Optimal Design of Full-Duplex Orbital Angular Momentum Mode-Division Multiplexing Systems

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***Abstract*—In this paper, we consider a single-pair full-duplex (FD) orbital angular momentum (OAM) mode-division multiplexing (MDM) system consisting of two FD OAM-MDM transceivers. Each transmitter sends multiple data signals via multiple OAM modes to the corresponding receiver and each receiver tries to detect multiple signals from the corresponding transmitter with multiple receive antennas in the FD OAM-MDM systems. In particular, we investigate the effect of receive antenna position on the achievable sum-rate in the FD OAM-MDM system. We propose a novel low-complexity receive antenna deployment scheme for improving the sum-rate of the FD OAM-MDM system and we compare the proposed scheme with the conventional maximum signal-to-noise ratio (SNR)-based and the exhaustive search (ES)-based antenna deployment schemes. The maximum SNR-based antenna deployment scheme determines the position of each receive antenna at the position where the received signal power of each OAM mode is maximized. However, this scheme may not effectively reduce the effect of self-interferences due to full-duplex operation and the inter-mode interferences in the FD OAM-MDM system. Through extensive computer simulations, it is shown that the proposed antenna deployment scheme outperforms the conventional maximum SNR-based antenna deployment scheme and results in a quite similar performance to the ES-based optimal antenna deployment scheme in terms of the achievable sum-rate in the FD OAM-MDM system.**

***Index Terms*—Orbital angular momentum (OAM), mode-division multiplexing (MDM), full-duplex (FD), self-interference, inter-mode interference, antenna deployment, achievable sum-rate.**

I. Introduction

In future 6G wireless networks, ubiquitous and unlimited wireless connectivity is expected to be realized with the 1Tbps peak data-rate requirement over autonomous and intelligent wireless networks, where the required spectrum efficiency will be 5-10 times higher than that of 5G wireless systems [1], [2]. One of the most promising techniques to fulfill such demanding requirements is to use more bandwidth beyond the millimeter-wave (mmWave) band in the terahertz (THz) frequency band [3], [4]. In the THz band, it has been known that wireless channels become sparse and thus the conventional multi-antenna techniques cannot provide spatial multiplexing gain. In general, multi-input multi-output (MIMO) channels in the THz band are considered as line-of-sight (LoS) MIMO channels. Recently, *orbital angular momentum* (OAM)-based mode-division multiplexing (MDM) techniques have received much attention from both industry and academia as an emerging low-complexity but spectrally-efficient physical-layer solution to provide spatial multiplexing gain even in LoS MIMO channel environments like wireless backhaul networks, unmanned aerial vehicle (UAV) networks, low earth orbit (LEO) satellite networks, etc [5]–[8].

In the literature, many experimental studies on the OAM-MDM system have been performed with lensed-horn antennas and spiral phase plates (SPP) [5], with uniform circular antenna arrays (UCAs) [6]–[11], with patch antennas [12], and with meta-material lens antennas [13], [14]. However, in these studies, the effect of inter-mode interferences on the communication performance has not been fully characterized even though it was verified through experiments that multiple independent communication signals can be transmitted and successfully detected at the receiver by using multiple OAM modes. Recently, several studies on not only the inter-mode interference but also intra-mode interference in the OAM-MDM system have been conducted based on the network information theory [15], [16], where the authors investigated a multi-pair OAM-MDM system consisting of multiple transmitter–receiver pairs exploiting the same multiple OAM modes with Laguerre-Gaussian (LG) beam model. In [17], the UCA-based OAM-MDM system was investigated based on the LoS-MIMO channel capacity analysis, where various aspects of LoS-MIMO capacity were characterized according to many system parameters such as the number of receive UCAs, transmit/receive antenna radius, transmitter-receiver alignment, transmitter-receiver lateral displacement, etc.

On the other hand, a full-duplex (FD) transceiver technique has been considered as one of the most emerging techniques for future wireless communication systems since it theoretically achieves twice the data-rate (equivalently spectral efficiency) without using additional frequency bandwidth, compared with half-duplex techniques [18]. The most critical technical challenge is to reduce the self-interference from the transmitter to the receiver in the same device in FD wireless systems. If the OAM-MDM and the FD techniques are successfully combined, then its resultant data-rate performance can be significantly enhanced and the FD OAM-MDM system will be adopted for future wireless backhaul networks. Meanwhile, OAM beams in mmWave or THz bands have very high-directivity within Rayleigh distance and the effect of self-interference becomes very small if proper meta-material lens antennas are used [13]. Several studies on the in-band FD-

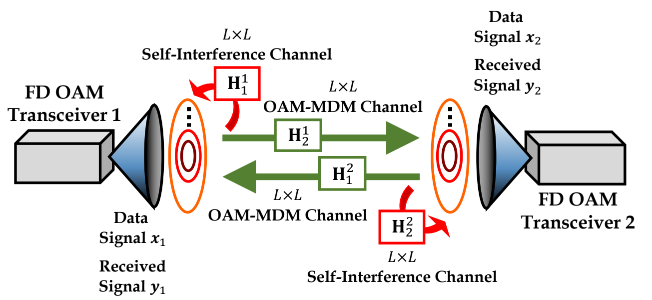

Fig. 1: System model of a single-pair FD OAM-MDM system.

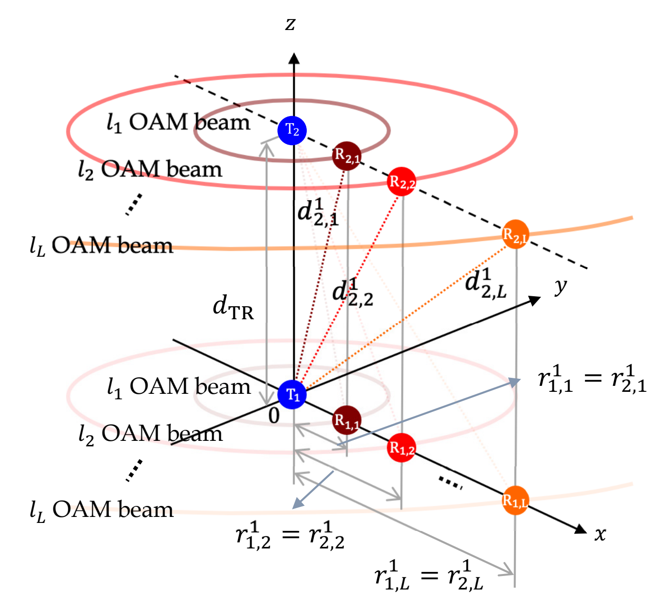

Fig. 2: Transmit (blue dots) and receive antenna (brown, red, orange dots) position of a single-pair FD OAM-MDM system in cylindrical coordiante system.

OAM techniques have conducted for UCA-based OAM systems [19], [20] and for horn-antenna-based OAM systems [21]. In [19], an optimal OAM model selection method to maximize the sum-rate by considering the self-interference in the FD OAM system, where both transmitter and receiver are placed on a common beam axis with a non-zero tilt angle that incurs the misaligned OAM beam reception. Similar OAM mode selection methods were proposed to effectively reduce the self-interference resulting from mutual coupling for UCA-based FD OAM system in [20], [21]. Hence, existing studies only consider the OAM mode selection for reducing the self-interference and improving the sum-rate for a given antenna deployment where the received signal-to-noise ratio (SNR) is maximized for each OAM mode in general.

In this paper, we consider a single-pair in-band FD OAM-MDM system consisting of two FD transceivers which are capable to transmit multiple signals via multiple OAM modes and to receive signals simultaneously. In particular, we investigate three antenna deployment schemes: the conventional maximum SNR-based deployment, the optimal exhaustive search (ES)-based deployment, and the proposed low-complexity heuristic algorithm-based deployment. To the best of our knowledge, we first propose an optimization framework of antenna deployment for the FD OAM-MDM system in the literature. The rest of this paper is organized as follows. Section II describes the single-pair in-band FD OAM-MDM system and the OAM channel model. The three antenna deployment schemes are explained and compared with each other in Section III. Simulation results are shown in Section IV and conclusions are drawn in Section V.

II. System and Channel Model

A. System Model

The Fig. 1 shows a single-pair FD OAM-MDM system consisting of two transceivers. Each transceiver can multiplex data signals via multiple OAM beams. So the data signal vector from the $i \in \{1,2\}$-th transceiver can be represented as $\mathbf{s}_i = [s_{i,1}, s_{i,2}, ..., s_{i,m}, ..., s_{i,L}]^T \in \mathbb{C}^{L\times 1}$, where the set of OAM modes is equal to $\mathcal{L} = \{l_1, l_2, ..., l_m, ..., l_L\}$, the index of OAM mode is equal to $m \in \{1,2,...,L\}$, and the cardinality (number of elements in a set) of OAM modes is equal to $|\mathcal{L}| = L$. We assume that the transmit power constraint satisfies $\mathbb{E}[||\mathbf{s}_i||^2] = P$. Then, we can represent the received signal vector at the j-th transceiver in a single-pair FD OAM-MDM system (in a $i \neq j$ case).

$$\mathbf{y}_j = \mathbf{H}_j^i \mathbf{x}_i + \mathbf{H}_j^j \mathbf{x}_j + \mathbf{n}_j, \tag{1}$$

where the $\mathbf{n}_j = [n_{j,1}, n_{j,2}, ..., n_{j,L}]^T \in \mathbb{C}^{L\times 1}$ denotes the additive noise vector at the j-th transceiver. In addition, the $\mathbf{H}_j^i$ and $\mathbf{H}_j^j$ denote the transmission channel matrix consisting of desired and inter-mode interference channels, and the self-interference channel matrix, respectively. The OAM channel matrix from the i-th transceiver to the corresponding $j \in \{1,2\}$-th transceiver is given by

$$\mathbf{H}_j^i = \begin{bmatrix} h_{j,1}^{i,1} & h_{j,1}^{i,2} & \cdots & h_{j,1}^{i,m} & \cdots & h_{j,1}^{i,L} \\ h_{j,2}^{i,1} & h_{j,2}^{i,2} & \cdots & h_{j,2}^{i,m} & \cdots & h_{j,2}^{i,L} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{j,n}^{i,1} & h_{j,n}^{i,2} & \cdots & h_{j,n}^{i,m} & \cdots & h_{j,n}^{i,L} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{j,L}^{i,1} & h_{j,L}^{i,2} & \cdots & h_{j,L}^{i,m} & \cdots & h_{j,L}^{i,L} \end{bmatrix} \in \mathbb{C}^{L\times L}, \tag{2}$$

where the index of receive antenna is $n \in \{1,2,...,L\}$. Thus, the $h_{j,n}^{i,m} \in \mathbb{C}$ indicates that the OAM channel from the i-th transceiver via the m-th OAM mode to the n-th receive antenna of j-th transceiver.

B. Channel Model

The OAM channel $h_{j,n}^{i,m}$ can be calculated from the LG beam parameter as shown Fig. 2. Firstly, we consider the cylindrical coordinate system (r, ϕ, z) for OAM channel characterization. Let $r_{j,n}^i$, $\phi_{j,n}^i$ and $z_{j,n}^i$ be the radial position, the azimuth angle and the axial distance from the transmit antenna of

$$u_{p,l_m}(r^i_{j,n},\phi^i_{j,n},z^i_{j,n}) = \sqrt{\frac{2p!}{\pi(p+|l_m|)!}}\frac{1}{w(z^i_{j,n})}\left(\frac{r^i_{j,n}\sqrt{2}}{w(z^i_{j,n})}\right)^{|l_m|}\exp\left(-\left(\frac{r^i_{j,n}}{w(z^i_{j,n})}\right)^2\right)L_p^{|l_m|}\left(\frac{2(r^i_{j,n})^2}{w^2(z^i_{j,n})}\right)$$
$$\times\exp\left(-\frac{ik(r^i_{j,n})^2}{2R(z^i_{j,n})}\right)\exp\left(i\left(|l_m|+2p+1\right)\psi(z^i_{j,n})\right)\exp\left(-il_m\phi^i_{j,n}\right), \tag{3}$$

$$R = 2\log_2\left(\det\left(\mathbf{I}_L + \frac{1}{N_0}\mathbf{H}^2_1(\mathbf{H}^2_1)^H\left(\mathbf{I}_L + \frac{1}{N_0}\mathbf{H}^1_1(\mathbf{H}^1_1)^H\right)^{-1}\right)\right), \tag{4}$$

the i-th transceiver to the n-th receive antenna at the j-th transceiver, respectively. The transmission distance between FD transceivers is denoted by d_{TR}. Then, the wireless OAM channel $h^{i,m}_{j,n} = \sqrt{P}u_{p,l_m}(r^i_{j,n},\phi^i_{j,n},z^i_{j,n})$ can be mathematically characterized by the Eq. (3) in cylindrical coordinate $(r^i_{j,n},\phi^i_{j,n},z^i_{j,n})$, where the beam waist at z-plane is equal to $w(z) = w_0\sqrt{1+(z/z_{\mathsf{R}})^2}$, the radius of curvature is equal to $R(z) = (z^2+z^2_{\mathsf{R}})/z$, and the Gouy phase is equal to $\psi(z) = \arctan(z/z_{\mathsf{R}})$, when the $z = z^i_{j,n}$ is given and the Rayleigh distance is equal to $z_{\mathsf{R}} = \pi w_0^2/\lambda$, respectively. Furthermore, we assumed that the radial index p is equal to 0, the OAM channel can be more simplified.

The achievable sum-rate in a single-pair FD OAM-MDM system is given by Eq. (4), where the noise power at each receive antenna is equal to N_0 [22].

III. Optimal Antenna Deployment

In general, the OAM beam has a property of diverging according to the propagation distance. In particular, as the index of the OAM mode increases, the OAM beam diverges more according to the transmission distance. Most of literature considering OAM communication systems using only one OAM mode, a receive antenna at the maximum intensity radius for SNR maximization is best in terms of achievable rate. However, the achievable sum-rate in FD OAM-MDM systems depends on the antenna deployment due to the effects of self- and inter-mode interferences. Thus, we investigate three antenna deployment schemes based on the conventional maximum SNR (MaxSNR), exhaustive search (ES), and the proposed heuristic algorithm in this paper.

A. Conventional Maximum SNR-based Antenna Deployment

The antenna deployment at the maximum intensity radius can maximize SNR in the viewpoint of communication theory. The maximum intensity radius considering the OAM mode m at the plane z can be easiliy calculated by $r_{\mathsf{max}}(z,m) = w(z)\sqrt{|l_m|/2}$. Then, multiple receive antennas corresponding to multiple OAM modes can be placed at maximum intensity radius considering each OAM mode. For example, if two OAM modes $(+1,+3)$ are exploited, radial positions of receive antennas at the corresponding transceiver at the z-plane are equal to $w(z)\sqrt{|+1|/2}$ and $w(z)\sqrt{|+3|/2}$, respectively.

B. Exhaustive Search-based Optimal Antenna Deployment

As one of the methods to maximize the achievable sum-rate, we can consider the *full search*-based antenna deployment. Let $\mathcal{P} = \{1,\ 2,\ \ldots,\ \lfloor\rho_{\max}/\Delta\rho\rfloor\}$ be a set of the quantized position indices, where $\rho_{\max}$ is the length of OAM transceiver radius and $\Delta\rho$ is the interval between two consecutive position indices defined as $\Delta\rho = 0.1\lambda$ from the wavelength. Also, in order to take into account the sum-rate according to the position of the receive antennas, we redefine (4) as follows:

$$R(\mathbf{x}) = 2\log_2\left(\det\left(\mathbf{I}_L + \frac{1}{N_0}\mathbf{H}^2_1(\mathbf{x})(\mathbf{H}^2_1(\mathbf{x}))^H \times\left(\mathbf{I}_L + \frac{1}{N_0}\mathbf{H}^1_1(\mathbf{x})(\mathbf{H}^1_1(\mathbf{x}))^H\right)^{-1}\right)\right), \tag{5}$$

where $\mathbf{x}$ $(= [x_1\ x_2\ldots x_n\ldots x_L])$ denotes a vector consisting of the position index for the n-th OAM mode receive antenna, i.e., $x_n \in \mathcal{P},\ \forall n$, and

$$\mathbf{H}^i_j(\mathbf{x}) = \begin{bmatrix} h^{i,1}_{j,x_1\Delta\rho} & \cdots & h^{i,m}_{j,x_1\Delta\rho} & \cdots & h^{i,L}_{j,x_1\Delta\rho} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ h^{i,1}_{j,x_n\Delta\rho} & \cdots & h^{i,m}_{j,x_n\Delta\rho} & \cdots & h^{i,L}_{j,x_n\Delta\rho} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ h^{i,1}_{j,x_L\Delta\rho} & \cdots & h^{i,m}_{j,x_L\Delta\rho} & \cdots & h^{i,L}_{j,x_L\Delta\rho} \end{bmatrix}. \tag{6}$$

Here, $h^{i,m}_{j,x_n\Delta\rho}$ represents that the OAM channel between the i-th transceiver with the m-th OAM mode and the n-th receive antenna deployed at $x_n\Delta\rho$ of the j-th transceiver. Intuitively, we can observe that each channel coefficient, $h^{i,m}_{j,x_n\Delta\rho}$, is obtained according to the deployed position of the receive antennas.

Then, the ES-based antenna deployment problem can be formulated as follows:

$$\mathbf{x}^{Ex} = \arg\max_{\mathbf{x}\in\mathcal{P}^L} R(\mathbf{x}), \tag{7}$$

where $\mathbf{x}^{Ex} = \left[x^{Ex}_1\ x^{Ex}_2\ \ldots\ x^{Ex}_L\right]$ is a vector consisting of the position index of the n-th OAM mode receive antenna deployed by the *Exhaustive Search* method.

C. Proposed Low-Complexity Antenna Deployment

Since the aforementioned *Exhaustive Search* manner has high-complexity according to the number of OAM modes and the number of quantized position indices, we propose a low-complexity antenna deployment algorithm based on the heuristic method for FD OAM-MDM systems. We will numerically prove through extensive computer simulations in

Algorithm 1 Proposed Antenna Deployment

1: **Input:** $\mathbf{H}_j^i(\mathbf{x}), \forall i, j, n$ and $\epsilon = \epsilon_0$

2: **Initialization:** $S^{(0)} = 0,\ \mathbf{x}^{(1)} = [1\ 1 \cdots 1] \in \mathbb{N}^L,\ t = 1$

3: $S^{(t)} = R\left(x_1^{(t)}, x_2^{(t)}, \ldots, x_L^{(t)}\right)$

4: **while** $\left|S^{(t)} - S^{(t-1)}\right| \geq \epsilon$ **do**

5: $\quad x_1^{(t+1)} \leftarrow \underset{x_1 \in \mathcal{P}}{\arg\max}\, R\left(x_1, x_2^{(t)}, \ldots, x_{L-1}^{(t)}, x_L^{(t)}\right)$

6: $\quad x_2^{(t+1)} \leftarrow \underset{x_2 \in \mathcal{P}}{\arg\max}\, R\left(x_1^{(t+1)}, x_2, \ldots, x_{L-1}^{(t)}, x_L^{(t)}\right)$

7: $\quad \vdots$

8: $\quad x_{L-1}^{(t+1)} \leftarrow \underset{x_{L-1} \in \mathcal{P}}{\arg\max}\, R\left(x_1^{(t+1)}, x_2^{(t+1)}, \ldots, x_{L-1}, x_L^{(t)}\right)$

9: $\quad x_L^{(t+1)} \leftarrow \underset{x_L \in \mathcal{P}}{\arg\max}\, R\left(x_1^{(t+1)}, x_2^{(t+1)}, \ldots, x_{L-1}^{(t+1)}, x_L\right)$

10: $\quad S^{(t+1)} = R\left(x_1^{(t+1)}, x_2^{(t+1)}, \ldots, x_L^{(t+1)}\right)$

11: $\quad t \leftarrow t + 1$

12: **end while**

13: **Output:** $\mathbf{x}^* = [x_1^{(t)}\ x_2^{(t)}\ \cdots\ x_L^{(t)}]$

IV that this algorithm has almost the same achievable sum-rate performance as the exhaustive method while having low-complexity[1].

Algorithm 1 represents the overall process of the proposed antenna deployment algorithm. Briefly, this algorithm converts the *full-search* to *partial-search* for each OAM mode. Specifically, first of all, the initialization is performed as shown in line 2 and 3 of Algorithm 1. Here, it is assumed that all channel coefficients according to the antenna position, $h_{j,x_n\Delta\rho}^{i,m}$, are given (this is actually possible by measuring). Then, for each OAM mode n, after fixing the antenna position indices of other modes, the receive antenna position index, x_n, is updated to a position index where the achievable sum-rate is maximized. Once this is done for all OAM modes, the achievable sum-rate derived from the current loop (line 10) and the achievable sum-rate derived from the previous loop are compared. If the difference between the two values is less than the threshold ϵ, then the element of the finally updated antenna index vector, $\mathbf{x}^*$, is determined as the position index of the each OAM mode receive antenna.

IV. Numerical Results

In this section, we evaluate the antenna size of a FD transceivers and the achievable sum-rate in FD OAM-MDM systems with respect to various system parameters via computer simulations. All transceivers multiplexed data signals via the carrier frequency 86.5 [GHz] with channel bandwidth 500 [MHz]. Then, the wavelength is $\lambda = 0.00346581$ [m]. The OAM mode set $\mathcal{L} = \{+1, +3, +5\}$ and the number of OAM modes $L = 3$ are assumed. In addition, the total transmit power with multiple OAM modes $P = 50$ [W] and equal power allocation P/L for all OAM modes are assumed. The noise power at a receive antenna is $N_0 = -174$ [dBm/Hz]. Moreover, the radial positions of 1st, 2nd and 3rd receive antennas indicate $r_{j,1}^i, r_{j,2}^i$ and $r_{j,3}^i$ for all i and j in Fig. 3 and 5, respectively. The largest antenna position indicates the required antenna size for a FD transceiver.

[1]Intuitively, the ES-based antenna deployment method requires $L^{|\mathcal{P}|}$ search, whereas the proposed heuristic method only requires $C|\mathcal{P}|L$ search, where C is a constant that represents the number of loops. Specifically, both algorithms calculate (5) according to the position of the receive antennas. Since the computational time for (5) in each algorithm is the same, we can conclude that the proposed heuristic antenna deployment algorithm has a lower computational complex of $O(C|\mathcal{P}|L)/O(L^{|\mathcal{P}|})$ compared to the ES method.

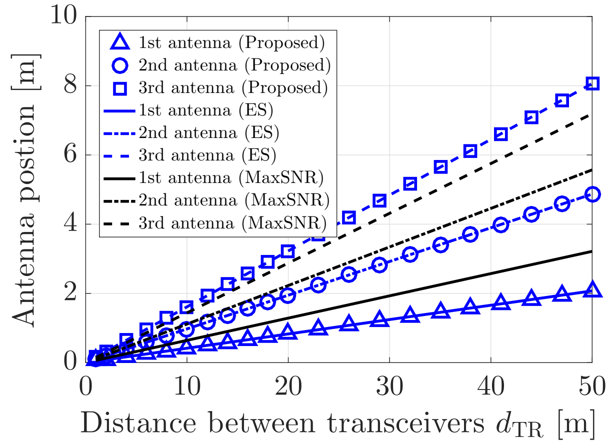

Fig. 3: Antenna position for all antennas corresponding OAM modes with respect to various distances between FD transceivers.

Fig. 3 illustrates the antenna position for all antennas corresponding OAM modes with respect to various distances between a single-pair FD transceiver when the initial beam waist is $w_0 = 3.5\lambda$ [m]. In general, due to beam divergency, as the distance between transceivers or the OAM mode increases, the required antenna size (the radial position of 3rd antenna) increases. Interestingly, the 1st and 2nd antennas in the MaxSNR are larger than the 1st and 2nd antennas in the proposed antenna deployment, respectively, however, the 3rd antennas are smaller due to the effect of self-interferences and inter-mode interferences. In the MaxSNR, the effect of self-interferences and inter-mode interferences between multiple OAM beams is not considered, so each antenna is placed in a position where the SNR for each OAM beam can be maximized. However, the proposed and the ES-based antenna deployment considering the effect of self-interferences and inter-mode interferences for achievable sum-rate maximization are almost the same in terms of antenna position. Moreover, the proposed and the ES-based antenna deployment require a slightly larger antenna size (an approximate 1 [m] at $d_{\text{TR}} = 50$ [m]) than the MaxSNR antenna deployment.

Fig. 4 illustrates the achievable sum-rate with respect to various distances between a single-pair FD transceiver when the initial beam waist $w_0 \in \{1.5\lambda,\ 3.5\lambda\}$ [m]. As the distance between transceivers increases, the achievable sum-rate decreases. In addition, as the initial beam waist increases from 1.5λ to 3.5λ, the achievable sum-rate increases due to high beam directivity. The proposed and ES-based antenna

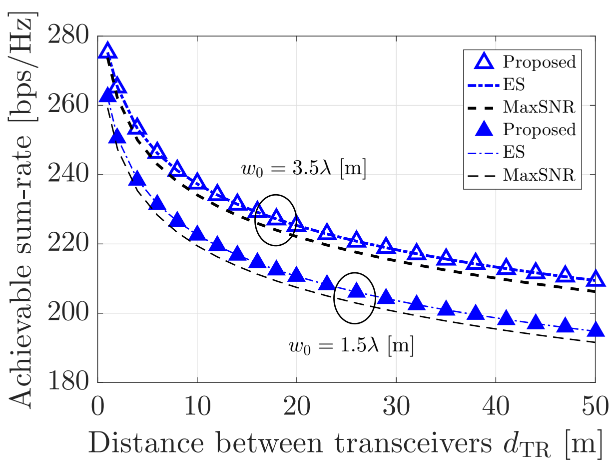

Fig. 4: Achievable sum-rate with respect to the distance between FD transceivers.

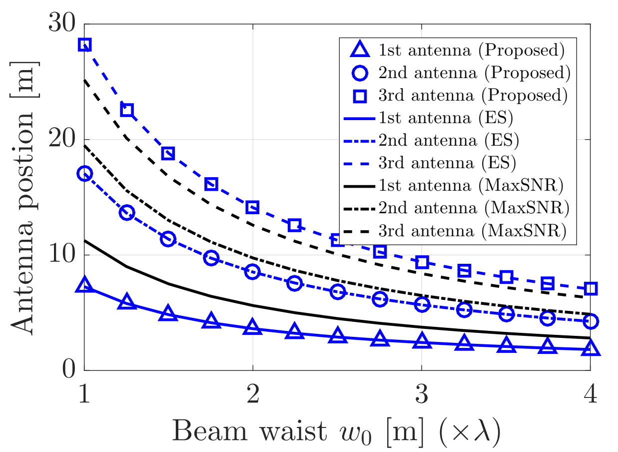

Fig. 5: Antenna position for all antennas corresponding OAM modes with respect to various initial beam waists.

deployment considering the effect of interferences between multiple OAM beams outperform the MaxSNR in terms of achievable sum-rate.

Fig. 5 illustrates the antenna position for all antennas corresponding OAM modes with respect to various initial beam waists when distance between a single-pair FD transceiver $d_{\text{TR}} = 50$ [m]. When the initial beam waist is 1λ, required antenna size is an approximate 28 [m] for a 50 [m] FD communication system. Since it is necessary to design a realistic antenna size, the initial beam waist as large as possible is required. As the initial beam waist increases, required antenna size reduced due to high beam directivity. So when the initial beam waist is 3.5λ [m], required antenna size effectively reduced to an approximate 7 [m] in proposed and ES-based antenna deployment.

Fig. 6 illustrates the achievable sum-rate with respect to various initial beam waists when distance between a single-pair FD transceiver $d_{\text{TR}} \in \{10, 50\}$ [m]. In general, as the initial beam waist increases, the achievable sum-rate increases

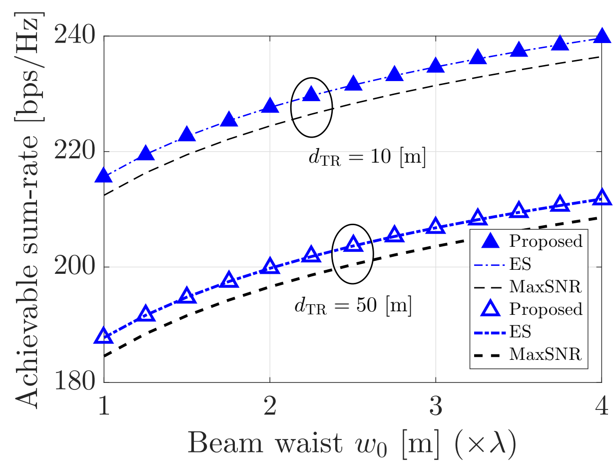

Fig. 6: Achievable sum-rate with respect to various initial beam waists.

due to high beam directivity. In addition, as the distance between transceivers decreases from 50 [m] to 10 [m], the achievable sum-rate increases. Still the proposed and ES-based antenna deployment outperform the MaxSNR-based antenna deployment in terms of achievable sum-rate.

V. Conclusions

In this paper, we investigated the effect of receive antenna deployment on the achievable sum-rate in the in-band full-duplex (FD) orbital angular momentum (OAM)-based mode division multiplexing (MDM) systems. In general, the higher the OAM mode higher beam divergence. Thus, with the conventional maximum signal-to-noise ratio (SNR)-based antenna deployment scheme, the size of receive antenna needs to be increased for maximizing the received SNR as the OAM mode increases. However, with the proposed low-complexity heuristic algorithm-based antenna deployment, the size of each receive antenna is carefully adjusted by considering not only the self-interferences but also inter-mode interferences to maximize the achievable sum-rate of the in-band FD OAM-MDM system. Computer simulation results show that the proposed antenna deployment scheme requires slightly larger antenna size than the conventional maximum SNR-based antenna deployment scheme but it improves the achievable sum-rate of the in-band FD OAM-MDM system.

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