Impact of fiber core diameter on dispersion and multiplexing in multimode-fiber links

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Abstract: Large-core silica multimode fibers, whose core diameters are generally 50 µm or 62.5 µm, form the bulk of short and medium haul optical fiber links in existence today, owing to their low cost and ease of deployment. However, modal dispersion significantly limits the maximum data rates that they support. Recently, the ability to multiplex several streams of data through optical fibers has spawned the development of few-mode multimode fibers. These fibers possess the low-dispersion characteristics of single-mode fibers and the ability to multiplex several data streams using multiple-input multiple-output (MIMO) techniques and mode-specific filtering to increase data rates. While fibers with larger core diameters possess a larger number of spatial modes, they do not support data rates as high as few-mode fibers. In this paper, we describe a simulation based approach to characterize the tradeoffs between fiber diameter, achievable data rates and alignment tolerances of coherent links that employ graded-index multimode fibers (MMFs) of various dimensions, using the information theoretic outage capacity as the metric. The simulations used fibers’ intermodal coupling characteristics to measure its multiplexing abilities and dispersion limitations with mode-specific filters and launch and detection spatial filter arrays. The simulations indicate that the bandwidth-length product achievable over few-mode fibers with MIMO techniques can exceed 250 Gb/s-km, while heavy mode spreading and limited mode selectivity limits the bandwidth-length product to under 25 Gb/s-km in fibers core diameters larger than 50 µm.

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References and links
1. E. Ip, A. P. T. Lau, D. J. Barros, and J. M. Kahn, “Coherent detection in optical fiber systems,” Opt. Express 16, 753–791 (2008).
2. C. R. Fludger, T. Duthel, D. Van den Borne, C. Schulien, E.-D. Schmidt, T. Wuth, J. Geyer, E. De Man, K. Giok-Djian, and H. de Waardt, “Coherent equalization and POLUMUX-RZ-DQPSK for robust 100-GE transmission,” J. Lightw. Technol. 26, 64–72 (2008).
3. S. Randel, R. Ryf, A. Sierra, P. J. Winzer, A. H. Gnauck, C. A. Bolle, R.-J. Essiambre, D. W. Peckham, A. McCurdy, and R. Lingle, “6× 56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6× 6 MIMO equalization,” Opt. Express 19, 16697–16707 (2011).
4. T. Hayashi, T. Tara, O. Shimakawa, T. Sasaki, and E. Sasaoka, “Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber;” Opt. Express 19, 16576–16592 (2011).
5. S. Jansen, I. Morita, and H. Tanaka, “10 × 121. 9-Gb/s PDM-OFDM Transmission with 2-b/s/Hz Spectral Efficiency over 1,000 km of SSMF;” in “Optical Fiber Communication Conference,” (Optical Society of America, 2008).
6. S. Jansen, I. Morita, and H. Tanaka, “16 × 52. 5-Gb/s, 50-GHz spaced, POLMUX-CO-OFDM transmission over 4,160 km of SSMF enabled by MIMO processing;” in “Optical Communication-Post-Deadline Papers (published 2008),” 2007 33rd European Conference and Exhibition of,” (VDE, 2007), pp. 1–2.
7. Y. Ma, Q. Yang, Y. Tang, S. Chen, and W. Shieh, “1-Tb/s Single-Channel Coherent Optical OFDM Transmission with Orthogonal-Band Multiplexing and Subwavelength Bandwidth Access;” J. Lightw. Technol. 28, 308–315 (2010).
8. W. Shieh, Q. Yang, and Y. Ma, “107 Gb/s Coherent Optical OFDM Transmission over 1000-km SSMF Fiber using Orthogonal Band Multiplexing;” Opt. Express 16, 6378–6386 (2008).
9. R. Ryf, S. Randel, A. Gnauck, C. Bolel, A. Essiambre, P. Winzer, D. Peckham, A. McCurdy, and R. Lingle, “Space-Division Multiplexing over 10 km of Three-Mode Fiber using Coherent 6 × 6 MIMO Processing;” in “Optical Fiber Communication Conference,” (Optical Society of America, 2011).
10. A. Li, A. Al Amin, X. Chen, and W. Shieh, “Reception of Mode and Polarization Multiplexed 107-Gb/s CO-OFDM Signal over a Two-Mode Fiber;” in “National Fiber Optic Engineer Conference,” (Optical Society of America, 2011).
11. R. Ryf, S. Randel, A. Gnauck, C. Bolel, A. Sierra, S. Mumtaz, M. Esmaeelpour, E. Burrows, R. Essiambre, P. Winzer, D. Peckham, A. McCurdy, and R. Lingle, “Mode-Division Multiplexing Over 96 km of Few-Mode Fiber Using Coherent 6 × 6 MIMO Processing;” J. Lightw. Technol. 30, 521–531 (2012).
12. M. Salsi, C. Koebele, D. Sperli, P. Tran, P. Brindel, H. Mardoyan, S. Bigo, A. Boutin, F. Verluise, P. Sillard, M. Astruc, L. Provost, F. Cerou, and G. Charlet, “Transmission at 2×100Gb/s, over Two Modes of 40km-long Prototype Few-Mode Fiber, using LCOS based Mode Multiplexer and Demultiplexer;” in “National Fiber Optic Engineers Conference;” (Optical Society of America, 2011).
13. J. Sakaguchi, Y. Awaji, N. Wada, A. Kanno, T. Kawanishi, T. Hayashi, T. Taru, T. Kobayashi, and M. Watanebe, “109-Tb/s (7x97x172-Gb/s SDM/WDM/PDM) QPSK Transmission through 16.8-km Homogeneous Multi-core Fiber;” in “Optical Fiber Communication Conference,” (Optical Society of America, 2011).
14. B. Lee, D. Kuchta, F. Doany, C. Schow, C. Baks, R. John, P. Pelpejegoski, T. Taunay, B. Zhu, M. Yan, G. Ould-ensen, D. Vaidya, W. Luo, and N. Li, “120-Gb/s 100-m transmission in a single multicore multimode fiber containing six cores interfaced with a matching VCSEL array;” in “Photonics Society Summer Topical Meeting Series, 2010 IEEE;” (IEEE, 2010), pp. 223–224.
15. B. Zhu, T. F. Taunay, M. F. Yan, J. M. Fini, M. Fishteyn, E. M. Monberg, and F. V. Dimarcello, “Seven-core Multicore Fiber Transmissions for Passive Optical Network;” Opt. Express 18, 11117–11122 (2010).
16. R. E. Freund, C.-A. Bunge, N. N. Ledentsov, D. Molin, and C. Caspar, “High-speed transmission in multimode fibers;” J. Lightw. Technol. 28, 569–586 (2010).
17. A. Hanner, “Iso/iec 11801;” in “Communications Cabling: EC’97:[proceedings of the EuroCable Conference 1997],” (IOS Press, 1997), p. 316.
18. J. Abbott, S. Bickham, P. Dainese, and M.-J. Li, “Fibers for Short-Distance Applications;” Optical Fiber Telecommunications Volume VIA: Components and Subsystems p. 243 (2013).
19. D. Klazovich, P. Bouvry, and S. U. Khan, “GreenCloud: a packet-level simulator of energy-aware cloud computing data centers;” The Journal of Supercomputing 62, 1263–1283 (2012).
20. H. R. Stuart, “Dispersive Multiplexing in Multimode Optical Fiber;” Science 289 (2000).
21. C. Tsekrekos, A. Martinez, F. Huijskens, and A. Koonen, “Mode Group Diversity Multiplexing Transceiver Design for Graded-Index Multimode Fibers;” in “Optical Communication, 2005. ECOC 2005. 31st European Conference on;” vol. 3 (IET, 2005), vol. 3, pp. 727–728.
22. C. Tsekrekos, A. Martinez, F. Huijskens, and A. Koonen, “Design Considerations for a Transparent Mode Group-Division-Multiplexing System With Optimized Joint Detection;” IEEE Photon. Technol. Lett. 18, 2359–2361 (2006).
23. H. Chen, H. van den Boom, and A. Koonen, “30-Gb/s 3 × 3 Optical Mode Group-Division-Multiplexing System With Optimized Joint Detection;” IEEE Photon. Technol. Lett. 23, 1283–1285 (2011).
24. L. Raddatz, I. White, D. Cunningham, and M. Nowell, “An experimental and theoretical study of the offset launch technique for the enhancement of the bandwidth of multimode fiber links;” J. Lightw. Technol. 16, 324 (1998).
25. B. Thomsen, “MIMO enabled 40 Gb/s transmission using mode division multiplexing in multimode fiber;” in “Optical Fiber Communication Conference,” (IEEE, 2010), pp. 1–3.
26. K. Appiah, S. Vishwanath, and S. R. Bank, “Advanced Modulation and Multiple-Input Multiple-Output Multimode Fiber Links;” IEEE Photon. Technol. Lett. 23, 1424–1426 (2011).
27. N. Bikhazi, M. Jensen, and A. Anderson, “MIMO Signaling over the MMF Optical Broadcast Channel with Square-law Detection;” IEEE Trans. Commun. 57, 614–617 (2009).
28. A. R. Shah, R. C. J. Hsu, A. Tarighat, A. H. Sayed, and B. Jalali, “Coherent Optical MIMO (COMIMO);” J. Lightw. Technol. 23 (2005).
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1. Introduction

The advent of optical fiber communication has enabled the transmission of large amounts of data at speeds exceeding terabits-per-second over communication networks over the past few decades. The development of optical fiber technology has revolutionized telecommunications, enabling high-speed data transmission across significant distances. This technology has been critical in the growth of the internet, enabling the seamless transmission of information across the globe.

29. A. Tarighat, R. C. Hsu, A. Shah, A. H. Sayed, and B. Jalali, “Fundamentals and challenges of optical-multiple-input multiple-output multimode fiber links [Topics in Optical Communications],” IEEE Commun. Mag. 45, 57–63 (2007).
30. W. Shieh and C. Athaudage, “Coherent Optical Orthogonal Frequency Division Multiplexing,” Electronics Letters 42 (2006).
31. R. C. Hsu, A. Tarighat, A. Shah, A. H. Sayed, and B. Jalali, “Capacity enhancement in coherent optical mimo (comimo) multimode fiber links,” IEEE Commun. Lett. 10, 195–197 (2006).
32. I. Mollers, D. Jager, R. Gaudino, A. Nocivelli, H. Kragl, O. Ziemann, N. Weber, T. Koonen, C. Lezzi, A. Bluschke, and S. Randel, “Plastic optical fiber technology for reliable home networking: Overview and results of the EU project pof-all,” IEEE Commun. Mag. 47, 58–68 (2009).
33. G. Yahre, “Influence of core diameter on the 3-dB bandwidth of graded-index optical fibers,” J. Lightw. Technol. 18, 668 (2000).
34. I. Gasulla and J. Capmany, “Transfer function of multimode fiber links using an electric field propagation model: Application to Radio over Fibre Systems,” Opt. Express 14, 9051–9070 (2006).
35. J. Siuzdak and G. Stepniak, “Influence of modal filtering on the bandwidth of multimode optical fibers,” Optica Applicata 37, 31 (2007).
36. H. Mrabet, I. Dayoub, R. Attia, and W. Hamouda, “Wavelength and beam launching effects on silica optical fiber in local area networks,” Optics Communications 283, 4234–4241 (2010).
37. G. P. Agrawal, Fiber-Optic Communication Systems (Wiley, 1997).
38. D. Marcuse, Light Transmission Optics (Van Nostrand Reinhold New York, 1982).
39. M. Shemirani, W. Mao, R. Panicker, and J. Kahn, “Principal Modes in Graded-Index Multimode Fiber in Presence of Spatial and Polarization-Mode Coupling,” J. Lightw. Technol. 27, 1248–1261 (2009).
40. K. Ho and J. Kahn, “Mode-dependent Goss and Gain: Statistics and Effect on Mode-division Multiplexing,” Opt. Express 19, 16661–16635 (2011).
41. D. Tse and P. Viswanath, Fundamentals of Wireless Communication (Cambridge Univ Press, 2005).
42. K. Appiah, S. Zisman, S. Vishwanath, and S. R. Bank, “Analysis of Laser and Detector Placement in MIMO Multimode Optical Fiber Systems,” in “Communications (ICC), 2012 IEEE International Conference on,” (IEEE, 2012), pp. 2972–2976.
43. S. Shaklan, “Selective mode injection and observation for few-mode fiber optics,” Applied optics 30, 4379–4383 (1991).
44. B. Zhu, T. Taunay, M. Fishteyn, X. Liu, S. Chandrasekhar, M. Yan, J. Fini, E. Monberg, and F. Dimarcello, “112-Tb/s space-division multiplexed DWDM transmission with 14-b/s/Hz aggregate spectral efficiency over a 76.8-km seven-core fiber,” Opt. Express 19, 16665–16671 (2011).
45. J. Siuzdak, “RF carrier frequency selection for incoherent MIMO transmission over MM fibers,” J. Lightw. Technol. 27, 4960–4963 (2009).
46. E. Jones, T. Oliphant, and P. Peterson, “SciPy: Open source scientific tools for Python,” (2001–).
47. X. Shen, J. Kahn, and M. Horowitz, “Compensation for Multimode Fiber Dispersion by Adaptive Optics,” Opt. Letters 30, 2985–2987 (2005).
48. E. Zeeb, B. Moller, C. Reiner, M. Ries, T. Hackbarth, and K. Ebeling, “Planar Proton implanted VCSEL’s and Fiber-Coupled 2-D VCSEL Arrays,” Selected Topics in Quantum Electronics, IEEE Journal of 1, 616–623 (1995).
49. L. Tang and D. Miller, “Metallic Nanodevices for Chip-scale Optical Interconnects,” Journal of Nanophotonics 3, 030302 (2009).
50. J. Heinrich, E. Zeeb, and K. Ebeling, “Butt-coupling efficiency of VCSELs into multimode fibers,” IEEE Photon. Technol. Lett. 9, 1555–1557 (1997).
51. C. Cryan, “Two-dimensional multimode fibre array for optical interconnects,” Electronics Letters 34, 586–587 (1998).
52. D. Lenz, B. Rankov, D. Erni, W. Bachtold, and A. Wittneben, “Mimo channel for modal multiplexing in highly overmoded optical waveguides,” in “Communications, 2004 International Zurich Seminar on,” (IEEE, 2004), pp. 196–199.
53. J. W. Goodman and E. G. Rawson, “Statistics of modal noise in fibers: a case of constrained speckle,” Opt. Letters 6, 324–326 (1981).
54. K. O. Hill, Y. Tremblay, and B. S. Kawasaki, “Modal noise in multimode fiber links: theory and experiment,” Opt. Letters 5, 270–272 (1980).
55. R. A. Panicker, J. P. Wilde, J. M. Kahn, D. F. Welch, and I. Lyubomirsky, “10× 10 Gb/s DWDM transmission through 2.2-km multimode fiber using adaptive optics,” IEEE Photon. Technol. Lett. 19, 1154–1156 (2007).
decades. While technologies such as wavelength division multiplexing (WDM) have enabled these speed increases, the constantly growing demand for supporting higher data rates requires new approaches to complement existing techniques. Recent developments in fiber optics have enabled the use of coherent detection [1] along with polarization multiplexing over single-mode fibers (SMFs) [2] to enhance data rates over SMFs. However, to increase achievable data rates to beyond the limits of SMFs, multiplexing through multimode fibers using multiple-input multiple-output (MIMO) signal processing techniques has been studied as a scalable approach. In addition to conventional multimode fibers, modern fiber media such as few-mode fibers [3] and multicore fibers [4] have been developed with the aim of making fibers effective for multiplexing. While several theoretical and experimental studies have shown the benefits of using multimode fiber media, the impact of fiber geometry on multiplexing has yet to be characterized. In this paper, we develop a simulation model that characterizes multiplexing benefits in graded-index multimode fibers of various diameters, and analyze the impact of system parameters such as spatial mode filters or laser/detector arrays on the fiber’s data carrying capacity. By matching the model parameters to recently reported experimental data, we simulate the variation of outage capacity of the fiber link with fiber diameter, axial launching and detection in the fiber, and laser/detector properties.

The use of MIMO techniques is not restricted to MMFs. MIMO implementations in SMFs have been realized using polarization diversity [5, 6] and orthogonal band multiplexing [7, 8]. However, the focus of this paper is restricted to spatial multiplexing over the modes of silica multimode fibers. Prior research on multiplexing based approaches in MMFs can be categorized into two types: one that involves modern fibers that are designed for multiplexing, and the other that uses conventional (large-core) multimode fibers that are used over shorter lengths. Few-mode fibers (FMFs) are multimode fibers whose diameters are made marginally larger than single-mode fibers to permit few (generally 2 or 3) spatial modes. With the additional overlay of polarization multiplexing, experiments have revealed a six-fold increase over SMFs in data transmission rates using few-mode fibers [9–11]. Launching and detection of signals into these fibers is generally achieved using mode-specific filters [12]. In general, the high bandwidths transmitted through these fibers is enabled by using appropriate pulse shaping, modulation and signal processing techniques [13]. Multicore fibers are also designed with similar aims, although they generally consist of several cores, each of which permit parallel data transmission with little or no cross-channel interference [14, 15].

While modern fiber media is effective for multiplexing, most currently deployed short and medium haul fiber consists of conventional large-core multimode fiber (OM1, OM2, OM3 and OM4), whose core diameter is generally 50 µm or 62.5 µm [16–18]. In addition, ease of deployment and high tolerance to offset alignments makes them an attractive and low-cost choice for short-haul links, such as data centers [19]. Thus, enhancing the speeds achievable through such fiber links whose lengths range from 10 m to a few km is significant for existing legacy fiber links as well as new fiber-optic networks. The application of MIMO techniques to these fibers was first demonstrated by Stuart [20], albeit at modest data rates. Subsequent considerations of MIMO techniques on conventional MMFs have taken one of two approaches: (1) using intensity modulation and incoherent detection and (2) using coherent detection. MMF based multiplexing approaches that use intensity modulation generally use mode group diversity multiplexing [21–23] or a similar mode-multiplexing approach [24–26]. The inherent non-linearity in the detection process in incoherent MMF links limits their capacity. Moreover, for longer fiber links, the interactions between fiber modes is complicated to model with square-law detection, thereby complicating capacity analysis [27]. Most modern multimode fiber links employ coherent detection, since such an approach offers better receiver sensitivity and more robustness to nonlinearities [28–30]. Moreover, mode interactions can be considered to be lin-
ear with coherent detection, thus allowing us to build a model to predict the capacity of MMF links accurately [31]. Thus, we restrict our study to coherent MIMO-MMF links in this paper.

In this paper, we restrict our study to graded-index silica multimode fibers, since the propagation properties for plastic fibers differ significantly from silica fibers, and would necessitate the use of different propagation models [32]. Prior studies on the variations in fiber performance based on fiber core diameter has generally been restricted to cases that involve incoherent modulation and single streams, as opposed to multiplexing [33]. The influence of axial offset launching and mode filtering on different multimode fibers has been studied in detail albeit in the context of incoherent detection [34–36]. The influence of the geometry of the fiber itself, as well as the launching and detection conditions, particularly in the case of modern, coherent MMF links, has yet to be characterized. In this paper, we use a simulation based approach to predict and study the impact of fiber and laser and detector dimensions. A schematic of the system model we employed is shown in Fig. 1. In particular, we characterize the effect of core diameter, mode filtering and tolerance to offsets for multimode fibers using simulations. Although our analysis is restricted to graded-index MMFs, we expect similar performance trends when step-index MMFs are used. While step-index fibers have a larger number of modes for the same core diameter, the larger group-delay dispersion limits data rates to lower values, when compared to graded-index MMFs.

The rest of this paper is organized as follows: Section 2 discusses the propagation characteristics of silica multimode fibers of various diameters. Section 3 describes the propagation model used in our simulator. Section 4 describes the information theoretic metrics used to characterize coherent MMF links. Section 5 describes the scenarios simulated in the paper, and the results of these simulations. Section 6 discusses some of the results from the simulations. Finally, Section 7 summarizes the results and indicates future research topics.

2. Properties of fiber modes

Propagation of signals through a multimode fibers is restricted to a finite set of modes. The modes of the fiber arise naturally, as a consequence to the boundary conditions imposed by the dielectric boundary condition at the interface of the fiber core and cladding [37]. Modes of a waveguide possess two distinguishing characteristics that determine their impact on signal propagation: their spatial footprint across the waveguide crosssection, and their group delay. While these are well studied effects, this section briefly describes the mode properties that are
pertinent to the fiber models discussed in this paper.

The modes of an optical fiber are obtained by solving the Helmholtz wave equation under appropriate boundary conditions. With commonly used approximations for graded-index MMFs, it can be shown that the Laguerre-Gaussian field distributions form solution sets to describe these modes [38]. The simulations in this paper use the Laguerre-Gaussian polynomials, although the results do not vary significantly with the Hermite-Gaussian solution system that is used in [39]. Fig. 2 shows the spatial profile of some Laguerre-Gaussian fiber modes that propagate in multimode fibers. Therefore, any signal that propagates through the fiber can be expressed as an appropriate linear combination of the fiber modes with complex coefficients. Thus, a vector that contains the coefficients of each mode characterizes the propagating signal at any point in the fiber. This is referred to as “mode vector”.

In addition to the modes’ spatial properties, different modes have different temporal propagation properties, since the effective refractive indices seen by each mode can differ slightly. This variation of the delays introduced by the various modes accrues over the length of the fiber, and this collective dispersive effect diminishes the data rate that the fiber can support. In subsequent sections, we analyze the impact of this modal delay spread on the data rate as a function of fiber core size and the selectivity of mode excitation.

3. Propagation model

This section briefly discusses the propagation model used for the fiber modeling and simulations discussed in this paper.

Since all fibers considered in this paper are multimode fibers, we can represent the signal propagating within the fiber by means of a vector in the basis of propagation modes. Suppose that the fiber has $M$ propagating modes. Then the propagating signal at a distance $l$ from the launch position can be represented for the $x$ and $y$ polarizations using the complex mode vectors $\mathbf{b}_x$ and $\mathbf{b}_y$ as:

![Fig. 3. A representation of various sections of the fiber. The channel variations due to bends and twists are assumed to be aggregated over these sections to determine channel conditions.](image)

![Fig. 4. The physical effects that cause intermodal coupling along each fiber section.](image)
where $b_{ix}$ and $b_{iy}$ are the amplitudes of the $i$-th mode with $x$ and $y$ polarized vector respectively.

To compute the net transfer function of the fiber, it is necessary to characterize the evolution of the $b_{ix}$ and $b_{iy}$ along the length of the fiber. As discussed in [38], the evolution of $b_{ix}$ and $b_{iy}$ can be described using coupled mode theory. In this paper, we approximate the mode coupling within the fiber by a concatenation of ideal fiber sections that undergo “block” mode coupling. Such an approach permits a finite-element approach to evaluate the fiber channel properties. A representation of this approximation is shown in Fig. 3.

Within each fiber section, we model the transformation of the vectors $b_x$ and $b_y$ using a matrix multiplication, with the individual effects shown in Fig. 4. For instance, if the section length is $\delta l$, then the transformation effected within the $i$-th section can be described as

$$
\begin{bmatrix}
    b_{x}(l + \delta l) \\
    b_{y}(l + \delta l)
\end{bmatrix} = U_i \begin{bmatrix}
    b_{x}(l) \\
    b_{y}(l)
\end{bmatrix}
$$

where $U_i$ is a $2M \times 2M$ matrix that encapsulates the modal transformations effected by the fiber section, including mode-dependent losses. With this formulation, the combined modal transformation effected by $N$ consecutive fiber section can be captured by the $2M \times 2M$ matrix $U_{total}$, given by

$$
U_{total} = U_N U_{N-1} \cdots U_2 U_1
$$

Thus, modeling $U_i$ matrices based on fiber properties allows us to calculate the aggregate spatio-temporal properties of the fiber channel. This formulation can be used to model and simulate the impact of channel variations on data rates achievable through the fiber. For an ideal fiber, the modes of the fiber modes would propagate without coupling with each other, thus making $U_{total}$ a diagonal matrix. However, practical multimode fibers usually exhibit significant intermodal coupling during propagation. To model the impact of mode coupling, we adopt the techniques described in [39], where a statistical model of random twists and turns of the fiber are used to evaluate the impact of intermodal coupling in the strong coupling regime. To account for mode-dependent losses in each section, a random matrix is generated within each section and included as part of the matrix $U_i$, as described in [40].

4. Metrics for evaluating performance

To evaluate the performance of the MIMO-MMF links under consideration in this paper, we use the information theoretic outage capacity. Conventionally, the information theoretic capacity is used as the metric to evaluate the performance of communication links. The capacity specifies the data rate limits of communication links, and trends in the capacity with various signaling techniques offer good indication of the data rates practical modulation schemes can be achieved. For wireless MIMO channels that undergo channels that vary quickly in comparison to the data rate, the ergodic capacity is a useful metric to consider while characterizing the achievable data rates through the channel [41]. In the MIMO-MMF case, however, we restrict ourselves to considering the outage rate due to the fact that the channel variations are slow in comparison to the signaling rate through the fiber, making the outage capacity a more appropriate metric [40].

The links considered in this paper are assumed to be thermal noise limited, as opposed to shot noise limited. Given this, the outage capacity is given by:

$$
C_{outage}(\epsilon) = \sup \{ r : P [\log |I + HC \mathbf{x}^H| < r] \leq \epsilon \}
$$

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where $H$ is the $2N_R \times 2N_T$ channel matrix (the factor of two arising from polarization multiplexing), and $C_X$ is the optimizing input covariance matrix for each $H$. The $H$ matrix is obtained for each $U_{\text{total}}$ by performing an overlap of the electric field that each laser and detector couples to with the fiber modes, and is described in detail in [42], although the analysis therein concerns incoherent detection. For the case of coherent MMF links, the evaluation of the capacity differs from the wireless MIMO communications scenario in two ways, as described below.

First, in the wireless MIMO case, the power constraint is assumed to be a sum power constraint. So, if the net power available across all the $N_T$ transmitters is $P$, the constraint on $C_X$ is that its trace should be within $P$, i.e. $\text{trace}(C_X) \leq P$. In the MIMO-MMF case, however, each laser is assumed to be independently controlled. Thus, if the $i$-th laser is constrained to emit a power of $P_i$ over both polarizations, the constraint becomes $[C_X]_{i,i} + [C_X]_{i+N_T,i+N_T} \leq P_i$ (i.e., sum of the diagonal elements of the covariance matrix corresponding to the two polarizations derived from the $i$-th laser are within the power constraint of that laser).

More significantly, in the conventional Rayleigh fading wireless MIMO channel, the distribution of $H$ is well known, thanks to a convenient characterization of the entries of $H$ as complex normal random variables. For the case where the entries of $H$ are i.i.d. entries with a sum power constraint of $P$ on the transmitters, the design of $C_X$ simplifies to choosing it as $\frac{1}{NT} P$. However, in the MIMO-MMF case, characterizing the distribution of $H$ is highly nontrivial, since the entries are not generally independent or identically distributed. Moreover, since they are generated using a model that involves mode coupling over several sections of the fiber, obtaining a closed form solution for the joint distribution of the entries of $H$ is complicated. Thus, the computation is performed numerically. It is assumed in these simulations that the information about the fiber channel is available to the transmitter to evaluate the optimal $C_X$.

5. Simulation results

5.1. Description of simulations

Based on the models and metrics described in sections 3 and 4 respectively, this section describes simulation results for fibers of various dimensions and various coupling scenarios. In particular, the simulations aim to compare the performance of:

- Large-core multimode fibers
- Few-mode fibers
- Multicore fibers

Large-core multimode fibers are the conventionally found in short haul as well as legacy fiber links. They possess diameters of 50 $\mu$m or more. Due to their large core diameter, they possess a large number of modes, but the bandwidth-length product achievable over these fibers using conventional modulation methods are generally restricted to around 2 Gb/s-km because of modal dispersion [37]. It has been experimentally shown that the use of signal processing techniques and multiplexing can far exceed the this limited bandwidth-length product [28]. The simulations considered in this section investigate the limits of data rates that can be achieved using these modulation and multiplexing techniques.

Few-mode fibers are multimode fibers that possess a core diameter marginally larger than single-mode fibers, so as to possess two or three propagating modes. They are specially engineered to possess this characteristic, so that controlled, selective launching and detection in the propagating modes, along with signal processing, facilitates increases in data rates [43]. They generally possess bandwidth-length products that far exceed those of single-mode fibers and large-core multimode fibers. The relatively few modes allows effective spatial mode filtering,
so that signals can be coupled into, and recovered from, the fiber with great fidelity. Examples such spatial mode filtering based approaches are found in [9, 11].

Multicore fibers are also specially engineered fibers that resemble external dimensions of other fiber types, though they possess multiple cores that can all carry parallel data streams. Although the data rates could be limited by cross-talk among fiber cores, modern multicore fibers with \( N \) cores possess performance comparable to \( N \) parallel single mode fiber links. In general, the data rates achievable over modern multicore fibers is comparable to the the data rates that can be attained with the cores behaving as independent, parallel SMF links [13, 44]. Since the propagation characteristics of multicore fibers differ significantly from those of multimode fibers, we restrict most of our consideration to multimode fibers, but comment on the performance of multicore fibers with varying launch offsets.

For conventional (large-core) MMFs, whose diameter exceeds 50 \( \mu \)m, intensity modulation and incoherent detection is generally preferred [45]. However, to allow for a fair comparison between fibers of all core diameters, the achievable rates considered in these simulations were all for the case of coherent detection. While the use of incoherent detection would limit the data rates through large-core MMFs, the data rate trends using coherent detection are still indicative of the speed increases achievable with incoherent detection for short fiber lengths with mode-group diversity multiplexing [21].

For each of the above fiber types, we performed the following simulations:

1. The impact of the granularity of laser and detector arrays and mode-specific filtering on mode selectivity and fiber coupling
2. The variation of data rates with fiber dimensions and properties.
3. The effect of radial offsets from the fiber axis during launch and detection on data rates.

The simulations were performed in a custom fiber-optic simulator to optimize laser and detector configurations that yielded the greatest 1% outage capacity over the ensemble of channel realizations under various scenarios. The simulator was written using the SciPy package [46]. For each scenario, based on the MIMO system considered, the system matrices \( \mathbf{H} \) was derived from \( \mathbf{U}_{\text{total}} \) matrices, as discussed in Section 4. The 1% outage capacity was evaluated using an ensemble of randomly generated \( \mathbf{U}_{\text{total}} \) matrices that corresponded to the ensemble of system realizations. To generate each \( \mathbf{U}_{\text{total}} \), the model split the graded-index fiber several sections, each 10 cm in length. The 10 cm length was chosen since this closely modeled the mode mixing characteristics within the fiber [39]. The fiber had a core refractive index of 1.444 and a numerical aperture of 0.19. The lasers were assumed to operate at a wavelength of 1.55 \( \mu \)m, and the spatial electric field pattern they produced was assumed to be circularly symmetric. This choice of wavelength was made since since this wavelength corresponds to the lowest loss window of the fiber. This field propagation approach for modeling MMF behavior closely corresponds to a model that has been experimentally verified to be accurate [47]. The statistical variations induced within the fiber are caused by the curvature and twists in each section. These curvatures and twists are represented as \( \kappa_i \) and \( \theta_i \), respectively, as shown in Fig. 5. Both of these parameters are considered to be Gaussian random variables with \( \kappa_i \) having a standard deviation of 0.95 \( \text{m}^{-1} \) and \( \theta_i \) having a standard deviation of 0.6 radians. These parameters were determined by correlating experimentally observed beam profiles obtained after propagation through a 1 km graded-index multimode fiber for tuning the model to match physical parameters. To reduce the number of variables in the simulation, the device configurations were restricted to two dimensional structures that were coupled directly to the fiber axis. The motivation for this assumption comes the fact that the fabrication of devices with this geometry has been demonstrated in practice [48, 49].
5.2. Granularity of launch/detection couplers

In this section, we investigate the tradeoffs in using different coupling methods during launch and detection, and simulate the impact of the granularity of the launch and detection geometries on the achievable rate over few-mode fibers as well as conventional large-core multimode fibers. This is a useful approach to consider, since it is a natural way to enable mode filtering at both the transmitter and receiver. While transmission using spatial light modulators allows greater control over the launch geometry and signal phase, the use of laser detectors at the transmitter and detector arrays at the receiver leads to lower implementation complexity. Practical approaches that utilize such laser and detector arrays have been discussed in [48,50–52]. Fig. 6 shows some of the simulation cases considered. In the figure, the “FMF - arrays” case corresponds to a few-mode fiber that has a core diameter of 11 µm, with three spatial fiber modes. This arrangement captures the mode filtering achieved by a mode filter arrangement, such as the approach described in [9]. The “MMF - arrays” case represents a multimode fiber that had a core diameter of 50 µm. Using the analysis of spatial and polarization modes for graded index fibers discussed in [39], we find that the fiber has 55 spatial spatial modes. With two polarizations for each spatial mode, the fiber then has 110 usable modes for multiplexing. In each case, square grid arrangements were evaluated, and the arrangement of the launch and detector geometries were identical. Optimizing the grids to increase data rates is not considered here. For few-mode fibers, the maximum grid size was restricted to a 7 × 7 grid, that corresponds to a 49 × 49 MIMO system. The maximum grid size in the multimode fiber case was restricted to a 9 × 9 grid case, which corresponds to a 81 × 81 MIMO system. For each of these cases, using grids that contain launch and detection spatial filters whose diameter is below 4 µm could result in severe specular noise at the detector. Nevertheless, the simulation is used for few-mode fibers to provide an indication of the how more granularity affects data rates. For the purposes of capacity evaluation, the detectors were assumed to be balanced detectors that could decode the magnitude and phase coherently, as shown in Fig. 1.

For each case, the net power launched into the fiber was kept a constant to ensure fair comparison. In addition, the baseline for comparison was considered to be an arbitrarily fine grid that can modulate each mode of the fiber individually. The actual data rate that can be achieved is considered in the following section. The results of the simulations is shown in Fig. 7, which plots the scaling of the 1% outage capacity with laser/detector array granularity. The outage capacity is plotted as a fraction of the outage capacity that can be obtained if each individual fiber mode could be modulated and detected separately (in other words, using the notation of Section 3, the ability to modulate every individual fiber mode would correspond to the case where $H = U_{\text{total}}$). From the plot, it is evident that increasing granularity of the launch/detection spatial arrays increases the achievable rate, although the benefits cease to become significant for the few-mode fibers beyond small grids. This can be attributed to the fact that the sparse grid
Fig. 6. Multimode fibers with different launch/detection array geometries. The size and the spacing between successive launch and detection filters is shown for these illustrative examples. The actual mode filtering could be implemented using fibers, free-space coupling or similar approaches. For the cases where the detector sizes fall below 4 μm, specular noise is likely to dominate and diminish the achievable data rate.

Fig. 7. The fraction of the maximum (1%-outage) capacity of the fiber that can be achieved using laser/detector arrays. The outage capacity is evaluated assuming that every individual mode of the fiber can be launched and detected independently.

structures are sufficient to couple effectively to the modes of the fiber, and further granularity does not improve achievable rate. The ability to excite a diverse group of modes selectively is essential to utilize the multiplexing properties of the fiber. Since the use of very fine grids is not practical from an implementation perspective, we assume that mode-specific filters are used with few-mode fibers [9]. For the conventional large-core MMF case, since there are hundreds of modes, finer grids permit better access to a diversity of modes, both during launching and detection, thus improving the achievable rate. The details are discussed in the following sections.
5.3. Outage capacity

Fig. 8. Achievable at a rate as a function of the core diameter. It is evident that fibers with a smaller core diameter are better in terms of a data rate perspective since dispersion becomes a significant limiting factor at higher diameters for all lengths.

Next, we consider the 1% outage capacity through few-mode and multimode fibers. In these simulations, for few mode fibers whose diameters are $11\,\mu m$, we assumed that mode-specific filters were used to launch into the fiber. For the larger core fibers, the most appropriate laser/detector grid that achieved the highest possible data rate was chosen based on the simulation results in Fig. 7. This is because launch/detection spatial arrays achieve data rates comparable to mode-specific filters for fibers that have a larger core diameter [42], while being easier to realize than mode-specific filters for large core MMFs. The achievable data rates through fibers of various diameters are shown in Fig. 8. For a fair comparison, the net launched power into the fiber was restricted to $13\,\text{dBm}$, and the fiber loss was assumed to be $0.5\,\text{dB/km}$. From the figure, it is clear that an increase in the number of modes causes dispersion effects to have a dominant impact on data rates, thus severely restricting the achievable data rates through large core MMFs. For few-mode fibers, the small number of modes permits selective excitation of modes and effective multiplexing when mode-specific filters are used, thus providing a sharp growth in the achievable data rate for small core diameters, though that effect diminishes quickly into the dispersion limited regime with increasing fiber diameter. As data rate diminishes with fiber length, few-mode fibers offer a much higher data rate at all lengths. The possible causes and impacts of dispersion in large-core MMF is discussed in Section 6.

5.4. Sensitivity to coupling offsets

Finally, we consider the offset tolerance of fibers of various diameters. The offsets at the detector were evaluated since the penalty was found to be much greater than offsets at the transmitter side. The characterization of offsets was performed by radially offsetting the detector-side array or mode filters, as shown in Fig. 9. Fig. 10 plots the impact of radial offsets at the detector end on the data rate. The multicore fiber consisted of seven cores and an inter-core cross talk of about $-40\,\text{dB}$ (cf. [44]). The few-mode fiber was assumed to have a core diameter of $11\,\mu m$, with three spatial fiber modes, and the large-core MMF was assumed to possess a core diameter of $50\,\mu m$, with 110 spatial modes.

From Fig. 10, it is evident that the multicore fiber has the least tolerance to offsets. This can be explained by the similarity between multicore fibers and parallel single-mode fibers. The
Fig. 9. Radial offset coupling at the interface of fibers, showing a radial offset of \( r \).

The presence of only a single-mode in each core results in a significant reduction in signal overlap at the interface with radial offsets, thus making them extremely sensitive to offsets. Few-mode fibers also possess modes that are quite sensitive to offsets, although their marginally larger core diameter, in conjunction with signal processing, endows them with more resistance to offsets than multicore fibers. The 50 \( \mu \)m MMF’s large number of modes allows it to be the most tolerant to offsets among the fibers being compared. They are, thus, better suited for short-range deployment that have a greater offset tolerance requirements.

6. Discussions

The results from Section 5 need to be viewed in the context of the amplitude of fiber modes during propagation. Propagation of modes through longer fiber sections results in significant intermodal coupling, thereby spreading the energy across several fiber modes. To observe this effect, we simulated the modes of a 50 \( \mu \)m diameter MMF excited by a 16 laser configuration, arranged in a 4 \( \times \) 4 grid as shown in Fig. 6. The results of this simulation for 10 m and 1 km are shown in Fig. 11. From the figure, it is clear that for fibers of longer length, the spread of energy across the modes is much more pronounced. This indicates that obtaining the multiplexed signals effectively would require accurate decoding of all of these modes. Unfortunately, using spatial mode filters or detector-side arrays would not capture the spread across all modes, thus effectively losing a significant portion of the multiplexing benefits that could be obtained from the multiplicity of modes. Regaining the energy spread across these modes, would require the ability to differentiate and filter these modes effectively, either by means of a finer detector grid, or by using several mode-specific filters. Neither of these approaches is easy, though, since finer

Fig. 10. The variation of achievable data rate with offsets at the detector. Multicore fibers are found to be much more sensitive to offsets than multimode fibers.
Fig. 11. The amplitude of across each spatial mode (indexed on the x-axis) for a 50 µm MMF, for 10 m section and a 1 km section. A longer length causes more signal spread across mode groups, thus accentuating the impact of dispersion.

detector grids are susceptible to speckle [53, 54], while realizing modal filters for higher order fiber modes for large-core MMFs is also difficult. One possible solution to this problem is to estimate and signal using the principal modes of the fiber [55], although this necessitates the use of spatial light modulation and regular feedback of the mode transformation effected by the fiber to transmitter. A hybrid solution that utilizes channel-state feedback in conjunction with appropriately sized detector-side arrays that do not suffer from speckle, could alleviate spreading of the signals across several fiber modes during filtering while limiting cost and complexity. This is a topic for future consideration.

7. Conclusion

The use of multimode fibers in conjunction with signal processing and multiplexing significantly improves data rates. However, the data rates achievable over these fibers are not uniform across multimode fibers of different diameters. In this paper, we have used a simulation based approach to characterize the impact of fiber dimensions and how different methods of launching and detecting signals in the fiber can affect the data rate performance. Simulating the MIMO outage capacity of the fiber indicates that the dispersion effect is accentuated in large-core MMFs due to coupling of signals across several modes that are not effectively separable to be decoded at the receiver. While large-core MMFs suffer from dispersion limitations at longer lengths, they are much more resistant to offsets, thus making them well suited for applications that require low-cost short-range deployments. Future work should focus on developing effective mode-specific encoding and decoding techniques that utilize more modes of large-core MMFs to relax dispersion constraints significantly enhance the data rates they can support.

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