Effectiveness Evaluation of Dual-Polarized OAM Multiplexing Employing SC-FDE in Urban Street Canyon Environments

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ABSTRACT This study investigates the system capacity of dual-polarized orbital angular momentum (OAM) multiplexing that employs single-carrier with frequency domain equalization (FDE) in urban street canyon environments. To overcome the impact of multipaths, two types of FDE, designed with and without the consideration of the cross-polarization interference (XPI), are introduced. We derive the effects of the residual inter-mode interference (IMI), inter-symbol interference (ISI), and XPI when applying such FDE and incorporate their impacts into the system capacity analysis. Moreover, we adopt the urban street canyon model based on a ray-tracing simulation, which enables performance evaluation in a realistic multipath environment. The numerical results show that although the computational complexity is increased, the consideration of the XPI in the FDE weight design improves the system capacity, and its effectiveness is remarkable in the cases of short link distances.

INDEX TERMS Orbital angular momentum (OAM), uniform circular array (UCA), mode multiplexing, polarization, single-carrier with frequency domain equalization (SC-FDE), system capacity.

I. INTRODUCTION The diversification of mobile network services has led to an increase in the number of wireless devices and, hence, the growth of mobile traffic. By 2023, global mobile connections are expected to grow to 13.1 billion [1]. Fifth-generation (5G) mobile communications systems provide increased functionality and performance, and the target peak data rate is set to 20 Gbps [2]. Moreover, in sixth-generation (6G) mobile communications systems, which aim to be realized by 2030, a peak data rate of 1 Tbps is expected to be provided across a large dimensional and autonomous network that encompasses space, air, ground, and underwater networks [3]. To achieve such advanced mobile systems that support gigabit or terabit connections, it is necessary to upgrade the small-cell backhaul and enhance existing access link technologies [4]. For small-cell backhaul, line-of-sight wireless communications with fixed transmitter and receiver locations are more attractive than fiber solutions in terms of flexibility, scalability, and capital expenditure [4]. In this context, orbital angular momentum (OAM) multiplexing is gaining increasing attention owing to its potential to simultaneously transmit multiple data streams through a single aperture pair [5]–[12].

In OAM multiplexing, the phase-front twists along the propagation direction, resulting in a ring-shaped intensity profile. To generate such OAM signals, several approaches, such as making use of spiral phase plates [5] and holographic plates [6], have been proposed. In these approaches, although the antenna can be easily fabricated by three-dimensional printing, antennas placed at different locations and beam splitters are required for mode multiplexing. In contrast, a uniform circular array (UCA) antenna enables simultaneous transmission of multiple modes and can be regarded as a practical approach for realizing OAM multiplexing [7]–[11].

In a realistic scenario, OAM multiplexing involves performance degradation owing to inter-mode interference (IMI) and inter-symbol interference (ISI) present in multipath environments such as reflections from the ground and buildings [13]–[15]. Thus, the effects of both IMI and ISI on OAM multiplexing must be weakened. To avoid the IMI, a previous study has proposed the adoption of linear spatial filtering and investigated its performance [13]. Moreover,
as a countermeasure for the ISI, the application of orthogonal frequency-division multiplexing (OFDM) to OAM multiplexing has been proposed, because a guard interval (GI) can effectively suppress the ISI [14], [15]. In particular, in [15], both IMI and ISI were successfully suppressed using OFDM, and its performance was analyzed. However, OFDM has the inherent drawback of a high peak-to-average power ratio (PAPR), which introduces severe nonlinear distortion caused by power amplifiers.

To avoid the impact of nonlinear distortion, single-carrier with frequency-domain equalization (SC-FDE) [16], [17] has been adopted for OAM multiplexing owing to its lower PAPR than that of OFDM [18], [19]. In [18], transmission performance was experimentally evaluated in a field environment. We successfully derived the system capacity of OAM multiplexing by employing SC-FDE and verified its robustness against the IMI and ISI in a multipath environment [19]. However, in [19], because an ideal two-ray ground reflection model consisting of direct and reflected waves was assumed to be a multipath environment, more practical evaluations of a realistic channel model considering more than two rays [20], [21] are expected. In addition, the OAM technology can adopt polarization multiplexing as well as mode multiplexing to further enhance the system capacity [22]–[25]. Therefore, it is important to clarify the potential of dual-polarized OAM multiplexing employing SC-FDE in realistic multipath scenarios.

Considering the background described above, herein, we investigate the system capacity of dual-polarized OAM multiplexing by employing SC-FDE in urban street canyon environments. In our study, two types of FDE are introduced to mitigate interference due to multipaths. Specifically, type-1 FDE, which is a natural extension of single-polarized OAM multiplexing, suppresses the IMI and ISI independently in each polarization plane. Type-2 FDE, which is designed considering cross-polarization interference (XPI), IMI, and ISI, eliminates the interference across different polarization planes. We also derive the effects of the residual IMI, ISI, and XPI when applying the two types of FDE, and incorporate their impacts into the system capacity analysis. Moreover, we adopt the urban street canyon model based on a ray-tracing simulation [21], which enables us to evaluate the transmission performance in a realistic multipath environment. The numerical results of this study demonstrate the effects of polarization and FDE on the system capacity and computational complexity.

II. DUAL-POLARIZED OAM MULTIPLEXING EMPLOYING SC-FDE

A. SYSTEM CONCEPT

Fig. 1 shows UCA-based OAM multiplexing in multipath environments, wherein OAM modes \( l = +1 \) and \( +2 \), carrier frequency \( f_c = 39 \) GHz, number of UCA antenna elements \( N = 16 \), radius of the transmitting UCA antenna \( R = 0.60 \) m, and link distance \( D = 100 \) m were considered, and the vertical polarization was assumed as the polarization plane. As shown in Figs. 1(a) and (c), the intensity and phase distributions of the OAM signals follow uniform and spiral patterns, respectively, in an ideal scenario such as direct wave only. However, in a realistic scenario, reflections from the ground and buildings distort the intensity and phase distributions, as shown in Figs. 1(b) and (d), and then destroy

![FIGURE 1. UCA-based OAM multiplexing in multipath environments.](image-url)
the orthogonality among the OAM modes, resulting in performance degradation due to the IMI [13], [15], [19]. In SC broadband transmissions, the ISI is also caused by the multipath delay between the direct and reflected waves as well as the IMI [19]. Furthermore, in the application of polarization multiplexing to further enhance the system capacity of OAM multiplexing, XPI affects the transmission performance [23], [24]. Therefore, in this study, we derive the system capacity of OAM multiplexing considering polarization and evaluate it in a practical multipath scenario.

Fig. 2 shows the effects of the IMI, ISI, and XPI on dual-polarized OAM multiplexing employing SC-FDE. As shown in Fig. 2, although the insertion of the GI prevents the inter-block interference (IBI), the ISI is caused in addition to the IMI and XPI. In this study, the minimum mean square error (MMSE) is considered as an equalization criterion to alleviate the effect of noise enhancement by minimizing the undesired components comprising IMI, ISI, XPI, and noise.

**FIGURE 2. Interference in dual-polarized OAM multiplexing employing SC-FDE.**

Fig. 3 shows the system configuration of dual-polarized OAM multiplexing employing SC-FDE, wherein \( N_F \) and \( L \) denote the number of fast Fourier transform (FFT) points and OAM modes, respectively. At the transmitter, the GI is inserted into the modulated signal of each OAM mode, and then OAM multiplexing is performed using the inverse discrete Fourier transform (IDFT) for each polarization plane. At the receiver, after conducting a discrete Fourier transform (DFT) for OAM mode separation, FDE is performed for each subchannel. Herein, we investigated two types of FDE, as mentioned previously. Type-1 FDE, as shown in Fig. (3b), is a natural extension of single-polarized OAM multiplexing employing SC-FDE [11]. In this FDE, the effect of XPI is ignored, and the IMI and ISI are suppressed independently in each polarization plane. On the other hand, in type-2 FDE, as shown in Fig. (3c), FDE weights are designed considering the XPI, IMI, and ISI, and interference suppression by FDE is applied across different polarization planes. Although the computational cost for generating weights is higher, type-2 FDE is considered to eliminate interference more effectively than type-1 FDE.

**B. SYSTEM CAPACITY ANALYSIS**

In this section, we analyze the system capacity of dual-polarized OAM multiplexing using SC-FDE. Specifically, we derive the residual IMI, ISI, and XPI after performing FDE and incorporate their impacts into the system capacity analysis.

The transmit signal vector, consisting of vertically and horizontally polarized signals at time \( n \), is expressed as \( s_n = [s_{V,n}^T, s_{H,n}^T]^T \in \mathbb{C}^{2N} \), and the transmit signal block vector, \( s = [s_0^T, \ldots, s_{N_F-1}^T]^T \in \mathbb{C}^{2NN_F} \), is represented by

\[
s = \text{diag}([F_H^H, \ldots, F_H^H])x.
\]

\[1\]
where $\mathbf{x} = [\mathbf{x}_1^T \ldots \mathbf{x}_{N_F-1}^T]^T \in \mathbb{C}^{2L N_F}$ is the modulated signal block vector, $\mathbf{n}_k = [\mathbf{x}_{V,n}^T \mathbf{x}_{H,n}^T]^T \in \mathbb{C}^{2L}$, and $\mathbf{F}_N^H \in \mathbb{C}^{N \times L}$ is the IDFT matrix for OAM multiplexing. At the receiver, assuming there is no effect of the IBI owing to the sufficiently long GI, the received signal block vector, $\mathbf{r} = [\mathbf{r}_0^T \ldots \mathbf{r}_{N_F-1}^T]^T \in \mathbb{C}^{2 N_F N}$, is represented by

$$\mathbf{r} = \mathbf{H} \mathbf{s} + \mathbf{n},$$

where $\mathbf{H} \in \mathbb{C}^{2 N_F N \times 2 N_F N}$ and $\mathbf{n} = [\mathbf{n}_0^T \ldots \mathbf{n}_{N_F-1}^T]^T \in \mathbb{C}^{2 N_F N}$ are the channel impulse response matrix and noise vector, respectively. Here, $\mathbf{H}$ can be block-diagonalized by $[19],[26]$

$$\mathbf{H} = (\mathbf{F}_N^H \otimes \mathbf{I}_{2N}) \text{diag}([\mathbf{H}_0 \ldots \mathbf{H}_{N_F-1}]) (\mathbf{F}_N \otimes \mathbf{I}_{2N}),$$

where $\otimes$ denotes the Kronecker product, $\mathbf{I}_{2N} \in \mathbb{C}^{2N \times 2N}$ and $\mathbf{H}_k \in \mathbb{C}^{2N \times 2N}$ are the identity matrix and channel frequency response matrix of the $k$-th subchannel, respectively, $\mathbf{F}_N \in \mathbb{C}^{N \times N}$ is the $N_F$-point FFT matrix, and $(k,n)$ element of which $f_{k,n}$ is defined as

$$f_{k,n} = \frac{1}{\sqrt{N_F}} \exp \left( -j \frac{2 \pi k n}{N_F} \right).$$

By using Eqs. (2) and (3), the received signal after OAM mode separation, $\mathbf{y} = [\mathbf{y}_0^T \ldots \mathbf{y}_{N_F-1}^T]^T \in \mathbb{C}^{2L N_F}$, is given as

$$\mathbf{y} = \text{diag}(\mathbf{F}_N \ldots \mathbf{F}_N^H) \mathbf{r},$$

where $\mathbf{F}_N \in \mathbb{C}^{L \times N}$ and $\mathbf{I}_{2L} \in \mathbb{C}^{2L \times 2L}$ denote the DFT and identity matrices, respectively, and $\mathbf{n} = [\mathbf{n}_0^T \ldots \mathbf{n}_{N_F-1}^T]^T \in \mathbb{C}^{2L N_F}$ is the noise vector, whose elements follow the same distribution as that of $\mathbf{n}$. Note that $\mathbf{H} \in \mathbb{C}^{2L \times 2L}$ is composed of channel frequency responses among the OAM modes and polarization planes.

In Eq. (5), the desired signal suffers from the effects of the IMI, ISI, and XPI. Dual-polarized OAM multiplexing employing SC-FDE suppresses them by performing equalization for each subchannel, and then the equalized signal vector, $\hat{\mathbf{x}} = [\mathbf{x}_0^T \ldots \mathbf{x}_{N_F-1}^T]^T = [\mathbf{x}_{V,0}^T \ldots \mathbf{x}_{V,N_F-1}^T, \mathbf{x}_{H,0}^T \ldots \mathbf{x}_{H,N_F-1}^T]^T \in \mathbb{C}^{2L N_F}$, is represented by

$$\hat{\mathbf{x}} = (\mathbf{F}_N^H \otimes \mathbf{I}_{2L}) \text{diag}(\mathbf{W}_0 \ldots \mathbf{W}_{N_F-1}) (\mathbf{F}_N \otimes \mathbf{I}_{2L}) \mathbf{y},$$

where $\mathbf{W}_k \in \mathbb{C}^{2L \times 2L}$ is the equalization weight matrix of the $k$-th subchannel, which is generated based on the channel frequency response matrix $\Sigma_k$. Here, $\mathbf{W}_k$ and $\Sigma_k$ can be partitioned as follows:

$$\mathbf{W}_k = \begin{bmatrix} \mathbf{W}_{V,V,k} & \mathbf{W}_{V,H,k} \\ \mathbf{W}_{H,V,k} & \mathbf{W}_{H,H,k} \end{bmatrix},$$

$$\Sigma_k = \begin{bmatrix} \Sigma_{V,V,k} & \Sigma_{V,H,k} \\ \Sigma_{H,V,k} & \Sigma_{H,H,k} \end{bmatrix}.$$  

Assuming MMSE as the equalization criterion, the weight matrix of type-1 FDE without considering the XPI is represented by

$$\mathbf{W}_k = \text{diag}(\mathbf{W}_{V,V,k}, \mathbf{W}_{H,H,k}) \quad \text{(Type 1)},$$

where $\mathbf{W}_{V,V,k}$ and $\mathbf{W}_{H,H,k}$ are expressed as follows $[19],[27]$

$$\mathbf{W}_{V,V,k} = \left( \Sigma_{V,V,k} + \frac{P_n}{P_x} \mathbf{I}_L \right)^{-1} \Sigma_{V,V,k},$$

$$\mathbf{W}_{H,H,k} = \left( \Sigma_{H,H,k} + \frac{P_n}{P_x} \mathbf{I}_L \right)^{-1} \Sigma_{H,H,k}. \quad \text{(Type 2).}$$

At time $n$, the equalized signal of the $l$-th mode with vertical polarization $\hat{x}_{V,n,l}$ or the $l$-th element of the $l$-th subchannel is represented by Eq. (14), as shown at the bottom of the next page, where $x_{V,n'}$ and $x_{H,n''}$ are the $l'$-th elements of $x_{V,n'}$, respectively; $x_{V,H,k,l}$ and $x_{V,H,k,l'}$ are the $l$-th row vectors of $\mathbf{W}_{V,V,k}$ and $\mathbf{W}_{V,H,k}$, respectively; $\sigma_{V,H,k'\ell'}$, $\sigma_{V,H,k',l'}$, and $\sigma_{V,H,k',l''}$ are the $l'$-th column vectors of $\Sigma_{V,V,k}$, $\Sigma_{V,H,k}$, $\Sigma_{H,H,k}$, and $\Sigma_{H,H,k}$, respectively.

In Eq. (14), the first term contains the desired signal and IMI-plus-ISI components, the second term is the XPI component, and the third term is the noise component. The powers of these components are calculated using Eqs. (15)–(18), as shown at the bottom of the next page. From Eqs. (15)–(18), the signal-to-interference-plus-noise ratio (SINR) of the $l$-th mode with vertical polarization $\gamma_{V,l}$ is given as

$$\gamma_{V,l} = \frac{P_{\text{Desired},V,l}}{P_{\text{IMI+ISI},V,l} + P_{\text{XPI},V,l} + P_{\text{Noise},V,l}}. \quad \text{(19)}$$

For horizontal polarization, SINR $\gamma_{H,l}$ can be calculated in the same manner as that for vertical polarization.

Consequently, the system capacity of dual-polarized OAM multiplexing employing SC-FDE is represented by

Capacity

$$\text{Capacity} = \frac{N_F T_S}{N_F T_S + T_G \sum_l \{ \log_2(1 + \gamma_{V,l}) + \log_2(1 + \gamma_{H,l}) \}}. \quad \text{(20)}$$

where $T_S$ and $T_G$ are the symbol period and GI length, respectively.
C. COMPUTATIONAL COMPLEXITY

In this section, we clarify the computational complexity of the two types of FDE in terms of the number of floating-point operations (FLOPs). The number of FLOPs required for each matrix operation is as follows:

- Multiplication of $M \times N$ and $N \times P$ complex matrices: $8MNP - 2MP$
- Inversion of an $M \times M$ complex matrix: $(8/3) \cdot M^3 + 15M^2 - (2/3) \cdot M$

The number of FLOPs required to generate FDE weights for vertically or horizontally polarized OAM multiplexing is given by

$$C_{\text{Vertical}} = C_{\text{Horizontal}} = \frac{44}{3}L^3 + 16L^2 - \frac{2}{3}L - 17.$$  \hspace{1cm} (21)

III. NUMERICAL RESULTS

A. TRANSMISSION PERFORMANCE EVALUATION

In this section, we verify the effectiveness of dual-polarized OAM multiplexing employing SC-FDE in terms of both
SINR and system capacity in urban street canyon environments based on a ray-tracing simulation. Fig. 4 illustrates the urban street canyon model for wireless backhaul [21]. As shown in Fig. 4, transmitting and receiving UCA antennas were installed at a height of $d_h = 5.0$ m on a 20 m wide road between 20 m high buildings. The link distance, $D$, was set between 40 m and 200 m. The materials of the roads and buildings were assumed to be concrete [28]. To consider diffuse scattering effects, which are significant in millimeter-wave bands, we adopted the directive model [29] with a scattering coefficient $S = 0.322$ and parameters related to the width of the scattering lobe $\alpha_R = 4$. Moreover, the cross-polarization factor that determines the diffuse scattering power ratio of co- and cross-polarization [30] is set to $K_{xpol} = 0.4$. Table 1 lists the simulation parameters. In our performance evaluation, the OAM mode number, $l$, was limited between $-3$ and $+3$ for practical reasons [25], with the same transmit power among all OAM modes. Moreover, the GI length was set to $T_G = 256T_s$, which was sufficiently long to completely suppress the IBI.

Fig. 5 shows the channel impulse response between the transmitting antenna element #1 and receiving antenna element #1, where the link distance, $D$, was set to 100 m. From Fig. 5, it can be seen that multipath scattering is caused by reflection and diffuse scattering from the ground and buildings. Moreover, it is found that cross-polarization occurs and cannot be ignored. Furthermore, the multipath effects in vertical polarization tend to be stronger than those in horizontal polarization. This is because the reflected power from buildings in vertical polarization is larger owing to their physical properties.

Fig. 6 shows the SINR of each OAM mode for dual-polarized OAM multiplexing employing SC-FDE, where $D$ was set to 100 m. In Fig. 6, the SINR in the case of a direct wave only is shown for reference. From Fig. 6, it is found that the SINR of type-2 FDE is improved in relation to that of type-1 FDE, regardless of the OAM modes or polarization. This is because the XPI is effectively eliminated in type-2 FDE, whereas it exists in type-1 FDE. Moreover, it is observed that the SINRs in the presence of multipaths are degraded in relation to the case wherein only the direct waves are involved, irrespective of the FDE type. This is because the impact of the residual ISI after FDE increases in the presence of multipaths.

Fig. 7 shows the system capacity versus the link distance for dual-polarized OAM multiplexing employing SC-FDE. In Fig. 7, the system capacities for single-polarized OAM multiplexing are shown for reference. From Fig. 7, it is
found that the system capacity of dual polarization is higher than that of vertical or horizontal polarization, regardless of the FDE type, because the number of streams is doubled. Moreover, type-2 FDE considering the XPI presents a higher system capacity than type-1 FDE and achieves a transmission performance similar to that of the case with only direct waves. In particular, in the case of a short link distance, the improvement effect of type-2 FDE is remarkable. This is because the impact of the XPI is relatively stronger than that of noise in such a case.

B. COMPUTATIONAL COMPLEXITY EVALUATION
Finally, we demonstrate the computational complexity of dual-polarized OAM multiplexing using SC-FDE. Table 2 shows the number of FLOPs required for FDE weight generation. From Table 2, it is said that the computational complexity of dual polarization with type-1 FDE is twice as large as that of a single polarization, regardless of the number of OAM modes. This is because in type-1 FDE, the equalization is performed independently in each polarization plane. Moreover, it is found that the computational complexity of type-2 FDE is increased to nearly four times that of type-1 FDE, owing to the consideration of the XPI.

IV. CONCLUSION
In this study, we investigated the system capacity of dual-polarized OAM multiplexing using SC-FDE. Specifically, an urban street canyon model based on a ray-tracing simulation was adopted as a realistic multipath model. Moreover, two types of FDE with and without the consideration of the XPI owing to multipaths were introduced; we analytically evaluated the impacts of such FDE on the system capacity and computational complexity. Numerical results showed that the system capacity of dual polarization is higher than that of vertical or horizontal polarization only because the number of streams is doubled. Moreover, type-2 FDE that considers the XPI presents a higher system capacity than type-1 FDE and achieves a transmission performance similar to the case with direct waves only; however, the computational complexity of type-2 FDE increases to nearly four times that of type-1 FDE.

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