

# Experimental evaluation of interference reduction effect; Eigen-beamforming and digital subtraction by using MIMO-OFDM signals

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**Abstract:** In this letter, we experimentally validate an interference reduction technique that combines a digital subtraction technique, and eigen-beam-forming with an end-fire arrangement of linear array antennas. The eigen-beamforming significantly reduces the self-interference at the cost of a slight drop in the degrees-of-freedom of the antenna. We experimentally evaluate the degree of interference reduction using two linear sleeve-dipole arrays in end-fire arrangement. This experiment uses MIMO (Multiple-Input Multiple-Output)-OFDM (Orthogonal Frequency Division Multiplexing) signals to evaluate the realistic performance of this technique. The results of the experiment show the combination of eigen-beamforming and digital subtraction can significantly reduce,  $-76$  dB, the interference.

**Keywords:** full-duplex, interference, beamforming, digital subtraction

**Classification:** Antennas and Propagation

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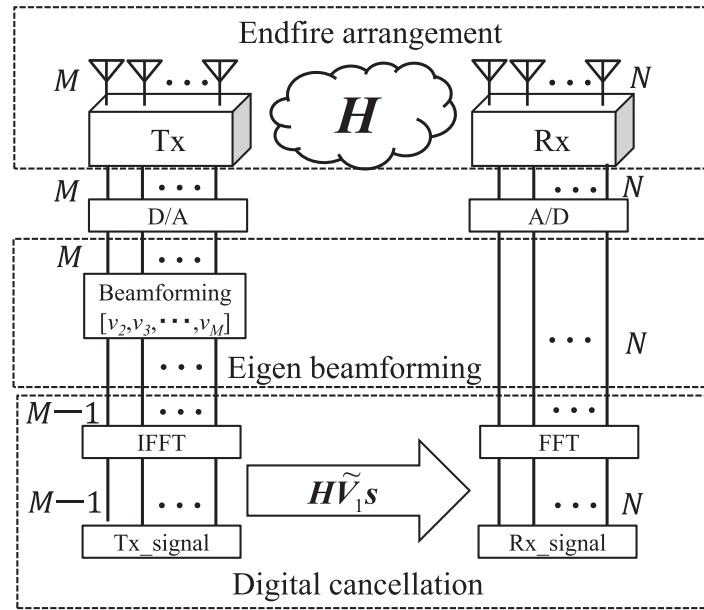
## 1 Introduction

Full-duplex communication is being studied recently for application to the 5G wireless network [1]. Full-duplex communication establishes two-way communication using the same frequency and time resources [2]. However, full-duplex communication cannot be realized without resolving the self-interference problem, i.e. the strong transmitting signal is captured by its receiving antennas which interferes with the desired receiving signals. Ideally, self-interference can be eliminated by digital subtraction since the self-interference is known signal [3]. However, the self-interference is significantly stronger than the desired signal, and causes RF (Radio Frequency) front-end saturation, which produces nonlinear signal distortion. In this case, digital subtraction is unable to adequately suppress the self-interference [4]. Therefore, the self-interference needs to be suppressed before the RF front-end at the receiver. To combat this, three methods have been studied [5, 6, 7]. Antenna cancellation uses an additional transmitting antenna to form a null point at the receiving antenna [5]. Balun cancellation places a balun circuit between the transmitting and receiving antennas to subtract the self-interference signals from the received signals [6]. Note that these methods cannot be directly applied to MIMO systems because the interference among all combinations of transmitting and receiving antennas must be considered and implementation is difficult. To resolve this problem, eigen-beamforming using linear array antennas in the end-fire arrangement was proposed for self-interference reduction in the MIMO full-duplex system [7]. This method offers very high interference reduction with the consumption of only one degree-of-freedom of the antenna array; this antenna arrangement degenerates the rank of the interference channel to 1. Only the S-parameter of the antennas has been used to verify the performance of this method, meaning that the total cancellation performance, including signal subtraction, has yet to be evaluated.

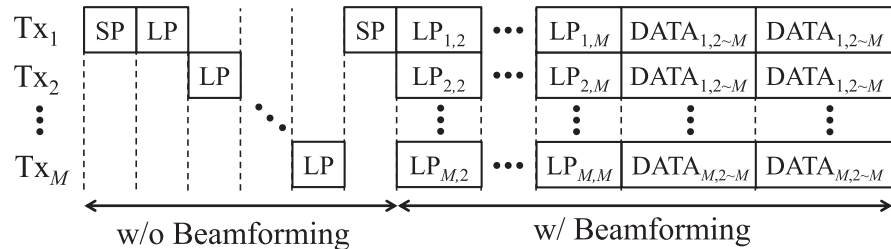
This letter experimentally evaluates the interference cancellation performance of the method proposed in [7] by using real MIMO-OFDM signals. A signal frame-

format is newly developed for this experiment, and the total performance of the self-interference reduction method including digital subtraction technique is investigated, where the remaining interference caused by the saturation of the RF front-end and imperfection of the antenna arrangement is evaluated.

## 2 Self-interference reduction method using eigen-beamforming and digital subtraction



(a) System model



(b) MIMO-OFDM frame format

**Fig. 1.** System model and MIMO-OFDM frame format

Fig. 1(a) shows a system model of the in-house-developed full-duplex testbed with linear array antennas in the end-fire arrangement.  $M$  and  $N$  are the number of transmitters (Tx) and receivers (Rx), respectively,  $H$  is the interference channel, and  $s$  is the transmission signal. Let us describe the eigen-beamforming scheme in this experiment. The singular value decomposition of the interference channel  $H$  is given by

$$H = U\Sigma V^H, \tag{1}$$

where  $\{\cdot\}^H$  represents Hermitian transpose.  $V$  and  $U$  are eigen-vector matrices of Tx and Rx, respectively. The number of eigen-values is given by

$$N_i = \min(M, N), \quad (2)$$

and  $\mathbf{V}$  and  $\mathbf{\Sigma}$  are defined by

$$\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_M] \quad (3)$$

$$\mathbf{\Sigma} = \text{diag}(\sqrt{\lambda_1}, \sqrt{\lambda_2}, \dots, \sqrt{\lambda_{N_i}}), \quad (4)$$

where  $\mathbf{v}_i$  is the  $i$ -th transmission weight vector, and  $\lambda_i$  is the  $i$ -th eigen-value. The eigen-values correspond to the received signal strength of the eigen-modes. Eigen-beamforming is the interference reduction technique that uses the eigen-mode weight vector described in (3). The  $i$ -th transmission mode is formed by the  $i$ -th transmission weight vector. In the eigen-beamforming scheme, the eigen-vectors excluding those corresponding to several of the largest eigen-values are used. This lowers the degree-of-freedom of the antennas, where the number is determined by the number of suppressed modes. When transmitting and receiving linear array antennas are placed in an end-fire arrangement, the rank of the transmission modes is expected to degenerate to 1. This means, the required number of the antenna-degrees-of-freedom is minimized to 1, ideally. However, the rank of the interference channel in the actual antenna array cannot be made 1 because of the channel imperfections created by the mutual coupling among the antennas and the finite distance between the transmitting and receiving arrays. The self-interference remains as the interference channel is imperfect. The remaining interference can be digitally subtracted because the transmitted signals are known. If transmit-beamforming is not used, the interference signals significantly impact the RF front-end at its receiver, and subtraction become ineffective as the interfering signals are nonlinearly distorted.

Fig. 1(b) shows the frame format of the MIMO-OFDM signals. SP (Short Preamble) synchronizes Tx and Rx, and LP (Long Preamble) is used to estimate the interference channel.  $LP_{i,j}$  and  $DATA_{i,j}$  are the signals for  $j$ -th eigen-modes transmitted from the  $i$ -th antenna. The interference power is defined by the DATA signals observed at the receiver. In this scheme, the first channel estimation (w/oBF LP) is performed to get the interference channel  $\mathbf{H}$ . Eigen-beamforming is realized by using the transmission weight matrix consisting of eigen-vectors,  $[\mathbf{v}_2, \dots, \mathbf{v}_M]$ . The second channel estimation (w/BF LP) is also performed to estimate the interference channel, where the transmission weight without the major interference mode is used at Tx side. The received signal after digital subtraction is given by

$$\mathbf{y}_{\text{SUB}} = \mathbf{y} - \mathbf{H}_i \tilde{\mathbf{V}}_1 \mathbf{s}, \quad (5)$$

where  $\mathbf{y}_{\text{SUB}}$  is the received signal after digital subtraction,  $\mathbf{y}$  is the received signal, and  $\mathbf{s}$  is the transmitted signal.

### 3 Experiments using MIMO-OFDM signals

#### 3.1 Experimental setup

Fig. 2 shows the measurement environment. The transmitting and receiving antennas are linear array antennas consisting of four element half-wavelength sleeve antennas. The center frequency is 2.47 GHz. For the linear array antennas, the

center-to-center distance between Tx and Rx is  $d_{Tx-Rx} = 10\lambda_0$  ( $\lambda_0$ : wavelength in a vacuum), and the element spacing  $d_{element}$  is changed from  $0.25\lambda_0$  to  $1.5\lambda_0$ . Sheet-like microwave absorbers are placed below the antennas in order to prevent reflection from the fixtures.

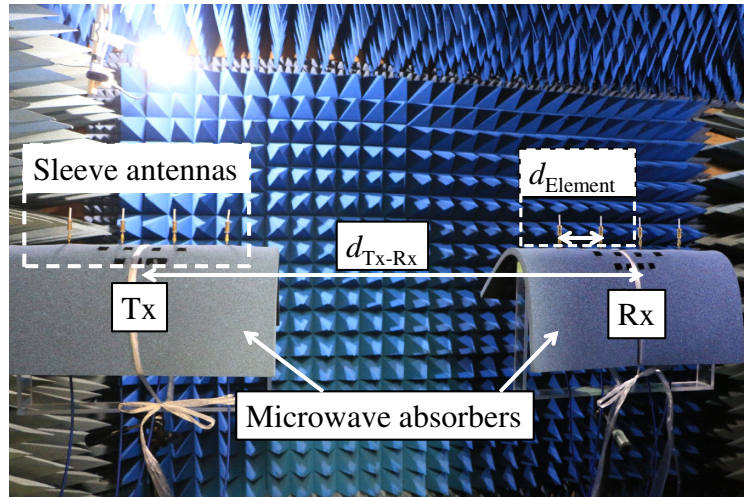
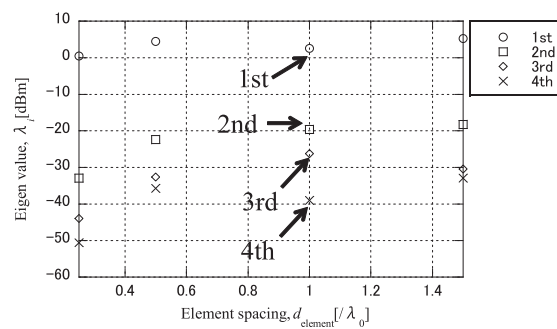
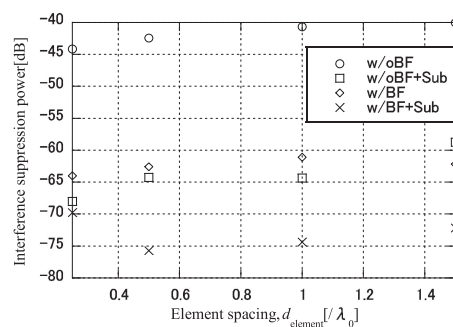


Fig. 2. Measurement environment



(a) Eigenvalue versus Element spacing



(b) Interference suppression power versus Element spacing

Fig. 3. Measured results

### 3.2 Simulation results

Fig. 3(a) shows the eigen-value distribution versus element spacing. The maximum difference between the first and second eigen-values is 32 dB at  $d_{element} = 0.25\lambda_0$ , and the minimum difference is 23 dB at  $d_{element} = 1.5\lambda_0$ . From this result, the eigen-

weight without first eigen-mode can suppress the interference by more than 23 dB. Further, the narrower the element spacing becomes, the more eigen-beamforming suppresses the interference.

Fig. 3(b) shows the interference level versus element spacing. The interference level is defined as the level of the total received power at Rx side relative to the total input power at Tx side. Comparing the interference levels without eigen-beamforming (w/o BF) and with eigen-beamforming (w/ BF) shows that eigen-beamforming suppresses the interference by at least 20 dB for all element spacing's examined. We also found the minimum interference level,  $-64$  dB, is achieved with eigen-beamforming at  $d_{\text{element}} = 0.5\lambda_0$ . The combination of an eigen-beamforming and digital subtraction (w/ BF + Sub) can suppress the interference to  $-76$  dB at  $d_{\text{element}} = 0.5\lambda_0$ , which is 12 dB lower than that without subtraction. This result shows that digital subtraction further suppresses the self-interference power.

#### 4 Conclusion

Experiments confirmed that our combination of eigen-beamforming and digital subtraction, where linear array antennas in end-fire arrangement are used, can significantly reduce the self-interference reduction. When the element spacing is  $d_{\text{element}} = 0.5\lambda_0$ , the interference level reduction achieved by eigen-beamforming is  $-64$  dB, while with eigen-beamforming and digital subtraction the reduction is  $-76$  dB. Further interference reduction is needed to implement this technique in actual full-duplex systems and will be the target of future work.

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