Mutual Coupling Cancelation for Compact Transmit
Antenna Arrays

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Abstract—Mutual coupling between elements in compact trans-mit antenna arrays is taken into account in performance predic-tion and system design of multiple-input multi-output (MIMO) systems. The transmitter-end coupling matrix comprised of array impedance matrix and effective load impedance matrix is derived. The impact of transmitter-end mutual coupling on spatial corre-

lation, radiated power, and system capacity is studied. It is shown that for MIMO systems with compact transmit antenna arrays, transmitter-end mutual coupling seriously degrades system capacity. To mitigate the capacity degradation, a simple transmitter-end coupling cancelation method is proposed. It is shown through numerical experiments that the proposed method can significantly improve system capacity in the case that transmit antennas are placed closely.

I. INTRODUCTION

In multiple-input multiple-output (MIMO) systems, increasing the number of antennas at the transmitter or the receiver can improve channel capacity, not only when the subchannels are spatially uncorrelated [1], [2] but also when the subchannels are correlated [3]–[5]. In practice, the size of an antenna array is physically limited. Increasing the elements in an antenna array not only brings the issue of spatial correlation but also makes the issue of mutual coupling between antenna elements arise. Therefore, although more antenna elements benefit channel capacity, the impact of mutual coupling on system capacity needs to be investigated.

The study on the role of mutual coupling can be traced back to the 60s and earlier. Most studies at that time focused on the impact of mutual coupling on the parameters of phased arrays and means of compensation via circuit design, e.g. [6]–[9]. In recent studies, researchers put more interests on the joint effect of mutual coupling and spatial correlation in MIMO systems [10]–[17].

The system model with coupling matrices can be represented by

$$y = C_rH C_t x + z$$

(1)

where $C_r$ is the receiver-end coupling matrix, $C_t$ is the transmitter-end coupling matrix, $x$ is the transmitted signal vector, $H$ is the channel matrix, $z$ is the additive noise vector, and $y$ is the received signal vector for processing at the receiver.

The channel matrix $H$ can be represented by

$$H = \Psi_t^{1/2} H_w (\Psi_t^{1/2})^†$$

(2)

where $H_w$ is the channel matrix composed of i.i.d. $CN(0,1)$ entries, $\Psi_t$ is the transmit spatial correlation matrix,

$$\Psi_t = \Psi_t^{1/2} (\Psi_t^{1/2})^†,$$

(3)

and $\Psi_r$ is the receive spatial correlation matrix,

$$\Psi_r = \Psi_r^{1/2} (\Psi_r^{1/2})^†.$$  

(4)

[3].

In [18], the receiver-end coupling matrix $C_r$ is derived via circuit network analysis,

$$C_r = Z_r^I (Z_r^r + Z_r^L I)^{-1}$$

(5)

where $Z_r^I$ is the load impedance for each receive antenna, and $Z_r^r$ is the receiver-end array impedance matrix. It coincides with the left terms in the expressions of the transfer network [13], [14].

In [11], the expression of coupling matrix is

$$C = (Z_A + Z_L) (Z + Z_L I)^{-1}$$

(6)

where $Z_A$ is the self impedance, $Z$ is the impedance matrix, and $Z_L$ is the load impedance. Comparing the expression (6) with (5), we see that they are in fact different, though it was claimed in [11] that the expression (6) was from (5). Since the expression of coupling matrix (6) is questionable, the result in [11] that mutual coupling would increase system capacity is doubtful.

As our interest in this paper is to investigate the effect of mutual coupling at the transmitter, the transmitter-end coupling matrix $C_t$ is to be figured out. The expression of transmitter-end coupling matrix derived in [12] is not correct as the circuit network therein used to represent the relationship between input voltages and terminal voltages is questionable. Briefly, in [12], the terminal voltages $v$ in the expression of transmitter-end coupling matrix are not real terminal voltages, but the input voltages for the transmitter-end array impedance matrix.

An alternative way to analyze the effect of mutual coupling is via transfer network analysis, see [13]–[15] for example. However, we do not agree mixing transfer networks with the system model (1) as done in [13], [15], because we do not think that the channel matrix $H$ can be simply substituted into the expression of the transfer network. For instance, in [13], [15],
H is substituted into the expression of the transfer network by letting \( H = Z_{RT} \) where \( Z_{RT} \) is the transfer impedance matrix. It is not reasonable because \( H \) is a coefficient matrix without unit whereas \( Z_{RT} \) is an impedance matrix.

In this paper, the effect of mutual coupling when more and more antennas are put in a fixed-length linear transmit array is studied and the method to compensate the transmitter-end mutual coupling is proposed. For studying the effect of transmitter-end mutual coupling, the transmitter-end coupling matrix comprised of array impedance matrix and effective load impedance matrix is derived via circuit network analysis similar to [18].

II. TRANSMITTER-END COUPLING MATRIX

Fig.1 depicts a transmit antenna array treated as an \( M \)-port active circuit network, where there are \( M \) antenna elements, \( v_{s,j} \) is the input voltage for the \( j \)-th transmit antenna, \( v_j \) is the terminal voltage for the \( j \)-th transmit antenna, \( i_j \) is the terminal current for the \( j \)-th transmit antenna, and \( Z_{L,j} \) is the effective load impedance for the \( j \)-th transmit antenna. For simplicity, we do not take source impedances into account herein.

In terms of Kirchoff’s voltage law (KVL), we have the equation array of terminal voltages

\[
\begin{align*}
    v_1 &= i_1 Z_{11} + \ldots + i_j Z_{1j} + \ldots + i_M Z_{1M} + v_{0,1} \\
    &\vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \\
    v_j &= i_1 Z_{j1} + \ldots + i_j Z_{jj} + \ldots + i_M Z_{JM} + v_{0,j} \\
    &\vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \\
    v_M &= i_1 Z_{M1} + \ldots + i_j Z_{Mj} + \ldots + i_M Z_{MM} + v_{0,M}
\end{align*}
\]

(8)

where \( Z_{jj} \) is the self impedance of the \( j \)-th antenna, \( Z_{ij} (j_1 \neq j_2) \) is the mutual impedance between the \( j_1 \)-th antenna and the \( j_2 \)-th antenna, and \( v_{0,j} \) are terminal voltages when the \( M \) ports are all open, i.e., \( i_j = 0, j = 1, 2, \ldots, M \). On the other side, when the \( M \) ports are all open, terminal voltages should be equal to input voltages as there is no terminal current and thus no mutual coupling,

\[
v_j = v_{s,j}, \hspace{2cm} j = 1, 2, \ldots, M.
\]

(9)

Consequently, given (8) and (9),

\[
v_{0,j} = v_{s,j}, \hspace{2cm} j = 1, 2, \ldots, M.
\]

(10)

The relationship between current and load impedance is

\[
i_j = -\frac{v_j}{Z_{L,j}}, \hspace{2cm} j = 1, 2, \ldots, M.
\]

(11)

Substituting (10) and (11) into (8), we have (7) on the bottom of this page. That is, with known array impedance matrix and effective load impedance matrix, terminal voltages can be figured out by

\[
v = C_t v_s
\]

(12)

where \( C_t \) is the transmitter-end coupling matrix,

\[
C_t = Z_t^l (Z_t^l + Z_t^l I)^{-1}
\]

(13)

with \( Z_t^l \) the transmit impedance matrix composed of self and mutual impedances,

\[
Z_t^l = \begin{pmatrix}
Z_{11}^l & Z_{12}^l & \ldots & Z_{1M}^l \\
Z_{21}^l & Z_{22}^l & \ldots & Z_{2M}^l \\
\vdots & \vdots & \ddots & \vdots \\
Z_{M1}^l & Z_{M2}^l & \ldots & Z_{MM}^l
\end{pmatrix}
\]

(14)

and \( Z_t^l \) the diagonal matrix composed of effective load impedances,

\[
Z_t^l = \begin{pmatrix}
Z_{L,1}^l & 0 & \ldots & 0 \\
0 & Z_{L,2}^l & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & Z_{L,M}^l
\end{pmatrix}
\]

(15)

When the effective load impedances are equal, \( Z_{L,1}^l = Z_{L,2}^l = \ldots = Z_{L,M}^l = Z_{L}^l \), we have

\[
C_t = Z_t^l (Z_t^l + Z_t^l I)^{-1}
\]

(16)

Comparing (16) with (5), we see that the transmitter-end coupling matrix \( C_t \) is in the similar form of the receiver-end coupling matrix \( C_r \).

III. TRANSMITTER-END MUTUAL COUPLING EFFECT

A. Assumptions

For investigating the effect of mutual coupling at the transmitter, we assume in the following a MISO system with \( M \) transmit antennas and 1 receive antenna. The channel model (1) is thus simplified to

\[
y = \mathbf{h C}_t \mathbf{x} + z
\]

(17)

where \( z \) is the additive Gaussian noise, \( z \in \mathbb{C}\mathbb{N}(0, 1) \). The \( M \)-length channel vector \( \mathbf{h} \) can be represented by

\[
\mathbf{h} = \mathbf{h}_w (\Psi_t^{1/2})
\]

(18)

where entries in \( \mathbf{h}_w \) are i.i.d. complex symmetric Gaussian random variables \( \mathbb{C}\mathbb{N}(0, 1) \), and \( \Psi_t \) is the transmit spatial correlation matrix.

Using the spatial correlation model given in [3] based on the “one-ring” model by Jakes [19], each entry of \( \Psi_t \) is simulated as

\[
\Psi_{t,ij} = J_0 (2\pi d_{ij}/\lambda), \hspace{2cm} i, j = 1, 2, \ldots, M,
\]

(19)

where \( \lambda \) is the wavelength, \( J_0(\cdot) \) is the zeroth-order Bessel function, and \( d_{ij} \) is the distance between the \( i \)-th transmit antenna and the \( j \)-th transmit antenna.

The antenna array at the transmitter is assumed to be composed of identical dipole antennas with length 0.5\( \lambda \) and radius
antennas in

Let the matrix for the mutual coupling reduces, and mutual coupling relatively degrades effective spatial correlation, due to inadequate precoding and worse effective channel caused by transmitter-end mutual coupling, system capacity is not improved but decreased.

In the following, we use $Z_{nn}^\prime$ to denote self impedance. Self and mutual impedances in the transmit impedance matrix $Z'$ are calculated in terms of the formulas given in [20]. For simplicity, we assume each effective load impedance is self-match to each transmit antenna, i.e., $Z_L = Z_{nn}^\prime$.

B. Mutual coupling degrades spatial correlation

From (17) and (18), the effective channel spatial correlation matrix for $x$ is

$$\Psi_t = C_t^\dagger \Psi_t C_t.$$  \hspace{1cm} (21)

Let $r_t$ and $r_t'$ denote the correlation degrees for the first two antennas in $\Psi_t$ and $\Psi_t'$ respectively,

$$r_t = \left| \frac{\Psi_t(1,2)}{\sqrt{\Psi_t(1,1)\Psi_t(2,2)}} \right|,$$

$$r_t' = \left| \frac{\Psi_t'(1,2)}{\sqrt{\Psi_t'(1,1)\Psi_t'(2,2)}} \right|. \hspace{1cm} (22)$$

Assume the length of the linear antenna array is fixed to the wavelength, $L = \lambda$. Fig.2 shows that both correlation degrees increase as the distance between the two neighbouring antennas reduces, and mutual coupling relatively degrades effective spatial correlation.

It is known that spatial correlation decreases channel capacity [3]–[5], but we will see in Section III-D that although mutual coupling reduces spatial correlation, due to inadequate precoding and worse effective channel caused by transmitter-end mutual coupling, system capacity is not improved but decreased.

C. Mutual coupling impacts radiated power

From (17), the power radiated to the space is

$$P_t = \text{tr}(C_t C_t^\dagger Q) \hspace{1cm} (23)$$

where $Q$ is the signal covariance matrix, $Q = E\{x x^\dagger\}$. Note that $E\{x\} = 0$.

Let $P_a$ denote PA (power amplifier) output power,

$P_a = E\{x^\dagger x\}. \hspace{1cm} (24)$

When the transmitter does not know the effective channel $h C_t$, the signal covariance matrix is

$$Q_{\text{NCSIT}} = \frac{P_a}{M} I. \hspace{1cm} (25)$$

In this case, from (23), the radiated power is

$$P_{t,\text{NCSIT}} = \frac{\text{tr}(C_t C_t^\dagger) P_a}{M}. \hspace{1cm} (26)$$

When the transmitter knows the effective channel $h C_t$, the signal covariance matrix is

$$Q_{\text{CSIT}} = \frac{C_t h^\dagger h C_t P_a}{\|h C_t\|^2}. \hspace{1cm} (27)$$

In this case, from (23), the radiated power is

$$P_{t,\text{CSIT}} = \frac{\|h C_t^2\|^2}{\|h C_t\|^2} P_a. \hspace{1cm} (28)$$

When transmit antennas are far spaced, mutual impedances between antennas can be neglected. The transmitter-end mutual coupling matrix can thus be approximated by

$$C_{t,f} = \frac{Z_{nn}^\prime}{Z_{nn}^\prime + Z_{nn}^\prime \|I. \hspace{1cm} (29)$$

\begin{align*}
\begin{pmatrix}
1 + \frac{Z_{11}'}{Z_{L,1}'} & \frac{Z_{12}'}{Z_{L,2}'} & \cdots & \frac{Z_{1M}'}{Z_{L,M}'} \\
\frac{Z_{21}'}{Z_{L,1}'} & 1 + \frac{Z_{22}'}{Z_{L,2}'} & \cdots & \frac{Z_{2M}'}{Z_{L,M}'} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{Z_{M1}'}{Z_{L,1}'} & \frac{Z_{M2}'}{Z_{L,2}'} & \cdots & 1 + \frac{Z_{MM}'}{Z_{L,M}'}
\end{pmatrix}
\begin{pmatrix}
v_1' \\
v_2' \\
\vdots \\
v_M'
\end{pmatrix}
= 
\begin{pmatrix}
v_{s,1} \\
v_{s,2} \\
\vdots \\
v_{s,M}
\end{pmatrix},
\end{align*}

(7)
In this case, from (26) and (28), the radiated power is

$$P_{t,f,\text{NCSIT}} = P_{t,f,\text{CSIT}} = \frac{|Z_{nn}^t|^2 P_a}{|Z_{nn}^t + Z_{nn}^t|^2}. \quad (30)$$

Fig. 3 shows the effect of transmitter-end mutual coupling on radiated power. We see that self impedance causes the loss of radiated power. When channel state information is not known at the transmitter, mutual coupling increases radiated power; whereas, when channel state information is known at the transmitter, mutual coupling does not have much effect on radiated power.

Radiated power can be a metric of electromagnetic radiation. It does not determine system capacity solely, which will be shown in Section III-D.

D. Mutual coupling degrades system capacity

System capacity is jointly determined by effective channel, precoding, and radiated power [1].

For deriving the upper bounds on system capacity in different cases, we ideally assume that $C_i$ is an identity matrix and the subchannel are uncorrelated, $\mathbf{h} = \mathbf{h}_w$. When channel state information is not known at the transmitter, the upper bound on system capacity is

$$C_{i,\text{NCSIT}} = \log_2 \left(1 + \frac{P_a}{M} \|\mathbf{h}_w\|^2 \right). \quad (31)$$

When channel state information is known at the transmitter, the upper bound on system capacity is

$$C_{i,\text{CSIT}} = \log_2 (1 + P_a \|\mathbf{h}_w\|^2). \quad (32)$$

Assume transmit antennas are far spaced and thus mutual impedances and spatial correlation can be neglected. When channel state information is not known at the transmitter, the system capacity is

$$C_{f,\text{NCSIT}} = \log_2 \left(1 + \frac{P_a |Z_{nn}^t|^2}{M |Z_{nn}^t + Z_{nn}^t|^2} \|\mathbf{h}_w\|^2 \right). \quad (33)$$

When channel state information is known at the transmitter, the system capacity is

$$C_{f,\text{CSIT}} = \log_2 \left(1 + \frac{P_a |Z_{nn}^t|^2}{|Z_{nn}^t + Z_{nn}^t|^2} \|\mathbf{h}_w\|^2 \right). \quad (34)$$

The effect of self impedance on system capacity is shown in Fig. 4. Comparing system capacities $C_{f,\text{NCSIT}}$ and $C_{f,\text{CSIT}}$ for far-spaced transmit antennas with the upper bounds $C_{i,\text{NCSIT}}$ and $C_{i,\text{CSIT}}$, we see that self impedance causes system capacity loss because it makes radiated power decrease.

Assume the length of the linear antenna array is fixed. With the effect of mutual coupling, when channel state information is not known at the transmitter, the system capacity is

$$C_{L,\text{NCSIT}} = \log_2 \left(1 + \frac{P_a}{M} \|\mathbf{C}_f\|^2 \right); \quad (35)$$

when channel state information is known at the transmitter, the system capacity is

$$C_{L,\text{CSIT}} = \log_2 \left(1 + P_a \|\mathbf{h}_w\|^2 \right). \quad (36)$$

In this paper, we suppose the length of the linear antenna array is fixed to the wavelength, $L = \lambda$.

The effect of mutual coupling on system capacity is shown in Fig. 4. Comparing system capacities $C_{L,\text{NCSIT}}$ and $C_{L,\text{CSIT}}$ for fixed-length transmit antenna array with $C_{f,\text{NCSIT}}$ and $C_{f,\text{CSIT}}$ for far-spaced transmit antennas respectively, we see that when channel state information is not known at the transmitter, though mutual coupling makes radiated power increase as shown in Fig. 3, it degrades system capacity due to effective inadequate precoding and worse effective channel; when channel state information is known at the transmitter, the gap between $C_{L,\text{CSIT}}$ and $C_{f,\text{CSIT}}$ is mainly due to the worse effective channel.

The system capacities with and without CSIT calculated with

$$\mathbf{C}_f = \mathbf{Z}^t(\mathbf{Z}^t + Z_{nn}^t \mathbf{I})^{-1} \quad (37)$$

derived in [12] are also plotted in Fig. 4, identified by $C_{f,\text{CSIT}}$ and $C_{f,\text{NCSIT}}$ respectively. It is seen that with the incorrect formula of transmitter-end coupling matrix given in [12], transmitter-end mutual coupling would benefit system capacity a lot, which is not reasonable.

IV. TRANSMITTER-END COUPLING CANCELLATION

It is shown in the previous section that transmitter-end mutual coupling would cause serious performance deterioration for MIMO systems with compact transmit antenna arrays, that is,
When the size of a transmit antenna array is limited, after a critical value, increasing transmit antennas cannot increase but degrades system capacity. In this section, a simple method is proposed to compensate mutual coupling between transmit antennas. It significantly improves system capacity for MIMO systems with compact transmit antenna arrays.

**Radiated power constraint:** Assume the power radiated to the space is constraint to $P_t$. Given (17), we have

$$E(\|C_t \tilde{x}\|^2) \leq P_t.$$  \hspace{1cm} (38)

The PA output power constraint is not used herein because we consider that as a system condition, the radiated power constraint is more proper than the PA output power constraint if what we concern is interference and electromagnetic radiation.

**Transmitter-end coupling cancelation:** At the transmitter, the inverse of the transmitter-end coupling matrix is multiplied to the transmitted signal vector $\tilde{x}$,

$$\tilde{x} = C_t^{-1} \tilde{x}$$  \hspace{1cm} (39)

where

$$E(\|\tilde{x}\|^2) \leq P_t$$  \hspace{1cm} (40)

under the radiated power constraint (38).

### A. In MIMO systems without CSIT

With the coupling cancelation process (39), given (40), when channel state information is not known at the transmitter, the transmitted signal vector $\tilde{x}$ is supposed to satisfy

$$E(\tilde{x}^\dagger \tilde{x}) = \frac{P_t}{M} I.$$  \hspace{1cm} (41)

Given (17) and (41), the system capacity is

$$C_{TCC,NCSIT} = \log_2 \left( 1 + \frac{P_t}{M} \|h\|^2 \right).$$  \hspace{1cm} (42)

If a MIMO system scales its PA output power under the radiated power constraint (38) without taking the transmitter-end mutual coupling effect into account,

$$E\{\tilde{x} \tilde{x}^\dagger\} = \frac{P_t}{\text{tr}(C_t C_t^\dagger)} I.$$  \hspace{1cm} (43)

Consequently, the system capacity is

$$C_{NTCC,NCSIT} = \log_2 \left( 1 + \frac{P_t}{\text{tr}(C_t C_t^\dagger)} \|hC_t\|^2 \right).$$  \hspace{1cm} (44)

Let $C_{TCC,NCSIT}$, $C_{LTCC,NCSIT}$ and $C_{LTCC,NCSIT}$ denote the capacities of the systems with far-spaced transmit antennas and transmitter-end coupling cancelation, with fixed-length transmit antenna array and transmitter-end coupling cancelation, and with fixed-length transmit antenna array but no transmitter-end coupling cancelation, respectively, when channel state information is not known at the transmitter.

Fig.5(a) exhibits the effect of the coupling cancelation method for MIMO systems with compact transmit antenna arrays when CSIT is unknown. We see that for a MIMO system with a compact transmit antenna array, if mutual coupling effect is not taken into account, after a critical value, increasing the number of transmit antennas causes serious performance degradation; whereas, with the coupling cancelation process given in (39), the system capacity $C_{LTCC,NCSIT}$ is very close to the upper bound $C_{LTCC,NCSIT}$ which is given when a loose antenna array without length limitation is installed at the transmitter. The minor gap between $C_{LTCC,NCSIT}$ and $C_{TCC,NCSIT}$ is the channel capacity loss caused by spatial correlation.

### B. In MIMO systems with CSIT

With the transmitter-end coupling cancelation process (39), when channel state information is known at the transmitter, the transmitted signal vector $\tilde{x}$ is

$$\tilde{x} = \sqrt{\frac{P_t}{\|h\|}} \tilde{\tilde{x}}.$$  \hspace{1cm} (45)

where $\tilde{\tilde{x}}$ is the transmitted symbol to be precoded and

$$E\{|\tilde{\tilde{x}}|^2\} = 1.$$  \hspace{1cm} (46)

Consequently, the system capacity is

$$C_{TCC,CSIT} = \log_2 (1 + P_t \|h\|^2).$$  \hspace{1cm} (47)

If a MIMO system treats $hC_t$ as effective channel and scales its PA output power in terms of the radiated power constraint.
Consequently, the system capacity is

\[ C_{NTCC,CSIT} = \log_2 \left( 1 + \frac{|hC_t C_l^H h|^2}{\|hC_t C_l^H h\|^2} \right). \]  

(49)

Let \( C_{f,TCC,CSIT} \), \( C_{L,TCC,CSIT} \) and \( C_{L,NTCC,CSIT} \) denote the capacities of the systems with far-spaced transmit antennas and transmitter-end coupling cancelation, with fixed-length transmit antenna array and transmitter-end coupling cancelation, and with fixed-length transmit antenna array but no transmitter-end coupling cancelation, respectively, when channel state information is known at the transmitter.

Fig. 5(b) exhibits the effect of the coupling cancelation method for MIMO systems with compact transmit antenna arrays when CSIT is known. We see that for a MIMO system with a compact transmit antenna array, if the transmitter-end mutual coupling effect is not taken into account, after a critical value, increasing the number of transmit antennas cannot help much for improving system capacity; whereas, with the coupling cancelation process given in (39), the system capacity \( C_{L,TCC,CSIT} \) is very close to the upper bound \( C_{f,TCC,CSIT} \) and increases significantly with the number of transmitter antennas. The minor gap between \( C_{L,TCC,CSIT} \) and \( C_{f,TCC,CSIT} \) is the channel capacity loss caused by spatial correlation.

**V. CONCLUSION AND DISCUSSION**

The mutual coupling between closely-spaced antenna elements should be taken into consideration in system performance prediction and system design for MIMO systems with compact antenna arrays. For investigating the impact of the mutual coupling at the transmitter, the expression of transmitter-end coupling matrix comprised of array impedance matrix and effective load impedance matrix is derived. System capacity is jointly determined by precoding, radiated power, and effective channel. If the transmitter-end mutual coupling between closely-spaced antennas is not taken into account in system design, although it decreases transmit spatial correlation and may increase radiated power relative to the case of far-spaced transmit antennas, it seriously degrades system capacity for MIMO systems with or without CSIT. A simple transmitter-end coupling cancelation method is proposed for solving the capacity degradation problem under the radiated power constraint. It is demonstrated by simulations that it significantly improves system capacity.

For implementing the coupling cancelation method in practice, the transmitter-end coupling matrix is to be known at the transmitter, which requires impedance matrix measurements or coupling matrix estimation [21].

Someone may wonder if the same coupling cancelation method can be implemented at the receiver. The same coupling cancelation method has been proposed to be implemented at the receiver for recovering antenna pattern [22]. However, it does not help for preventing system capacity degradation as the linear transformation on received signals does not change the mutual information [23]. For coupling cancelation at the receiver to improve system capacity, an alternative way is to be studied.

**REFERENCES**