

# Misalignments in Orbital Angular Momentum-based Optical Wireless Communication Systems

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**Abstract**—Orbital angular momentum (OAM) has demonstrated significant potential under ideal conditions, but its performance is highly sensitive to misalignments. The impact of misalignments on the system capacity in the OAM multiplexed optical wireless communication (OWC) system remains unexplored. This paper studies the effects of receiver aperture and misalignment on the received power and total capacity of OAM-multiplexed OWC systems. It also investigates the effect of different mode selection strategies, namely Continuous Mode Selection (CMS), Fixed Mode Selection (FMS), and Exhaustive Search (ES), on the system capacity. We found that smaller receiver apertures experience an exponential increase in received power as aperture size increases, up to a certain threshold. Additionally, misalignment has different effects on different modes. For lower-order modes, power consistently decreases with increasing misalignment, whereas higher-order modes exhibit an initial increase in power under small misalignments. Furthermore, simulations indicate that total channel capacity improves as the number of users increases under ideal or near-ideal alignment. However, capacity significantly drops with misalignment due to reduced received power and increased cross-talk from modal coupling. Appropriate mode selection can reduce this power loss and cross-talk, improving the system's capacity, particularly for moderate misalignments. Among the mode selection strategies, ES provides the highest capacity across all misalignment ranges but is computationally intensive. FMS, on the other hand, offers a practical balance by significantly outperforming CMS in terms of capacity under moderate misalignment conditions while maintaining reduced complexity. Overall, this study highlights the importance of an optimal mode selection strategy to enhance system capacity and improve misalignment resilience in OAM-multiplexed OWC systems.

**Index Terms**—OAM, optical wireless communication, misalignment

## I. INTRODUCTION

The growth of connectivity and wireless communication has led to a range of critical challenges, including a shortage of radio spectrum, substantial energy consumption, limited data rates, and security issues. To overcome these challenges, future sixth-generation (6G) networks aim to achieve ultra-high aggregated data rates of terabits per second (Tbps), increased area traffic capacity of 1 gigabit per second (Gbps)/m<sup>2</sup>, and enhanced security. Light fidelity (LiFi) is envisioned as a promising technology capable of supporting 6G networks by enabling ultra-high data rates, securing communication links, and reducing energy consumption [1]–[3].

Traditional LiFi systems use light-emitting diode (LED)-based transmitters with a limited bandwidth, which restricted

the achievable data rate. Researchers are now exploring laser diode (LD)-based transmitters for LiFi systems because they offer better conversion efficiency and a higher modulation bandwidth. Studies have shown that eye-safe LD-based LiFi systems can be effectively implemented [1]. Recent experiments demonstrated a 100 Gbps LiFi link using LD transmitters combined with wavelength division multiplexing (WDM) [4]. Multiplexing techniques are essential for achieving high data rates, and in addition to WDM, properties of light such as polarization and orbital angular momentum (OAM) can also be employed for this purpose. This paper will focus on OAM-based multiplexing.

Allen *et al.* [5] laid the groundwork for OAM research by proving that OAM-carrying light beams can be produced in conventional optics labs. OAM is a property of photons in a light beam characterized by a helical or twisted phase front, which can be described mathematically by the phase factor  $\exp(il\phi)$ , where  $l$  is the topological charge and  $\phi$  is the azimuthal angle [6], [7]. Theoretically, OAM can support an infinite number of orthogonal modes, each characterized by a distinct helical phase structure. Communication systems can utilize these different OAM beams to carry independent information that can be multiplexed together and transmitted over the same channel. Under ideal conditions, the receiver can efficiently demultiplex these beams with minimal crosstalk due to the orthogonality of OAM modes. Therefore, OAM multiplexing can support multiple data channels on a single wavelength or polarization, significantly increasing data transmission capacity without the need for additional bandwidth [8]. Wang *et al.* [9] utilizes OAM in conjunction with polarization division multiplexing to achieve a data rate of 1.37 Tbps. Nevertheless, their work is under the assumption of ideal conditions and perfect alignment.

Achieving and maintaining perfect alignment in a practical scenario is challenging, as misalignment may occur due to unavoidable environmental disturbances. When there is misalignment and the receiver aperture is limited, significant power can leak into unwanted modes, preventing the receiver from fully recovering the azimuthal phase change and inducing inter-modal power couplings [10]. These power couplings result in crosstalk and interference between OAM modes and significantly degrade overall system performance.

In this paper, we investigate the effects of misalignment on the overall capacity of an OAM-multiplexed optical wireless

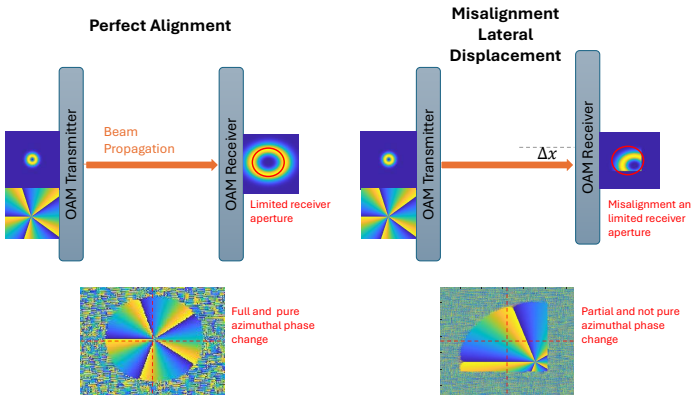


Fig. 1. Misalignment in OAM-based optical wireless communication

communication system. Using simulations, we analyze the impact of receiver aperture size and misalignments on received power and overall system capacity. Furthermore, we explore the effects of different mode selection strategies on system capacity under varying degrees of misalignment. More specifically, our work highlights the need for appropriate receiver aperture sizing and optimal mode order selection to ensure reliable OAM-based OWC in the presence of misalignments.

The rest of the paper is organized as follows: Section II summarizes the related work. The OAM system model is described in Section III. Results and discussions are presented in Section IV, and conclusions are given in Section V.

## II. RELATED WORK

Several studies have investigated the design factors for OAM-multiplexed links. These studies largely focused on power loss, channel crosstalk, and power penalties caused by misalignment and receiver aperture sizes [8], [10]. More specifically, Xie *et al.* [10] explored performance metrics and design parameters for OAM-multiplexed OWC communication links including link distance, transmitted beam size, transmitter and receiver aperture sizes, and OAM mode spacing. Their analysis focused on system power loss, channel crosstalk, and system power penalty [10]. However, these studies failed to thoroughly examine the influence of misalignment on the capacity of the system or the consequences of receiver aperture in different misalignment scenarios.

Su *et al.* [11] investigated how receiver aperture affects received power, crosstalk, and signal-to-interference ratio in non-line-of-sight (NLoS) THz links, but their analyses were focused on THz scenarios. In another study by Su *et al.* [12], the authors simulated and examined the effects of multipath propagation and receiver aperture on a THz wireless communication link using multiplexed OAM beams. Unlike previous studies, this work investigates the degradation effects by analyzing modal power coupling in 2D Laguerre-Gaussian (LG) modal spectra. The findings indicate that the combined impact of multipath and receiver aperture effects results in a decrease in power and power coupling. This leads to the degradation of the signal-to-noise ratio (SNR) and imposes penalties on the SNR when compared to single-channel systems.

In another study by Willner *et al.* [13], authors reviewed recent experimental demonstrations of OAM-based THz mode division multiplexing communication systems, including multiplexing different OAM modes, combining OAM with FDM and PDM, multiplexing different 2D LG modes, and using an integrated THz OAM emitter. The performance of THz OAM links was simulated and analyzed, considering the effects of turbulence, divergence, and multipath. Our study differs from previous ones as it focuses on OAM-based LiFi systems, which offer larger bandwidth and smaller divergence compared to THz systems [6]. To the best of our knowledge, this is the first work to analyze the effect of misalignment in OAM-based optical wireless communication systems in terms of overall system capacity. Our work offers a study of the effects of misalignment, and receiver aperture on signal power and overall capacity. Furthermore, our work highlights the importance of optimal mode selection strategies in the presence of misalignment and limited receiver aperture sizes.

## III. OAM SYSTEM MODEL FOR MISALIGNMENT ANALYSIS

OAM beams can be mathematically represented by LG beams, which are given by [6]:

$$\text{LG}(r, \phi, z; l, p) = \frac{C_{p,l}}{w(z)} \left( \frac{r\sqrt{2}}{w(z)} \right)^{|l|} L_p^{|l|} \left( \frac{2r^2}{w^2(z)} \right) \exp \left( -\frac{r^2}{w^2(z)} \right) \exp \left( -ik \frac{r^2}{2R(z)} \right) \exp(i l \phi) \exp(-i(2p + |l| + 1)\zeta(z)) \quad (1)$$

where  $r$  and  $\phi$  are the radial distance and azimuthal angle around the beam axis,  $z$  is the distance along the beam axis,  $l$  and  $p$  are the azimuthal and radial indices representing the OAM and number of radial nodes, respectively.  $C_{p,l}$  is a normalization constant. The beam radius at distance  $z$ ,  $w(z)$ , is given by  $w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$ , where  $w_0$  is the beam waist and  $z_R$  is the Rayleigh range.  $L_p^{|l|} \left(\frac{2r^2}{w^2(z)}\right)$  is the generalized Laguerre polynomial of order  $p$  and degree  $l$ . The wave number  $k$  is defined as  $k = \frac{2\pi}{\lambda}$ , where  $\lambda$  is the wavelength. The radius of curvature of the beam's wavefront at distance  $z$ ,  $R(z)$ , is given by  $R(z) = z \left(1 + \left(\frac{z}{z_R}\right)^2\right)$ . The Gouy phase shift  $\zeta(z)$  is given by  $\zeta(z) = \tan^{-1} \left(\frac{z}{z_R}\right)$ .

The propagation of OAM beams follows the Fresnel diffraction integral, with channel impulse response expressed as [14]:

$$h(x, y, z) = \frac{1}{i\lambda z} \exp(ikz) \exp \left[ i \frac{k}{2z} (x^2 + y^2) \right] \quad (2)$$

where  $z$  is the propagation distance along the beam axis. The OAM beam at distance  $z$  can be calculated as:

$$\text{LG}_{l,\text{out}} = \text{LG}(r, \phi, z; l, p) \otimes h(x, y, z) \quad (3)$$

To study the effect of lateral displacement in the system, the wave propagation equation needs to account for lateral shifts.

For misalignment based on lateral displacement  $(\Delta x, \Delta y)$ , the channel impulse response  $h_{\text{misaligned}}(x, y)$  shifts accordingly:

$$h_{\text{misaligned}}(x, y, z) = \frac{1}{i\lambda z} \exp(ikz) \exp \left[ i \frac{k}{2z} \left( (x - \Delta x)^2 + (y - \Delta y)^2 \right) \right] \quad (4)$$

The transfer function with misalignment becomes:

$$H_{\text{misaligned}}(f_x, f_y) = H(f_x, f_y) \cdot \exp \left[ i \frac{k}{2z} (\Delta x^2 + \Delta y^2) \right] \cdot \delta \left( f_x - \frac{k\Delta x}{2\pi z}, f_y - \frac{k\Delta y}{2\pi z} \right) \quad (5)$$

where  $H(f_x, f_y)$  denotes the transfer function without misalignment and is given by:

$$H(f_x, f_y) = \mathcal{F}[h(x, y)] = \exp \left[ -i \frac{\pi \lambda z}{2} (f_x^2 + f_y^2) \right] \exp(ikz) \quad (6)$$

Thus, the OAM beam, after accounting for misalignment is given by:

$$\text{LG}'_{l,\text{out}}(x, y) = \mathcal{F}^{-1} [\mathcal{F}(\text{LG}_l) \cdot H_{\text{misaligned}}(f_x, f_y)] \quad (7)$$

The electric field of the aperture-limited and misalignment-affected OAM beam at the receiver is given by:

$$E'_{l,\text{out}}(x, y) = \text{LG}'_{l,\text{out}}(x, y) \cdot \mathcal{A}(x, y) \quad (8)$$

where, for a fixed receiver aperture size  $R_{\text{AP}}$ , receiver aperture  $\mathcal{A}(x, y)$ , is defined as:

$$\mathcal{A}(x, y) = \begin{cases} 1, & \sqrt{x^2 + y^2} < R_{\text{ap}} \\ 0, & \sqrt{x^2 + y^2} \geq R_{\text{ap}} \end{cases} \quad (9)$$

The received power for a particular LG mode  $l$ , can be calculated as:

$$P_q = \left| \iint E'_{l,\text{out}}(x, y) \text{LG}_l^*(x, y) dx dy \right|^2 \quad (10)$$

whereas, the power coupling between mode  $q$  and  $l$  can be calculated using:

$$P_{q,i} = \left| \iint E'_{l,\text{out}}(x, y) \text{LG}_i^*(x, y) dx dy \right|^2 \quad (11)$$

Assuming multiple transmitters and receivers in the OAM-multiplexed system operating on  $L$  different modes, the received signal-to-interference noise ratio (SINR) at the  $q^{\text{th}}$  OAM mode is given by:

$$\text{SINR}_q = \frac{P_q}{\sigma^2 + \sum_{i=1, i \neq q}^L P_{q,i}} \quad (12)$$

where  $P_q$  indicate received power for the desired  $q^{\text{th}}$  mode and  $P_{q,i}$  indicates the power in other modes due to modal coupling between the  $q^{\text{th}}$  transmitting mode and the  $i^{\text{th}}$  receiving mode, which are defined in eq. (10) and (11).  $\sigma^2$  represents the noise power.

TABLE I  
SYSTEM PARAMETERS.

Parameter	Value
Wavelength, $\lambda$	1330 nm
Propagation distance, $z$	1 m
Beam waist, $w_0$	20 $\mu\text{m}$
Receiver Aperture size, $R_{\text{ap}}$	5 cm
Transmitter Power	10 mW
Transmitter Bandwidth, $B$	1 GHz
Number of Users, $N_u$	1, 2, 3, 4, 5
Modal Spacing, $\mathcal{M}_s$	1, 2
OAM orders for each transmitter, $\mathcal{N}_s$	[1, 1+ $\mathcal{M}_s$ , 1+2 $\mathcal{M}_s$ , ...]

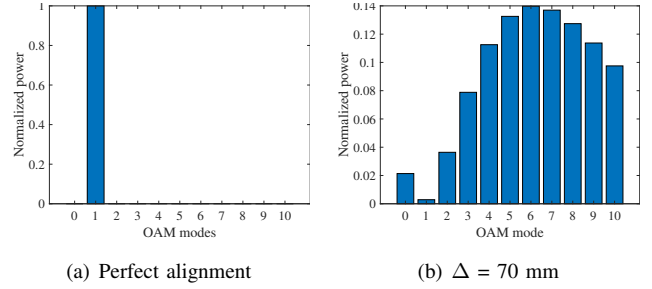


Fig. 2. Impact of misalignment ( $\Delta$ ) when only OAM mode  $l = 1$  is used for transmission. Transmitter beam width  $w_0 = 20 \mu\text{m}$ , receiver aperture size  $R_{\text{ap}} = 5 \text{ cm}$ , at propagation distance  $z = 1 \text{ m}$ .

The achievable spectral efficiency of the  $q^{\text{th}}$  OAM mode can be computed as:

$$\eta_q = \log_2(1 + \text{SINR}_q) \quad (13)$$

Assuming there are  $N_u$  users each using a different OAM mode and transmitter bandwidth  $B$ . The total system capacity will be given by:

$$C_s = \sum_{i=1}^{N_u} B \eta_i \quad (14)$$

#### IV. RESULTS AND DISCUSSION

This section analyzes how misalignment ( $\Delta$ ) and limited aperture size ( $R_{\text{ap}}$ ) affect the received power and total system capacity of an OAM-multiplexed OWC system. The analysis is conducted using MATLAB simulations with parameters defined in Table I. In this study,  $N_u$  represents the number of users, where each user is assumed to be multiplexed onto a unique OAM mode. The transmitter architecture is designed to generate and multiplex these OAM modes, with a transmitter beam width  $w_0 = 20 \mu\text{m}$  and transmitter bandwidth  $B = 1 \text{ GHz}$ . The propagation distance is set at  $z = 1 \text{ m}$ , and the receiver aperture  $R_{\text{ap}}$  is varied to assess its impact on the received power under different misalignment conditions. Furthermore, three different mode selection strategies are considered to determine the effect of mode order on overall system capacity.

##### A. OAM Beam Propagation

The OAM beam intensity and phase at  $z = 0$  and  $z = 1 \text{ m}$ , is shown in Fig. 1. We observe that the beam diverges as it propagates, and the limited receiver aperture clips some intensity components. In the presence of limited aperture and

misalignment, the phase profile of the OAM beam is also adversely affected, as shown in Fig. 1. In such cases, the receiver might fail to identify the full phase changes in the azimuthal direction and ring-shaped intensity distribution. As a result, the receiver may wrongly detect other undesired modes, leading to modal power coupling [15]. Fig. 2 illustrates the effect of misalignment on the communication system. When only OAM mode  $l = 1$  is used and  $\Delta = 70$  mm, only 0.5% of the power is received in the desired mode ( $l = 1$ ). In contrast, a much larger fraction of power is coupled among other modes, resulting in significant cross-talk and interference in the OAM-based OWC system.

### B. Received Power

To understand the effect of misalignment and receiver aperture on received power, we conducted simulations with  $N_u = 4$ , and each user was assigned a different OAM mode with a modal spacing,  $\mathcal{M}_s = 2$ . We varied the  $R_{ap}$  from 1 to 10 cm and calculated the received power using equation (8). Additionally, we considered (a) perfect alignment ( $\Delta = 0$ ), (b) 30 mm misalignment, and (c) 60 mm misalignment. Based on these conditions, Fig. 3 was obtained, illustrating the effect of misalignment and receiver aperture on received power.

In the smaller aperture range, we observe that the received power increases exponentially with the size of the receiver apertures. This is because smaller receivers are unable to capture the entire signal. By increasing the size of the receiver aperture, more signal components can be captured effectively, resulting in higher received power. Once the aperture reaches a certain size, the power stabilizes and remains constant. This plateau occurs when the aperture reaches a size that allows it to catch the entire received OAM beam. Further increasing the aperture size does not have any additional benefit in terms of the received power. It may be noted that the aperture size at which power saturates depends on the mode order  $l$ . In the case of perfect alignment ( $\Delta = 0$ ), the higher-order modes will require a wider receiver aperture to reach this saturation point.

Fig. 3 also illustrates the effect of receiver aperture on different modes in the presence of misalignment. While for lower order modes ( $l = 1, 3$ ), the power reduces with increasing misalignment, for higher order modes ( $l = 9$ ) received power increases with misalignment. More specifically, it can be observed that when  $R_{ap} = 3$  cm, the power for  $l = 1$  decreases by approximately 7.08 dBm at  $\Delta = 30$  mm, compared to the case of perfect alignment ( $\Delta = 0$ ). Further reducing  $R_{ap}$  to 1 cm results in a more significant power loss of approximately 15.53 dBm as compared to perfect alignment. This happens because the small aperture size ( $R_{ap} = 1$  cm) only captures the partial OAM signals; for lower order modes, the intensity profile has limited radial OAM rings; thus, even the smallest misalignment causes more of the signal to fall out of the smaller aperture area, resulting in more severe power loss. In contrast, for higher-order modes ( $l = 6$  and  $9$ ), the OAM beams, due to their wider beam spot and unique doughnut-like shape, may benefit from some degree of misalignment, as small misalignment will cause more of the wider higher-order

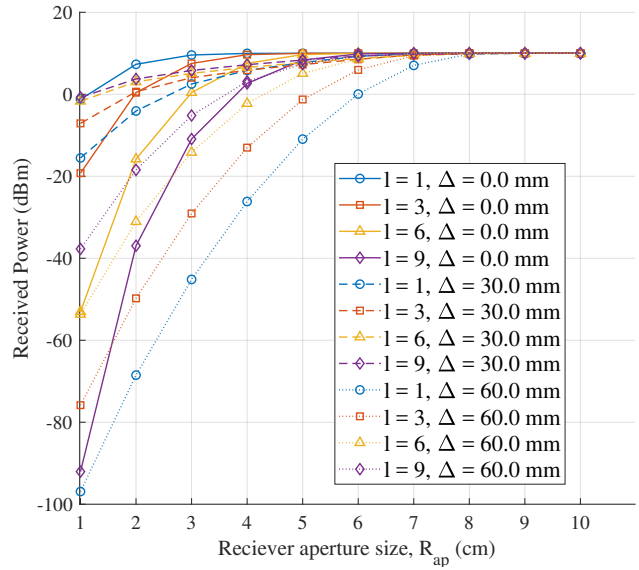


Fig. 3. Effect of misalignment ( $\Delta$ ) and receiver aperture ( $R_{ap}$ ) on received power for different distance OAM modes ( $l$ ). Transmitter beam width  $w_0 = 20 \mu\text{m}$  at propagation distance  $z = 1$  m.

OAM ring to align to receiver area, resulting in more signal power reaching the receiver. In the case of  $l = 9$  and  $R_{ap} = 3$  cm, when  $\Delta = 30$  mm, there is a notable power gain of 16 dBm compared to perfect alignment ( $\Delta = 0$ ). However, with an additional misalignment, the received power starts to decrease, i.e.  $\Delta = 60$  mm reduces this gain over perfect alignment to 5.74 dBm. Similarly,  $l = 6$  and  $\Delta = 30$  mm results in an increase of 5.80 dBm in received power for  $R_{ap} = 3$  cm. However, for larger misalignments ( $\Delta = 60$  mm), the received power decreases by 14.61 dBm as compared to perfect alignment ( $\Delta = 0$ ). This highlights the importance of the need for appropriate mode selection; even in the case of limited aperture size, optimal mode selection can improve the received power.

Nonetheless, when  $R_{ap} > 9$  cm, the received power under misalignment converges to the received power for perfect alignment. This validates that a large enough receiver could help combat the effect of misalignments in the OAM multiplexed system. A larger receiver will increase the system's cost, reduce the effective receiver bandwidth, and make it difficult to implement in practice. One possible solution is to use lenses at the transmitter to focus the transmitted OAM beams to reduce the power loss caused by beam divergence and limited size receiver [16].

### C. Total Capacity

To understand the effect of the number of users, mode order, and misalignment on the overall system capacity, we conducted simulations with varying numbers of users ( $N_u = 1$  to  $5$ ) and three different mode selection strategies. We conducted simulations for a receiver aperture size,  $R_{ap} = 5$  cm. The system's total capacity was calculated using equation (14) to obtain Fig. 4. The mode selection strategies are defined as follows:

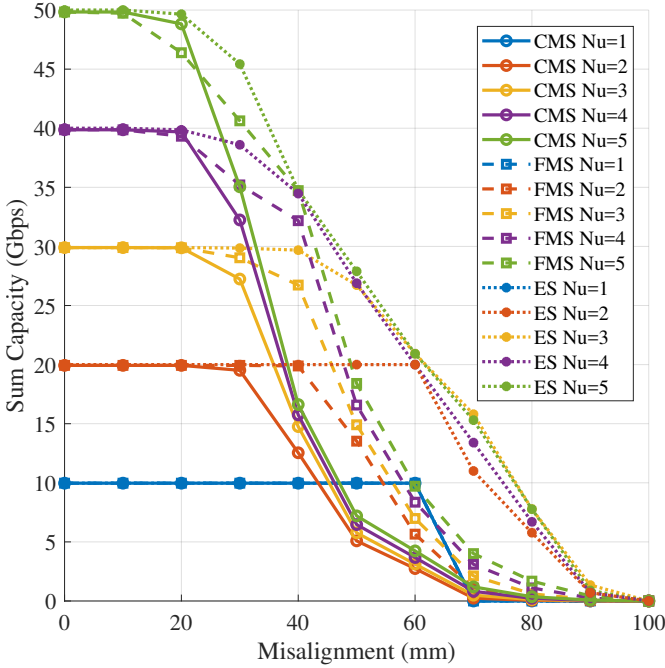


Fig. 4. Impact of misalignment ( $\Delta$ ) on the total system capacity for different numbers of users and mode selection strategies. Beam width  $w_0 = 20 \mu\text{m}$ , transmitter bandwidth  $B = 1 \text{ GHz}$ , receiver aperture size  $R_{\text{ap}} = 5 \text{ cm}$ , at propagation distance  $z = 1 \text{ m}$ .

- Continuous Mode Selection (CMS) strategy: Users are assigned continuous mode orders starting from  $l = 1$ , maintaining the modal spacing  $\mathcal{M}_s = 1$ .
- Fixed Mode Selection (FMS) strategy: Users are assigned modes at a fixed modal spacing of  $\mathcal{M}_s = 2$ .
- Exhaustive Search (ES) strategy: Systematically explores all potential combinations of mode orders to identify the optimal combination that will maximize the capacity for a given number of users, misalignment, and aperture size.

It can be seen that, for perfect and near-perfect alignment ( $\Delta < 10 \text{ mm}$ ), increasing  $N_u$  directly improves the total capacity across all mode selection schemes. This is because higher  $N_u$  in lower misalignment means more users have been multiplexed on the same channel without introducing significant interference or signal degradation, resulting in a higher total system capacity. In this case, the improvement in total capacity is significant as it increases from 10 to 50 Gbps with  $N_u = 1$  to  $N_u = 5$ .

As misalignment increases to intermediate values ( $20 < \Delta < 50 \text{ mm}$ ), the system's total capacity decreases. However, the rate of this decline depends on the mode selection strategy. For CMS, the capacity starts to drop rapidly with increasing misalignments. This happens because the CMS selects closely spaced, lower-order modes (e.g.,  $l = 1, 2, 3, \dots$ ), which are more vulnerable to power loss due to misalignment, as shown in Fig. 3. Therefore, the overall capacity reduces exponentially as the misalignment grows, making this scheme unsuitable for higher misalignment levels. The FMS exhibits better resilience to misalignment, particularly for moderate values ( $20 < \Delta <$

$50 \text{ mm}$ ). For example, for  $N_u = 3$  at  $\Delta = 40 \text{ mm}$ , FMS still maintains a capacity of around 26 Gbps, which is 73% higher than the CMS. This highlights that even suboptimal mode selection strategies like FMS can significantly enhance robustness against moderate misalignment because appropriate modal spacing reduces modal coupling and cross-talk, which helps in improving the total system capacity. ES provides the best performance across all misalignment ranges. At  $\Delta = 60 \text{ mm}$ , it maintains a capacity of 20 Gbps for  $N_u = 2, 3, 4$ , and 5, as compared to FMS in which capacity drops down to  $< 10 \text{ Gbps}$ . The ES strategy achieves this by optimally selecting the mode orders that minimize the inter-modal cross-talk in addition to maximizing the received power.

Beyond 60 mm misalignment, it is interesting to observe that the  $N_u = 1$  performs better than a higher number of users for CMS and FMS. It is interesting because this suggests that under severe misalignment if the OAM modes are not carefully selected, a larger number of users will introduce more interference, thus, they will not contribute meaningfully to the total capacity. Overall, ES consistently offers the highest capacity across all misalignment ranges, significantly outperforming CMS and FMS. However, this advantage comes at the cost of higher computational complexity.

CMS and FMS have significantly lower computational complexity. This is because each user is assigned a mode in a predefined sequence without any additional computational overhead, resulting in computational complexity of  $O(N_u)$ . In contrast, ES evaluates all possible selections of  $N_u$  modes from a total of  $L$  modes. The number of combinations for ES is given by the binomial coefficient and each combination requires the evaluation of the sum capacity, which involves iterating through each user and calculating their contribution to the total capacity. Thus, the time complexity of the ES is proportional to the number of combinations multiplied by the complexity of calculating the capacity for each combination. The capacity evaluation for each user involves operations such as modal decomposition and overlap calculations. However, these operations are constant to  $N_u$  so the dominant term in the complexity arises from the binomial coefficient. For large  $L$  and  $N_u$ , the binomial coefficient can be approximated to  $\binom{L}{N_u}^{N_u}$ . Thus, the overall time complexity of the ES can be expressed as:  $O\left(\left(\frac{L}{N_u}\right)^{N_u} \times N_u\right)$ . This complexity grows exponentially with the number of users  $N_u$ , making the ES computationally infeasible for large systems. There is a need for a more feasible solution in terms of computational resources, which will be the focus of our future research.

## V. SUMMARY AND CONCLUSION

This paper investigates the impact of limited receiver aperture and misalignment on the received power and total system capacity of OAM-multiplexed OWC systems. Furthermore, it studies the performance implications of using different mode selection strategies, i.e., CMS, FMS, and ES on the overall system capacity.

We found that smaller receiver apertures exhibit an exponential increase in received power with increasing aperture size, but this power stabilizes once the aperture is sufficiently large to capture the entire received signal. However, the aperture size at which power saturates depends on the mode order, with higher-order modes requiring larger apertures. Additionally, misalignment has different effects on different modes. Lower-order modes experience decreased power with increasing misalignment, while higher-order modes show increased power with smaller misalignments. Beyond a 9 cm receiver aperture, the received power under misalignment approaches that of perfect alignment, indicating that a larger receiver can mitigate misalignment effects. However, larger receivers increase system costs.

Furthermore, it is noted that for perfect or near-perfect alignment ( $\Delta < 10$  mm), aggregated channel capacity increases with the number of users: specifically, there is a linear increase from 10 to 50 Gbps for  $N_u$  increasing from 1 to 5. However, as misalignment increases ( $20 < \Delta < 50$  mm), capacity declines, especially for CMS, due to power loss and higher interference from closely spaced modes. In contrast, the FMS offers better resilience; it provides almost double the overall capacity of the CMS at  $\Delta = 40$  mm. Nonetheless, it's important to note that this improvement in capacity with higher modal spacing is limited to a specific threshold of misalignment: for instance, at  $\Delta > 70$  mm, the overall capacity achieved by FMS will converge with CMS. Furthermore, it is interesting to note that for  $\Delta > 60$  mm, higher  $N_u$  leads to worse performance in CMS and FMS due to excessive interference happening because of non-optimal mode selection. Lastly, the ES method provides the best performance. The advantage of ES is more pronounced in higher misalignment, as the performance of suboptimal FMS converges to CMS. More specifically, when the  $\Delta > 60$  mm, FMS provides a marginal advantage over CMS, whereas the ES offers a substantial gain of 100% over CMS for  $\Delta > 90$  mm. Nevertheless, the ES method is computationally intensive and unfeasible for a large number of users and modes.

Overall, our work highlights the importance of appropriate receiver aperture sizing and modal selection strategies to ensure higher system capacity. While optimal receiver aperture minimizes power loss, selecting appropriate mode orders can reduce crosstalk and further enhance system capacity. Our current results confirm that optimal ES mode selection can help mitigate some effects of misalignment on system capacity. In future works, we will identify alternative mode selection solutions that are more computationally feasible. Additionally, we will focus on developing and integrating an analytical model to complement the simulation-based analysis.

#### ACKNOWLEDGMENT

This work was supported by the Economic and Social Research Council (ESRC) under the CHIST-ERA grant number EP/X034542/2, titled "MEMS-Metasurface Based Tunable Optical Vortex Lasers for Smart Free-Space Communication (Meta-LiFi)." H. Caglayan acknowledges the support of the

CHIST-ERA grant CHIST-ERA-21-NOEMS-002, funded by the Research Council of Finland (357746). The authors would also like to express their gratitude to Dr. Iman Tavakkolnia for his valuable research inputs. For open access, the author has applied a Creative Commons Attribution (CC BY) license to any author-accepted manuscript version arising.

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