Mode Selection in Mode Division Multiple Access System for In Building Solution in Mobile Networks

Ahmed S. Mohamed[1], and Eszter Udvary[1, 2]

***Abstract*—This paper introduces the application of Mode Division Multiple Access (MDMA) in the context of In-Building Solutions (IBS) for mobile networks. The study showcases the successful generation and selection of light modes which are then efficiently multiplexed and demultiplexed at the Remote Radio Unit (RRU) end. Despite the proven operational capabilities, the findings reveal a decline in signal quality as the distance increases, thus limiting the use of MDMA for long-distance fronthaul applications. The proposed system also simplifies the RRU by centralizing key functionalities at the Central Office (CO), potentially reducing costs and the operational expenses (OPEX/CAPEX) associated with in- building solutions and other mobile network deployments. This work extends previous research and paves the way for future studies, particularly in the application of the Power over Fiber (PWoF) approach to reduce RRU complexities further.**

***Index Terms*—In-Building Solutions, Mode Division Multiplexing, Spatial Laser Modulator**

I . INTRODUCTION

As LTE networks become increasingly common, there's a growing interest in Centralized Radio Access Networks, or CRANs. These networks are appealing because they can significantly lower both operational and initial costs. In a CRAN configuration, the system is divided into the baseband unit (BBU) and the remote radio unit (RRU). Essentially, a centralized group of BBUs handles the intense baseband processing and manages control and oversight tasks for numerous RRUs. The connection between the RRUs and BBUs, known as the fronthaul, depends on the well-established Common Public Radio Interface (CPRI) standard to work effectively.[1].

To address the complex needs of 5G and 6G networks and their advanced antenna systems, experts are increasingly considering Wavelength Division Multiplexing (WDM) as a solution for transmitting CPRI data across fronthaul networks. WDM offers several advantages: it enhances network efficiency, supports various types of data seamlessly, and helps save energy. However, the main challenge is making this technology affordable and flexible, especially in relation to the remote radio unit (RRU) components of the network[1]. The expense tied to the lasers used in RRUs poses a significant challenge to the commercial feasibility of this technology[1].

[1] Department of Networked Systems and Services, Faculty of Electrical Engineering and Informatics Budapest University of Technology and Economics, Budapest, Hungary

[2] ELKH-BME Information Systems Research Group, Budapest, Hungary (e-mail: asayed@hit.bme.hu)

DOI: 10.36244/ICJ.2025.2.10

As the call for more transmission capacity grows, Mode-Division Multiplexing (MDM) is also gaining traction. MDM is being scrutinized for its capacity to manage swift optical transmissions and enhance access networks, potentially serving an expanding number of users [2][3], [4]. Notably, MDM systems are not restricted by wavelength demands, which is a major plus for network services that require non-specific wavelength capabilities. This characteristic could lead to substantial cost cuts for the RRUs[1]. Moreover, the multiple access technique plays a vital role for access networks. In classical mobile communication networks, various multiple access techniques have been standard, such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), and Orthogonal Frequency-Division Multiple Access (OFDMA). FDMA works by splitting the available bandwidth into several distinct frequency bands, each assigned to an individual user. TDMA, on the other hand, segments time into separate frames, which are further divided into slots, with each time slot allocated to a different user to enable multiple users to share the same frequency channel[5]. CDMA employs spread spectrum technology, where a pseudo-random code modulates the data signal, widening its bandwidth before it's transmitted over a carrier wave[6]. However, these traditional multiple access methods have limitations in terms of resource allocation and are unable to cater to the massive connectivity and high-volume requirements of 5G networks. As a result, there's a pressing need for innovative multiple access strategies that can fulfill the demands of next-generation mobile communications, which emphasize supporting a large number of concurrent users and connections[6]. Frequency, time, code, and space are all dimensions that can independently separate users in communication systems, offering distinct degrees of freedom for multiple access methods. For instance, CDMA exploits frequency, time, and code in conjunction to differentiate between users, giving it three degrees of freedom. In contrast to these traditional dimensions, optical modes present an additional degree of freedom for millimeter-wave communications[5][7].

Despite the fact that the traditional multiple access techniques mentioned above provide the air interface to the end users devices in mobile networks, this paper introduces and explores a different multiple access strategy for millimeter-wave communication systems, a strategy that leverages the orthogonality and high dimensionality of optical modes where the access units here are the RRUs. The main contribution presented herein is the proposed adaptation of contribution presented herein is the proposed adaptation of the Mode Division Multiple Access (MDMA) scheme, which utilizes the spatial characteristics of optical modes for multi-antenna millimeter-wave communication systems based on Mode Division Multiplexing (MDM). It is demonstrated that the use of optical modes as a new degree of freedom has the potential to significantly enhance the capacity and spectral efficiency of communication systems, with a particular advantage for In-Building Solutions (IBS). Moreover, this paper shows that a bidirectional MDM transmission system that centralizes the generation and excitation of modes at the point of transmission origin can streamline the design of Remote Radio Units (RRUs), potentially making them less complex and more cost-effective to produce[1].

II. System Concept

MDM is recognized as a potent method that has the potential to vastly expand transmission capacities within high-speed optical data transport and access networks, thereby enabling the support of considerably expanded user bases[2] . MDM technique is distinct from conventional methods that use single-mode fibers (SMF), which transmit a single data stream, and multimode fibers (MMF), which have less control over the transmitted signals. MDM utilizes the orthogonal properties of light modes to create multiple independent data channels within a single fiber, offering a stark contrast to wavelength-based multiplexing techniques such as Coarse and Dense Wavelength Division Multiplexing (CWDM and DWDM), which segregate channels by different wavelengths of light. [1]. While multimode fibers (MMFs) have the theoretical capability to support numerous modes and thereby enhance capacity, their practical application over extended distances is limited due to issues like crosstalk, where there is unwanted energy transfer between modes, and modal dispersion, which can cause signal distortion[8] . These issues compromise the integrity of the signal, which can result in a high Bit Error Rate (BER). Consequently, this substantially restricts the bandwidth-distance product, a measure of the data-carrying capacity of the fiber over a given distance. [8]. To address these challenges, Few Mode Fibers (FMFs) have been introduced. They are engineered with a core size that is intermediate between that of Single Mode Fibers (SMFs) and Multimode Fibers (MMFs), allowing FMFs to support a finite, manageable number of modes. This innovation curtails crosstalk and improves signal clarity, rendering FMFs a more viable option for long-distance communication[9].

Expanding on MDM, MDMA further improves network adaptability. In an MDMA framework, distinct modes are allocated to different remote devices RRUs. This method sets up separate transmission paths within the same optical fiber, thus achieving a level of physical layer isolation. [10]. A solitary FMF linking the Central Office (CO) to various Remote Radio Units (RRUs) is capable of sustaining numerous dedicated channels. This configuration presents an effective IBS, equipped with ample capacity to cater to multiple RRUs simultaneously.

Although MDM and MDMA offer considerable benefits, its full-scale commercial deployment encounters various hurdles. The technologies for effectively multiplexing and demultiplexing light modes are still in the developmental phase and require additional enhancements to achieve peak functionality [1]. Furthermore, to address issues such as crosstalk and modal dispersion, there is often a need to implement sophisticated Digital Signal Processing (DSP) methods. While these DSP techniques are potent, they have the potential to add to the system's intricacy [11][12].

A bidirectional and symmetrical MDM system with MDMA as the multiple access technique that is designed for high-speed mobile fronthaul applications, is proposed. For simplicity, the system under consideration involves a single CO and two RRUs, necessitating the use of four spatial modes, two modes for the downlinks and the other for the uplinks. The transmission of the downlink RF signal is facilitated by the first two modes, while the transmission of an unmodulated carrier from the Baseband Unit (BBU) pool is carried out by the second two modes. At the RRU, the carrier is received and modulated with the uplink RF signal. This method centralizes mode generation, thereby reducing the complexity and cost of the RRU by obviating the need for costly laser components. Crosstalk issues, often encountered in wavelength-reuse schemes, are minimized by this design, which enables symmetrical bidirectional transmission [1]. Figure 1 shows the system's concept structure, featuring the paths for the carrier, the RF/Downlinks, and the RF/Uplinks. At the CO, four optical modes are generated and sent to the RRU through an FMF. The modes designated for downlinks are then picked up at the RRU, where they are filtered, and the Radio Frequency (RF) signals are dispatched to their respective antennas. Conversely, the RF signals for uplinks, collected by the antennas, undergo filtering and amplification before modulating the latter two optical modes, which initially act as carriers. These modulated modes are subsequently merged back into the FMF via one or more circulators back to the CO.

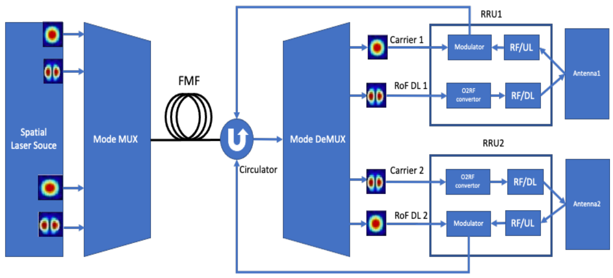

Fig. 1. System Concept

Beyond centralizing mode generation to simplify the RRU design, incorporating a PWoF solution could offer additional advantages. By delivering both power and data through the same optical fiber, PWoF eliminates the need for separate electrical infrastructure at the RRU site [13]. This approach is particularly valuable in scenarios where space or access to power is limited, such as in-building or remote installations. As this technology continues to mature, integrating PWoF into MDMA-based systems could lead to more compact, energy-efficient, and cost-effective fronthaul architectures [14].

III. Simulation and Modelling

The modeling of the system was carried out on 400m FMF utilizing the VPI Photonics simulation environment. This platform is esteemed for its extensive use in crafting and examining designs in the fields of integrated photonics, fiber optics, optoelectronic components, and optical transmission systems. It served as the principal tool in simulating the intricate details of our photonic system.

A. FMF Modelling

In MDM systems that utilize FMFs, unlike in conventional multimode fibers (MMFs) where mode excitation is a spontaneous process, a high degree of precision is required to govern the excitation of specific types and numbers of modes. This careful control over mode excitation is critical to achieve optimal transmission properties before the modes are coupled into the FMF. [1][15]. As previously stated, our proposal includes the use of an FMF that is designed to support four modes. The selection of the FMF's core diameter was determined by applying the natural frequency formula, considering the refractive indices of both the core and the cladding materials that are found in commercially available fibers [1] [16]. This analysis led to the selection of a fiber with a core diameter of 20 µm, which is not commercially available but can be ordered for customized research purposes like this study [17]. Various mode selection techniques have been developed by researchers to establish this level of control. [18]–[21]. The parameters of the Few Mode Fiber (FMF) utilized in the simulation were meticulously defined, drawing upon the mathematical calculations expounded in the preceding section. The excitation of the designated number of modes within the simulated FMF was confirmed. As shown in Figure 2, the simulation results affirm the precision of our theoretical model, demonstrating that a 20µm fiber supports four modes.

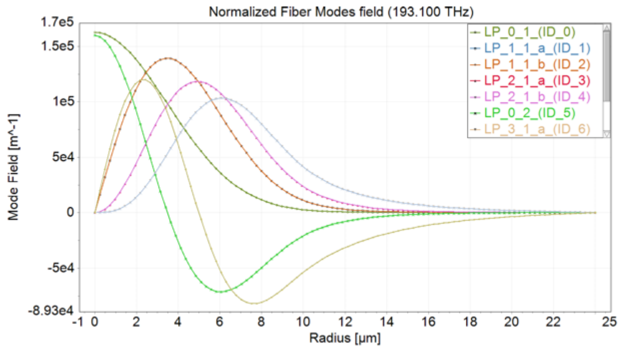

Fig. 2. Excited modes

B. Mux/DeMux

The task of effectively multiplexing and demultiplexing light modes continues to be a dynamic field of study. [1]. Photonic lanterns are especially distinguished among the various strategies suggested for multiplexing and demultiplexing in MDM due to their structural simplicity. [22]. In this method, a specific quantity of Single Mode Fibers (SMFs), each featuring unique core and cladding dimensions, are fine-tuned to align with the required mode number. These altered SMFs are collectively encased within a single sheath and undergo a meticulous tapering process, induced by controlled heating, to meet the adiabatic criterion, thus creating a photonic lantern. Nonetheless, the slimmed-down core of the tapered SMF makes the light field of the guided mode more prone to escaping into the cladding. Given that the refractive index of the quartz sleeve is less than that of the SMF cladding, a novel waveguide structure emerges between the cladding of the tapered fiber and the quartz sleeve [22]. Figure 3 presents the conceptual design of photonic lanterns. In this configuration, a component with reciprocal functionality is utilized to multiplex (MUX) and demultiplex (DeMUX) the modes into and out of the FMF, with its parameters appropriately adjusted for the process.

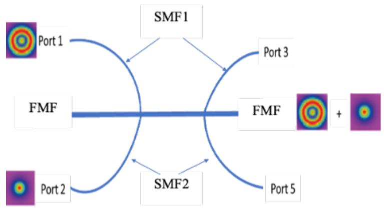

Fig. 3. Photonic Lanterns [22]

Within the simulation environment, the corresponding component named "CombinerSplitterMM" was utilized to emulate the photonic lanterns and to multiplex/demultiplex the modes within the FMF.

C. Modes Selection

In this configuration, we use a leading simulation software called VPI Photonics, which specializes in photonics design across integrated photonics, fiber optics, optoelectronics, and optical transmission systems. Spatial Light Modulators (SLM) are one of the simplest approaches used in modes selection where phase plates that have phase profiles match the targeted mode are used[15], [21].

The setup of this study consists of using laser sources equivalent to the number of modes. As mentioned in the previous section, a component named "CombinerSplitterMM" was utilized to emulate the photonic lanterns and to multiplex/demultiplex the modes within the FMF. To simulate SLM in the simulator, an equivalent component named "CouplerBeamMM" is used as the setup's SLM. By setting the suitable parameters, it was possible to select the higher order modes LP11a, LP21a and LP31a. On the other hand, the fourth mode of choice is LP01, as it is the fundamental mode, SLM is not required to generate it. Fundamental mode LP01 and the excited higher order modes are shown in Figure 4. The utilization of these four modes is mentioned in table 1 below.

TABLE I
Modes Utilization

Mode	Utilization
LP01	Downlink of RRU1
LP11a	Downlink of RRU2
LP21a	Uplink of RRU1
LP31a	Uplink of RRU2

Utilizing the MUX/DEMUX component in the simulator, four modes have been selected as the data channels. LP01 (Fundamental mode) and LP11a have been selected for the downlinks of RRU1 and RRU2 respectively. On the other hand, LP21a and LP31a have been selected for the uplinks. It was considered that each mode belongs to a different mode group to reduce the impact of the mode coupling that occurs during the propagation of these modes inside the FMF, Figure 4 shows the selected 4 modes and their initial powers.

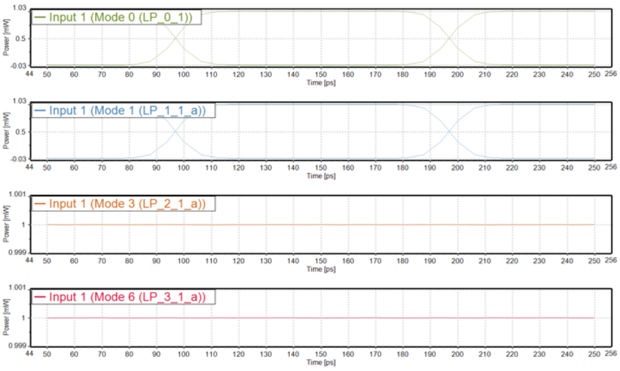

Fig. 4. Excited modes before launching them into the FMF at the CO side, LP01 and LP11a are modulated (Downlinks), LP21a and LP31a are carriers only (Uplinks)

D. Multiplexing Technique

The proposed setup considers Mode Division Multiplexing (MDM) as the multiplexing technique for the downlinks, where one mode carries the data towards its destination Remote Radio Unit (RRU). On the other hand, due to the bidirectional setup, the uplink modes suffer from a second round of mode coupling—a physical phenomenon that occurs during the propagation of light modes inside the fiber [1] — on their journey back to the Central Office (CO). To mitigate this impact, Mode Group Division Multiplexing (MGDM) has been selected as the multiplexing technique for the uplinks. Here, all coupled modes that belong to the same group are considered as a single data stream similar to the operating principle of the ordinary Multimode transmission systems.

IV. Results And Discussion

A. Crosstalk

While the use of FMF reduces crosstalk between modes [1], it remains a factor during light mode propagation along the transmission fiber. Crucially, no crosstalk is observed with the fundamental mode LP01, as it belongs to a distinct mode group. However, our simulation setup reveals crosstalk between the degenerate modes LP11a and LP11b, and as shown in Figures 5 and 6.

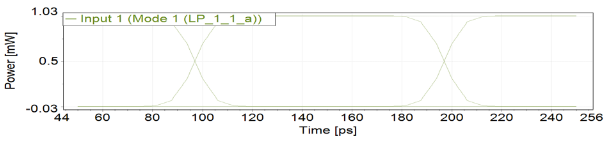

Fig. 5. Launched LP11a

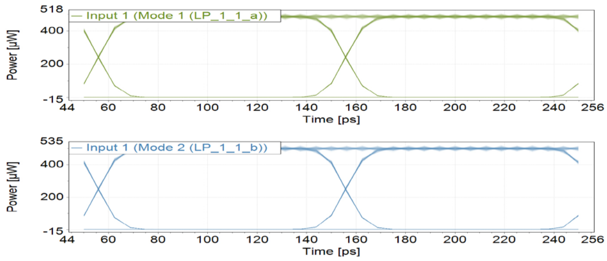

Fig. 6. Crosstalk between LP11a and LP11b

Moreover, severe crosstalk has been figured out in LP21a where its energy has been transferred to LP21b and LP02 and as shown in Figures 7 and 8.

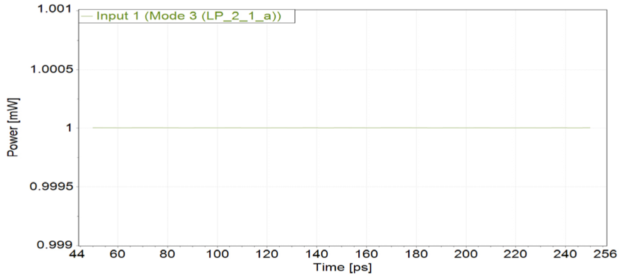

Fig. 7. Launched LP21a

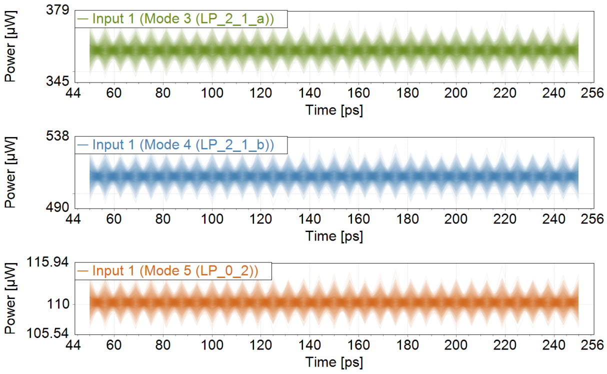

Fig. 8. Crosstalk between LP21a, LP21b, and LP02

For LP31a, higher energy transfer has been observed, energy has been transferred to LP31b, LP12a, and LP12b with more aggressive mode coupling impact and as shown in Figures 9 and 10.

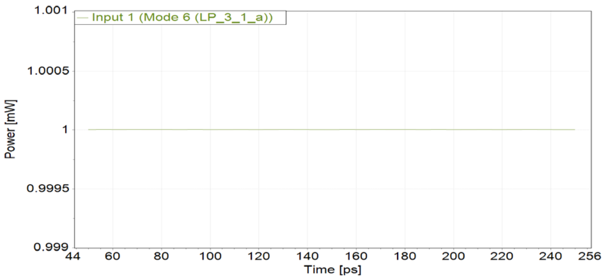

Fig. 9. Launched LP31a

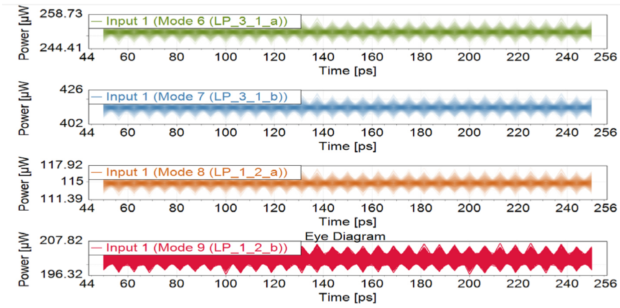

Fig. 10. Crosstalk between LP31a, LP31b, LP12a and LP12b

B. SLM Functionality

As mentioned in the previous sections, SLMs have been used for mode selection at the RRU side as a way to combat the crosstalk and ensure that only the mode of choice reaches its target destination, all other modes except the mode of choice are “filtered out”, even if they belong to a different mode group. Figure 11 below shows an example of the SLM functionality to filter the unneeded mode LP11b.

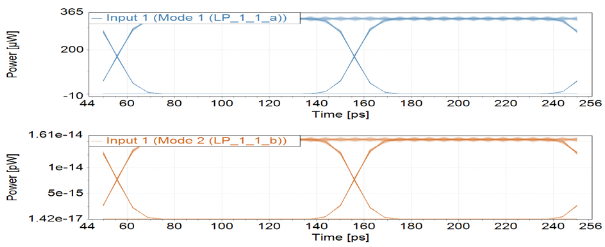

Fig. 11. SLM Functionality on LP11b

C. Analysis of the Eye Diagrams

Checking the obtained eye diagrams for the downlinks and the uplinks at 400m of fiber length, it is possible to say that adapting the concept of MDMA as a multiple access technique is feasible, the figures below show the obtained eye diagrams for the various links.

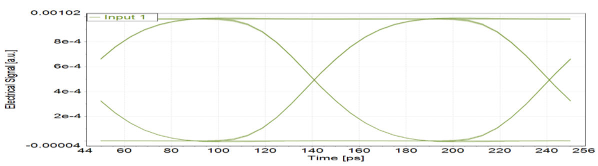

Fig. 12. RRU1 Downlink

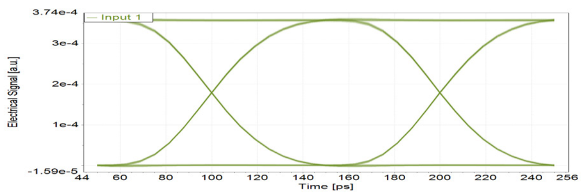

Fig. 13. RRU2 Downlink

The eye diagram openness indicates successful detection of the downlinks at the RRU side where high Optical Signal to Noise Ratio (OSNR) and low jitter are expected. Moreover, the implementation of MGDM shows promising results which can be expected with the obtained eye diagrams shown in the below figures.

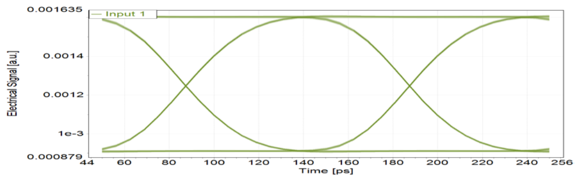

Fig. 14. RRU1 Uplink

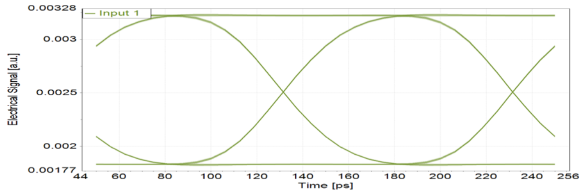

Fig. 15. RRU2 Uplink

V. CONCLUSION

In this study, we presented a proof of concept for using Mode Division Multiple Access (MDMA) as a viable alternative to the multiple access techniques available on the market. The modes were effectively generated and selected by the SLMs, after which they were multiplexed and demultiplexed on the RRU side. Furthermore, our proposed system can streamline RRU operations by centralizing the key mode generation process at the CO equipment. This paper shows the MDMA proof of concept through the simulation and analysis results and draws comparisons with our earlier works [1], [17], where the conceptual model and the behavior of the MDM system are elaborated. Additionally, we indicate that future research will explore reducing RRU complexities further by implementing the Power over Fiber (PWoF) approach.

VI. ACKNOWLEDGEMENT

The work has been supported by the National Research Development and Innovation Office (NKFIH) through the OTKA Grant K 142845.

REFERENCES

[1] A. S. Mohamed and E. Udvary, “Mode Division Multiplexing Bidirectional Transmission System using Double Clad Fiber for Mobile In-Building Solutions,” in *2023 46th International Conference on Telecommunications and Signal Processing (TSP)*, 2023, pp. 144–147. DOI: 10.1109/TSP59544.2023.10197803.

[2] K. Zou, K. Pang, H. Song, J. Fan, Z. Zhao, H. Song, R. Zhang, H. Zhou, A. Minoofar, C. Liu, X. Su, N. Hu, A. McClung, M. Torfeh, A. Arbabi, M. Tur, and A. E. Willner, “High-capacity free-space optical communications using wavelength- and mode-division-multiplexing in the mid-infrared region,” *Nat Commun*, vol. 13, no. 1, p. 7662, Dec. 2022. DOI: 10.1038/s41467-022-35327-w.

[3] J. Zhou, J. Wu, and Q. Hu, “Tunable arbitrary unitary transformer based on multiple sections of multicore fibers with phase control,” *Opt Express*, vol. 26, no. 3, p. 3020, Feb. 2018. DOI: 10.1364/oe.26.003020.

[4] R. Mercy Kingsta and R. Shantha Selvakumari, “A review on coupled and uncoupled multicore fibers for future ultra-high capacity optical communication,” *Optik (Stuttg)*, vol. 199, Dec. 2019. DOI: 10.1016/j.ijleo.2019.163341.

[5] P. Zhang, X. Xu, C. Dong, K. Niu, H. Liang, Z. Liang, X. Qin, M. Sun, H. Chen, N. Ma, W. Xu, G. Wang, and X. Tao, “Model division multiple access for semantic communications,” *Frontiers of Information Technology & Electronic Engineering*, vol. 24, no. 6, pp. 801–812, Jun. 2023. DOI: 10.1631/FITEE.2300196.

[6] L. Wang, F. Jiang, Z. Yuan, J. Yang, G. Gui, and H. Sari, "Mode division multiple access: a new scheme based on orbital angular momentum in millimetre wave communications for fifth generation," *IET Communications*, vol. 12, no. 12, pp. 1416–1421, Jul. 2018. DOI: 10.1049/iet-com.2017.1182.
[7] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, "Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes," *Phys Rev A (Coll Park)*, vol. 45, no. 11, p. 8185, 1992.
[8] M. Matsuura, A. Ikukawa, H. Kuboki, and Y. Kawamura, "Investigation of Crosstalk between Data Signals and Feed Light in Power-over-Fiber," *Photonics*, vol. 9, no. 6, p. 369, May 2022. DOI: 10.3390/photonics9060369.
[9] J. Yu, F. Tan, and C. Yu, "Few-Mode Fiber Characterization System Based on the Spatially and Spectrally Imaging Technique," *Sensors*, vol. 22, no. 5, p. 1809, Feb. 2022. DOI: 10.3390/s22051809.
[10] L. Wang, F. Jiang, Z. Yuan, J. Yang, G. Gui, and H. Sari, "Mode division multiple access: A new scheme based on orbital angular momentum in millimetre wave communications for fifth generation," *IET Communications*, vol. 12, no. 12, pp. 1416–1421, Jul. 2018. DOI: 10.1049/iet-com.2017.1182.
[11] R. Mercy Kingsta and R. Shantha Selvakumari, "A review on coupled and uncoupled multicore fibers for future ultra-high capacity optical communication," *Optik (Stuttg)*, vol. 199, Dec. 2019. DOI: 10.1016/j.ijleo.2019.163341.
[12] Y. Su, Y. He, H. Chen, X. Li, and G. Li, "Perspective on mode-division multiplexing," *Applied Physics Letters*, vol. 118, no. 20. American Institute of Physics Inc., 17-May-2021. DOI: 10.1063/5.0046071.
[13] V. Prajzler and M. Zikmund, "Power over fiber using a multimode optical power with a core diameter of 50 μm," *Opt Quantum Electron,* vol. 56, no. 8, p. 1307, Jul. 2024. DOI: 10.1007/s11082-024-07231-8.
[14] A. S. Mohamed and E. Udvary, "Enabling Enhanced In- Building Solutions Fronthaul Connectivity: The Role of Mode Division Multiple Access in Mobile Networks," in *2024 24th International Conference on Transparent Optical Networks (ICTON)*, 2024, pp. 1–5. DOI: 10.1109/ICTON62926.2024.10647457.
[15] K. Igarashi, D. Souma, T. Tsuritani, and I. Morita, "Performance evaluation of selective mode conversion based on phase plates for a 10-mode fiber," *Opt Express,* vol. 22, no. 17, p. 20881, Aug. 2014. DOI: 10.1364/oe.22.020881.
[16] F. A. Shnain and A. R. Salih, "Design and Study of Few- Mode Fibers at 1550 nm," *Journal of Educational and Scientific Studies*, vol. 18, no. 1, pp. 83–95, 2021.
[17] A. S. Mohamed and E. Udvary, "Modes selection in fronthaul Mode Division Multiplexing bidirectional transmission system for mobile In-building solutions," in *2nd Workshop on Intelligent Infocommunication Networks, Systems and Services*, Online, 2024, pp. 101–106. DOI: 10.3311/WINS2024-018.
[18] J. Carpenter, B. C. Thomsen, and T. D. Wilkinson, "Degenerate Mode-Group Division Multiplexing," *Journal of Lightwave Technology*, vol. 30, no. 24, pp. 3946–3952, Dec. 2012. DOI: 10.1109/JLT.2012.2206562.
[19] N. K. Fontaine, S. G. Leon-Saval, R. Ryf, J. R. Salazar Gil, B. Ercan, and J. Bland-Hawthorn, "Mode-Selective Dissimilar Fiber Photonic-Lantern Spatial Multiplexers for Few-Mode Fiber."
[20] J. von Hoyningen-Huene, R. Ryf, and P. Winzer, "LCoS- based mode shaper for few-mode fiber," *Opt Express,* vol. 21, no. 15, p. 18 097, Jul. 2013. DOI: 10.1364/OE.21.018097.
[21] W. Q. Thornburg, B. J. Corrado, and X. D. Zhu, "Selective launching of higher-order modes into an optical fiber with an optical phase shifter," *Opt Lett*, vol. 19, no. 7, p. 454, Apr. 1994. DOI: 10.1364/OL.19.000454.
[22] Z. Xuan, "A Research about Mode Multiplexing/Demultiplexing Technology," in *Proceedings of 2019 2nd World Symposium on Communication Engineering, WSCE* 2019, 2019, pp. 38–41. DOI: 10.1109/WSCE49000.2019.9040949.

Ahmed S. Mohamed received his B.Sc. from the university of Technology/ Iraq in 2007 and M.Sc. from the Universiti Utara Malaysia (UUM) in 2016. He is currently pursuing his PhD in Budapest University of Technology and Economics/Hungary in optical networks for mobile networks applications.

Eszter Udvary received her Ph.D. degree in electrical engineering from the Budapest University of Technology and Economics (BME), Budapest, Hungary, in 2009. She is currently an Associate Professor at BME, Mobile Communication and Quantum Technologies Laboratory. Dr. Udvary's research interests are in the broad area of optical communications, including microwave photonics, optical access network, visible light communication, and quantum communication.