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Rotationally-symmetrical array for self-interference reduction in full-duplex MIMO

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Abstract: In order to realize a full-duplex wireless communication, the authors have proposed a spatial self-interference reduction technique with an end-fire array (EFA) which consumes only one degree of the multiple-input multiple-output (MIMO) freedom. However, this technique has a limited interference reduction performance due to an insufficient rank-degenerated interference channel because amplitude differences of the paths increase the rank of the channel in the EFA. In this letter, the authors propose a rotationally-symmetrical array (RSA) suitable for our conventionally proposing scenario to reduce the self-interference, where geometrical symmetry of the MIMO paths achieves a perfectly one-ranked channel and suppresses all of the self-interference in theory. Performance evaluation on the interference reduction level P_{BF} clarifies that the RSA reduces more interference than the EFA: $P_{BF} = 47.3$ dB (RSA), 23.0 dB (EFA) while array length of the transmitter (Tx), element spacing of the receiver (Rx), and distance between the Tx and Rx are 3.5 wavelengths, 0.5 wavelengths, and 5 wavelengths, respectively.

Keywords: MIMO, full-duplex, interference reduction, rotationally-symmetrical array, eigen-beamforming

Classification: Antennas and Propagation

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1 Introduction

In-band full-duplex radio [1, 2], where terminals simultaneously transmit and receive on the same frequency band, doubles channel capacity of the conventional frequency division duplex (FDD) communication by sharing spectrum resources which are conventionally used for both transmitted and received signals. Full-duplex stations, however, suffer from an interference transmitted by themselves (self-interference). This *loud* interference hides *whispering* desired signals from other terminals. Some spatial approaches try to reduce the interference by uses of antenna directivities [3], and spatial compositions of signals [4]. [3] places transmitting and receiving antennas so that beams are not directed at each other, which unfortunately separate the station's coverage for transmission and reception. [4] controls phases of signals to be transmitted and urges them to cancel at the receiving antennas. This is capable of multiple-input multiple-output (MIMO) transmission; however, it wastes many degrees of freedom (DoFs) for MIMO transmission because of making cancellation signals. To this end, the authors have proposed a combination technique of an end-fire array (EFA) and eigen-null-steering, which reduces the interference by up to 75.2 dB while consuming only one DoF [5]. Since this technique relies on the characteristics of interference channel degenerated by the EFA, the defect in a rank-degeneracy causes a limited interference reduction performance because amplitude differences among the paths increase the rank of the channel. In this letter, the authors propose a rotationally-symmetrical array (RSA) for [5]'s scenario, where geometrical symmetry of paths achieves a perfectly one-ranked channel and suppresses all of the self-interference in theory. A principle of the proposed technique is discussed; its interference reduction performance is calculated and compared with that of the EFA in order to clarify an effect of the symmetrical approach on the scenario.

2 Self-interference reduction technique using RSA

Fig. 1(a) shows a full-duplex system model dealt with in this letter, where the separated transmitter (Tx) and receiver (Rx) of the base station use the same frequency f_0. Signals via the self-interference channel $\boldsymbol{H}_{\mathrm{i}}$ interfere with the uplink

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signal at Rx from the user terminal. Fig. 1(b) describes a concept of a self-interference reduction technique proposed in [5], where M_T and M_R denote a number of antenna elements in Tx and Rx, respectively, N_i is the maximum number of interference eigenvalues. $\boldsymbol{w}_{\mathrm{iT}(n)}$ ($1 \leq n \leq M_\mathrm{T}$) and $\lambda_{\mathrm{i}(k)}$ ($1 \leq k \leq N_\mathrm{i}$) mean the nth transmitting weight and the kth eigenvalue in descending order. The technique induces the rank degeneration of $\boldsymbol{H}_\mathrm{i}$ e.g. by careful antenna arrangement, and then nulls the dominant interfering mode by Tx's eigen-beamforming technique. This scenario provides the significant interference reduction with a cost of only one DoF. Fig. 1(c) shows a model of a rotationally-symmetrical array antenna, which is a key idea of this letter. An uniform linear array (ULA) as the Rx array is located on the y axis, then an uniform circular array (UCA) as the Tx array is placed in the zx plane to form a circle around the y axis, where the circumference of the Tx-UCA and the element spacing of the Rx-ULA are defined by l_Tx and d_Rx, respectively, distance between the Tx-UCA and Rx-ULA is $D_{\mathrm{Tx-Rx}}$. By means of this, all of elements in the Tx have a rotational symmetry about each element in the Rx. Assume all of the antenna elements are point wave sources in a line-of-sight (LOS) far field each other, and there is no mutual coupling in both Tx and Rx arrays. Element patterns of the Tx-UCA comprehensively make a rotational symmetry about y axis, and all of element patterns in the Rx-ULA also have the symmetry. Then an ideal self-interference channel matrix $\boldsymbol{H}_\mathrm{i}$ is written as

$$\boldsymbol{H}_\mathrm{i} = \begin{bmatrix} h_{\mathrm{i}(1)} & \cdots & h_{\mathrm{i}(1)} \\ \vdots & \cdots & \vdots \\ h_{\mathrm{i}(M_\mathrm{R})} & \cdots & h_{\mathrm{i}(M_\mathrm{R})} \end{bmatrix}, \tag{1}$$

where $h_{\mathrm{i}(m)}$ ($1 \leq m \leq M_\mathrm{R}$) means a path from an arbitrary Tx element to the mth Rx element. Because all of the components of the correlation matrix $\boldsymbol{H}_\mathrm{i}{}^H\boldsymbol{H}_\mathrm{i}$ are same, the eigenvalues are

$$\lambda_{\mathrm{i}(k)} = \begin{cases} M_\mathrm{T}(|h_{\mathrm{i}(1)}|^2 + \cdots + |h_{\mathrm{i}(M_\mathrm{R})}|^2) & (k = 1) \\ 0 & (\text{other}) \end{cases}. \tag{2}$$

This claims that the ideal RSA absolutely degenerates the rank of the self-interference channel matrix, and that an eigen-beamforming to null the $\lambda_{\mathrm{i}(1)}$ suppresses all of the interference. According to a structure of (1), the Tx's 1st weight vector $\boldsymbol{w}_{\mathrm{iT}(1)}$ has uniform components, which means that the dominant interfering mode of the RSA is always realized by Tx's in-phase excitation. Therefore, all of the eigen-weight vectors to suppress the interference are orthogonal to the in-phase excitation. When the number of the Tx M_T is a power of two, the weight vectors can be picked up from Haramard matrices or discrete Fourier transform (DFT) matrices, i.e. the eigen-null-steering can be performed by not only a digital-beamforming (D-BF) whose weights are given by a singular value decomposition (SVD) of a simulated/measured $\boldsymbol{H}_\mathrm{i}$, but also an analog-beamforming (A-BF) simply realized by combinations of 180-degree hybrid couplers and fixed phase-shifters for the self-interference reduction of the RSA. The A-BF has an advantage to reduce a channel estimation process which takes some time and adds some calculation loads.

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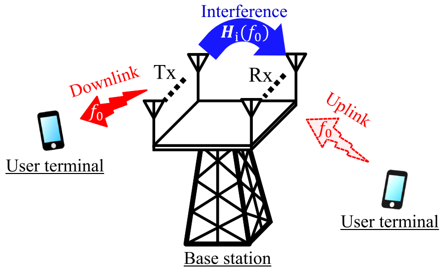
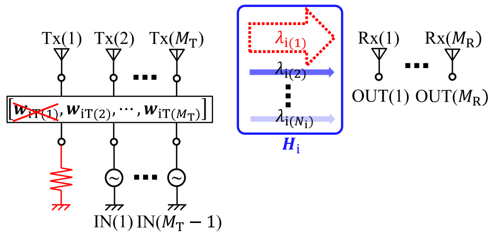
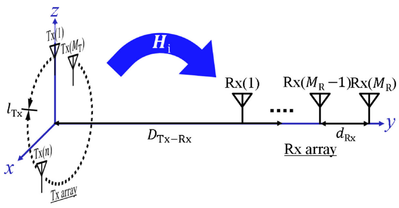


(a) Self-interference problem in full-duplex communication system.



(b) Proposed concept to reduce interference.



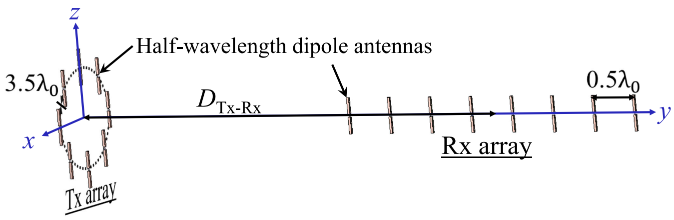
(c) Proposed rotationally-symmetrical array antenna.

Fig. 1. Conceptual sketches.

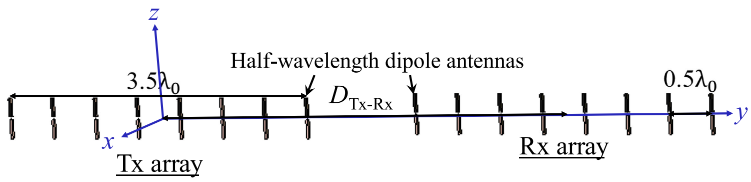
3 Simulation

3.1 Numerical parameters

Fig. 2(a)(b) show simulation models of (a) the RSA proposed in this letter, and (b) the EFA conventionally proposed in [5] for reference. Simulation is carried out by the method of moments. The number of the Tx and Rx elements are set to $M_T = M_R = 8$, and all of the antenna elements are vertical dipole antennas. The circumference of the Tx-UCA and the element spacing of the Rx-ULA are set to $l_{Tx} = (8 - 1)\lambda_0/2$ and $d_{Rx} = \lambda_0/2$, respectively. Here, by regarding the circumference of the RSA's Tx-UCA as the array length, the end-to-end distance of the EFA's Tx-ULA is also given as l_{Tx}. The distance between the Tx and Rx-ULA



(a) Roratationally-symmetrical array (RSA; proposed)



(b) End-fire array (EFA; conventional).

Fig. 2. Simulation models.

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$D_{\text{Tx–Rx}}$ is varied from 0 (the Rx-ULA is in the circle made by the Tx-UCA) to $20\lambda_0$ in the RSA, and from $4\lambda_0$ (one ULA is most likely to contact with the other) to $20\lambda_0$ in the EFA. In this letter, the interference power by the nth Tx port $p_{\text{i}(n)}$ $(1 \leq n \leq M_{\text{T}})$ is calculated by

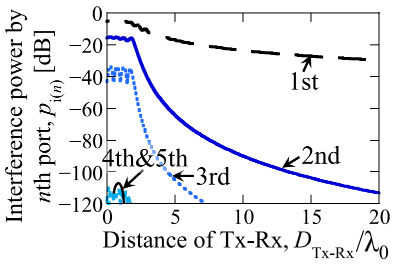
$$p_{\text{i}(n)} = |\boldsymbol{H}_{\text{i}}\boldsymbol{w}_{\text{iT}(n)}|^2, \tag{3}$$

and the interference reduction level P_{BF} is defined by

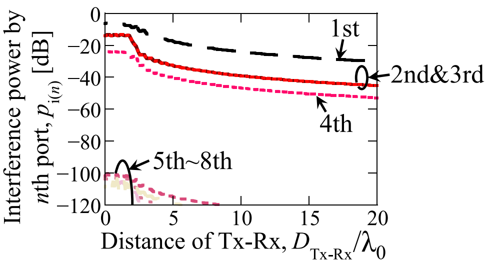
$$P_{\text{BF}} = \frac{p_{\text{i}(1)} + \cdots + p_{\text{i}(M_{\text{T}})}}{p_{\text{i}(2)} + \cdots + p_{\text{i}(M_{\text{T}})}}. \tag{4}$$

3.2 Numerical results

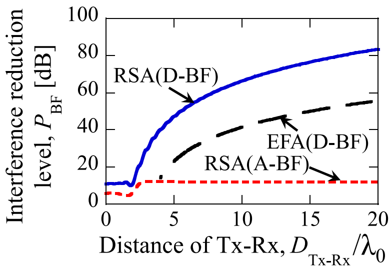
Fig. 3(a) shows the interference power by each D-BF port in the RSA, where $\boldsymbol{w}_{\text{iT}}$ is given by the SVD of the simulated $\boldsymbol{H}_{\text{i}}$: $p_{\text{i}(n)} = \lambda_{\text{i}(n)}$. Curves corresponding to modes lower than the 5th are too small to display in this range. This result points the extreme rank degeneration of the RSA. The more $D_{\text{Tx–Rx}}$ increases, the more deeply $\boldsymbol{H}_{\text{i}}$ degenerates. Fig. 3(b) presents the interference power by each A-BF port in the RSA, where $\boldsymbol{w}_{\text{iT}}$ is the power-normalized Hadamard matrix without the in-phase excitation. This result claims that the A-BF can be adopted to reduce the interference, however, and then leaks $\lambda_{\text{i}(1)}$ out to ports lower than the 1st. Increasing $D_{\text{Tx–Rx}}$ saturates the improvement of the interference reduction effect by itself. Fig. 3(c) indicates the comparison of the interference reduction levels between the RSA and EFA, where the RSA expects scenarios using the D-BF and A-BF while the EFA only uses the D-BF. Comparing their curves, the RSA is more effective for the interference reduction by the D-BF than the EFA. A benefit of the A-BF is saturated up to about $P_{\text{BF}} = 12$ dB. In $D_{\text{Tx–Rx}} = 5\lambda_0$, P_{BF} by the RSA using the D-BF, A-BF



(a) Interference power by each D-BF port.



(b) Interference power by each A-BF port.



(c) Comparison of interference reduction levels between RSA and EFA.

Fig. 3. Interference vs. distance between Tx and Rx.

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and the EFA using the D-BF are 47.3 dB, 12.1 dB, and 23.0 dB, respectively. The P_{BF} deterioration of the RSA in the small D_{Tx-Rx} is mainly caused by directional element patterns in vertical (yz) plane.

4 Conclusion

In this letter, the authors have proposed an RSA suitable for full-duplex station, where geometrical symmetry of the paths achieves a perfectly one-ranked channel and suppresses all of the self-interference in theory. A principle of the proposed technique was discussed with the derivation of the self-interference eigenvalues in the RSA; its interference reduction performance was calculated using two scenarios of the D-BF and A-BF, and compared with that of the EFA using the D-BF. RSA resulted $P_{BF} = 47.3$ dB (D-BF) and 12.1 dB (A-BF), whereas EFA resulted $P_{BF} = 23.0$ dB (D-BF). This clarified the effect of the RSA on the interference reduction performance of the scenario.

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