MIMO Array for Space Division Duplex

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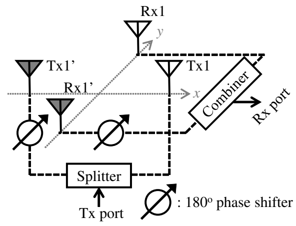
***Abstract*—We propose a novel self-interference cancellation (SIC) technique for space-division-duplex (SDD) multiple-input multiple-output (MIMO) array. The proposed SIC approach is as follows; first, an one-rank channel matrix, called a SI matrix in the paper, having only one dominant mode is formed between multiple transmitting (Tx) and receiving (Rx) antennas in a same SDD array. Then, the Tx/Rx ports are spatially isolated by cutting off the dominant mode giving eigenweight excitation to either the Tx or Rx array, that is, SIC is achieved at a cost of only one degree of freedom (DOF). For this SIC approach, we present a simple analog implementation using a cuboidal array configuration for the one-rank SI matrix and hybrid couplers for the eigenweight excitation. In this paper, theoretical aspects of the proposed technique are mainly focused on, and some numerical results are given demonstrating a good SIC effect even in some practical models.**

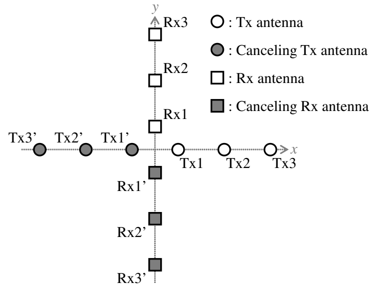
I. Introduction

Space division duplex (SDD) allows simultaneous transmission and reception by spatially separating transmitting (Tx) and receiving (Rx) systems with the use of multi-antenna techniques [1]. Moreover, combining it with multiple-input multiple-output (MIMO) technology, further improvement in the utilization efficiency of wireless resources and severalfold throughput can be expected compared to conventional full-duplex schemes [2]. However, the SDD scheme suffers from self-interferences (SI) emitted from its own Tx system and received at a selfsame Rx system, which spoils the decoding performance for desired receiving signals.

In order to address this problem, manly three SI cancellation (SIC) approaches were suggested [3]. The first is digital signal processing also known as an echo canceler. In this method, a desired signal is extracted by subtracting an already-known SI component from a received signal. However, in case that the SI power is much larger than the desired signal, the SI signal saturates a receiving system leading to its characteristic degradation, and what is worse, breakage failure. The second is the use of an passive analog network, which assures high isolation among multiple ports and suppresses the SI level to a certain acceptable value before it reaches a RF front-end. Although some decoupling and matching networks (DMN) were proposed for port isolation, a DMN configuration could be complicated in general when applying it to many-antenna MIMO array [4]. Additionally, since the network is directly connected between Tx/Rx ports, even a slight leakage due to its manufacturing error is critical.



(a) System configuration.



(b) Antenna arrangement.

Fig. 1. Conventional antenna cancellation approach.

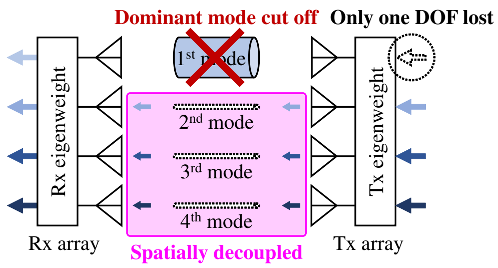


Fig. 2. Conceptual sketch of the proposed SIC approach.

To compensate the above-mentioned disadvantages, "antenna cancellation" was proposed as the third approach [2]. In this method, a canceling Tx antenna is used besides a SI-source Tx antenna, and they are excited with 180-degree phase difference as shown in Fig. 1(a). In this way, the SI signal is always canceled out on the plane where Rx antennas exist. Further, a higher-accuracy SIC is possible by taking the same measure at the Rx side to compensate potential manufacturing error and array misalignment. However, this method requires multiple canceling antennas as shown in Fig. 1(b), which actually do not contribute to the spatial degree of freedom (DOF). Hence, the system enlargement is unavoidable.

In this paper, we propose a novel SIC technique for a SDD MIMO array utilizing eigenmode characteristics. Figure 2 conceptually illustrates the proposed approach; first, an one-rank channel matrix, defined as a SI matrix in the paper, having only one dominant mode and other decayed modes is formed between multiple Tx/Rx antennas in a same SDD array. Then, the Tx/Rx ports are spatially decoupled by cutting off the dominant mode giving eigenweight excitation to either the Tx or Rx array, that is, SIC is achieved at a cost of only one DOF [5]. For this SIC approach, we present a simple analog implementation using i) a cuboidal array configuration for the one-rank SI matrix and ii) hybrid couplers for the eigenweight excitation. In the rest of the paper, the theoretical aspects of the proposed technique are explained. Furthermore, some numerical results are given demonstrating a good SIC effect and the effectiveness of the proposed technique.

II. Theory

As mentioned in Sec. I, the realizations of "one-rank SI matrix" and "eigenweight excitation" are key factors in the proposed technique. In this section, we present a simple implementation example to realize the above factors base on an analog approach employing special array configuration and network.

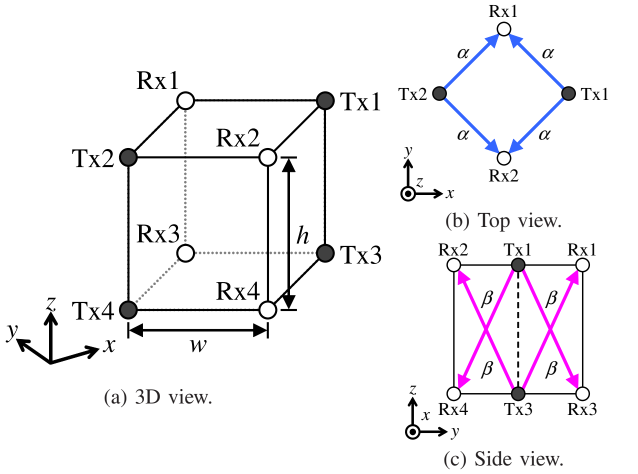
First, the proposed array configuration is described. The array has a cuboidal configuration and four-Tx and four-Rx antennas are positioned at its vertices as shown in Fig. 3(a). In the figure, colored and white circles represent Tx and Rx antennas, respectively, and the Tx/Rx-array planes are orthogonal to each other. The width and height of the virtual cuboid are defined as w and h, respectively. Now, focus on each SI component between the Tx/Rx antennas. As shown in Fig. 3(b), since the distances between the Tx/Rx antennas on the top surface Tx1-Rx1-Tx2-Rx2 are all equal, it is obvious that corresponding SI components are also same and replaced with a constant α. That is also true for those on the base. Likewise, the lengths of the diagonals on the sides Tx1-Rx1-Rx3-Tx3 and Tx1-Rx2-Rx4-Tx3 are all equal as shown in Fig. 3(c), so corresponding SI components are also same and replaced with a constant β. That is also true for those on the other sides. Therefore, a SI matrix $\boldsymbol{H}_{\mathrm{SI}}$ is expressed with a regular symmetry as

$$\boldsymbol{H}_{\mathrm{SI}} = \begin{matrix} & \text{Tx1} & \text{Tx2} & \text{Tx3} & \text{Tx4} \\ \text{Rx1} & \alpha & \alpha & \beta & \beta \\ \text{Rx2} & \alpha & \alpha & \beta & \beta \\ \text{Rx3} & \beta & \beta & \alpha & \alpha \\ \text{Rx4} & \beta & \beta & \alpha & \alpha \end{matrix} \tag{1}$$

where each matrix element represents a SI component between the Tx/Rx antennas noted out of the brackets.

Next, we explain the network for eigenweight excitation. Figure 4 shows the network configuration for Tx side. In the first stage, two 180-degree hybrid couplers are connected to the upper antenna pair of Tx1-Tx2 and the lower pair of Tx3-Tx4 each. Symbols "Σ" and "Δ" of a hybrid denote a sum port (for in-phase excitation) and a difference port (for out-of-phase excitation), respectively. Next, in the second stage, one more hybrid is cascade-connected to the sum ports of the first-stage hybrids, while their difference ports are directly-connected to Tx signal ports. Each Tx port is defined as Mode1∼4 and the weight matrix $\boldsymbol{W}$ of the network is expressed as

$$\boldsymbol{W} = -\begin{matrix} & \text{Mode1} & \text{Mode2} & \text{Mode3} & \text{Mode4} \\ \text{Tx1} & 1/2 & 1/2 & j/\sqrt{2} & 0 \\ \text{Tx2} & 1/2 & 1/2 & -j/\sqrt{2} & 0 \\ \text{Tx3} & 1/2 & -1/2 & 0 & j/\sqrt{2} \\ \text{Tx4} & 1/2 & -1/2 & 0 & -j/\sqrt{2} \end{matrix}. \tag{2}$$



(a) 3D view.
(b) Top view.
(c) Side view.

Fig. 3. Proposed array configuration.

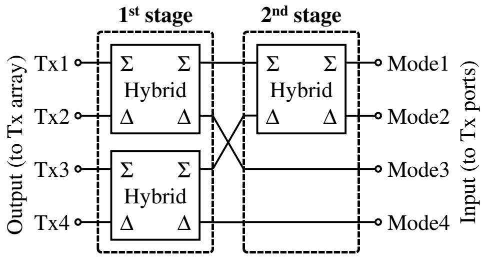


Fig. 4. Eigenweight excitation network for Tx side.

In (2), each column vector represents an eigenweight for each mode noted upside the brackets, and each weight is distributed to each Tx antenna noted on the left side. Note that the weight matrix in (2) is unitary, i.e. the network is lossless. For a Rx side, a same network is used but the inputs and outputs are switched, i.e. the Rx weight is a transpose of (2). Here, the SI matrix when the Tx/Rx networks connected is expressed as the product of the initial SI matrix and the weight matrices of the Tx/Rx networks, since the networks consisting of hybrids have neither reflection nor coupling at their inputs and outputs [6]. Thus, the complete SI matrix $\boldsymbol{H}'_{\mathrm{SI}}$ with the Tx/Rx networks is expressed as

$$\begin{aligned} \boldsymbol{H}'_{\mathrm{SI}} &= \boldsymbol{W}^T \boldsymbol{H}_{\mathrm{SI}} \boldsymbol{W} \\ &= \begin{matrix} \text{Rx}\backslash\text{Tx} & \text{Mode1} & \text{Mode2} & \text{Mode3} & \text{Mode4} \\ \text{Mode1} & 2(\alpha+\beta) & 0 & 0 & 0 \\ \text{Mode2} & 0 & 2(\alpha-\beta) & 0 & 0 \\ \text{Mode3} & 0 & 0 & 0 & 0 \\ \text{Mode4} & 0 & 0 & 0 & 0 \end{matrix} \end{aligned} \tag{3}$$

and diagonalized. In (3), the first to forth diagonal elements represent the orthogonalized SI components for Mode1∼4 respectively, and it should be noted that those for Mode3 and Mode4 are zero. The reason is understood from the electromagnetic viewpoint as follows; when eigenweight excitations of Mode3 and Mode4 are given to the Tx array for example, the upper antennas pair Tx1-Tx2 and the lower antenna pair Tx3-Tx4 are excited out of phase, respectively. Thus, null planes are formed right on the Rx-array plane resulting in SIC for these modes. Yet, Mode1 and Mode2 still remain, either of which must be decayed to obtain an one-rank SI matrix.

Now, let us try to decay Mode1 or Mode2 by optimizing the array parameters, w and h, so that

$$\alpha \pm \beta = 0. \tag{4}$$

In Fig. 5, two SI components α and β on the side Tx1-Rx1-Rx3-Tx3 are drawn. For simplicity, on the basis of geometric optic approximation (GOA) without distance attenuation, the SI components between Tx1-Rx1 and between Tx3-Rx1 are expressed as

$$\alpha = h_0 e^{-jkw} \tag{5}$$

and

$$\beta = h_0 e^{-jk\sqrt{w^2+h^2}}, \tag{6}$$

respectively. In the above equations, h_0 is an amplitude and a wave number $k = 2\pi/\lambda$ (λ is wavelength). From (5) and (6), a phase difference φ between α and β is give as

$$\varphi = k\left(\sqrt{w^2+h^2} - w\right) \tag{7}$$

and the sum and difference of α and β are expressed as

$$\alpha \pm \beta = h_0 e^{-jkw}\left(1 \pm e^{-j\varphi}\right). \tag{8}$$

In order that (8) becomes zero, either of the conditions

$$\varphi = \begin{cases} (2n-1)\,\pi & (\alpha+\beta=0) \quad \text{(9a)} \\ 2n\pi & (\alpha-\beta=0), \quad \text{(9b)} \end{cases}$$

where n is a positive integer, must be satisfied. From the above discussion, the relations between w and h satisfying (9a) and (9b), i.e. Mode1 and Mode2 are decayed, are given as

$$w = \begin{cases} \dfrac{h^2}{(2n-1)\,\lambda} - \dfrac{(2n-1)\,\lambda}{4} & \text{(10a)} \\ \dfrac{h^2}{2n\lambda} - \dfrac{n\lambda}{2} & \text{(10b)} \end{cases}$$

respectively. And finally, array design formulae for a one-rank SI matrix are derived.

Again, the proposed SIC technique is achieved by cutting off the remained SI mode. More specifically, it is performed by substituting the second-stage hybrid with 0- or 180-degree divider to cut off Mode2 or Mode1, respectively. Incidentally, although the two networks were assumed at Tx/Rx sides for the convenience of explanation, only either of them suffice in theory. Thereby, the loss of DOF can be minimized to only one, and seven of eight DOF are secured in total.

III. Numerical analysis

In this section, the SIC effect by the proposed technique is numerically evaluated. As a practical example, the parallel-arranged array (shown in Fig. 6 and named ∥-model) consisting very thin half-wavelength dipoles is simulated. As for array parameters, the spacings between feeding points of the adjacent Tx/Rx dipoles and of the upper and lower dipoles are defined as w and h, respectively, and varied from 0.5 λ to 10.0 λ in the simulation. In addition, a volume of a virtual cuboid with the width w and the height h is newly defined

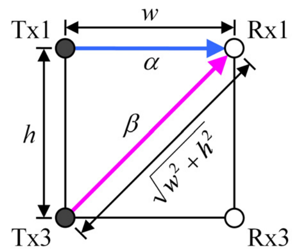
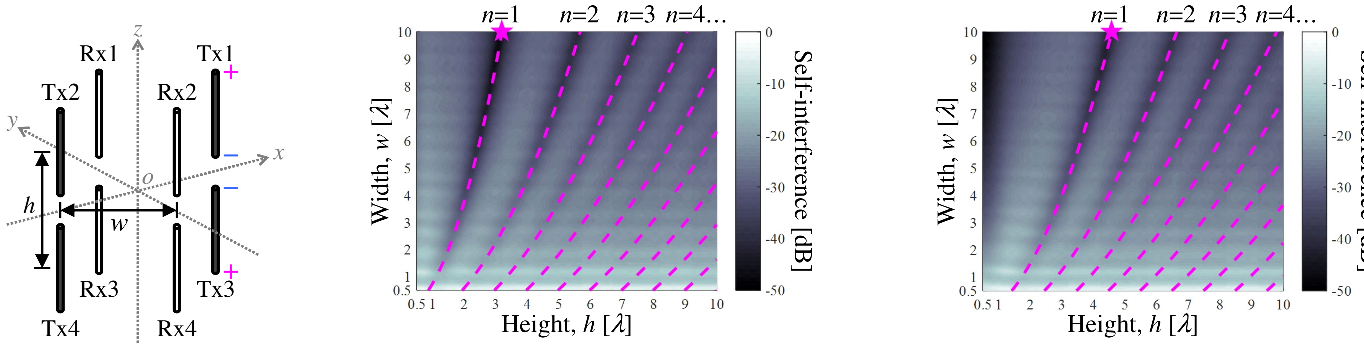


Fig. 5. SI components α and β on the side Tx1-Rx1-Rx3-Tx3.

as V as an index of array size. Signs "+" and "−" denote the polar directions of upper and lower dipoles at a certain moment. For electromagnetic analysis, NEC2, a moment-of-methods simulator, is used [7].

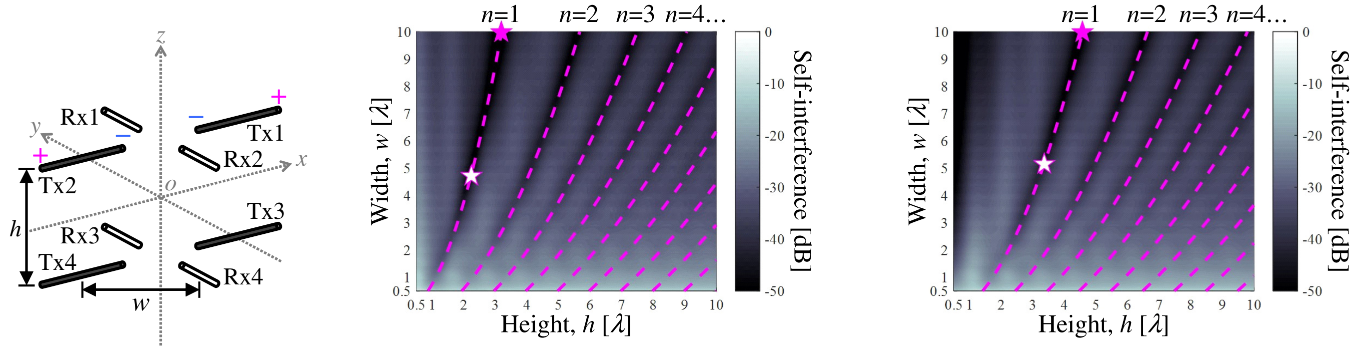
Figures 6(a) and (b) show SI power characteristics versus the array parameters for Mode1 and Mode2, respectively. Note that Mode3 and Mode4 are omitted since it is evident from (3) that these modes are naturally decayed. In the figures, vertical and horizontal axes represent w and h, respectively, and SI power is visualized with grayscale in dB. Also, the loci expressed as (10a) and (10b) are drawn with dash lines. As can be seen from the figures, SI power for each mode is mitigated on the loci, which proves the validity of the proposed array design formulae. However, the SI power cannot be completely suppressed even on the loci in particular when w is small. The degradation of SIC effect is attributed to the level difference between the SI components α and β; unlike GOA, the two SI components cannot be perfectly canceled out due to distance attenuation, near-field characteristics, and mutual coupling in such a realistic model. Here, stars in the figures mark the points of the minimal SI power in the analysis range, and parameters at the points are shown in TABLE I(a). This table indicates, although SIC effect could be improved as w becomes sufficiently larger compared to h since the relative level difference becomes smaller, another problem of array enlargement is inevitable.

In order to resolve the trade-off between SI power and array size, an orthogonally-arranged array (shown in Fig. 7 and named ⊥-model) is proposed as one of the simple solutions. In the array, Tx/Rx antennas are orthogonally arranged so that both α and β are preliminarily-reduced due to cross polarization resulting in the relatively-less level difference. In fact, from both Fig. 7(a) and (b), it can be seen that the SI power is more reduced over the whole analysis range compared to ∥-model. In the figures, open stars mark the points where the SI power is equal to the minimum value of ∥-model, and parameters at the points are shown in TABLE I(b). In the table, it is noteworthy that ⊥-model achieves the minimum values of ∥-model with approximately 80-% less array volume. Moreover, filled stars mark minimum SI points of ⊥-model and TABLE I(c) shows parameters at the points. This table shows that, assuming the same array volume, ⊥-model improves the SIC effect more than 10 dB compared to ∥-model. These results indicate that, if an antenna element itself is also optimized so that the two countervailing SI components



(a) Mode1. (b) Mode2.

Fig. 6. Self-interference characteristics for parallel-arranged array (||-model).



(a) Mode1. (b) Mode2.

Fig. 7. Self-interference characteristics for orthogonally-arranged array (⊥-model).

become equal, better SIC effect can be expected with smaller array size.

IV. Conclusion

In this paper, we proposed a novel SIC technique for a SDD MIMO array utilizing eigenmode characteristics. Further, a simple analog implementation was presented; an one-rank SI matrix is formed using an optimized cuboidal array configuration. Then, the dominant SI mode is cut off using eigenweight excitation network. Finally, SIC is achieved by sacrificing only one DOF.

In the numerical results, there were mainly three findings as detailed below. First, an one-rank SI matrix was partially achieved by the parallel-arranged dipole array configured based on the proposed array design formulae. Second, even with the proposed array, SI effect was deteriorated due to the the level difference between two countervailing SI components caused by the aforementioned factors. Third, using the orthogonally-arranged dipole array, the level difference became relatively-slighter due to cross polarization, as a result, fine SIC effect was observed even with small array size.

Supplementally, by optimizing the antenna element itself to adjust the two SI component levels, the SIC effect can be more enhanced. The antenna optimization suitable for the proposed technique will be discussed in our future work.

TABLE I. Parameters at marked points.

(a) For ||-model.

	w [λ]	h [λ]	V [λ^3]	SI [dB]
Mode1	10.0	3.20	320	−48.5
Mode2	10.0	4.58	458	−43.6

(b) For ⊥-model (open star).

	w [λ]	h [λ]	V [λ^3]	SI [dB]
Mode1	4.72	2.23	49.7	−48.4
Mode2	5.14	3.36	88.9	−43.6

(c) For ⊥-model (filled star).

	w [λ]	h [λ]	V [λ^3]	SI [dB]
Mode1	10.0	3.20	320	−60.7
Mode2	10.0	4.58	458	−55.0

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