1. Introduction

When performing the power transmission and signal reception simultaneously in wireless power transmission system, a strong transmitted signal leaks into the receiving antenna due to the mutual coupling between the transmitting and receiving antennas. Although a DN (Decoupling Network) is effective in suppressing this undesirable leakage [1], [2], there is a problem that the decoupling characteristic is degraded due to the movement of the scattering objects around the antenna.

In this paper, a tunable DN comprising transmission lines and lumped elements is proposed. The DN is configured with the bridge resistance and the transmission lines for phase rotation of the antenna mutual admittance. In order to achieve a simple tunable mechanism, either the value of the bridge resistance or the length of MSL (Microstrip Line) for phase rotation is set to be variable. To evaluate the DN performance, the mutual coupling characteristics is measured with a various distance between the antenna and the object. Based on the measurement results, it is denoted that the proposed DN can suppress the mutual coupling under the situation where the mutual coupling varies.

2. Configuration of the proposed tunable DN

This section describes configuration of the DN using transmission lines and lumped elements. Figure 1 shows the configuration of the proposed tunable DN. Here, \( Y_a \) is the admittance matrix of the antenna. \( Y_f \) is the admittance matrix of the transmission lines for tuning the phase of the mutual admittance of the antennas, and the length and characteristic impedance of these lines are defined as \( l_f \) and \( Z_f \), respectively. As shown in Figure 1 (a), a bridge resistance \( R \) is inserted between the two bridge MSLs with the characteristic impedance \( Z_0 \). When the line length of bridge MSLs are \( \lambda_g/2 \) (\( \lambda_g \): effective wavelength), the part of bridge circuit is simplified to a purely resistive element. The admittance matrix of the bridge circuit comprising the MSL and resistance is defined as \( Y_d \). Figure 1 (b) shows an equivalent circuit of the proposed tunable DN. In Fig. 1 (b), \( \gamma'_{12} \) is the mutual admittance, representing the mutual coupling between the antennas. When \( \gamma_b = \gamma'_{12} \), the mutual admittance between the feeding port 1 and port 2 would be zero, and the mutual
coupling is cancelled. Since \( R = 1/y_b \), \( y'_{12} \) must be real positive value to be successfully cancelled by the bridge resistance. Therefore, the length, \( l_f \), of the MSL for the phase rotation is determined to transform \( y'_{12} \) to a real value. However, if the scatterer around the antenna is moved, the decoupling effect is reduced due to the changes in the mutual admittance of the antenna. To resolve this issue, there are three scenarios that can be considered for the tunable DN. The first one is use of the tunable bridge resistance. The second one is use of the variable length MSL for the phase rotation. The third one is use of both tunable bridge resistance and variable MSL. In this study, for simplicity of DN configuration, the scenarios, where either of the resistance and MSL is variable, are considered.

3. Measurement and calculation

3.1 Calculation method of tunable parameters

First, the antennas are placed in some reference position. Then the MSL length \( l_f \) and the resistance value \( R \) are calculated by using the following formula.

The admittance matrix of the MSL for phase rotation, \( Y_f \), is split into four partitioned matrices as

\[
Y_f = \begin{pmatrix}
Y_{f11} & Y_{f12} \\
Y_{f21} & Y_{f22}
\end{pmatrix},
\]

where the subscript numbers represent the reference planes shown in Fig.1 (a). When the \( Y_f \) is connected to the \( Y_a \), the observed admittance matrix at the end of the phase rotation MSL is obtained as

\[
Y' = Y_{f11} - Y_{f12}(Y_a + Y_{f22})^{-1}Y_{f21}.
\]

The case of the lossless transmission lines, \( Y_f \) is determined by the line length \( l_f \) and the characteristic admittance \( Y_f \). Additionally, \( Y_{f11}, Y_{f12}, Y_{f21}, Y_{f22} \) is given by

\[
Y_{f11} = Y_{f22} = -jY_f \text{diag} [\cot \beta l_f, \cot \beta l_f] \quad (3)
\]

\[
Y_{f12} = Y_{f21} = jY_f \text{diag} [\csc \beta l_f, \csc \beta l_f] \quad (4)
\]

where \( \beta \) is a phase constant in the phase rotation MSL. From (2), the MSL length \( l_f \) which makes the imaginary part of \( y'_{21} \) (\( y'_{11} \) is the off-diagonal elements of (2)) zero is obtained by

\[
l_f = \frac{1}{\beta} \tan^{-1} \left( \frac{2A}{-B \pm \sqrt{B^2 - 4AC}} \right).
\]

Here, \( A, B, C \) is described as

\[
A = Y_f^2 y_{a12i} \quad (6)
\]

\[
B = -Y_f [y_{a12r}(y_{a11r} + y_{a22r}) + y_{a12i}(y_{a11i} + y_{a22i})] \quad (7)
\]

\[
C = y_{a12r}(y_{a11r}y_{a22i} + y_{a22r}y_{a11i} - y_{a12r}y_{a22r} - y_{a12i}y_{a22i}) - y_{a12i}(y_{a11r}y_{a22i} - y_{a11i}y_{a22i} + y_{a12r}y_{a22r}) \quad (8)
\]

At this time, the resistance value \( R \) is obtained from \( R = 1/\text{Real} \{y'_{21}\} \). Then, the bridge resistor is connected between the antennas to achieve decoupling effect. So the admittance matrix of the DN is represented by

\[
Y_d = \begin{pmatrix}
y_{b} & -y_{b} \\
-y_{b} & y_{b}
\end{pmatrix} = \begin{pmatrix}
1/R & -1/R \\
-1/R & 1/R
\end{pmatrix}.
\]

Since the DN is connected in parallel with antenna, the observed admittance matrix \( Y'' \) is denoted as

\[
Y'' = Y' + Y_d.
\]

From (10), it is found that the decoupling effect can be obtained because the off-diagonal elements of \( Y'' \) would be zero. Though the diagonal elements of \( Y'' \) would be changed, the effect on the reflection characteristics can be normally negligible because the element of \( Y_d \) is quite small compared with the diagonal component of \( Y' \).
3.2 Measurement model

This section describes the measurement model and the method of the calculation for decoupling distance property using the measurement value. Figure 2 shows the configuration of the measurement model dealt with in this report. Transmitting and receiving antennas are rectangular MSA (Microstrip Antenna) with vertical polarization, and the feeding ports 1 and 2 are used to transmit and receive, respectively. The terminal antenna is vertically polarized rectangular MSA and the feeding port 3 is terminated by 50 Ω resistance. In the transmitting and receiving antennas, the dimensions are given as \( d = 62.5 \) mm, \( W_1 = 62.5 \) mm, \( L_1 = 125 \) mm, and \( W_2 = L_2 = 40.98 \) mm. In the terminal antenna, the dimensions are \( W_3 = L_3 = 125 \) mm, \( W_4 = L_4 = 40.7 \) mm. In addition, the resonant frequency of all antennas is 2.4 GHz, and distance between the transmitting/receiving antenna and the terminal antenna is \( D \).

Then, distance, \( D \), is varied with the 2.5 mm step from 0.35 m to 0.65 m. The transmitting/receiving antennas are moved by the positioner using a LEGO NXT, and the S-parameters of transmitting/receiving antennas is measured at each distance. For the various the distance, the bridge resistance value \( R \) and the line length \( l_f \) of MSL is calculated. First, the bridge resistance value \( R \) and the line length \( l_f \) of MSL suitable for the reference distance are determined by the theory described in the previous section, where the reference distance is set to \( D = 0.5 \) m. After that, the DN performance under the constraint either of \( R \) and \( l_f \) is fixed is evaluated. In this evaluation, the value of the \( R \) or \( l_f \) is determined so as to minimize the mutual coupling.

4. Calculation results using the measurement value

Figure 3 shows the change in mutual admittance, \( y'_{21} \), when the MSL length \( l_f \) for phase rotation is changed from 0 to \( \lambda_g \). Here, the characteristic impedance of MSL for phase rotation is \( Z_f = 50 \) Ω, the calculation results with \( D = 0.4 \) m and \( D = 0.5 \) m are shown. By changing the MSL length, \( l_f \), it can be seen that the phase of the mutual admittance component, \( y'_{21} \), is rotated and \( y'_{21} \) can be transformed into a real number if the appropriate \( l_f \) is adopted. In addition, it can be also seen that the changes in \( y'_{21} \) is different if distance between the antennas is different. In Fig. 4, the behaviour of the MSL length \( l_f \) and the resistance value \( R \) versus the antenna distance, \( D \). Here, these values were calculated from (5). It can be confirmed that the changes in the MSL length \( l_f \) and the resistance value \( R \) are both depending on distance between transmitting/receiving antenna and terminal antenna. Also, the change in resistance value \( R \) is relatively greater than that of the MSL length \( l_f \). Figure 5 shows the distance property of reflection characteristic \( S_{11} \) at the resonant frequency. By comparing the results with and without DN, it is found that there is no significant change in \( S_{11} \) even when the tunable DN is used. Figure 6 shows the mutual coupling \( S_{21} \) versus the antenna distance. Here, the coupling characteristics of fixed DN, whose MSL length \( l_f \) and resistance value \( R \) are reference value, is also shown. From Fig. 6, it can be seen that the mutual coupling \( S_{21} \) is decreased in both cases of the parameter is fixed and tunable. However, compared to the case of fixed DN, there is no additional effect in reducing the mutual coupling \( S_{21} \) if the MSL length \( l_f \) for phase rotation is tunable. On the other hand, a large reduction in the mutual coupling is obtained if the bridge resistance value \( R \) is tunable. In terms of the average \( S_{21} \), the mutual coupling can be suppressed by about 32.1dB. For the results above, it is found that the improvement effect of mutual coupling is greater when the bridge resistance value \( R \) is tunable.

5. Conclusion
In this paper, a tunable DN comprising transmission lines and lumped elements has been proposed.
Even if there are changes in the distance between transmitting/receiving antenna and terminal antenna, the mutual coupling between antennas is greatly improved by using the proposed tunable DN. When the bridge resistance value $R$ was tunable, the mutual coupling has been improved by about 32.1dB in average with the various antenna distances. From the results above, it is revealed that the proposed DN with variable the bridge resistance yields high decoupling effect under the situation where the scattering object around the antenna moves.

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**References**
