Power-Aware IMI Cancellation for OAM Multiplexing under Beam Axis Misalignment

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***Abstract*—Orbital angular momentum (OAM) multiplexing offers high-capacity transmission for future wireless backhaul. However, in realistic deployments, beam misalignment between transmitter and receiver causes inter-mode interference (IMI), leading to performance degradation. While simplified cancellers targeting adjacent modes reduce complexity, they still apply interference suppression to all modes. This paper proposes a received-power-based simplified IMI canceller which applies interference suppression only to OAM modes whose received power is high enough that interference dominates over noise. In low-power modes, where noise is dominant, cancellation is omitted. Simulation results show that the proposed scheme achieves comparable system capacity to traditional cancellers with reduced computational cost.**

***Index Terms*—Orbital angular momentum (OAM), uniform circular array (UCA), mode multiplexing, inter-mode interference, computational complexity.**

I. Introduction

The growing demand for mobile broadband and emerging 6G applications—such as massive machine-type communications (mMTC), immersive reality, and tactile/haptic systems—necessitates terabit-per-second data rates and sub-millisecond latency [1]. To meet these stringent requirements and support gigabit-to-terabit connections, enhancements are essential for both small-cell backhaul infrastructure and access link technologies [2]. For backhaul, line-of-sight (LoS) wireless communication with fixed transmitter and receiver sites offers greater flexibility, scalability, and lower capital expenditure than fiber-based solutions [2].

In this context, orbital angular momentum (OAM) multiplexing has gained attention due to its ability to transmit multiple independent data streams through a single aperture pair by leveraging orthogonal spatial modes whose phase fronts twist along the propagation axis [3]– [9]. However, OAM multiplexing suffers from performance degradation in real deployments, where perfect alignment between transmitter and receiver cannot be maintained—such as under wind-induced vibrations [10]– [13]. Small-cell backhaul devices are often mounted on poles, street lamps, or buildings that are prone to subtle vibrations or shifts. These misalignments result in beam axis deviations, leading to IMI [10], [11]. Thus, IMI suppression is essential to maintain robust communication performance in practical OAM-based systems.

Several methods have been proposed for IMI suppression in OAM multiplexing [14], [15]. In [14], IMI is canceled after discrete Fourier transform (DFT) processing using a zero-forcing (ZF) approach. In contrast, [15] performs pre-DFT suppression based on estimated beam misalignment using angle-of-arrival information. While the ZF-based method in [14] can effectively eliminate IMI, it incurs high computational cost, assuming interference from all OAM modes. Previous studies have indicated that adjacent modes dominate IMI in the presence of beam axis misalignment [16], [17]. Exploiting this property allows the equalization complexity to be greatly reduced by considering only a limited set of interfering modes. Building on this, we previously proposed a simplified IMI canceller that focuses solely on adjacent OAM modes under misalignment , thus reducing the equalization burden [18].

This paper further extends that idea by proposing a power-aware IMI canceller aimed at reducing computational complexity in OAM multiplexing under beam axis misalignment. We leverage the fact that received signal power varies considerably across OAM modes. For low-power modes, the signal-to-noise ratio (SNR) tends to be low, making noise more dominant than interference. Accordingly, the proposed method omits IMI cancellation for low-power modes and selectively applies a simplified canceller only to higher-power modes where IMI is more harmful. This selective suppression lowers computational cost while preserving system performance. The effectiveness of the proposed method is evaluated via computer simulations, and compared with our previous simplified IMI canceller. The performance is assessed in terms of system capacity and computational complexity.

II. IMI Cancellation with Mode Selection

A. System Concept and its Configuration

In realistic OAM multiplexing scenarios, misalignment between the transmitter and receiver destroys the orthogonality among OAM modes, resulting in inter-mode interference (IMI) and significant performance degradation [10]– [18]. Figure 1 shows the power components received in OAM mode $l = 2$ when transmitting multiplexed OAM signals with uniform power allocation. The parameters are as follows: number of antenna elements $N = 16$, number of multiplexed OAM modes

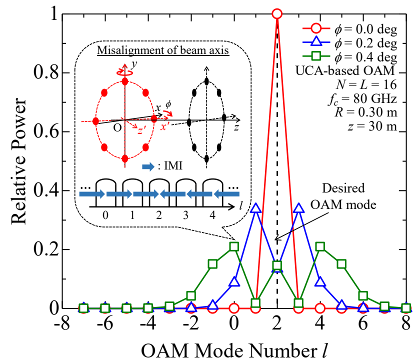


Fig. 1. Received power component derived from each OAM mode in the presence of misalignment of beam axis.

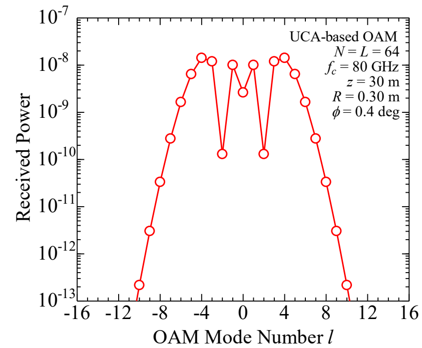
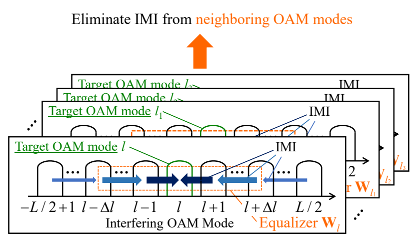
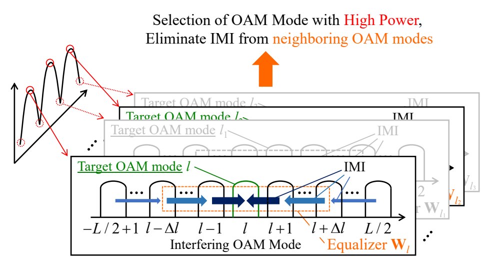


Fig. 2. Received power versus OAM modes in OAM multiplexing.



(a) Traditional



(b) Proposed

Fig. 3. Concept of the proposed method.

$L = 16$, carrier frequency $f_c = 80$ GHz, transmit UCA radius $R = 0.30$ m, and link distance $z = 30$ m. Regardless of the tilt angle ϕ of the transmit UCA, the IMI tends to concentrate around the desired mode $l = 2$, and the IMI spreads over a wider range of neighboring modes with an increase in the tilt angle ϕ. Leveraging this property, we previously proposed a simplified IMI canceller that targets only the adjacent modes under beam axis misalignment [18]. This approach mitigates interference from neighboring modes and reduces the computational cost of equalization.

In OAM multiplexing, however, substantial power disparities among modes occur even in the absence of beam misalignment. Figure 2 illustrates the received power for each OAM mode. For modes with lower received power, the signal-to-noise ratio (SNR) tends to be low, meaning that noise becomes more dominant than interference, and thus, IMI cancellation may have limited effect. Motivated by this observation, this paper proposes a further cost-efficient IMI cancellation method that applies cancellation only to OAM modes with high received power.

Figure 3 depicts the concept of the proposed method. In traditional approaches, IMI is assumed to arise from all multiplexed OAM modes and is mitigated using an equalization filter of size L [14]. In addition, considering that IMI primarily stems from neighboring OAM modes [16], [17], the traditional IMI canceller eliminates interference from a limited set of adjacent modes $\{l \pm 1, \ldots, l \pm \Delta l\}$ for each target mode as shown in Fig. 3(a) [18]. Moreover, based on the received power per mode, the proposed method applies the IMI canceller only to the subset of modes with the highest received power, significantly reducing the equalization cost while maintaining system performances shown in Fig. 3(b).

Figure 4 compares the system configurations of UCA-based OAM multiplexing using the proposed and traditional IMI cancellation schemes, where N and L denote the numbers of antenna elements and multiplexed OAM modes, respectively. Here, $L = N$, and the transmit power is evenly distributed across all OAM modes. The proposed method constructs a mode group $\mathcal{L}_{\text{High}}$ by selecting a fixed number of modes with the highest received power. The simplified IMI canceller is then applied only to the modes in $\mathcal{L}_{\text{High}}$, thereby achieving a balance between interference suppression and computational efficiency. Here, it is noted that mode selection introduces some computational overhead; however, since the selection is based on received power, its impact on overall complexity remains negligible.

At the transmitter, the transmit signal vector $\mathbf{s} \in \mathbb{C}^N$ is expressed as

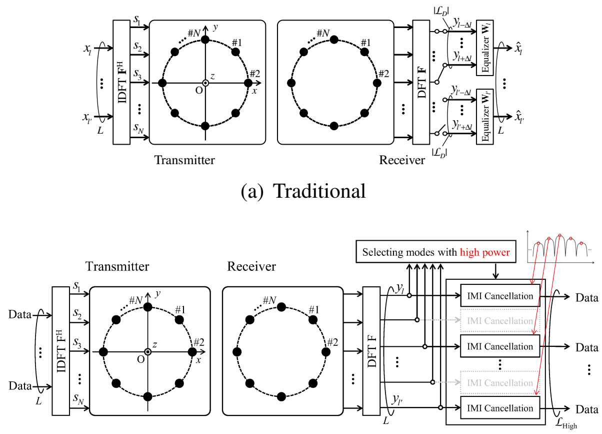
$$\mathbf{s} = \mathbf{F}^{\text{H}}\mathbf{x}, \tag{1}$$

where $\mathbf{F}^{\text{H}} \in \mathbb{C}^{N \times L}$ and $\mathbf{x} \in \mathbb{C}^L$ are the inverse discrete Fourier transform (IDFT) matrix and modulated signal vector, respectively.

At the receiver, the received signal vector $\mathbf{y} \in \mathbb{C}^L$ is represented by

$$\mathbf{y} = \mathbf{F}\left(\mathbf{H}\mathbf{s} + \mathbf{n}\right) = \mathbf{\Sigma}\mathbf{x} + \tilde{\mathbf{n}}, \tag{2}$$

$$\mathbf{\Sigma} = \mathbf{F}\mathbf{H}\mathbf{F}^{\text{H}}, \tag{3}$$



(a) Traditional

(b) Proposed

Fig. 4. Comparison of UCA-based OAM multiplexing with the proposed IMI cancellation method and that with the traditional IMI cancellation method.

where $\mathbf{F} \in \mathbb{C}^{L\times N}$ and $\mathbf{H} \in \mathbb{C}^{N\times N}$ are the DFT matrix and channel matrix, respectively. Moreover, $\mathbf{n} \in \mathbb{C}^{N}$ and $\tilde{\mathbf{n}} \in \mathbb{C}^{L}$ are the noise vectors, and their elements follow the same distribution. Assuming a free-space propagation, the channel condition between the m-th transmit antenna element and the n-th received antenna element in the UCA is expressed by [12]

$$h_{n,m} = \frac{\beta\lambda}{4\pi d_{n,m}} \exp\left(-j\frac{2\pi d_{n,m}}{\lambda}\right), \tag{4}$$

where β, λ, and $d_{n,m}$ are the antenna gain, wavelength, and distance between the transmit and received antenna elements, respectively.

B. System Capacity Analysis

In this section, we analyze the system capacity and computational cost of OAM multiplexing with the proposed IMI cancellation method and the traditional IMI cancellation method.

1) Traditional Method: Given that IMI from neighboring OAM modes is severe in the presence of a beam axis misalignment [16]- [18], the traditional IMI cancellation method eliminates IMI from the OAM modes $l \pm 1, \cdots$, and $l \pm \Delta l$. Therefore, the received signal of the l-th OAM mode is given by

$$y_l = \sum_{k\in\mathcal{L}_D} \sigma_{l,k} x_k + u_l + \tilde{n}_l, \tag{5}$$

$$u_l = \sum_{l'\in\mathcal{L}\setminus\mathcal{L}_D} \sigma_{l,l'} x_{l'}, \tag{6}$$

$$\mathcal{L} = \{L/2-1, \cdots, L/2\}, \tag{7}$$

where $\mathbf{w}_l = [w_{l,k}, \cdots, w_{l,k'}] \in \mathbb{C}^{L}$, $\boldsymbol{\sigma}_{l'} = [\sigma_{k,l'}, \cdots, \sigma_{k',l'}]^{\mathrm{T}} \in \mathbb{C}^{L}$ and u_l are the l-th row vector of $\mathbf{W}$, the l'-th column vector of $\boldsymbol{\Sigma}$ and the IMI from the non-neighboring OAM modes, respectively. Using linear filtering as an equalization technique, the received signal vector after equalization $\hat{\mathbf{x}}_l = [\hat{x}_{l-\Delta l}, \cdots, \hat{x}_{l+\Delta l}]^{\mathrm{T}} \in \mathbb{C}^{|\mathcal{L}_D|}$ is given by

$$\hat{\mathbf{x}}_l = \mathbf{W}_l\mathbf{y}_l = \mathbf{W}_l\boldsymbol{\Sigma}_l\mathbf{x}_l + \mathbf{W}_l\mathbf{u}_l + \mathbf{W}_l\tilde{\mathbf{n}}_l, \tag{8}$$

$$\boldsymbol{\Sigma}_l = [\sigma_{l,k}]_{l,k\in\mathcal{L}_D}, \tag{9}$$

where $\mathbf{W}_l \in \mathbb{C}^{|\mathcal{L}_D|\times|\mathcal{L}_D|}$, $\mathbf{y}_l = [y_{l-\Delta l}, \cdots, y_{l+\Delta l}]^{\mathrm{T}} \in \mathbb{C}^{|\mathcal{L}_D|}$,$\mathbf{x}_l = [x_{l-\Delta l}, \cdots, x_{l+\Delta l}]^{\mathrm{T}} \in \mathbb{C}^{|\mathcal{L}_D|}$, $\mathbf{u}_l = [u_{l-\Delta l}, \cdots, u_{l+\Delta l}]^{\mathrm{T}} \in \mathbb{C}^{|\mathcal{L}_D|}$, and $\tilde{\mathbf{n}}_l = [\tilde{n}_{l-\Delta l}, \cdots, \tilde{n}_{l+\Delta l}]^{\mathrm{T}} \in \mathbb{C}^{|\mathcal{L}_D|}$ are the equalization filter matrix, modulated signal vector, IMI vector from non-neighboring OAM modes, and noise vector, respectively. Using the linear filtering based on MMSE as the equalization criterion, $\mathbf{W}_l$ is given as

$$\mathbf{W}_l = \left(\boldsymbol{\Sigma}_l^{\mathrm{H}}\boldsymbol{\Sigma}_l + \frac{P_n}{P_x}\mathbf{I}_{|\mathcal{L}_D|}\right)^{-1}\boldsymbol{\Sigma}_l^{\mathrm{H}}, \tag{10}$$

where $\mathbf{I}_{|\mathcal{L}_D|} \in \mathbb{C}^{|\mathcal{L}_D|\times|\mathcal{L}_D|}$ is the identity matrix. In the proposed method, the equalization filter matrix $\mathbf{W}_l$ in Eq. (10) is generated as many times as the number of multiplexed OAM modes L. Thus, the computational cost of the proposed method is calculated as

$$C_P = L \times \left(\frac{7}{2}|\mathcal{L}_D|^3 + \frac{1}{2}|\mathcal{L}_D|^2\right). \tag{11}$$

From Eqs. (8)–(10), the received signal of the l-th OAM mode after equalization $\hat{x}_l$ is calculated as

$$\hat{x}_l = \mathbf{w}_{l,l}\boldsymbol{\sigma}_{l,l}x_l + \left(\sum_{l'\in\mathcal{L}_D\setminus\{l\}} \mathbf{w}_{l,l}\boldsymbol{\sigma}_{l,l'}x_{l'} + \mathbf{w}_{l,l}\mathbf{u}_l\right) + \mathbf{w}_{l,l}\tilde{\mathbf{n}}_l, \tag{12}$$

where $\mathbf{w}_{l,l} = [w_{l,l,l-\Delta l}, \cdots, w_{l,l,l+\Delta l}] \in \mathbb{C}^{|\mathcal{L}_D|}$ and $\boldsymbol{\sigma}_{l,l'} = [\sigma_{l-\Delta l,l'}, \cdots, \sigma_{l+\Delta l,l'}]^{\mathrm{T}} \in \mathbb{C}^{|\mathcal{L}_D|}$ are the l-th row vector of $\mathbf{W}_l$ and the l'-th column vector of $\boldsymbol{\Sigma}_l$, respectively. From Eq. (12), the desired signal component $P_{D,l}$, IMI component $P_{I,l}$, and noise component $P_{N,l}$ are calculated as

$$P_{D,l} = E\left[|\mathbf{w}_{l,l}\boldsymbol{\sigma}_{l,l}x_l|^2\right] = \left|\sum_{k\in\mathcal{L}_D} w_{l,l,k}\sigma_{k,l}\right|^2 P_x, \tag{13}$$

$$\begin{aligned} P_{I,l} &= E\left[\left|\sum_{l'\in\mathcal{L}_D\setminus\{l\}} \mathbf{w}_{l,l}\boldsymbol{\sigma}_{l,l'}x_{l'} + \mathbf{w}_{l,l}\mathbf{u}_l\right|^2\right] \\ &= \sum_{l'\in\mathcal{L}\setminus\{l\}} \left|\sum_{k\in\mathcal{L}_D} w_{l,l,k}\sigma_{k,l'}\right|^2 P_x, \end{aligned} \tag{14}$$

$$P_{N,l} = E\left[|\mathbf{w}_{l,l}\tilde{\mathbf{n}}_l|^2\right] = \sum_{k\in\mathcal{L}_D} |w_{l,l,k}|^2 P_n. \tag{15}$$

From Eqs. (13)–(15), the SINR of the l-th OAM mode and the system capacity of the traditional IMI cancellation method can be calculated, respectively.

$$\gamma_l = \frac{P_{D,l}}{P_{I,l} + P_{N,l}}, \tag{16}$$

$$C_{sum} = \sum_{l\in\mathcal{L}} \log_2(1+\gamma_l). \tag{17}$$

TABLE I
SYSTEM PARAMETERS

Carrier frequency f_c	80 GHz
Number of antenna elements N	64
Number of multiplexed OAM modes L	64
Radius of UCA R	0.30 m
Antenna gain	10 dBi
Total transmit power	23 dBm
Noise power	−80 dBm
Filter size $\|\mathcal{L}_D\|$	9
Angle of transmitting UCA ϕ	0 – 0.4 deg

2) Proposed Method: In the proposed method, considering the significant received power disparities among OAM modes, IMI cancellation from adjacent modes is applied selectively only to modes with relatively high received power. For these high-power modes, interference filters based on the simplified canceller [18] are generated and applied.

In contrast, for modes with lower received power, IMI cancellation is omitted, as noise is expected to dominate over interference. This omission is equivalent to setting the filter size to $|\mathcal{L}_D| = 1$, i.e., no interference cancellation is performed. The signal-to-interference-plus-noise ratio (SINR) for the group of low-power modes is therefore calculated using the following equation:

$$\gamma_{l,L} = \frac{|w_{l,l,l}\sigma_{l,l}|^2 P_x}{\sum_{l' \in \mathcal{L}\setminus\{l\}} |w_{l,l,l}\sigma_{l,l'}|^2 P_x + |w_{l,l,k}|^2 P_n}. \tag{18}$$

Let $\mathcal{L}_{\text{High}}$ and $\mathcal{L}_{\text{Low}}$ denote the groups of modes with high and low received power, respectively. Then, the overall system capacity given by Eqs. (17) can be rewritten using Eqs. (16) and (18) as:

$$C_{sum} = \sum_{l \in \mathcal{L}_{\text{High}}} \log_2\left(1 + \gamma_l\right) + \sum_{l \in \mathcal{L}_{\text{Low}}} \log_2\left(1 + \gamma_{l,L}\right). \tag{19}$$

Furthermore, let L_H and L_L be the number of modes in $\mathcal{L}_{\text{High}}$ and $\mathcal{L}_{\text{Low}}$, respectively. Since the simplified IMI canceller is applied only to L_H modes, the total number of filter matrix generations in Eq. (10) is reduced to L_H. As a result, the computational cost of the proposed method can be expressed by the following equation:

$$\begin{aligned} C_{proposed} &= L_H \times \left(\frac{7}{2}|\mathcal{L}_D|^3 + \frac{1}{2}|\mathcal{L}_D|^2\right) + L_L \times \left(\frac{7}{2} + \frac{1}{2}\right) \\ &= L_H \times \left(\frac{7}{2}|\mathcal{L}_D|^3 + \frac{1}{2}|\mathcal{L}_D|^2\right) + 4L_L. \end{aligned} \tag{20}$$

III. NUMERICAL RESULTS

This section evaluates the effectiveness of the proposed scheme through computer simulations in terms of system capacity and computational cost, comparing it with a traditional scheme [18] that applies a simplified IMI canceller to all modes. Table I summarizes the system parameters. In this evaluation, the number of antenna elements is set to $N = 64$, and the number of multiplexed OAM modes L is equal to N. The received power is set equally across all modes, and the tilt angle ϕ due to beam axis misalignment is set within $0 < \phi < 0.4$ degrees, based on empirical data [13]. Moreover, in this study, we assume a fixed wireless communication scenario, in which the channel matrix $\mathbf{H}$ remains static and

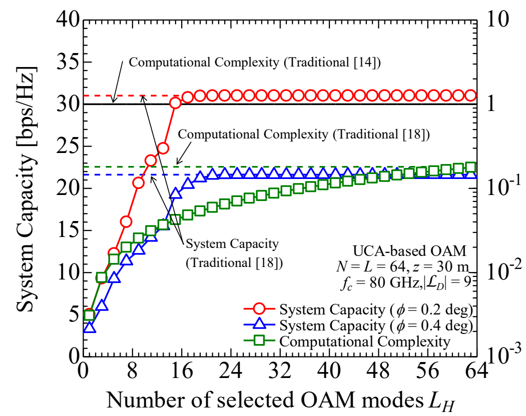


Fig. 5. System capacity and computational complexity versus number of selected OAM modes L_H.

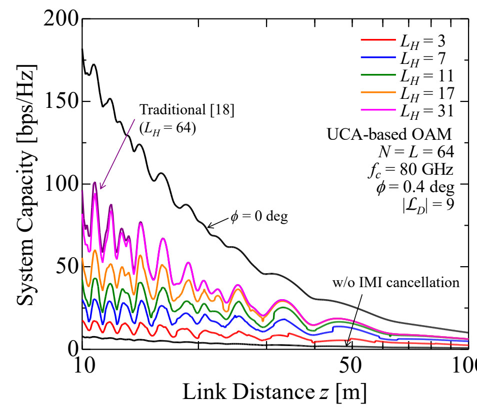


Fig. 6. System capacity versus link distance z.

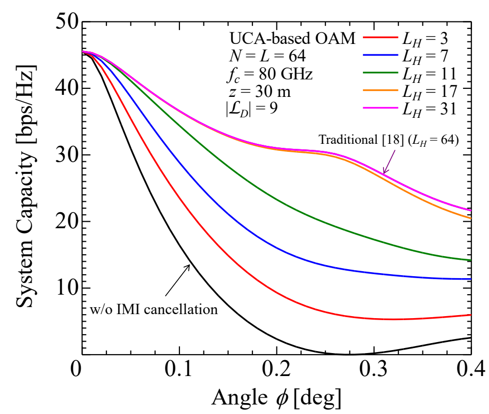


Fig. 7. System capacity versus tilt angle ϕ.

exhibits no time selectivity.

Figure 5 shows the system capacity and the normalized computational complexity as a function of the number of selected modes L_H. The cost is normalized based of the full-filter cancellation method [14], and the computational load of the traditional method [18] is also shown for comparison. As Fig. 5 indicates, the proposed method achieves comparable system capacity to traditional method with $L_H = 64$ by selecting more than $L_H = 17$ modes, regardless of the tilt angle ϕ. This confirms that limiting IMI cancellation to high-power modes effectively maintains capacity while reducing computational cost. As for the computational cost, reducing the number of filter generation L_H leads to a significant cost reduction. Particularly, with $|\mathcal{L}_D| = 9$ and $L_H = 17$, the proposed method reduces computational cost to approximately 27 % of the traditional scheme.

Figure 6 shows system capacity versus link distance z, including the performance of the traditional scheme [18]. As the tilt angle increases and L_H decreases, the effectiveness of the IMI canceller drops, resulting in capacity degradation. However, as distance increases, noise becomes dominant, and the capacity gap between the proposed and the traditional methods narrows.

Figure 7 shows system capacity versus tilt angle ϕ at $z =$ 30 m, including the results for the traditional scheme. As with Fig. 7, lower L_H reduces cancellation effectiveness, decreasing capacity. Nevertheless, with $L_H = 17$, the proposed method maintains comparable capacity to the traditional method [18] across all tilt angles, demonstrating that IMI cancellation can be limited to $L_H = 17$ instead of $L_H = 64$.

IV. Conclusion

This paper proposed a received-power-based simplified IMI cancellation scheme for OAM multiplexing systems with beam axis misalignment. By applying cancellation only to high-power modes where interference is dominant, and skipping cancellation for low-power modes where noise prevails, the proposed scheme achieves substantial computational savings while maintaining system capacity. Numerical results confirmed that the proposed scheme achieves system capacity comparable to the traditional method that applies IMI cancellers to all modes, while significantly reducing the number of modes requiring interference suppression. In particular, whereas the traditional method applies cancellers to all OAM modes (e.g., 64 modes), the proposed scheme limits cancellation to approximately one-fourth of the modes (e.g., 17 modes), resulting in a reduction of computational cost by about 73%. This research presents a promising approach for realizing efficient OAM multiplexing in practical deployment scenarios and is expected to contribute to 6G wireless backhaul networks.

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