Numerical study on a rotationally-symmetrical dipole array antenna position for a MIMO full-duplex system

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Abstract: In this letter, a rotationally-symmetrical array (RSA) arrangement of a receiving dipole array antenna is optimized to maximize the performance of the null-beamforming method for the suppression of self-interference. The optimum RSA for a receiving dipole array with four elements is clarified. Through numerical simulations, we found that the optimized RSA arrangement suppressed the self-interference significantly.

Keywords: MIMO full-duplex, self-interference, antenna arrangement, null-beamforming

Classification: Antennas and Propagation

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1 Introduction

Full-duplex system and multiple-input multiple-output (MIMO) technology are promising technologies that can improve communication capacity without using additional frequency bands [1, 2]. The full-duplex system enables simultaneous two-way wireless communication in the same frequency band while the MIMO technology improves frequency utilization efficiency using multiple antennas. The combination of the MIMO technology and the full-duplex system is called the MIMO full-duplex system. However, it is well-known that the full-duplex system suffers from the so-called self-interference [3]. The self-interference problem leads to the saturation of the radio frequency (RF) front-end because the level of the transmitting signal is considerably higher than that of the receiving signal. Consequently, the RF front-end suffers from undesired nonlinearity and can be damaged.

In addition, the eigen-beamforming (EBF) method is a technique to improve the communication quality by controlling the radiation pattern at the transmitter side using transmission weight vector [4]. The control of the radiation pattern at the transmitter side can be also effective in circumventing the self-interference because the interference cannot reach the receiving antennas ideally. The null-beamforming (NBF) method is defined as the EBF method used to suppress self-interference using transmission weight vectors obtained by singular value decomposition (SVD) of the self-interference channel [5]. The performance of the NBF method is strongly affected by the nature of self-interference channel, in terms of spatial correlation. In general, high spatial correlation leads to higher performance of the NBF method.

Previously, an array antenna arrangement such as rotationally-symmetrical array (RSA) has been proposed to increase the spatial correlation and improve the performance of the NBF method [6]. In RSA, the NBF method can considerably suppress the self-interference if all antennas are point wave sources. However, the actual antenna has mutual coupling from other antennas.

Due to the highly symmetric arrangement of the RSA, the self-interference can be suppressed but the influence of asymmetry of mutual coupling between the array antenna elements can negatively impact its performance. The mutual coupling between the array antenna depends on the position of the array antenna.

In this letter, the receiving antenna arrangement for the RSA is optimized from the viewpoint of self-interference channel between the transmitting and receiving array antena elements. Both transmitting and receiving antennas are array antenna consisting of four-element dipole antennas.

2 Antenna arrangement suitable for NBF method

Fig. 1 shows a system model of our proposed MIMO full-duplex system. N and M are the number of transmitting antenna (Tx) and receiving antenna (Rx), respectively. $\boldsymbol{H}$ is the self-interference channel, λ_i is the i-th singular value of $\boldsymbol{H}$ in
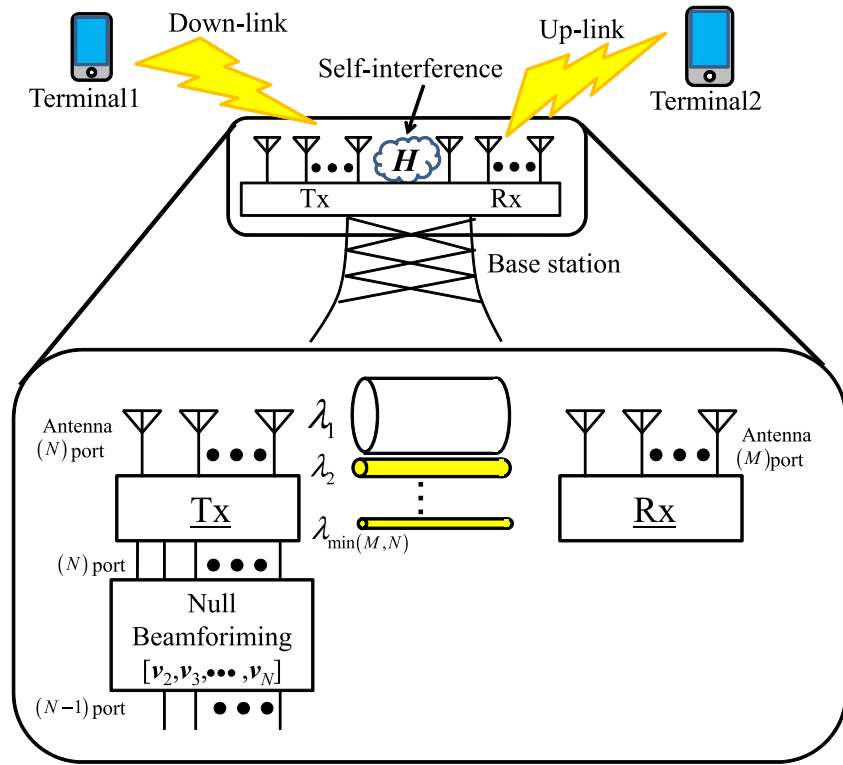
Fig. 1. System model

descending order, and $\boldsymbol{v}_i$ is the i-th transmission weight vector obtained by SVD of $\boldsymbol{H}$. By arranging the array antenna so that the rank of $\boldsymbol{H}$ becomes 1, the singular values other than the first singular value degenerate. The NBF method uses the transmission weight vectors excluding the first singular value. The magnitude of the self-interference channel norm using NBF method is given by

$$\|\boldsymbol{H}\tilde{\boldsymbol{V}}_1\|_{\mathrm{F}}^2 = \sum_{i=2}^{\min(M,N)} \lambda_i^2, \tag{1}$$

where $\tilde{\boldsymbol{V}}_1$ is the transmission weight matrix excluding the first singular value, $\tilde{\boldsymbol{V}}_1 = [\boldsymbol{v}_2, \cdots, \boldsymbol{v}_N]$. This means that Tx weighted by $\tilde{\boldsymbol{V}}_1$ forms a null in Rx direction to suppress λ_1 using the NBF method.

Fig. 2 shows the antenna arrangement to gain high spatial correlation. The Tx linear array is located on the z-axis. The Rx circular array is located on the circumference around the z-axis. D is the distance from the end of the Tx array to the origin of the Rx array, d_{e} is the element spacing of the Tx array, and r_{e} is the radius in the Rx array. We assume that all antennas are point wave sources and there is no mutual coupling.

In RSA, Line-of-sight paths from the arbitrary transmitting element to all of Rx elements are the same strength and phase because the distance between an arbitrary transmitting point and all of receiving point wave sources are equal. Therefore, all elements in each column vector of the self-interference channel matrix, $\boldsymbol{H}$, are identical, and the rank of self-interference channel $\boldsymbol{H}$ equals 1.

The self-interference power $P_{\mathrm{w/NBF}}$ and $P_{\mathrm{w/oNBF}}$ are defined as
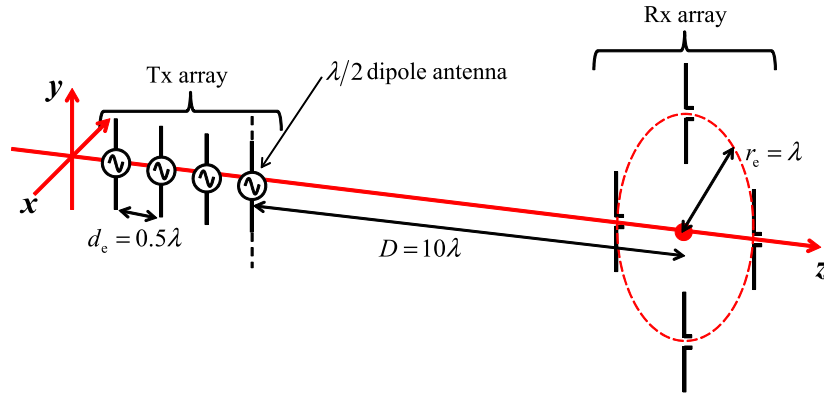
(a) Rotationally Symmetrical Array arrangement (RSA)
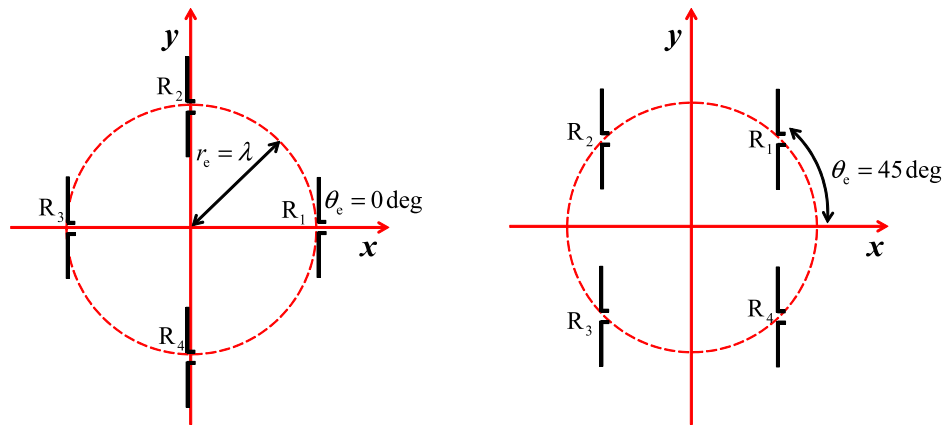
(b) Front view of RSA($\theta_\mathrm{e} = 0°, 45°$)

Fig. 2. Antenna arrangement

$$P_{\mathrm{w/NBF}} = \frac{P}{N-1} \sum_{i=2}^{\min(M,N)} \lambda_i^2, \tag{2}$$

$$P_{\mathrm{w/oNBF}} = \frac{P}{N} \sum_{i=1}^{\min(M,N)} \lambda_i^2, \tag{3}$$

where P is the sum of the transmission power. The singular value of the self-interference channel becomes 0 except for first singular value if the rank of $\boldsymbol{H}$ is 1. Therefore, the self-interference power with and without NBF method are $P_{\mathrm{w/NBF}} = 0$ and $P_{\mathrm{w/oNBF}} = P\lambda_1^2/N$. Therefore, the NBF method can suppress the self-interference by excluding only the first singular value.

However, the gain of each Rx antenna varies if the mutual coupling of the Rx array antenna is asymmetric due to the mutual coupling among Rx. In this letter, the symmetry of the mutual coupling of the RSA antenna is evaluated from the magnitude of the mutual coupling of each Rx antenna.

3 Numerical analysis results

3.1 Simulation setup

The antenna arrangement used for numerical analysis is shown in Fig. 2. The antenna is a half-wavelength dipole antenna. The distance from the end of the Tx array to the origin of the Rx array, the element spacing of the Tx array and the

radius of the Rx array are set to $D = 10\lambda$, $d_e = 0.5\lambda$ and $r_e = 0.5\lambda$, respectively (λ: wavelength in a vacuum). θ_e is the rotation angle of the receiving antennas moving in the direction from x-axis to y-axis. In this numerical analysis, we changed the rotation angle θ_e from 0° to 90°.

3.2   Simulation results
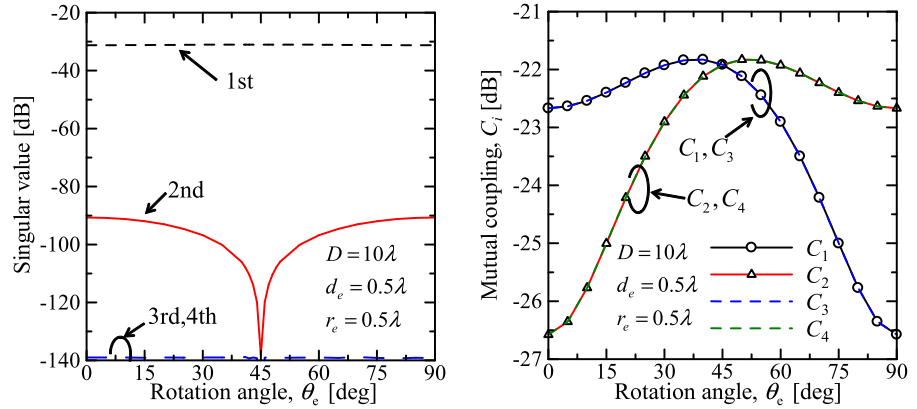
(a) Singular value characteristics

(b) Mutual coupling versus rotation angle
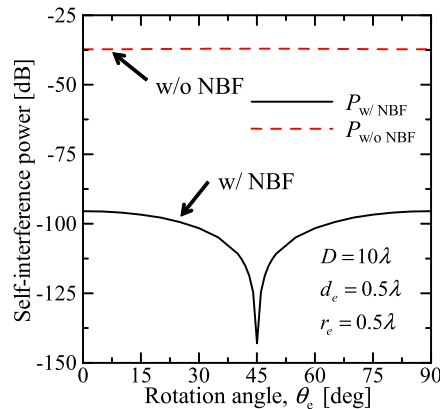
(c) Interference suppression power versus rotation angle

Fig. 3.   Simulation results

Fig. 3(a) shows the singular value characteristics. The first singular value was almost the same at all rotation angles, the second singular value become smaller as it approaches $\theta_e = 45°$. We found that the second singular value at $\theta_e = 45°$ was, at maximum, 48 dB lower than that at $\theta_e = 0°$. From the results, we found that the spatial correlation become higher as approach at $\theta_e = 45°$.

Fig. 3(b) shows the mutual coupling of the Rx antenna versus rotation angle. The mutual coupling of i-th Rx antenna C_i is given as

$$C_i = \sum_{k=1}^{N} |S_{i,k}|^2 \quad (i \neq k), \tag{4}$$

where $S_{i,k}$ is S-parameter from k-th Rx antenna to i-th Rx antenna. The mutual coupling difference of each Rx antenna become smaller as it approaches $\theta_e = 45°$. In particular, all mutual coupling at $\theta_e = 45°$ were almost equal. The sum of mutual

coupling from the adjacent antenna ($\theta_e \pm 90°$) is equal if the directivity of the RSA antenna is point-symmetric. Therefore, C_i is affected by the mutual coupling of the diagonal RSA antenna ($\theta_e + 180°$). The dipole antenna is omnidirectional on the xz-plane perpendicular to the element axis (y-axis) and forms a null at the end of element on the xy-plane. Thus, the mutual coupling C_1 and C_3 were large, and C_2 and C_4 were small at $\theta_e = 0°$. However, mutual coupling between Rx antennas at $\theta_e = 45°$ were almost equal because the mutual coupling of the dipole antennas on the diagonal was equal. Therefore, the mutual coupling at $\theta_e = 45°$ was symmetrical.

Fig. 3(c) shows the self-interference power versus rotation angle. The self-interference power without NBF method ($P_{w/oNBF}$) was -37 dB at all rotation angles. In other hand, the self-interference power with NBF method ($P_{w/NBF}$) was suppressed by more than 95 dB at all rotation angles. In particular, the self-interference power was suppressed by 143 dB at $\theta_e = 45°$. This shows that the NBF method at $\theta_e = 45°$ suppresses the self-interference significantly because the self-interference channel including the influence of mutual coupling was symmetrical.

4   Conclusions

Numerical analysis confirmed that the self-interference power with NBF method varies with the rotation angle of the receiving dipole array antenna of RSA. The self-interference power was changed according to the rotation angles because the mutual coupling of the receiving dipole array antennas alters the symmetry. The self-interference power with NBF method ($P_{w/NBF}$) was suppressed by 143 dB at $\theta_e = 45°$. Therefore, we found that the most efficient arrangement of the dipole array antenna in RSA is at $\theta_e = 45°$.

Acknowledgments