A simultaneous conjugate-matching algorithm for $N$-element array antennas

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Abstract: This paper presents an automatic impedance-matching algorithm that can sequentially realize a simultaneous conjugate-matching state for all the elements in an $N$-element array antenna. The analytical results show that the converged solution obtained from the proposed algorithm agrees well with the solution calculated by the analytical deterministic equation, confirming the validity of the proposed method. The method can be applied to MIMO array antennas.

Keywords: simultaneous conjugate-matching, sequential algorithm, MIMO array antenna

Classification: Antennas and Propagation

References


1 Introduction

In mobile terminals, degradation of throughput occurs because of the bio-electromagnetic effects generated between the users and the terminal. In [1], it is reported that the multiple-input multiple-output (MIMO) antenna applied to the conjugate-matching, denoted as CM in [1], has a higher channel capacity compared with the self-matching condition, denoted as Z11 in [1], when the bandwidth is less than ±1% with an antenna separation of 0.05λ (see Figs. 16 and 17 in [1]). In the LTE systems, the frequency bandwidth is 20 MHz, which is 1% for the center frequency of 2 GHz. Therefore, the conjugate-matching is advantageous to the LTE MIMO systems to increase the channel capacity.

In [2], it is reported that the matching efficiency of the multiport conjugate match is higher than that of the input impedance match (see Fig. 10 in [2]), in which the input impedance match is equivalent to the conjugate-matching introduced in [1]. Therefore, the matching efficiency of the conjugate-matching will be lower than that of the multiport conjugate match. However, the multiport conjugate match needs to be applied to both transmitting and receiving sides simultaneously. Thus, we use the conjugate-matching because it can be achieved only at receiving side.

The methods described in [2, 3, 4, 5] must determine the analytical solution for non-linear equation to achieve the conjugate-matching. However, it is difficult for a MIMO mobile terminal to achieve the conjugate-matching using the analytical method because self and mutual impedances are needed to analyze the non-linear equation. Moreover, self and mutual impedances may be affected significantly when the terminal is used in the vicinity of the human body or the metal object. Therefore, a sequential method for achieving the conjugate-matching is required.

In this paper, we propose an optimum algorithm that can sequentially realize simultaneous conjugate-matching state for all the elements in an N-element array antenna [6]. The validity of the proposed method was verified, which indicates that our algorithm can be applied to MIMO array antennas.

2 Automatic matching algorithm

Fig. 1 shows the structure of an N-element array antenna including an impedance matching circuit (MC). In Fig. 1, \( Z_{Lk} \) and \( Z_{nk} \) (\( k = 1 ~ N \)) indicate the complex impedance at the load side and at the antenna side, respectively.

The purpose of the proposed method is to achieve a conjugate match \( Z_{Lk} = Z_{nk}^* \) in each element, where the asterisk (*) denotes the complex conjugate. The following procedure demonstrates the proposed algorithm when \( N = 2 \):

1. Determine \( Z_{in1} \) (\( Z_{L2} = 50 \Omega \) as an initial value).
2. Make \( Z_{L1} = Z_{in1}^* \) by adjusting MC1.
3. Determine \( Z_{in2} \).
4. Make $Z_{L2} = Z_{in2}^*$ by adjusting MC2.
5. Back to the step 1 to determine $Z_{in1}$.

Step 1 to Step 5 is repeated until $|Z_{Lk} - Z_{ink}^*| < \varepsilon$ (\varepsilon: Residual target).

Although the procedure mentioned above is exemplified for $N = 2$, the proposed method can be applied to any number of elements. For example, when $N = 3$, the algorithm can be used by adding the following two steps between Step 4 and Step 5: Determine $Z_{in3}$, Make $Z_{L3} = Z_{in3}^*$ by adjusting MC3.

Using the abovementioned algorithm, simultaneous conjugate-matching state for all the elements in an $N$-element array antenna is possible, irrespective of the structure of the array antenna.

![Fig. 1. Proposed method of a sequential automatic impedance-matching.](image)

### 3 Realization of the proposed algorithm

In order to realize the proposed algorithm, the circuit configuration mounted on a terminal needs to be clarified. Fig. 2 shows the configuration of matching circuit for one element. The matching circuit (MC1) of the antenna #1 is shown in detail, and that of the other antennas is not shown for simplicity. The matching circuit shown in Fig. 2 is a typical example because the circuit configuration may change depending on the type of antenna. To achieve the conjugate-matching, the complex impedances $Z_{Lk}$ and $Z_{ink}$ ($k = 1 \sim N$), as shown in Fig. 1, are needed. In Fig. 2, the complex impedances can be obtained by extracting signals from the three ports (A1, B1 and C1) using two directional couplers and a switch SW1.

The voltage reflection coefficient $\Gamma_{in1}$ with respect to the reference-plane (a) between MC1 and antenna #1 shown in Fig. 2, is calculated from Eq. (1),

\[
\Gamma_{in1} = \frac{V_{1,Ar}}{V_{1,At}}
\]

where the voltage $V_{1,At}$ is a transmission voltage that is applied to MC1 from the source $V_{g1,At}$, and it is measured at port C1 when SW1 selects $S_A$. The voltage $V_{1,Ar}$ is a reflection voltage flowing from the antenna #1 to MC1, and it is measured at port
A1 when SW1 selects S_A. Then the complex impedance $Z_{in1}$ can be calculated using Eq. (2),

$$Z_{in1} = Z_0 \frac{1 + \Gamma_{in1}}{1 - \Gamma_{in1}}$$

where $Z_0 = 50\, \Omega$.

On the other hand, the voltage reflection coefficient $\Gamma_{L1}'$ with respect to the reference-plane (a)' shown in Fig. 2, is calculated from Eq. (3),

$$\Gamma_{L1}' = \frac{V_{1B'}}{V_{1B}}$$

where the voltage $V_{1B}$ is a transmission voltage that is applied to MC1 from the source $V_{g1B}$, and it is measured at port A1 when SW1 selects S_B and $V_{g1A} = 0$. The voltage $V_{1B'}$ is a reflection voltage flowing from MC1 to the source $V_{g1B'}$, and it is measured at port B1 when SW1 selects S_B and $V_{g1A} = 0$. To achieve the conjugate-matching, the voltage reflection coefficient $\Gamma_{L1}$ with respect to the reference-plane (a) in Fig. 2 should be evaluated, which can be calculated using $\Gamma_{L1}'$ from Eq. (3), as shown in the following equation,

$$\Gamma_{L1} = \Gamma_{L1}' e^{-j\theta_c}$$

where $\theta_c$ is the phase shift value of the directional coupler between the reference-plane (a) and (a)' in Fig. 2, where the insertion loss of the directional coupler is assumed to be negligibly small. Then the complex impedance $Z_{L1}$ can be calculated using Eq. (5),

$$Z_{L1} = Z_0 \frac{1 + \Gamma_{L1}}{1 - \Gamma_{L1}}$$

Using the circuit configuration shown in Fig. 2, the proposed algorithm can be realized. The experimental verification will be addressed in future studies.

![Fig. 2. Configuration of a matching circuit.](image)

### 4 Analytical verification of the proposed method

An investigation was carried out using the method of moments with half-wave-length dipole antennas at 900 MHz. Fig. 3(a) shows the configuration of the array when $N = 2$, 3, and 4 in a square arrangement. The element spacing $d$ was set to
The residual target $\varepsilon$ was set to 0.1. Fig. 3(b) shows the relationship between the iteration number and $Z_{in1}$. $Z_{in1}$ is the impedance looking into the antenna side from the reference-plane (a) shown in Fig. 2. In Fig. 3(b), the blue, red, and green lines show the relationship when $N = 2$, 3, and 4. The combination of the array elements used in different arrays is represented by boxes of the same color in Figs. 3(a), 3(b) and 3(c); the array for $N = 2$ is constructed with the elements #1 and #2, and the array for $N = 3$ is constructed with the elements #1, #2, and #3. The solid and dashed curves in Fig. 3(b) represent the real and imaginary part of the impedance, respectively.

The star symbols in Fig. 3(b) indicate the analytical solutions calculated from the matched-load-determination equation when $N = 2$ and 3 [4, 7]. Since the determination equations are non-linear when $N > 3$ [4], we carried out numerical analysis (Trust Region Method) using MATLAB to obtain the solution when $N = 3$. Extensive investigation is needed to obtain the solution when $N > 4$. This will be addressed in our future studies.

In Fig. 3(b), the convergence is achieved for both the real and imaginary part of the input impedance when iteration number is more than 10, irrespective of the element number $N$. We also see that the convergence values agree well with the analytical solutions, denoted by the star symbols. This assures that the proposed method can be used for a multiple-element array antenna.

Fig. 3(c) shows the relationship between the $VSWR$ of element #1 and the iteration number. The $VSWR$ was calculated by the following formulae:

$$\Gamma = \frac{Z_{in1}(i) - Z_{L1}(i - 1)^*}{Z_{in1}(i) + Z_{L1}(i - 1)}$$

Fig. 3. Analytical results when $N = 2$, 3, and 4.
As shown in Fig. 3(c), when the number of elements increases, the convergence condition varies. However, it can be seen that the VSWR converges to unity irrespective of the number of elements when iteration number is more than 10.

Fig. 3(d) shows the relationship between the VSWR and the residual target $\varepsilon$. If the VSWR needs to be limited to $VSWR = 1.2$, $\varepsilon$ should be less than 4 in the case of $N = 2$ whereas $\varepsilon$ should be less than 3 in the case of $N = 3$ and 4. Therefore, considering the desired $VSWR$ of different applications, $\varepsilon$ must be adjusted to the optimum value.

5 Conclusion

In this paper, we have proposed an automatic impedance-matching algorithm that can sequentially realize simultaneous conjugate-matching state for all the elements in an $N$-element array antenna. The analytical results show that the $VSWR$ converges to unity irrespective of the number of elements, demonstrating that the antenna performance is improved by applying the proposed method to MIMO array antennas. Future studies include experimental verifications of the proposed method.