

Article

A Multiple-Input Multiple-Output Transmission System Employing Orbital Angular Momentum Multiplexing for Wireless Backhaul Applications

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Abstract

This paper presents a long-range experimental demonstration of multi-mode multiple-input multiple-output (MIMO) transmission using orbital angular momentum (OAM) waves for Line-of-Sight (LoS) wireless backhaul applications. A 4×4 MIMO system employing distinct OAM modes is implemented and shown to support multiplexing data transmission over a single frequency band without inter-channel interference. In contrast, a 2×2 plane wave MIMO configuration fails to achieve reliable demodulation due to mutual interference, underscoring the spatial limitations of conventional waveforms. The results confirm that OAM provides spatial orthogonality suitable for high-capacity, frequency-efficient wireless backhaul links. Experimental validation is conducted over an 100 m outdoor path, demonstrating the feasibility of OAM-based MIMO in practical wireless backhaul scenarios.



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Keywords: orbital angular momentum (OAM); MIMO; wireless backhaul; spatial multiplexing; reflector antenna; long-range communication

1. Introduction

The rapid evolution of mobile communication technologies toward 5G and beyond has significantly increased the demand for high-capacity and scalable wireless backhaul solutions. Traditional backhaul methods, while robust, are increasingly strained under the pressure of dense small-cell deployments, bandwidth-hungry applications, and stringent latency requirements [1–4]. These challenges necessitate innovative approaches that offer higher spectral efficiency, spatial reuse, and long-range capabilities.

A detailed survey of current and future backhaul systems highlights the limitations of conventional microwave and millimeter-wave links, particularly in urban and heterogeneous network environments [5–7]. The transition to 6G further intensifies the requirements, demanding ultra-high data rates, ubiquitous connectivity, and intelligent, software-defined management of network resources [8–11].

To address these constraints, researchers have turned to the physical properties of electromagnetic waves, particularly Orbital Angular Momentum (OAM), which introduces a new degree of freedom for multiplexing. First proposed for light beams [12], OAM has demonstrated remarkable potential in radio and microwave domains due to its inherent orthogonality and spatial structure, allowing multiple independent data channels to coexist on the same frequency [13–18]. Zhu et al. [19] explored the use of radio vortex MIMO systems and demonstrated high-capacity communication using OAM modes. Building on this, Tamburini et al. conducted seminal experimental work on OAM-based multiplexing,

including the encoding of multiple channels on the same frequency [20] and tripling the point-to-point radio link capacity using electromagnetic vortices [21].

In practical systems, OAM multiplexing has shown impressive data rates. For instance, Yan et al. [22] achieved 32 Gbit/s at 60 GHz using polarization and OAM multiplexing. Similarly, Zhang et al. [23] and Gaffoglio et al. [24] validated the feasibility of OAM mode division multiplexing (MDM) in real-world setups using microwave antennas and digital television signals. A key challenge in OAM communication is the degradation of orthogonality and signal quality over long distances due to beam divergence, atmospheric effects, and alignment sensitivity [25–27]. Zhang and Zhao [28] proposed a nondegenerate index mapping method to preserve OAM mode separation during long-range propagation. Meanwhile, Yao et al. [29] investigated phase stability in OAM-based long-distance links, validating the transmission of stable phase structures over several kilometers.

Yagi et al. advanced the field by implementing dual-polarized OAM-MIMO systems, achieving 200 Gb/s at 28 GHz [30], and further developed a 40 GHz OAM system for field testing [31]. More recently, Sasaki et al. [32] demonstrated an ultra-high-speed OAM multiplexing system operating at sub-THz frequencies with 1.58 Tbps throughput using a wide-band Butler matrix. The foundational works by Thidé and colleagues [33,34] established the theoretical basis for radio OAM in low-frequency domains, and subsequent efforts validated its practicality in distributed antenna systems for long-range transmission [35]. Yao et al. [36] further analyzed OAM wave behavior in reflection and refraction scenarios, contributing to the design of reflector-based OAM systems.

Advanced antenna technologies have also been explored to optimize OAM performance. Meng et al. [37] introduced a phase-modulated transmit array lens, while Wu et al. [38] investigated attenuation effects using parabolic antennas. These studies provide insight into managing beam divergence and signal loss in practical deployment. Previous long-distance OAM transmission experiments by detailing key system parameters such as carrier frequencies, the number of OAM modes used, transmission distances, and corresponding data rates as performance metrics, are presented in Table 1. Metrics not explicitly reported in the referenced studies are denoted by “n/a”. The most recent advancement comes from Wu and Zhang [39], who demonstrated an OAM backhaul link supporting 1 Tbps over 1 km using a Cassegrain antenna, affirming the commercial viability of OAM systems for high-capacity, long-distance wireless backhaul.

Despite these advancements, the orthogonality degradation of OAM modes over long distances and the design of robust multi-mode structures for efficient backhaul transmission remain open challenges [40,41]. In this work, we propose a nearly orthogonal multi-mode structured wave transmission system using an OAM reflector antenna. The Schematic diagram of the system architecture has been illustrated in Figure 1. Our approach aims to optimize modal separation, reduce inter-mode interference, and enhance the link budget for scalable long-range backhaul applications in future 6G networks. Our experiment demonstrated successful 4-mode multiplexing at 10 GHz over a 100 m link with minimal bit error rates, clearly showing a performance comparable to or superior in robustness to previous work at similar distances, such as Yagi et al. [31].

Table 1. Prior work on long-distance OAM transmission.

Researcher	Frequency	Mode No.	Distance	Rate
Tamburini F. [20]	2.4 GHz	2	442 m	n/a
Tamburini F. [21]	17.128 GHz	3	150 m	33 Mbps
Yan Y. [22]	60 GHz	2	2.5 m	32 Gbps
Zhang W. [23]	10 GHz	4	10 m	300 Mbps
Gaffoglio R. [24]	198.5 MHz	2	40 m	15.8 Mbps
Zhang C. [28]	10 GHz	2	27.5 km	1 Mbps

Table 1. Cont.

Researcher	Frequency	Mode No.	Distance	Rate
Zhang C. [28]	10 GHz	2	172 km	4 Mbps
Yao Y. [29]	10 GHz	2	3 km	n/a
Yagi Y. [30]	28 GHz	2	10 m	200 Gbps
Yagi Y. [31]	39.5–41 GHz	2	100 m	119 Gbps
Sasaki H. [32]	136–168 GHz	2	1 m	1.58 Tbps
Wu Q. [39]	40 GHz	4	1 km	1 Tbps
Our Work	10 GHz	4	100m	NA

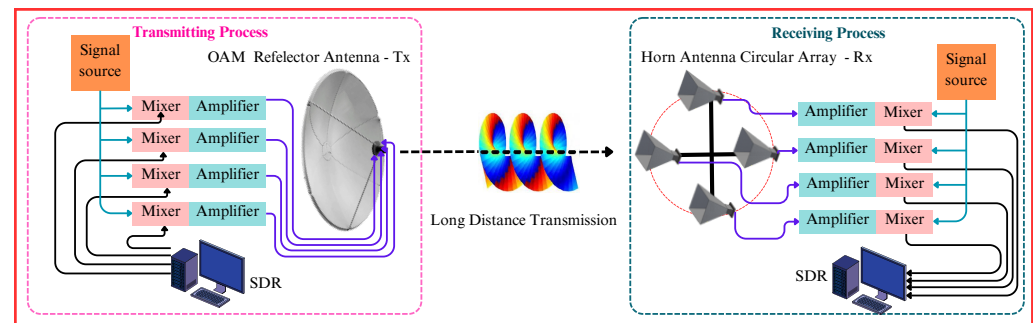


Figure 1. Schematic diagram of system architecture for long-distance transmission.

2. System Architecture

2.1. OAM Reflector Antenna Design

In this work, a reflector-based OAM antenna is employed, with similar in architecture to that introduced in [29], to generate electromagnetic waves carrying OAM for long-range transmission, as shown in Figure 2. The OAM reflector is composed of a high-gain parabolic reflector fed by a specially designed multi-concentric ring microstrip patch antenna placed at its focal point. This structure enables the generation of vortex wavefronts by exciting high-order transverse magnetic (TM) cavity modes, notably the $TM_{|l|+1,1}$ modes, where $|l|$ denotes the absolute value of the OAM mode number l .

The feeding microstrip patch is excited with orthogonal phases and uniform amplitude using an external feed network to synthesize the required helical phase front. Circular polarization, inherent in TM mode, is used to contribute to the total angular momentum of the emitted wave. Metallic via holes are inserted to ensure electromagnetic isolation between concentric rings, enabling the selective excitation of distinct OAM modes.

Due to the inherent divergence and low gain of patch-based OAM sources, a parabolic reflector with a 300 mm radius and a focal-to-diameter ratio of 0.326 is used to collimate and enhance the gain of the transmitted beam. The microstrip patch source is positioned precisely at the reflector's focal point using a 3D-printed dielectric support. This combination of microstrip feed and parabolic reflector enables the generation of OAM waves with well-defined vortex characteristics, low divergence, and high directionality over extended distances.

The generation of OAM modes with $l = 1$ and $l = 2$ is confirmed through near-field measurements of the fabricated antenna, showing characteristic azimuthal phase variations of $2\pi l$ in the phase distribution, consistent with theoretical vortex structures. The divergence angles for $l = 1$ and $l = 2$ are measured to be approximately 2.2° and 2.9° , respectively, making them suitable for long-range OAM transmission.

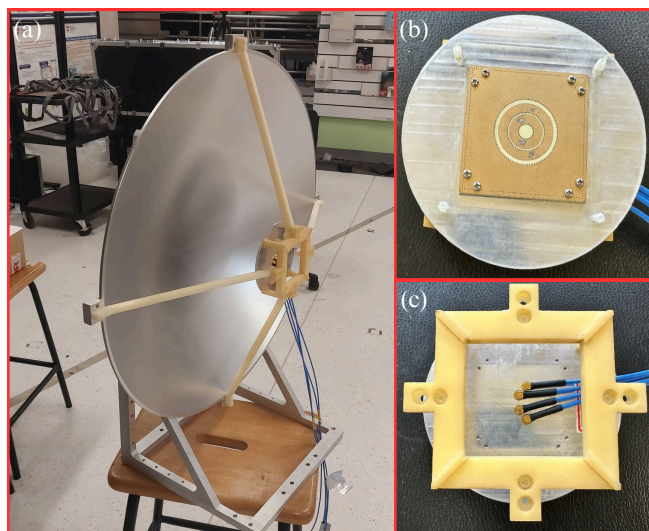


Figure 2. Structure of the OAM wave source: (a) OAM reflector antenna, OAM feeder (b) top-view and (c) back-view.

2.2. Receiver Configuration Using Horn Antennas

To receive and analyze the spatial structure of the transmitted OAM beams, we employed a custom-designed receiver array comprising four standard gain horn antennas arranged in a cross configuration on a planar surface. Each horn antenna is aligned toward the boresight of the incoming OAM beam, with a spatial separation optimized to capture the modal phase variation in the azimuthal direction.

This cross-shaped arrangement enables the sampling of the spatial phase profile across different azimuthal positions of the beam, which is essential for mode decomposition and inter-mode interference analysis. The received signals from the four antennas are down-converted, phase-synchronized, and processed using a software-defined radio (SDR) platform to extract phase and amplitude information.

The combination of a circular phased-array-fed reflector antenna as the transmitter and a distributed horn antenna array as the receiver facilitates accurate measurement and characterization of OAM modes in long-distance wireless backhaul scenarios.

3. Fabrication and Experiment

3.1. Transmitting Signal

To ensure accurate channel estimation and reliable signal recovery at the receiver, a structured transmission strategy is adopted. For each channel, the composite signal is formed by sequentially combining a pilot signal and a message signal, as illustrated in Figure 3. This structure enables precise channel characterization while supporting parallel transmission across spatial channels.

Each of the four channels, corresponding to the ports of the OAM feeder, is assigned a distinct pilot sequence. These pilot signals are transmitted using time division multiplexing (TDM), where each pilot is sent in a dedicated time slot while the other channels remain inactive. This method maintains pilot orthogonality and eliminates cross-channel interference during channel estimation.

After pilot transmission, all message signals are transmitted simultaneously. The spatial orthogonality of the OAM modes enables 4×4 MIMO communication at the same frequency without interference.

At the receiver, the horn antenna array captures the incoming signals. Pilot signals are used to estimate the channel response for each path, which is then applied to coherently demodulate the parallel message streams. This TDM-based pilot and simultaneous message

transmission strategy significantly improves the system's ability to handle multi-mode propagation in a long-range OAM-based MIMO channel. It also ensures robustness against atmospheric distortions and alignment deviations by providing dynamic channel state information for real-time adaptation.

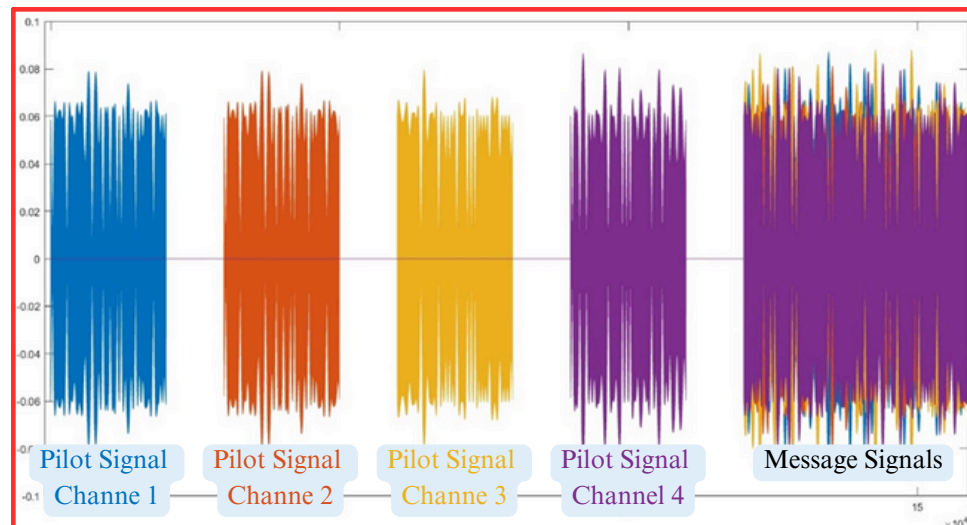


Figure 3. Transmitting signal structure.

3.2. Experimental Setups

To investigate the viability of MIMO transmission utilizing OAM waves and to benchmark it against conventional plane wave propagation, an experimental setup is established in an outdoor environment with an unobstructed LoS path spanning approximately 100 m between the transmitter and receiver. The testbed is configured to evaluate a 4×4 MIMO transmission employing OAM modes, followed by a 2×2 MIMO transmission using plane waves, both conducted at an RF frequency of 10 GHz with an intermediate frequency (IF) of 100 MHz, using quadrature phase-shift keying (QPSK) modulation. The experimental configurations for OAM and plane wave transmissions are illustrated in Figure 4a,c, respectively. The experiment parameters are listed in Table 2.

At the transmitter, a high-gain reflector antenna is employed as the radiation aperture for both configurations. For the OAM-based transmission, the reflector antenna is fed by a custom-designed four-port OAM feeder, which is designed to excite distinct azimuthal phase gradients corresponding to specific OAM modes ($l = \pm 1, \pm 2$). Each of the four feed lines is connected to an independent channel of a software-defined radio (SDR) platform. Modulated baseband signals, generated by SDR using QPSK modulation, are upconverted to the RF frequency of 10 GHz via frequency mixers operating with a 100 MHz IF. The upconverted signals are amplified to meet the link budget requirements for the 100 m transmission distance. Phase synchronization is maintained across the four SDR channels to ensure orthogonal OAM mode excitation and to preserve inter-channel isolation in the spatial domain.

Table 2. Experimental parameters.

Parameter	Value
Carrier frequency	10 GHz
Intermediate frequency	100 MHz
Modulation scheme	QPSK
Transmission distance	Around 100 m
Transmitted power	33 dBm
Signal bandwidth	10 MHz

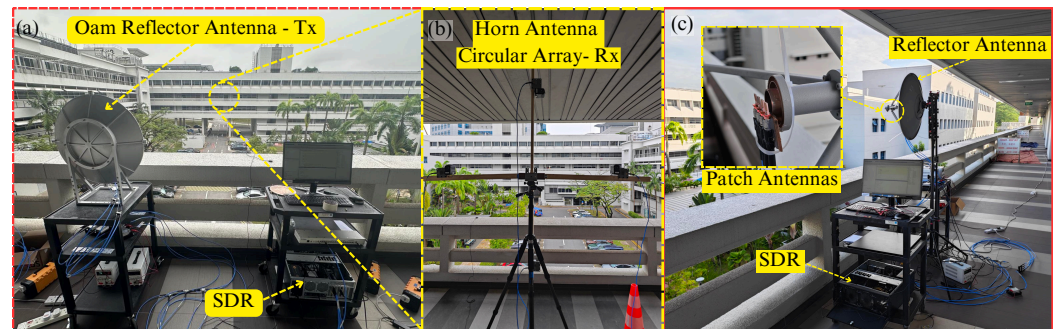


Figure 4. Experimental setup (a) OAM 4×4 transmission setup. (b) Horn antennas circular array receiving setup. (c) Plane wave 2×2 transmission setup.

Subsequently, the transmitter antenna is reconfigured for the plane wave-based 2×2 MIMO transmission. A separate reflector antenna, equipped with two patch antenna feeds, is utilized to radiate plane waves. Initially, data are transmitted simultaneously through both channels to evaluate the performance of the 2×2 MIMO configuration. Thereafter, one channel is deactivated, and transmission is conducted through a single channel to assess the impact of reduced spatial diversity. Unlike OAM waves, which propagate in spatially orthogonal helical modes, plane waves are characterized by a lack of inherent mode diversity, resulting in potential signal interference when multiple streams are transmitted concurrently at the same frequency.

As shown in Figure 4b, at the receiver side, a circular array of horn antennas is deployed to capture both the OAM and plane wave signals. For OAM reception, the horn antennas are arranged in a circular cross pattern to sample the azimuthal phase structure of the vortex beam, enabling the separation of the four OAM modes. For plane wave reception, a simpler two-channel horn antenna configuration is employed, aligned with the corresponding transmitter feeds. The received RF signals are amplified by low-noise amplifiers and down-converted to the 100 MHz IF using frequency mixers. The down-converted signals are processed by a second SDR unit, where demodulation and digital baseband analysis are performed to recover the transmitted QPSK data streams.

Compared to the system presented by Yagi et al. [31], which demonstrated a 40 GHz OAM multiplexing setup achieving a data rate of 119 Gbit/s over a 100 m outdoor link utilizing an 8×8 Butler matrix and uniform circular array (UCA) antenna, our work introduces a nearly orthogonal multi-mode structured wave system employing a reflector-based OAM antenna at 10 GHz. Notably, our approach distinctly validates superior spatial orthogonality and multiplexing efficiency, effectively eliminating inter-channel interference that significantly affects conventional plane wave MIMO transmissions. This advancement underscores the robustness of our proposed method, showcasing enhanced reliability and scalability for practical long-range wireless backhaul applications, particularly when spatial separation and inter-mode isolation are critical factors.

3.3. Experiment Results and Discussion

To assess the spatial multiplexing capability and transmission reliability of the proposed OAM-based system, two experimental configurations are evaluated: (1) a 4×4 multiple-input multiple-output (MIMO) transmission utilizing OAM modes, and (2) a 2×2 MIMO transmission employing conventional plane waves. Both configurations are operated at the same carrier frequency over an outdoor long-range line-of-sight (LoS) link spanning approximately 100 m.

In the OAM-based 4×4 MIMO configuration, four spatial channels are activated simultaneously, and independent data streams are transmitted in parallel. The spatial channels correspond to distinct azimuthal phase structures of different OAM modes rather

than physical spatial separations, enabling interference-free simultaneous transmission. At the receiver, signals from all four horn antennas are successfully demodulated with minimal inter-stream interference. The corresponding constellation diagrams, illustrated in Figure 5, exhibit well-defined and stable symbol clusters for each of the four channels, confirming effective channel separation and reliable demodulation. These results indicate that OAM modes provide inherent spatial orthogonality, enabling multiple data streams to coexist on the same frequency band without mutual interference.

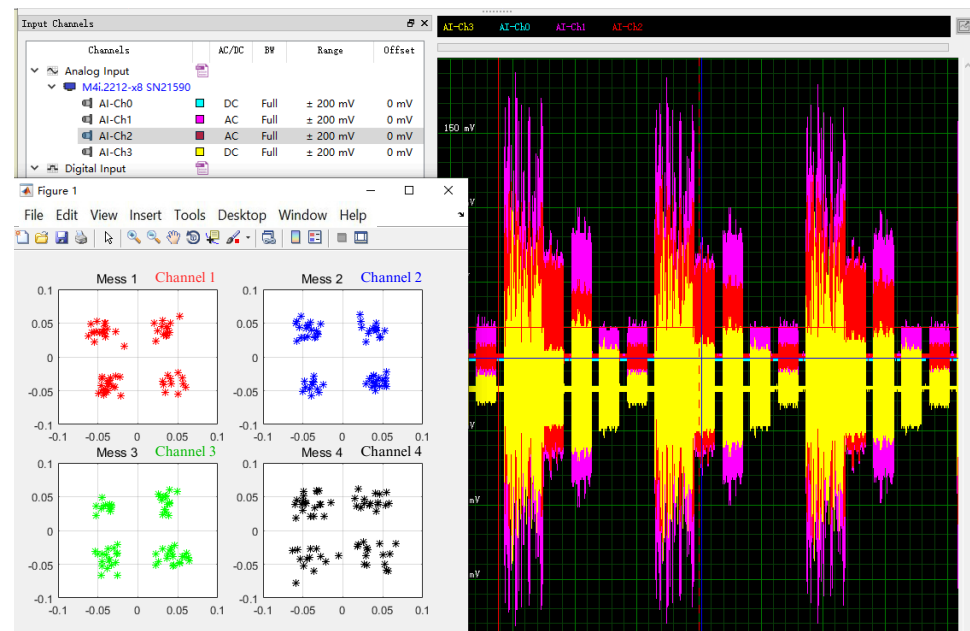


Figure 5. Constellation diagram for 4×4 MIMO OAM transmission, showing distinct symbol clusters for each channel.

To quantitatively assess signal integrity, the average bit error rate (BER) is measured for each channel and summarized in Table 3. It is observed that channels 1 and 2 exhibit zero BER, while channels 3 and 4 show low BER values of 0.0133 and 0.0334, respectively. The higher BER in channels 3 ($l = +2$) and 4 ($l = -2$) compared to channels 1 and 2 is attributed to the increased divergence angles and spatial complexity of higher-order OAM modes, causing greater sensitivity to atmospheric turbulence, alignment errors, and phase distortions. These measurements confirm that high-fidelity data recovery is achieved across all OAM channels, reinforcing the robustness and suitability of the system for frequency-constrained, long-distance MIMO communication.

Table 3. Average bit error rate (BER) for OAM and plane wave transmission.

Configuration	Chn 1	Chn 2	Chn 3	Chn 4
OAM 4×4 (All On)	0.00 ($l = +1$)	0.00 ($l = -1$)	0.0133 ($l = +2$)	0.0334 ($l = -2$)
P-Wave 2×2 (Both On)	0.4234	0.4426	—	—
P-Wave (One Chn On)	0.0114	0.4646	—	—

Chn: Channel; P-Wave: Plane Wave; l : OAM mode number.

In contrast, the plane wave-based 2×2 MIMO configuration was tested under identical experimental conditions to clearly illustrate the inherent limitations when compared to the OAM-based approach. As shown in Figure 6a, simultaneous transmission through both channels resulted in significant distortion in the constellation diagrams, characterized by pronounced overlapping of symbol clusters. Such severe inter-channel interference arises because conventional plane waves propagate without inherent spatial separation or orthogonality, causing signals from different streams to intermingle at the receiver.

This is quantitatively evident from the bit error rate (BER) measurements, where both channels exhibited extremely high error rates exceeding 0.42, clearly indicating that reliable demodulation under simultaneous operation is unfeasible.

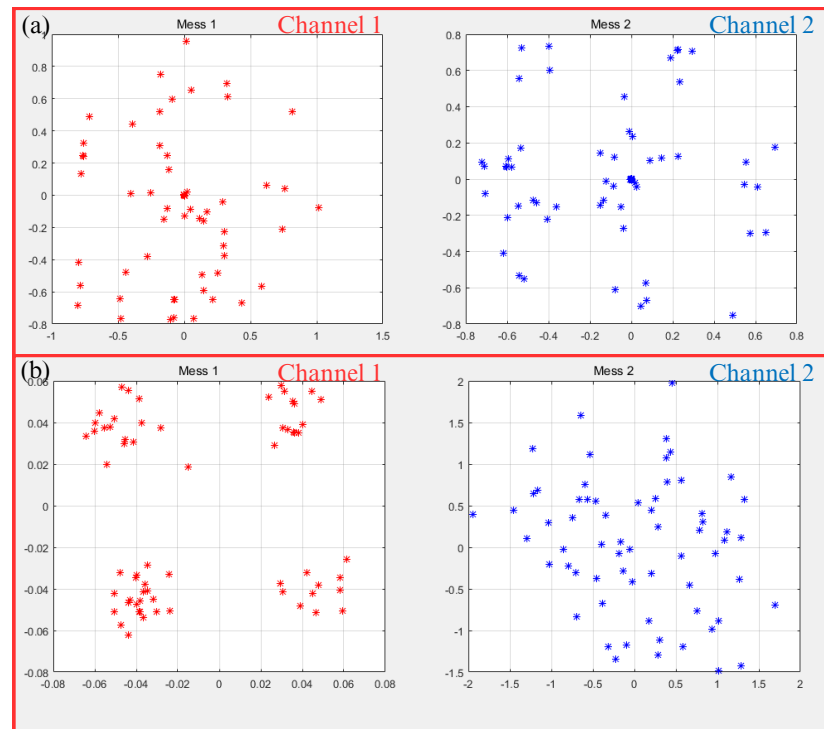


Figure 6. Constellation diagrams for 2×2 MIMO plane wave transmission: (a) send signal via two channel and (b) send signal via one channel.

To investigate further, we evaluated two scenarios clearly: (a) single-channel transmission, with only one plane wave channel activated at a time, and (b) simultaneous dual-channel transmission as illustrated in Figure 6. Under single-channel operation (scenario a), the active channel (Channel 1) demonstrated reliable demodulation with a low BER (0.0114). In contrast, simultaneous operation of both channels (scenario b) led to severe inter-channel interference, causing significantly higher BER (0.4234 for Channel 1 and 0.4426 for Channel 2). This comparison explicitly highlights the inability of conventional plane-wave systems to maintain reliable spatial multiplexing within the same frequency.

Comparatively, prior state-of-the-art studies, such as Yagi et al. [31] and Wu et al. [39], have successfully demonstrated effective spatial multiplexing and lower BER performance using OAM modes and specialized antenna structures, respectively. Yagi et al. [31], employing OAM-based multiplexing, achieved a robust performance at similar transmission distances without significant interference. Similarly, Wu et al. [39] demonstrated that structured OAM beams facilitate high-capacity, interference-free data transmission. These comparisons further underscore the fundamental disadvantage of plane wave-based MIMO configurations in frequency-constrained environments.

The comparative results are indicative of the superior spatial multiplexing capabilities of OAM waves. By exploiting the orthogonality of distinct OAM modes, the proposed system is enabled to achieve true MIMO transmission in a frequency-constrained environment, a feat not attainable with conventional plane wave propagation. The successful separation of four OAM channels, as evidenced by the clear constellation diagrams, highlights the potential of OAM to enhance spectral efficiency in long-range backhaul applications. In contrast, the limitations of plane wave-based MIMO transmission underscore the challenges of achieving spatial diversity without OAM's unique helical phase structure. These findings

establish OAM as a promising physical-layer technology for next-generation high-capacity wireless backhaul systems, particularly in scenarios requiring a robust performance over extended distances.

4. Conclusions

The effectiveness of nearly orthogonal multi-mode structure waves for long-range backhaul is demonstrated through a 100 meter outdoor experiment. A 4×4 MIMO configuration using OAM waves and a 2×2 MIMO configuration using plane waves are evaluated at 10 GHz with a 100 MHz IF, employing QPSK modulation. The OAM system is shown to achieve robust spatial multiplexing, with four data streams transmitted and demodulated without significant interference. Conversely, the plane wave configuration is found to suffer from signal overlap when both channels are active, with successful demodulation only achieved in single-stream transmission. These results confirm OAM's superior capability for high-capacity backhaul in frequency-constrained environments. Further research is recommended to optimize OAM antenna designs and explore higher-order MIMO configurations for enhanced 6G backhaul performance.

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References

1. Chia, S.; Gasparroni, M.; Brick, P. The next challenge for cellular networks: Backhaul. *IEEE Microw. Mag.* **2009**, *10*, 54–66. [\[CrossRef\]](#)
2. Zhang, C.; Zhao, Y.; Zhang, Y.; Li, F.; Jiang, S. Position aided open-loop passive magnetic MIMO transmission. *IET Commun.* **2017**, *11*, 1449–1457. [\[CrossRef\]](#)
3. Feng, X.; Zhao, Z.; Zhao, Y.; Zhao, Z.; Meng, L.; Guan, Y.L. OFDM-based waveform design for MIMO DFRC systems with reduced range sidelobes: A majorization-minimization approach. *IEEE Trans. Veh. Technol.* **2025**, *74*, 4582–4595. [\[CrossRef\]](#)
4. Zhang, C.; Zhao, Y. High precision deep sea geomagnetic data sampling and recovery with three-dimensional compressive sensing. *IEICE Trans. Fundam.* **2017**, *E100-A*, 1760–1762. [\[CrossRef\]](#)
5. Bojic, D.; Sasaki, E.; Cvijetic, N.; Wang, T.; Kuno, J.; Lessmann, J.; Schmid, S.; Ishii, H.; Nakamura, S. Advanced wireless and optical technologies for small-cell mobile backhaul with dynamic software-defined management. *IEEE Commun. Mag.* **2013**, *51*, 86–93. [\[CrossRef\]](#)
6. Luo, H.; Wang, J.; Lin, D.; Kong, L.; Zhao, Y.; Guan, Y.L. A novel energy-efficient approach based on clustering using gray prediction in WSNs for IoT infrastructures. *IEEE Internet Things J.* **2024**, *11*, 24748–24760. [\[CrossRef\]](#)
7. Lin, D.; Wan, J.; Wang, J.; Kong, L.; Zhao, Y.; Guan, Y.L. A novel topology-scale-adaptive and energy-efficient clustering scheme for energy sustainable large-scale SWIPT-enabled WSNs. *IEEE Trans. Mob. Comput.* **2024**, *23*, 13172–13188. [\[CrossRef\]](#)
8. Elmeadawy, S.; Shubair, R.M. 6G Wireless Communications: Future Technologies and Research Challenges. In Proceedings of the 2019 International Conference on Electrical and Computing Technologies and Applications (ICECTA), Ras Al Khaimah, United Arab Emirates, 19–21 November 2019; pp. 1–5.

9. Zhang, C.; Zhao, Y.; Wu, H. High precision electromagnetic momentum positioning with current Loop. *J. Magn.* **2017**, *22*, 150–154. [\[CrossRef\]](#)
10. Yang, Z.; Zhao, Y.; Ge, Y.; Fang, Y.; Guan, Y.L. Protograph-based LDPC-coded orbital angular momentum systems with index modulation. In Proceedings of the 2023 IEEE International Conference on Communications Workshops (ICC Workshops), Rome, Italy, 28 May–1 June 2023; pp. 11–16.
11. Zhao, Y.; Guan, Y.L.; Yuen, C.; Liu, X.; Ismail, A.M.; Ge, Y. Advanced artificial Doppler shift manipulation with rotational vortex beams in space-time digital-coding RIS system: A practical approach. In Proceedings of the 2024 IEEE VTS Asia Pacific Wireless Communications Symposium (APWCS), Singapore, 21–23 August 2024; pp. 1–5.
12. Allen, L.; Beijersbergen, M.W.; Spreeuw, R.J.C.; Woerdman, J.P. Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes. *Phys. Rev. A* **1992**, *45*, 8185–8189. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Zhao, Y.; Ma, X.; Guan, Y.L.; Liu, Y.; Ismail, A.M.; Liu, X.; Yeo, S.Y.; Yuen, C. Near-orthogonal overlay communications in LoS channel enabled by novel OAM beams without central energy voids: An experimental study. *IEEE Internet Things J.* **2024**, *11*, 39697–39708. [\[CrossRef\]](#)
14. Zhao, Y.; Feng, Y.; Ismail, A.M.; Wang, Z.; Guan, Y.L.; Guo, Y.; Yuen, C. 2-Bit RIS prototyping enhancing rapid-response space-time wavefront manipulation for wireless communication: Experimental studies. *IEEE Open J. Commun. Soc.* **2024**, *5*, 4885–4901. [\[CrossRef\]](#)
15. Yang, Z.; Ge, Y.; Zhao, Y.; Fang, Y.; Guan, Y.L. Protograph LDPC code and shaped index modulation design for multi-mode OAM systems. *IEEE Trans. Commun.* **2024**, *72*, 5162–5178. [\[CrossRef\]](#)
16. Zhao, Y.; Wang, Z.; Lu, Y.; Guan, Y.L. Multimode OAM convergent transmission with co-divergent angle tailored by Airy wavefront. *IEEE Trans. Antennas Propag.* **2023**, *71*, 5256–5265. [\[CrossRef\]](#)
17. Chen, M.; Chen, R.; Zhao, Y.; Yang, Z.; Guan, Y.L. Index-modulation OAM detectors resistant to beam misalignment. *IEEE Trans. Veh. Technol.* **2024**, *73*, 2836–2841. [\[CrossRef\]](#)
18. Zhao, Y.; Guan, Y.L.; Ismail, A.M.; Ju, G.; Lin, D.; Lu, Y.; Yuen, C. Holographic-inspired meta-surfaces exploiting vortex beams for low-interference multipair IoT communications: From theory to prototype. *IEEE Internet Things J.* **2024**, *11*, 12660–12675. [\[CrossRef\]](#)
19. Zhu, Q.B.; Jiang, T.; Qu, D.M.; Chen, D.; Zhou, N.R. Radio vortex multiple-input multiple-output communication systems with high capacity. *IEEE Access* **2015**, *3*, 2456–2464. [\[CrossRef\]](#)
20. Tamburini, F.; Mari, E.; Sponselli, A.; Thidé, B.; Bianchini, A.; Romanato, F. Encoding many channels on the same frequency through radio vorticity: First experimental test. *New J. Phys.* **2012**, *14*, 033001. [\[CrossRef\]](#)
21. Tamburini, F.; Mari, E.; Parisi, G.; Spinello, F.; Oldoni, M.; Ravanelli, R.A.; Coassini, P.; Someda, C.G.; Thidé, B.; Romanato, F. Tripling the capacity of a point-to-point radio link by using electromagnetic vortices. *Radio Sci.* **2015**, *50*, 501–508. [\[CrossRef\]](#)
22. Yan, Y.; Li, L.; Zhao, Z.; Xie, G.; Wang, Z.; Ren, Y.; Ahmed, N.; Sajuyigbe, S.; Talwar, S.; Tur, M.; et al. 32-Gbit/s 60-GHz millimeter-wave wireless communication using orbital angular momentum and polarization multiplexing. In Proceedings of the 2016 IEEE International Conference on Communications Workshops (ICC Workshops), Kuala Lumpur, Malaysia, 22–27 May 2016; pp. 1–6.
23. Zhang, W.; Zheng, S.; Hui, X.; Dong, R.; Jin, X.; Chi, H.; Zhang, X. Mode Division Multiplexing Communication Using Microwave Orbital Angular Momentum: An Experimental Study. *IEEE Trans. Wirel. Commun.* **2017**, *16*, 1308–1318. [\[CrossRef\]](#)
24. Gaffoglio, R.; Cagliero, A.; Vita, A.D.; Sacco, B. OAM multiple transmission using uniform circular arrays: Numerical modeling and experimental verification with two digital television signals. *Radio Sci.* **2016**, *51*, 645–658. [\[CrossRef\]](#)
25. Zhao, Y.; Guan, Y.L.; Chen, D.; Ismail, A.M.; Ma, X.; Liu, X.; Yuen, C. Exploring RCS diversity with novel OAM beams without energy void: An experimental study. *IEEE Trans. Veh. Technol.* **2025**, *74*, 8321–8326. [\[CrossRef\]](#)
26. Zhao, Y.; Zhang, C. Compound angular lens for radio orbital angular momentum coaxial separation and convergence. *IEEE Antennas Wirel. Propag. Lett.* **2019**, *18*, 2160–2164. [\[CrossRef\]](#)
27. Zhao, Y.; Zhang, C. Orbital angular momentum beamforming for index modulation with partial arc reception. *Electron. Lett.* **2019**, *55*, 1271–1273. [\[CrossRef\]](#)
28. Zhang, C.; Zhao, Y. Orbital angular momentum nondegenerate index mapping for long distance transmission. *IEEE Trans. Wirel. Commun.* **2019**, *18*, 5027–5036. [\[CrossRef\]](#)
29. Yao, Y.; Liang, X.; Zhu, W.; Geng, J.; Jin, R. Experiments of Orbital Angular Momentum Phase Properties for Long-Distance Transmission. *IEEE Access* **2019**, *7*, 62689–62694. [\[CrossRef\]](#)
30. Yagi, Y.; Sasaki, H.; Yamada, T.; Lee, D. 200 Gb/s Wireless Transmission Using Dual-Polarized OAM-MIMO Multiplexing with Uniform Circular Array on 28 GHz Band. *IEEE Trans. Antennas Propag.* **2021**, *20*, 833–837. [\[CrossRef\]](#)
31. Yagi, Y.; Sasaki, H.; Lee, D. Prototyping of 40 GHz Band Orbital Angular Momentum Multiplexing System and Evaluation of Field Wireless Transmission Experiments. *IEEE Access* **2022**, *10*, 130040–130047. [\[CrossRef\]](#)
32. Sasaki, H.; Yagi, Y.; Kudo, R.; Lee, D. 1.58 Tbps OAM Multiplexing Wireless Transmission with Wideband Butler Matrix for Sub-THz Band. *IEEE J. Sel. Areas Commun.* **2024**, *42*, 1613–1625. [\[CrossRef\]](#)

33. Thidé, B.; Then, H.; Sjöholm, J.; Palmer, K.; Bergman, J.; Carozzi, T.D.; Istomin, Y.N.; Ibragimov, N.H.; Khamitova, R. Utilization of photon orbital angular momentum in the low-frequency radio domain. *Phys. Rev. Lett.* **2007**, *99*, 087701. [[CrossRef](#)] [[PubMed](#)]
34. Mohammadi, S.M.; Daldorff, L.K.S.; Bergman, J.E.S.; Karlsson, R.L.; Thidé, B.; Forozesh, K.; Carozzi, T.D.; Isham, B. Orbital angular momentum in radio-A system study. *IEEE Trans. Antennas Propag.* **2010**, *58*, 565–572. [[CrossRef](#)]
35. Zhao, Y.; Zhang, C. Distributed Antennas Scheme for Orbital Angular Momentum Long Distance Transmission. *IEEE Antennas Wirel. Propag. Lett.* **2020**, *19*, 332–336. [[CrossRef](#)]
36. Yao, Y.; Liang, X.; Zhu, M.; Zhu, W.; Geng, J.; Jin, R. Analysis and experiments on reflection and refraction of orbital angular momentum waves. *IEEE Trans. Antennas Propag.* **2019**, *67*, 2085–2094. [[CrossRef](#)]
37. Meng, Y.; Yi, J.; Nawaz, B.S.; Lei, K.; Zhang, H.; Werner, D.H. Phase-modulation based transmitarray convergence lens for vortex wave carrying orbital angular momentum. *Opt. Express* **2018**, *26*, 22019–22029. [[CrossRef](#)]
38. Wu, Q.; Jiang, X.; Zhang, C. Attenuation of Orbital Angular Momentum Beam Transmission with Parabolic Antenna. *IEEE Antennas Wirel. Propag. Lett.* **2021**, *20*, 1849–1853. [[CrossRef](#)]
39. Wu, Q.; Zhang, C. OAM backhaul link supporting 1 Tbps over 1 km transmission based on Cassegrain antenna. *IEEE Trans. Wirel. Commun.* **2025**, *73*, 4829–4839. [[CrossRef](#)]
40. Zhang, C.; Jiang, J. Euclidean space with orbital angular momentum. In Proceedings of the 2019 IEEE International Conference on Communications Workshops (ICC Workshops), Shanghai, China, 20–24 May 2019; pp. 1–6.
41. Zhang, C.; Jiang, X.; Zhao, Y. Efficient instantaneous channel propagation modeling for aeronautical communications systems with compressed sensing. *IEEE Trans. Antennas Propag.* **2022**, *70*, 1211–1220. [[CrossRef](#)]

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