

Mode-Based Method of Estimating Channel Characteristics for a Near-Field MIMO

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Abstract

A wireless channel can be parallelized by using MIMO technology. In contrast to the conventional MIMO, however, the near-field MIMO system operates in near-field region of antenna elements, and each antenna directly communicates with each other. In order to construct a near-field 2×2 MIMO system, the antenna array, which is composed of short electric dipole and small loop (short magnetic dipole) antennas, can be used as the transmitting and receiving arrays. When the small antennas are used, the characteristics of the channel matrix can be simply analyzed based on the addition theorem, and thus the capacity can be also easily estimated.

Keywords : Near-field MIMO, the addition theorem, small antennas

1. Introduction

MIMO technology has been developed to increase the maximum available amount of information for limited wireless resources. According to the MIMO theory, a wireless channel can be parallelized using the transmitting and receiving arrays. In contrast to a conventional MIMO system, which operates in a far-field region under the rich multi-path environment, a near-field MIMO operates in near-field region of antenna elements, comprising the transmitting and receiving array, and each antenna directly communicates with each other without a multi-path environment [1]. In near-field MIMO, each eigenmode of the antenna array can be considered an independent multiplexed channel, and the coupling of transmitting and receiving antennas conventionally needs to be analyzed using full-wave analysis [2].

If the antenna arrays, which are composed of short electric dipole and small loop (short magnetic dipole) antennas, are used for the transmitting and receiving antenna arrays, the near-field 2×2 MIMO system can be effectively constructed, because each antenna in the array produces orthogonal spherical TM_{10} and TE_{10} modes, respectively. Recently, the analysis method for a 2×2 MIMO array composed of short electric and magnetic dipoles was proposed in [3]. From [3], the coupling between the transmitting and receiving antennas can be calculated as the projected component of the transmitted field at the receiving antenna. However, it is difficult to be applied in the general case that each antenna of the transmitting and receiving array is tilted in an arbitrary orientation. Therefore, the analysis method needs to be generalized so that it can be easily applicable to cases of arbitrary configurations.

2. Mode-Based Analysis of Near-field 2×2 MIMO Channels

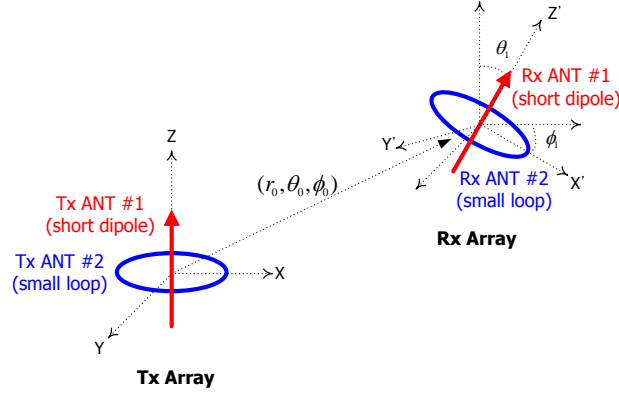
The outside of an antenna is composed of orthogonal spherical waves. Hence, the coupling between small antennas can be described as the interaction of TM_{10} or TE_{10} modes, based on the addition theorem of spherical waves, because a small antenna predominantly generates a spherical TM_{10} or TE_{10} mode [4]. Recently, many studies of near-field coupled small antenna have been reported, as in [5] and [6].

When the transmitting and receiving arrays are composed of a short electric dipole and small magnetic loop, respectively, as shown in Figure 1a, the near-field 2×2 MIMO system can be represented by the equivalent circuit in Figure 1b. Similar to [4], if the transmitting and receiving

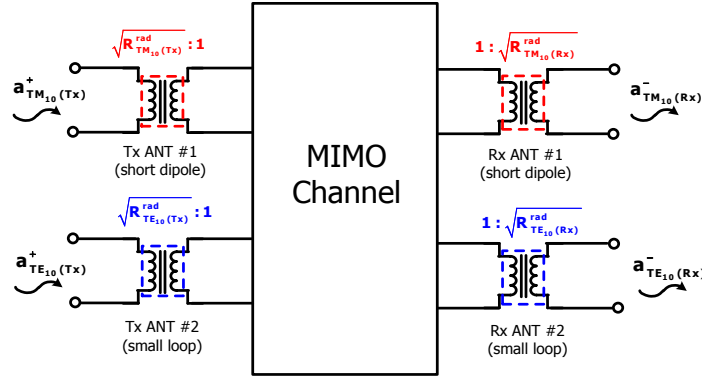
antennas are matched, the outgoing transmitted signals and incoming received signals of each antenna can be defined as

$$a_{TM_{10}}^+(Tx) = \frac{V_{TM_{10}}(Tx)}{\sqrt{R_{TM_{10}}^{rad}(Tx)}} \quad a_{TE_{10}}^+(Tx) = \frac{V_{TE_{10}}(Tx)}{\sqrt{R_{TE_{10}}^{rad}(Tx)}} \quad (1)$$

$$a_{TM_{10}}^-(Rx) = \frac{V_{TM_{10}}(Rx)}{\sqrt{R_{TM_{10}}^{rad}(Rx)}} \quad a_{TE_{10}}^-(Rx) = \frac{V_{TE_{10}}(Rx)}{\sqrt{R_{TE_{10}}^{rad}(Rx)}} \quad (2)$$



(a) System configuration



(b) Equivalent circuit

Figure 1: Near-field 2x2 MIMO system.

However, in contrast to the analysis for mutual impedance, where the receiving antennas are open-circuited, the receiving antennas of a MIMO system need to be matched. Therefore, based on the addition theorem of spherical waves, the transmission parameter between coupled antennas can be given as

$$\frac{a_{TM_{10}}^-(Rx)}{a_{TM_{10}}^+(Tx)} = \frac{a_{TE_{10}}^-(Rx)}{a_{TE_{10}}^+(Tx)} = \frac{1}{2} A_{10,10}' = \frac{1}{2} (\cos \theta_1 A_{10,10} + \sin \theta_1 \cos \phi_1 A_{11'10} + \sin \theta_1 \sin \phi_1 A_{11'10}) \quad (3)$$

$$\frac{a_{TE_{10}}^-(Rx)}{a_{TE_{10}}^+(Tx)} = \frac{a_{TM_{10}}^-(Rx)}{a_{TE_{10}}^+(Tx)} = \frac{1}{2} B_{10,10}' = \frac{1}{2} (\sin \theta_1 \cos \phi_1 B_{11'10} + \sin \theta_1 \sin \phi_1 B_{11'10}) \quad (4)$$

where the related parameters are given as [4]

$$A_{10,10} = P_0 (\cos \theta_0) h_0^{(2)}(kr_0) + P_2 (\cos \theta_0) h_2^{(2)}(kr_0) \quad (5)$$

$$A_{11_{\phi_0}} = -\frac{1}{2} P_2^1 (\cos \theta_0) \frac{\cos}{\sin} \phi_0 h_2^{(2)}(kr_0) \quad (6)$$

$$B_{11_{\phi_0}} = \pm \frac{3}{2} P_1^1 (\cos \theta_0) \frac{\sin}{\cos} \phi_0 h_1^{(2)}(kr_0) \quad (7)$$

Hence, the channel matrix of a near-field 2×2 MIMO system can be given as

$$H = \frac{1}{2} \begin{bmatrix} A_{10,10} & B_{10,10} \\ B_{10,10} & A_{10,10} \end{bmatrix} \quad (8)$$

3. Capacity Analysis of Near-field 2×2 MIMO Systems

The capacity of the MIMO channel can be calculated by the eigenvalue analysis of a channel matrix. According to the Shannon theorem, if the M×M channel matrix (\mathbf{H}) is given, the capacity of the channel can be given as

$$C = \sum_i^M \log_2 \left(1 + \lambda_i \frac{\gamma_0}{M} \right) = \log_2 \prod_i^M \left(1 + \lambda_i \frac{\gamma_0}{M} \right) \quad (9)$$

where M is the number of antennas, λ_i is the i^{th} eigenvalue of $\mathbf{H}^H \mathbf{H}$ (with superscript H , which means the conjugate transpose), and γ_0 is the signal-to-noise ratio of the channel [2]. If the channel matrix is given, each eigenvalue can be calculated by the characteristic equation, which is defined as

$$\det(\lambda \mathbf{I} - \mathbf{H}^H \mathbf{H}) = 0 \quad (10)$$

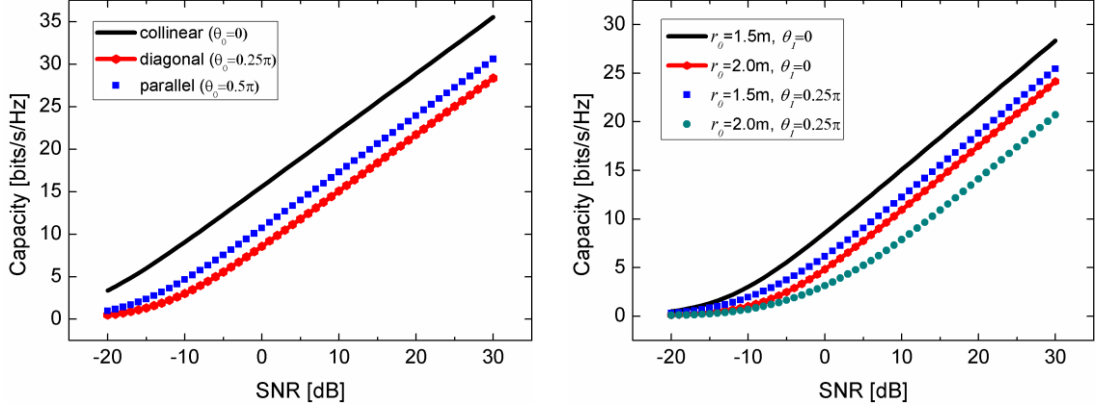
Hence, from the channel matrix of a near-field 2×2 MIMO system, the characteristic equation is given as

$$\lambda^2 - \frac{1}{2} \left(|A_{10,10}|^2 + |B_{10,10}|^2 \right) \lambda + \frac{1}{16} \left| (A_{10,10} + B_{10,10})(A_{10,10} - B_{10,10}) \right|^2 = 0 \quad (11)$$

and thus the capacity of the system can be given as

$$C = \log_2 \left[\left\{ 1 + \frac{\gamma_0}{8} \left(|A_{10,10}|^2 + |B_{10,10}|^2 + \sqrt{\left(|A_{10,10}|^2 + |B_{10,10}|^2 \right)^2 - \left| (A_{10,10} + B_{10,10})(A_{10,10} - B_{10,10}) \right|^2} \right) \right\} \right. \\ \left. \left\{ 1 + \frac{\gamma_0}{8} \left(|A_{10,10}|^2 + |B_{10,10}|^2 - \sqrt{\left(|A_{10,10}|^2 + |B_{10,10}|^2 \right)^2 - \left| (A_{10,10} + B_{10,10})(A_{10,10} - B_{10,10}) \right|^2} \right) \right\} \right] \quad (12)$$

From (12), the capacity is calculated for various relative configurations under the condition that the operating frequency is 13.56 MHz, ϕ_0 is 0.5π , and ϕ_l is 0, as shown in Figure 2. The capacity values for three configurations without tilting (θ_l is 0) are compared in Figure 2a for a 1.5 m distance, and the results of diagonal configuration ($\theta_0=0.25\pi$) at 1.5m and 2m distance for the cases with tilting about the y-axis (θ_l is 0.25π) and without tilting (θ_l is 0) are shown in Figure 2b.



(a) For different configurations ($r_0=1.5$ m) (b) For the diagonal configuration ($\theta_0=0.25\pi$)

Figure 2: Capacity of the near-field 2x2 MIMO

4. Conclusion

If an antenna array consisting of short electric dipole and small loop (short magnetic dipole) antennas are used for transmitting and receiving antenna arrays, respectively, a near-field 2x2 MIMO system can be constructed, due to the orthogonality of spherical TM_{10} and TE_{10} modes. By using the addition theorem, the characteristics of the channel matrix are easily analyzed, because the coupling between small antennas can be described as the interaction of TM_{10} or TE_{10} modes. Consequently, from the estimated eigenvalues of the given MIMO channel, the capacity of the MIMO system can be also estimated.

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Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2011-0001270)