Pre-Coding OAM Based MIMO System for Multi-User Communications

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ABSTRACT Recently, orthogonal Orbital Angular Momentum (OAM) modes of electromagnetic waves have been widely applied to achieve high spectral efficiency in the radio and microwave regimes. This study investigates utilizing multimodal OAM carrying waves in communications between a central unit and distributed receiving units. Accommodated by a planner grid-array of antenna elements and backed by appropriate pre-coding, the central unit can transmit to each receiving unit multi-OAM modes. A receiving unit comprises a simple circular array. Pre-coding at the transmitting unit is a two-fold process: preventing user-to-user interference and enforcing any predetermined combination of OAM modes to reach its destination. Accordingly, the parallel transmission of multiple channels to each receiver is possible. Channels aimed at the same receiver are distinguished by different modes, but the same group of modes can be simultaneously used upon transmission to other receivers. The numerical results show that significant increase in the transmission capacity is achieved. For instance, in a system including 6 receivers, 25 channels are delivered in parallel to each receiver while maintaining an acceptable low bit-error rate. Results are judged by considering the theoretical single-user quadrature phase shift keying modulation performance as a benchmark for comparison. This study also examines channel perturbations when interfering modes exist.

INDEX TERMS Antenna array, interference, MIMO, multi-user, OAM, perturbation, pre-coding, subspace.

I. INTRODUCTION

As wireless communications migrate from Fourth Generation (4G) to Fifth Generation (5G) and beyond, it becomes crucial to meet the requirements of explosive data traffic. 5G and future generations are approaching data rates approximately 1,000 times that of 4G [1]. Many advanced radio spectrum efficiency enhancement techniques are expected to play a role in this technology transition. Among these are massive Multiple-Input Multiple-Output (MIMO), co-frequency, co-time, full-duplex, and millimeter-wave (mm-wave) techniques [2]. In addition, a new and promising resource for spectrum efficiency hinges on Allen et al.’s [3] discovery in the early ’90s, namely, the orthogonal Orbital Angular Momentum (OAM) modes possessed by electromagnetic waves. Since then, keen interest has been witnessed in OAM for optics [4] and radio [5], [6], making significant benefit from the superiority of OAM to conventional MIMO in complexity [7].

Waves carrying OAM exhibit helical phase-fronts owing to the azimuthal dependence of its spatial phase distribution \(e^{i\ell \phi}\), where \(\ell = \pm 1, \pm 2, \ldots\) is the OAM mode and \(\phi\) is the azimuthal angle. The field intensity varies in the form of annular rings in the transverse plane and vanishes along the propagation axis due to destructive interferences [8].

Beams carrying OAM can be generated in plenty of ways, most famous are the Spiral Phase Plate (SPP) method [8] and the Uniform Circular Array (UCA) method [9], [10]. In the latter method, the radiating elements in the UCA are excited by signals having the same amplitudes but constant phase increment between adjacent array elements. Two typical problems are entangled in radio vortex
transmission using SPP or UCA. First, the transmitter and receiver planes must be aligned [11]. Without this alignment, the phase of the received signal will contain some phase turbulence in addition to the phase of the desired OAM mode, making it difficult to decompose the OAM modes. Secondly, there raises the problem of beam divergence, where the size of the amplitude null at the axis of the beam expands during propagation, demanding the use of large receivers. This issue may reduce the transmission distance severely, particularly for high-order OAM modes, where the null is quite large. Raising transmission frequency helps confine the wave over more considerable distances, making OAM-based solutions more practical for high-frequency mm-wave networks [7].

The literature provides solutions to maintain the sustainable convergence of OAM waves in radio. In [12], a parabolic antenna reforms the OAM wave for far communications. Additionally, a lens antenna in [13] imposes gradual change on the refractive index to modify the wave while preserving the angular identification features of each mode.

Based on such solutions, previous research concerned with OAM generation and OAM integration to MIMO systems was established in [14], [15], [16], and [17], to mention a few. Zhang et al. [14] proposed a plane-spiral OAM-based MIMO system, while Oldoni et al. [15] established space-division de-multiplexing OAM-based MIMO radio system and compared the achieved capacity to a conventional MIMO system. Murata et al. [16] proposed an analogue eigenmode transmission technique based on OAM for short-range communications. Moreover, Cheng et al. [17] proposed an OAM-embedded massive MIMO model based on multi-UCAs and parabolic antennas to focus the radiation.

Recently, a UCA-based downlink multi-user wireless backhaul system was presented in [18]. The system enables joint spatial division and coaxial multiplexing. Compared with traditional multi-user MIMO systems, it requires less training overhead for estimating the channel matrix. The problem of OAM subchannel mismatching in the downlink was also addressed in [19] via an OAM-based beam selection scheme. The necessary inter-user interference elimination condition was obtained. In [20], a multiple-arm spiral antenna has been developed to radiate OAM waves in a wide band. Other approaches for achieving high-capacity wireless transmission merge OAM multiplexing with other multiplexing techniques, such as the OAM and orthogonal frequency division multiplexing hybrid system in [21].

This paper follows a different approach for generating and integrating OAM waves into MIMO systems. The generation process is restricted to specific design criteria, ensuring data delivery under perfect interference mitigation in a multi-user environment. In the beginning, we focus on multi-OAM modes transmission to one receiver. This strategy is accomplished through a planner grid of dipole elements. By proper excitation of the transmitting grid, the radiated field is synthesized such that its maximum intensity matches the locations of the sensing elements at the receiver. These elements are located and distributed over the circular circumference of the receiver. The grid-array can be implemented as a lighter alternative to the bulky parabolic and spiral antennas [5]. In the transmission process, firstly, the desired field characteristics at the receiver are predetermined according to the required combination of OAM modes at that receiver. Consequently, the proper excitation of the transmitting grid elements is set. Therefore, the field form can be synthesized to match the receiver aperture size, avoiding OAM wave divergence and shadowing the receiver by the central radiation null of the OAM wave.

Next, the basic method is extended, and a MIMO system that supports multimodal OAM transmission in a multi-user scenario is addressed. A transmitter may communicate simultaneously with many users at different locations. At this stage, pre-coding is applied for two goals. The first is to synthesize the field form needed to enable the transmission of more than one signal per user at a time. Having each signal carried by a wave of a particular OAM mode, the field forms a superposition of a combination of modes, which can be used by other users simultaneously. Hence, and in a multi-user environment, the pre-coder’s other goal is to cancel any potential interference from other users in the system. This work meets these two goals by designing the pre-coder in a two-fold process to address each goal at a time. The obtained pre-coder parameters are then used to determine the appropriate excitation of a planner grid-array. Clearly, the number of elements in the array plays a role in determining the operation conditions of the system. This relation is investigated based on the number of users and number of transmitted OAM modes per user.

Communications are held without alignment between the transmitter and receiver as the destructive effect of misalignment is equalized by the pre-coder. Evidently, explicit knowledge of channel information is needed in this design. The prime degradation in system performance is usually attributed to noise and potential channel perturbations. Noise effect and channel perturbations are examined as they can cause undesired modes. The system is subjected to first-order perturbation analysis from which the Mean-Square-Error (MSE) of perturbation is derived.

The remainder of this paper is organized as follows: Section II includes a general overview of the proposed OAM-generating system and describes the signal model. In that section, multimodal reception with one receiver is considered, followed by general transmission to more than one receiver. Then, practical implications related to noise and other perturbations are examined at the end of the section. Numerical results and demonstrations are considered for different configurations in Section III. Finally, conclusions are drawn in Section IV.

II. OAM-GENERATING SYSTEM AND SIGNAL MODEL
A. MULTIMODAL RECEPTION WITH ONE RECEIVER

This section proposes a MIMO system that supports multimodal OAM transmission. The MIMO system consists of a planner transmitting grid of \(N\)-elements and a receiver
of $M$-elements. The transmitting grid focuses the OAM carrying wave over the receiver location. As is well known, different OAM modes can be discerned in space via the number of times the wave’s phase completes a $360^\circ$ phase shift over one turn. Hence, the receiver sensing elements are distributed over a circular ring to detect the mode. The receiving ring must be placed within a larger grid to allow for complete duplex communications, as shown in Fig. 1, such that all grid elements are activated during the transmission phase.

We define the distance between the $n^{th}$ transmitting element and the $m^{th}$ receiving element as $r_{mn}$. The signal at the $n^{th}$ element of the transmitting grid is denoted $x_n$. The overall signals transmitted by $N$-elements are combined in the $N \times 1$ vector $X = [x_n]$, which, following the schematic in Fig. 1, takes the form

$$X = \sum_{l=1}^{L} W^l s^l, \quad (1)$$

where $s^l$ represents the $l^{th}$ $(1 \leq l \leq L)$ data symbol. From this design we aim to distinguish the $l^{th}$ mode. In designing the codes $(W^l)$, the $M$-elements of the receiver are represented by the $M \times 1$ vector $Y = [y_m]$ as

$$Y = HX + \text{Noise}. \quad (3)$$

The noise refers to a general term that might include Gaussian noise in addition to any perturbation effect. We will neglect the noise for a moment as we focus here on the system model. The noise precise definition and its potential effect on the system performance is considered in Subsection C. The received vector is reshaped into a desired vector form $(G^l)$ by computing the codes at the transmitter via the minimization

$$\min_{H} \left[ HW^l - G^l \right]^2, \quad (4)$$

which simply leads to

$$W^l = \left( H^T H \right)^{-1} H^T G^l. \quad (5)$$

Substituting the codes into (3) yields the received signal

$$Y = \sum_{l=1}^{L} G^l s^l. \quad (6)$$

In order to detect the signal corresponding to a specific OAM mode, say the $l^{th}$ mode, the received vector has to be multiplied by the Hermitian $(\cdot)^H$ of $G^l$ as follows

$$\frac{1}{\sqrt{M}} G^H Y = s^l. \quad (7)$$

This is extended in the next subsection to multi-user systems.

**B. MULTIMODAL RECEPTION USING MORE THAN ONE RECEIVER**

The general configuration is presented in Fig. 2. Here, signals belonging to $U$ users are transmitted simultaneously through a grid of $N$-elements to $U$ receivers distributed in space. $M_u$ denotes the number of elements at $u^{th}$ receiver $R_{x_u} \ (1 \leq u \leq U)$; in principle, receivers could have different numbers of elements. Signals of user $u$ are aimed at receiver $u$ and they form potential interference at the remaining receivers. The same set of $L$-OAM modes is used in transmitting signals to different users. The signal at receiver $u$ is given by the $M_u \times 1$ vector

$$Y_u = H_u W_u s_u + \sum_{i=1,i \neq u}^{U} H_u W_i s_i, \quad (8)$$

where $H_u$ is the $M_u \times N$ channel matrix that connects the $M_u$ receiving elements of receiver $u$ to the $N$-elements of the transmitting grid. For user $u$, the $N \times L$ coding matrix $W_u = [W^1_u, \ldots, W^L_u]$ is constructed such that its $l^{th}$ column $(W^l_u)$ represents user $u$ code for the $l^{th}$ OAM mode. In (8), the $L$ data symbols from user $u$ are stacked in the vector $s_u = [s^1_u, \ldots, s^L_u]^T$. As in the previous subsection, the pre-coding process enforces a certain combination of $L$ superimposed OAM modes at a receiver. In addition, in a multi-user environment the pre-coder should be able to cancel any potential interference from other users in the system. This two-fold goal is met for an arbitrary user $(u)$ via designing this user’s coding matrix in the general product form

$$W^l_u = W_u \tilde{W}_u. \quad (9)$$

here, the $\tilde{W}_u$ component is responsible for generating the desired combination of OAM signals at the receiver, while $W^l_u$ ensures satisfying the interference cancellation condition

$$H_i \tilde{W}_u = 0, \quad \forall i \neq u. \quad (10)$$

Including all interfering channels to receiver $u$ in one matrix

$$\tilde{H}_u = \left[ H^T_u, \ldots, H^T_{u-1}, \ldots, H^T_U \right]^T, \quad (11)$$

the interference cancellation condition (10) restricts $\tilde{W}_u$ to lie in the null space of $\tilde{H}_u$ [22]. Defining $k_u$ as the rank of $H_u$, the $N \times (N - k_u)$ matrix $W_u$ is formed over the right singular vectors of the null space of $H_u$. From the number of columns in $\tilde{W}_u$, it is clear that a sufficient number of array elements should be available at the grid. The condition

$$N > \max \{k_1, \ldots, k_U\} \quad (12)$$
Finally, multiplying (16) by the received signal to:

\[ k_u \leq \sum_{i=1,i \neq u}^{U} M_i. \]  (13)

Taking into consideration both conditions (12) and (13), it is possible to increase the number of receivers in the system either by increasing the number of transmitting antennas \( N \) or by lowering the rank of the interference channel. The last choice is possible by reducing the number of antennas per receiver; however, this must be accompanied by the obligatory condition of lowering the users’ throughputs since the number of OAM modes per user would also need to be lowered, as mentioned before.

Transmission from a user to its corresponding receiver is formed via the \( \tilde{W}_u \) component of the coding matrix. Similar to the previous subsection, the desired combination of \( L \)-OAM modes at receiver \( u \) is formed using

\[ \tilde{W}_u = (\tilde{H}_u^T \tilde{H}_u)^{-1} \tilde{H}_u^T G_u, \]  (14)

where \( \tilde{H}_u = H_u \tilde{W}_u \) is a \( M_u \times (N - r_u) \) matrix and \( G_u = [G_u^1, \ldots, G_u^L] \) is a \( M_u \times L \) matrix. Its \( l \)-th is

\[ G_u^l = \exp \left( \frac{2\pi}{M_u} (m - 1) l \right) \quad \text{for} \quad 1 \leq m \leq M_u. \]  (15)

Substituting these codes into (8) simplifies the expression of the received signal to:

\[ Y_u = G_u S_u. \]  (16)

Finally, multiplying (16) by \( \frac{1}{M_u} G_u^H \) allows extracting the data symbols in a vector, having elements \( s_l^U \) for \( 1 \leq l \leq L \).

Analysis carried out so far neglects the presence of noise and assumes perfect knowledge of the channel matrix. Errors in estimating the channel matrix prevent perfect interference cancellation, which, in turn, degrades the system performance. This is discussed in the following subsection.

C. PERTURBATION ANALYSIS

In this subsection, we consider the effect of channel perturbation along with the usual noise effect on the system. As mentioned, the pre-coder is obtained based on subspace decomposition, therefore when the resulting eigenvectors are perturbed version of the “true” ones the estimated parameters of the pre-coder will be also perturbed. Perturbations could originate from many sources, such as errors in the channel estimation algorithm and finite data effect. Perturbation could also arise from uncertainties in determining the degree of misalignment between the transmitter and receiver as a consequence of mechanical movements or sensor errors.

Estimation of the pre-coding coefficients based on available perturbed parameters can be established by introducing Singular Value Decomposition (SVD) and exploiting the inherited orthogonality between the produced subspaces. SVD is applied in the form

\[ H_u W_u + \sum_{i=1,i \neq u}^{U} H_i W_i + N_u \]

\[ = [U_s U_n] \begin{bmatrix} \Sigma_s & 0 \\ 0 & \Sigma_n \end{bmatrix} \begin{bmatrix} V_u^T \\ V_n^T \end{bmatrix} \]  (17)

where \( N_u \) resembles noise matrix of size \( M_u \times N \), with entries drawn from \( \mathcal{CN}(0, \sigma_n^2) \) distribution. The singular vectors corresponding to the smallest singular values represent the noise subspace and are collected in the diagonal matrix \( \Sigma_n \), the corresponding eigenvectors which span the noise-subspace are included in \( U_n \). The remaining singular values included in \( \Sigma_s \) belong to the signal subspace and their corresponding eigenvectors form the columns of \( U_s \). The hat operator is used to indicate an estimate based on noise corrupted observations. The estimate of \( \tilde{W}_u \) is obtained by exploiting the orthogonality of the signal and noise subspaces. Hence, parameterized on \( \tilde{W}_u \) we seek the
minimization of \( \| (H_n W_n)^H U_n \|^2 \), that is
\[
\hat{W}_u = \arg \min_{\| Q \| = 1} \left\{ Q^H H_n^H U_n H_u^H Q \right\}.
\] (18)

Here, \( \| \cdot \| \) refers to the Frobenius norm of the matrix. By defining \( \hat{O} = H_u^H \tilde{U}_n \tilde{U}_n^H H_u \) it is straightforward that \( \Delta \hat{O} = \hat{O} - \hat{O} \) is influenced by the first and second orders of the subspace perturbation \((\Delta U_n)\) as
\[
\Delta \hat{O} = H_u^H \left( U_n \Delta U_n^H + \Delta U_n U_n^H + \Delta U_n \Delta U_n^H \right) H_u.
\] (19)

Subspace perturbations can be categorized into in-space and orthogonal subspace perturbations [23]. In-space perturbations appear in perturbation approximations of second-order. Only orthogonal space perturbation appears in first-order degree of approximation. A general form to express the noise subspace perturbation is
\[
\Delta U_n = U_n P_{nn} + U_u P_{sn}.
\] (20)

With \( P_{nn} \) representing contribution from the same space, and \( P_{sn} \) representing the contribution of the orthogonal space. Perturbation is considered here only to the first-order, this is especially justified in high SNR regime [24]. Hence, by neglecting \( P_{nn} \), the expression of \( \Delta U_n \) can be simplified to the first-order [25]
\[
\Delta u_n \cong - (H_u \tilde{W}_u)^T E_u^H U_n.
\] (21)

In a similar manner, it is possible to show that
\[
\Delta \tilde{W}_u \cong - O^T \Delta O^{H} \hat{W}_u
\] (22)
is the first-order perturbation approximate of \( \tilde{W} \). In these expressions the dagger operator stands for pseudo-inverse of a matrix. As noted from (21), noise subspace perturbation is inversely proportional to the noise-free signal space, and is directly related to \( E_u \), which involves any potential perturbation. As mentioned, there could be many possible sources to perturbation, in case of perturbation resulting from channel estimation error \( (\Delta H_u = \tilde{H}_u - H_u) \), one gets
\[
E_u = \sum_{i=1,i\neq u}^U H_i W_i + N_u
= -\Delta H_u \sum_{i=1}^U W_i + N_u.
\] (23)

Keeping only first-order perturbation approximations in (19), then substituting the resulting expression along with (21) into (22) yields
\[
\Delta \tilde{W}_u \cong T_u U_n^H E_u D_u,
\] (24)

where,
\[
T_u = O^H H_u^H U_n
\]
and
\[
D_u = (H_u \tilde{W}_u)^T H_u \tilde{W}_u.
\]

The mean-square error of perturbation is found as
\[
E \left\{ \| \Delta \tilde{W}_u \Delta \tilde{W}_u^H \| \right\} \simeq T_u U_n^H E \left\{ E_u D_u D_u^H E_u^H \right\} U_n T_u^H.
\] (25)

Using Moore–Penrose conditions of pseudo matrix inversion it is simply shown that \( D_u^H D_u \simeq I \), we will also consider that \( E \left\{ E_u E_u^H \right\} = \sigma_n^2 I \), such that the perturbation variance \( \sigma_n^2 \) involving both additive white noise and channel estimation error influences. Taking that into consideration along with \( U_n^H U_n = I \), the expression in (25) finally reduces to
\[
E \left\{ \| \Delta \tilde{W}_u \Delta \tilde{W}_u^H \| \right\} = \sigma_n^2 \| T_u \|^2.
\] (26)

In the simulations, the terms of the error matrix \( (\Delta H_i) \) are taken as percentage of the true channel matrix terms after being randomized over a uniform complex random distribution.

### III. SIMULATIONS AND DISCUSSION

Numerical simulations are presented here to demonstrate the system performance under different situations. Results are divided into three main parts. We consider multimodal OAM generation and detection for both single user and multi-users. In these simulations perfect channel estimation is assumed and only the noise process is involved in the performance study. Then we demonstrate the impact of channel perturbations.

The transmitting antenna is taken as a planner grid at which adjacent elements are separated at \( \lambda/2 \) for an operating frequency of 60 GHz. This frequency is arbitrary, so all distances are taken in reference to the wavelength. Also, in the simulations data symbols are randomly selected from a Quadrature Phase Shift Keying (QPSK) constellation.

### A. MULTIMODAL TRANSMISSION TO SINGLE RECEIVER

We investigate the effect of adjacent elements spacing on the system performance. The average Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR) is shown in Fig. 3 for a configuration involving one receiving ring placed at an axial distance of 50\( \lambda \) from the center of the transmitting grid. 30 OAM modes are simultaneously transmitted to the receiver with the lowest mode value being 1 and the highest mode being 30. The receiving elements on the ring are equally spaced with spacing determined according to the radius of the ring for each of the simulated configurations in Fig. 3. When a receiver with radius \( (R_r) \) of 10\( \lambda \) and a square transmitting grid of 11 \( \times \) 11 elements are used, the system performs poorly. The performance improves slightly as the receiver radius is increased to 12\( \lambda \). Increasing the receiver radius to 13\( \lambda \) improves the performance to match the theoretical limit of a QPSK system. Further increase in the receiver radius to 15\( \lambda \), or beyond, has little effect on the performance, showing that it is necessary to achieve a minimum separation distance to enable the receiver to resolve the different modes. It is important to note that this minimum distance is strongly related to the field concentration at the receiving elements’
FIGURE 3. System performance under simultaneous transmissions of 30 OAM modes to a single receiver. Different transmitting array grids (11 × 11 and 14 × 14 elements) and different values of the receiver radius (R_r) are examined. The inset views precisely good and close performance for cases succeed in fulfilling the receiver minimum required separation distance for resolving the different modes.

locations. The simulation stresses this dependence by using a larger transmitting grid of 14 × 14 elements to focus more field at the receiver. This retains the receiver ability to resolve the different modes, even at the small radius of 10λ. To sum up this part, performance close to the theoretical limit can be achieved by meeting the design requirements for perfect interference cancellation by raising the number of transmitting elements or increasing the separation distance among the elements at the receiver.

B. MULTIMOD TRANSMISSION TO MULTI RECEIVERS

In this subsection, we investigate the performance for multi-user transmissions. As mentioned, the symbols for each user pass throughout a coding process before being sent to a certain receiver. The same set of OAM modes is used for transmission by each user. The radius (R_r) of each receiving ring is fixed to 15λ, and the rings are located in a plane 50λ away from the transmitting grid plane. It is assumed that the centers of the adjacent ringreceivers are separated by a distance of 37.5λ.

Fig. 4 indicates good system performance whenever the dimensionality condition is met. Among the cases presented in the figure, one could realize the good performance for two cases: two users (R_x = 2) with transmitting grids of 11 × 11, and six users (R_x = 6) with 14 × 14 transmitting grids. In both cases, signals are transmitted simultaneously over 25 OAM modes (L = 25) to the corresponding receivers. It is clear from the figure that the difference in the number of users both cases show comparable performance, which indicates perfect inter-channel interference cancellation. When violating the dimensionality condition poor performance is expected. This is demonstrated in Fig. 4 when transmitting 25 modes to each of three receivers via 11 × 11 transmitting grid (the solid red curve). As stated in Section II, the necessary conditions for ensuring interference cancellation can be reinstated either by increasing the number of antennas at the transmitter or by reducing the throughput per user. Thus, following the former solution, the size of the transmitting grid is increased by 11 more elements using a 12 × 11 configuration (leading to the dotted red curve with triangular marks in Fig. 4); while, following the later solution, transmissions are reduced from 25 to 20 OAM modes per user (leading to the solid pink curve in Fig. 4). In both situations, good performance is restored as compared to the theoretical single user QPSK performance (solid black curve).

FIGURE 4. System performance under simultaneous transmission to more than one receiver. The configurations shown involve different sizes of transmitting array grids, different numbers of receivers (R_x : 2, 3, and 6), and different numbers of OAM modes (L = 20 and 25).

C. COMPARISONS TO OTHER SOLUTIONS

In this section, we compare the performance of the proposed grid-array against other solutions. As mentioned, a main advantage of the proposed system is the capability to focus the radiation at specified locations. This is emphasized in Fig. 5 by comparing a 16-element (4 × 4) grid-array and a conventional 16-element UCA [10]. The CST MWS numerical simulator is used to implement both structures and obtain the results. Adjacent elements in both arrays are separated by a fixed distance of λ/2. By comparing the phase distributions in the transverse propagation plane, it becomes clear that the arrays have similar capabilities of producing OAM waves. Clearly, that the wave mode presented here is two, where in one round, the phase distribution changes by 2π times the corresponding OAM mode. Furthermore, the field amplitudes in the direction of propagation are also shown in the figure. The shift from blue to red indicates an increase in the field. Interestingly, the beam produced by the UCA diverges faster than that of the grid. This confirms the proposed design can
utilize appropriate excitations to synthesize and direct the radiation.

In the next step, we expand the comparison to include multimodal transmission. In this case, comparing phases or amplitudes distributions for a superposition of modes is challenging. Instead, we use the BER for performance comparison. Table 1 summarizes the results. The systems in [18] and [26] are considered in the comparison.

D. CHANNEL PERTURBATION EFFECT

To show the potential influence of channel estimation errors we take as a benchmark one-mode transmission per user in an ideal situation (free of channel estimation errors). In this case, the phase of the received signal is known to follow linear distribution over the receiver circular circumference, with the slope being proportional to the OAM mode. This appears in Fig. 6(a), where the phase of each mode exhibits over one phase offset (one round around the receiving ring) a change of $360^\circ$ times the OAM mode. Also, under the ideal situation, the amplitude of a single OAM mode carrying wave should exhibit constant distribution over the receiving ring’s circumference. We aim to study the extent to which a channel perturbation could alter these ideal phase and amplitude distributions and to investigate what impact this may have on small and large mode numbers. Fig. 6(b) demonstrates the distortion in the phase distribution at a channel estimation error of 10%. It is clear that the linearity of the phase distributions has been altered. The loss in linearity could have a significant impact when the phase gradient method is used to detect the modes. In this case, a large number of slopes should be calculated to average out the phase distortion, which would demand a large number of antennas per receiver.

| Reference | Modulation | BER at SNR = 6 dB | Multimodal/ (No. of modes) | Structure/ (Size) |
|-----------|------------|-------------------|-----------------------------|-------------------|
| Theoretical | QPSK | $2.4 \times 10^{-3}$ | No/ (1) | UCA/ (63) |
| [18] | QPSK | $1.5 \times 10^{-1}$ | Yes/ (5) | UCA/ (32) |
| [26] | QPSK | $1.0 \times 10^{-1}$ | Yes/ (5) | UCA/ (32) |
| This work | QPSK | $5.0 \times 10^{-3}$ | Yes/ (20) | Grid-array/ (11x11) |
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FIGURE 7. Deviation from the ideal condition of no channel estimation error presented as (a) mode phase error, and (b) mode amplitude error. Different numbers of receivers (Rx) and modes are presented.

FIGURE 8. System performance under the effect of the channel estimation error. Different curves are shown for different percentages of channel errors, starting from no error (lowermost curve) and gradually increasing to a 15% error (uppermost curve).

FIGURE 9. Modes detected at receiver corresponding to a user deploying mode 5 in a system consisting of two users: (a) without channel estimation error, and (b) with 10% channel estimation error.

The root-mean-square deviation from ideal phase and amplitude distributions are shown respectively in Fig. 7(a) and (b) for different channel estimation errors. These plots reveal a main difference from the results obtained in [27] for UCA. The error for the UCA is obviously mode-dependent in the way that higher modes suffer from larger errors, which, in turn, limits the application of high modes in practical transmission. The different modes considered in Fig. 7 exhibit nearly similar error performances. This result is expected since the proposed method enforces the appearance of the modes (either large or small modes) within the receiver region.

For additional comparison, the mode error is shown in Fig. 7 for some modes at different numbers of users. Obviously, under imperfect interference cancellation, the error tends to relatively large values as the number of receivers increases.

The influence of channel estimation error is reflected over the performance of a system including two receiving rings in Fig. 8. Each receiver gets 20 OAM modes of transmission from its corresponding user and suffers from interference originating from the other user in the system.
The same set of OAM modes is assigned to both users. A grid of $14 \times 14$ elements is used for transmission to both users.

The degradation in performance noted in Fig. 8 is attributed to the interfering modes generated by the other user. To see how channel perturbations create such undesired modes the interfering user is allowed to deploy all the modes, while only one mode is used by the receiver’s permitted user. This mode is used as reference to which the levels of the detected modes are normalized. A case without channel estimation errors in Fig. 9(a) is compared against another case (in Fig. 9(b)) where channel estimation errors take place. As expected, in the first case, only the desired mode (chosen here as mode 5) appears at the receiver, while a large group of interfering modes show up over the entire spectrum in the second case.

IV. CONCLUSION

In this paper, the orthogonality of the OAM modes was exploited to improve the transmission capabilities. An appropriate pre-coding method was optimized and integrated into a grid-array to prevent interference and enforce a combination of OAM modes at each receiver. As a result, higher throughput were achieved per user; a grid of $11 \times 11$ elements could provide 30 OAM modes per user at $10^{-3}$ BER for an SNR of 7 dB.

Comparative results demonstrated that the proposed system outperformed other state-of-the-art approaches. Similar performance to the theoretical single-mode was reported with a slightly small difference of $2.6 \times 10^{-3}$ in BER value. This indicates excellent user-to-user and mode-to-mode interference cancellations.

Compared with the conventional UCA, the proposed technique demonstrated a good capability of focusing and steering radiation toward off-axis receivers. In this manner, the proposed technique overcome the limitations that usually appear in OAM based solutions, namely the need for transmitter-receiver alignment and beam divergence.

Necessary conditions for the system operation were derived and coordinated among the number of transmitting array elements, maximum throughput per user, and the number of users served by the system.

The spacing between adjacent elements at the receiver was investigated, revealing that a minimum separation distance was needed to enable the receiver to resolve the different modes. This distance is related to the field concentrations around the locations of the receiving elements, the resolution was improved by increasing the number of elements in the grid to focus more field at the receiver. For instance, a receiver with a radius of $10\lambda$ and transmitting grid of $11 \times 11$ elements failed to resolve the required 30 OAM modes per receiver. However, when the receiver radius was increased to $15\lambda$ or the transmitting grid was enlarged to $14 \times 14$, the system could successfully decode the modes.

The impact of channel perturbations over phase and amplitude spatial distributions of the OAM wave was explored. The findings showed that channel perturbations had similar effects over small and large modes, which presents a noticeable difference from the conventional UCA. Increasing the number of elements per receiver is suggested to average out the impact of perturbation. Results indicated that the proposed multi-user multimodal OAM system is practical.

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