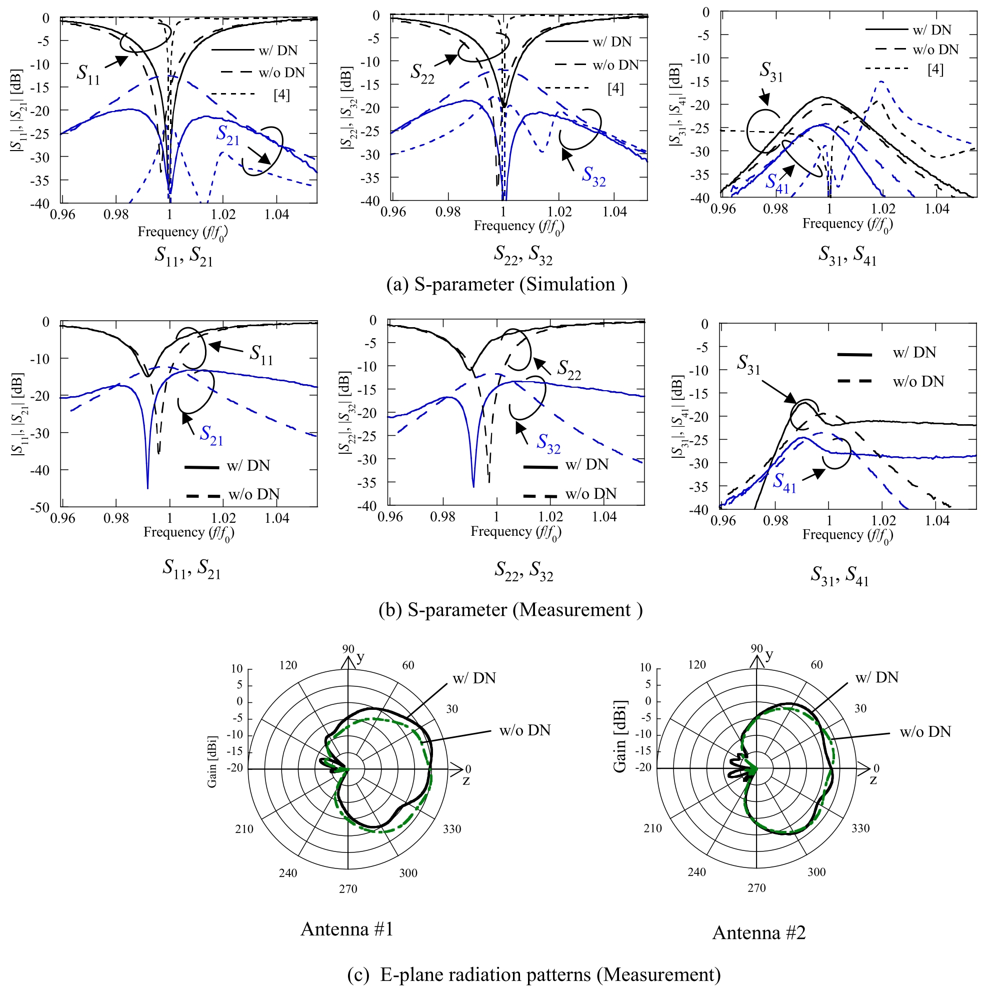

Fig. 3. Frequency characteristics of S-parameter and measured radiation pattern

between two neighboring antenna ports is suppressed less than −30 dB at the resonant frequency. These results prove that the proposed design method is effective in achieving DN with low circuit complexity.

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