Chapter

Multi-core Fiber Technology

Muhammad Irfan Anis and Hamdan Ali

Abstract

Traditional single-mode fiber capacity issues will be mitigated by using space-division multiplexing in future 5G, IoT, and M2M networks. Multi-core fibers are expected as a good candidate for overcoming the capacity limit of a current optical communication system. This chapter describes the recent progress on the Multi-core fibers technology for the application of high capacity space-division multiplexing to be utilized for long-distance transmission systems. Further various optical approaches that enable key functions are discussed, including SDM MUX/DeMUX, switches, transceivers to enable next generation optical network. Moreover, issues like crosstalk, non-linearity is a potential limitation on the achievable data-rates in optical fiber transmission systems using multi-core fibers will be discussed.

Keywords: All-optical signal processing, Crosstalk, Fiber capacity, Optical Network, Space division multiplexing

1. Introduction

Internet traffic infrastructure is underpinned by optical transmission systems and networks [1]. However, continuous supply of new services like video on demand, Virtual Reality and Augmented Reality have rising data volumes needed to satisfy the requirements of industry, academics, governments, and people presents new challenges to optical communication infrastructure [2]. Fiber-optic communication systems based on conventional single mode single core fibers (SMF) are almost saturated due to amplifier bandwidth, nonlinear noise, and fiber fuse phenomena due to this it's capacity consumption will be beyond capacity limitations by the year 2022 [3]. As a result, researcher has led to a steady push for new, higher bandwidth optical fibers that can replace the SMF.

Space division multiplexing (SDM) methods is one of the potential capacity expansion strategies for an optical transport network. It is transmission fibers that enable concurrent parallel data transmissions on multiple cores in a single cladding or several cores inside a single core to improve speed and data rate [4]. The first demonstration of an SDM link consisting of standard cladding diameter surpassing the typical size of 125 μm 7-core MCFs, highly efficient MC-EDFAs, and MCF connectors transmission above 100 Tbit/s across a 316 km has occurred and considerably greater capacity tests such as over 1 Pbit/s and 1 Ebit/s·km were performed using single mode multi-core fiber [5]. SDM fibers are defined as multi-core fibers (MCFs) and few-mode fibers (FMFs) or multi-mode fiber (MMF) [6]. MCF and multi-mode fiber technologies provide for additional fiber capacity proportional to the number of cores and modes per fiber [7]. Single-mode cores, contained in a shared cladding, are employed independently in the former. An FMF has one core, which enables several optical modes, each of which may transmit data independently. MCF is a promising technology for providing enormous bandwidth and capacity with regard to information [8]. The MCF help facilitate the data transmission and the transmission of power in high power devices. Multi-core fibers have many positive attributes over conventional fibers: they have significantly decreased core separation and are very regular when compared to free-standing fibers, and they also provide a monolithic package with several fiber features [9]. Moreover, multi-core fibers that allow a few-mode core to combine the fibers results in an extra 100 optical channels in each transmission, as well as throughputs of over 1 Pb/s [10]. Recently MCF-based fiber-optic transmission, a capacity of 1 Pb/s per 32-core fiber has been achieved [11].

Multi-Mode-Multi-Core Fiber (MM-MCF) significantly increases the number of spatial channels to 114 or more, and transmission of 10 Pbit/s was achieved utilizing this multi-mode MCF. Despite these benefits, the MCF may have limitations such as crosstalk (XT), non-linearities, dispersion, and so forth. Over long distances, the accumulation of MCF crosstalk may be the most limiting issue influencing the performance of an optical communications system. As a consequence, in recent years, research in this field has been driven by the development of ultralow crosstalk MCFs [12]. The impact of XT on MCF system capacity and range has recently been studied [13]. However, the results vary with modulation format and transmission reach, leading to the general notion that different network applications, from short-range to ultra-long haul, need different MCF designs. Standardization and mass production are essential for widespread commercial usage of emerging technologies like MCF. An XT standard per unit length of 55 dB/km has been proposed [14]. In an MCF system, the performance penalty must be evaluated against a non-XT system, regardless of unit size (i.e., a fiber bundle instead of an MCF). Capacity and reach penalties are required. Calculation on an optimal MCF core density for long-distances-independent crosstalk specifications have been done. The crosstalk process was originally described in [15], although the majority of crosstalk on a fiber is continuous, it is at discrete places where crosstalk amplifies the most, when core matching circumstances occur. Since the locations and phases of these sites may change randomly, crosstalk in MCFs follows a random chi-square distribution with 4 degrees in time and wavelength [16].

Using MCF's nonlinear distortions for power-over-fiber operations poses a number of challenges. The structure of MCF, which enables for high-power signal transmission via the fibers, has lately received attention. It is recommended that image processing be used; therefore, the present limitation of single mode fiber must be overcome [17].

A 7-core MCF with reduced inter-core crosstalk was used for trans-oceanic transmission. Using MCF and a spectrum efficient modulation scheme, 201 x 100 Gbit/s transmission across 7326 km produced a capacity-distance product surpassing 1 Exabit/skm [18]. These systems propose the MCF as one of many optical transmission techniques.

To transmit 52.2 Tbit/s across 10230 km, the CDP for SM-SCF transmission is 534 Pbit/s/km. The transmission rate was 1.03 Ebit/s km/h [19]. A preliminary test using seven spatial channels and PDM-QPSK yielded 53.3 Tb/s [20]. Using 8 spatial channels with PDM-8PSK, the capacity was 83.33 Tb/s. MMF allows transmission distances up to 1200 km (3 spatial modes x 40 Gbit/s DP-QPSK) and 13.9 Pbit/skm (CDP with MMF)[21]. Uncoupled MCF allows for considerably longer transmission. The 1500 km transmission used a propagation-direction interleaved design to minimize interference between neighboring cores [19].

This chapter investigates MCF-based novel technologies for creating next-generation optical networks. We first examine the roadmaps towards optical fiber and examine why there is a need for MCF. We also highlight the newest reports' in MCF paradigm covering design and application. Looking into the main technology as a key functional building blocks for next generation optical communication. Next, we demonstrate the experimental setup of MCF. In last section describe the MCF limitation before conclusion.

2. The roadmaps towards fiber optics

The global proliferation of hyper photonics, intelligent photonics and frontier wireless communication need an increasing data capacity of tens of percentage each year. Services including IoT, M2M, sensor networks, and linked vehicles will need even greater bandwidth to expand capacity and find more efficient connections via high-speed optical fiber networks, as **Figure 1** shows the innovation technologies. As a result, the forthcoming growth in data transmission will exceed the SMF's maximal transmission capacity due of its low loss and optical amplification of the transmission window. Traditional SMF cannot be ignored in DWDM transmission systems with Raman amplification [23]. An increase in optical infrastructure is required to meet capacity constraints. Introducing extra optical fibers and cables is considerably simpler when contemplating an alternate technology. The future capacity constraint may be averted simply by creating more SMFs. Thus, construction/renewal of the physical infrastructure would be required, which would add to the total expenses. SDM, a fifth physical dimension, may supplement time, wavelength, frequency, and polarization multiplexing, thereby easing future capacity problems [24].

Figure 2 shows the progress of cable density. 400-pair copper, 400-fiber ribbon, and 400 rollable fiber ribbon cables are indicated by black, blue, and red dots. A solid green line indicates the numerical limit for a hexagonally packed 250 mm fiber bundle with a 2 mm cable sheath [24].

The two spatial dimensions of mode and core are used in the design of optical fiber. MCF stands for multi-core fiber division multiplexing, while MMF stands for multi-mode fiber division multiplexing. For understanding description of a 2D representation of modes and cores inside optical fiber shown in **Figure 3**. With proper use of modes or cores, it is possible to surpass the present geometric limit of conventional optical fiber cable. Using the modes and cores in tandem will almost triple the spatial multiplicity. This recent study concludes that 6-mode and 19-core fiber can provide over 100 spatial channels [25]. It's required that a complicated transmission strategy be used because of the mode coupling and/or mode-dependent transmission properties in optical fiber. Also, MCF has been constantly studied and was pioneering in [24]. MCF is especially capable of using the newest

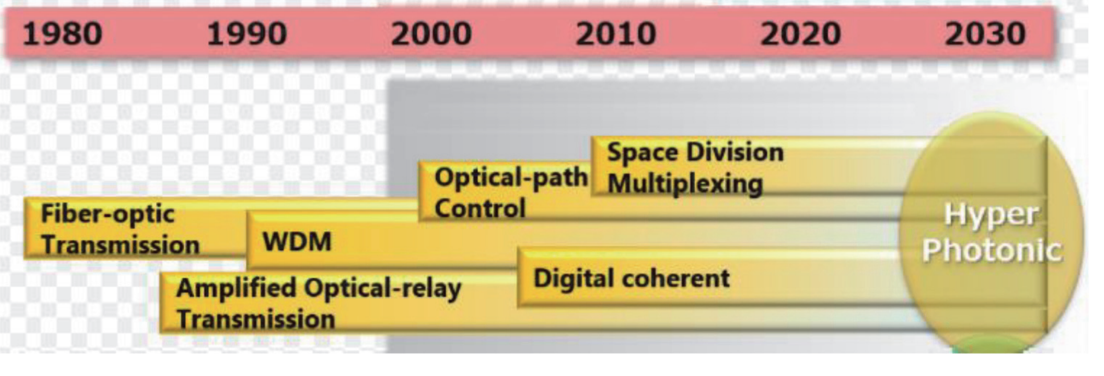

Figure 1.
History of optical network innovation technologies [22].

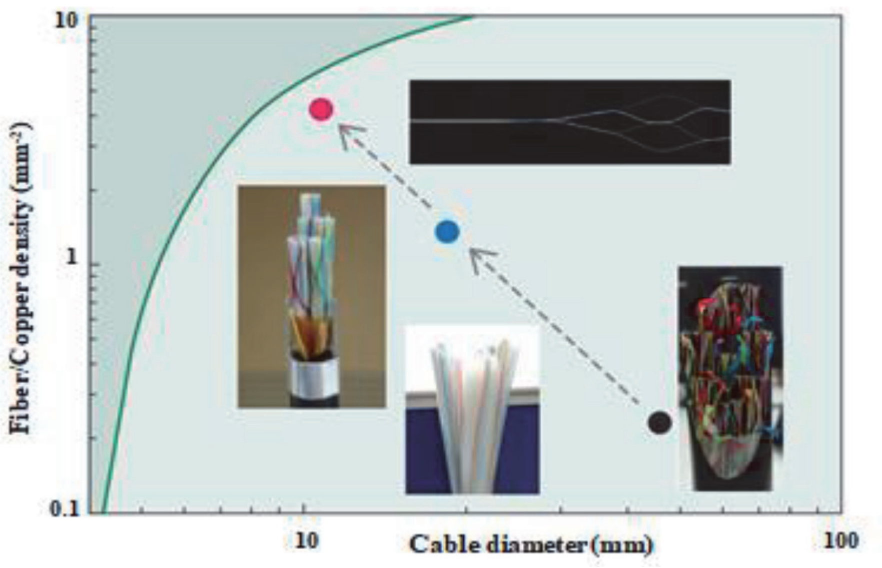

Figure 2.
Evolution of communication cable density over time [7].

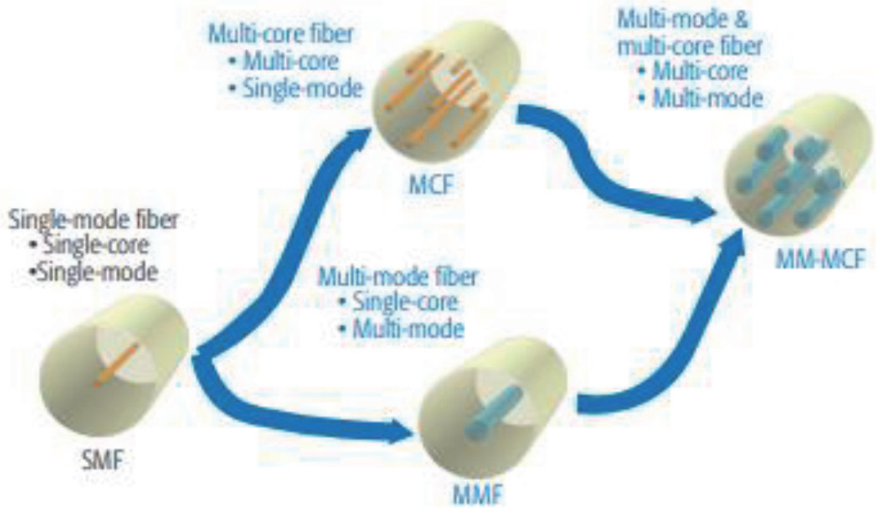

Figure 3.
Schematic image of the two spatial dimensions of mode and core in optical fiber [24].

single-mode technologies. Here, we'll talk about MCF and the capacity of MCF as an SDM transmission medium.

Signal mixing and propagation time skew are two important characteristics of SDM fibers that have a direct effect on transmission performance. SDM fiber groups are provided by two mixing levels. First, there are uncoupled MCFs (UC-MCFs), few-mode fibers, or few-mode MCFs, which mix signals from several spatial channels during transmission and have minimal inter-core coupling to minimize inter-core crosstalk (XT). Both the first group randomly coupled MCF (RC-MCF) and the second group randomly coupled MCF (RC-MCF) have significant random mode mixing between modes (RC-MCF). UC-MCFs have greater spatial channel density than SMFs with traditional transceivers. To compensate for random coupling, RC-MCFs need MIMO digital signal processing (DSP). However, random coupling may decrease spatial mode dispersion and therefore the MIMO DSP's computational complexity. Other core/mode-dependent restrictions are also prevented by random coupling [26, 27].

MCF with a 125 mm cladding diameter is needed to start MCF tech. A 125 mm cladding diameter MCF design that is optically compatible with current SMF.

	No of cores	Core layout	Cladding diameter [μm]	Cut off wave length [μm]	Mode field diameter [μm] @nm	Affective area [μm^2]@nm	Crosstalk [/km] @nm	Wavelength band	Applications	Parameter/feature	Ref.
Multi-core Uncoupled-type	7	⬡	150	≤1.51	9.8@1550	80@1550	6.0x10^{-9} @1625	C ~ L	LH	Ultra-low Crosstalk	[29]
	7	⬡	188	≤1.47	12.2@1550	124@1550	8.0x10^{-7} @1625	C ~ L	LH	High Optical SNR	[30]
	31	⬡	225	~1.47	n/a	57@1550	9.3x10	C ~ L	LH	High SSE	[31] [32]
	4	□	125	≤1.19	8.6@1310	—	5.0x10^{-5} @1625	O ~ L	LH	Standard diam. Cladding+ Full wavelength band	[32] [5]
	8	○	125	≤1.24	8.4@1310	—	3.2x10^{-7} @1310	O	SR	Standard diam. Cladding +8 cores	[33]
	8	2x4	180	≤1.20	8.4@1310	—	≤6.3x10^{-5}@1550	O ~ C	SR	Si photonics TRx mounted	[34]
	4	1x4	98x200	≤1.34	9.7@1550	n/a	3.0x10^{-4}@01550	C ~ L	SR	Non-circular clad.	[35]

	No of cores	Core layout	Cladding diam. [μm]	Cut off wave length [μm]	Mode field diameter [μm] @nm	Affective area [μm^2] @nm	Spatial mode dispersion [ps/ √km]	Wavelength band	Applications	Parameter/feature	Ref.
Multi-core coupled-type	3	△	125	~1.35	—	129@1550	30	S ~ L	LH	4,200-km MIMO transmission achieved.	[35]
	4	□	125	≤1.47	—	112@1550	3.1	C ~ L	LH	Has set low SMD and low-loss records for SDM fibers. 10,000 km transmission achieved.	[36]

Table 1.
Representative examples of reported MCFs [28].

Table 1 depicts conventional MCFs provided by Sumitomo Electric, as well as prototype MCFs created by the company via joint research.

2.1 Need for multi-core technology

The restricted bandwidth of low-loss transmission and optical amplification, as well as transmission power limitations due to fiber non-linearity, make expanding a single optical fiber's transmission capacity challenging. A growing need for higher-capacity optical fiber communications **Figure 4** shows high-capacity optical fiber transmission test results. Due to the limitations of single-mode single-core fiber, the maximum capacity is 100 Tbit/s. This high-capacity fiber capacity was achieved using MCF. SDM plus MCF or MMF may be able to outperform single-core fiber transmission systems [12, 26, 29].

3. MCF paradigm

This section investigates the design and the achievements in MCF technology, which seem promising in the short term yet have certain unknown risks.

3.1 Design of MCF

Due to fiber bandwidth depletion and the development of SDMF as a possible alternative to address extra capacity, the spectrum capacity of SSMF is nearing its end. The long-term goal of SDM is to increase the number of fiber cores, guided modes, or both. MCF has many cores in a single optical cable. The core of a conventional single-core fiber is positioned in the center of a 125-m diameter cladding, limiting design freedom. The MCF's success is dependent on more than simply the number of cores. MCFs enable the designer to optimize core design, the number of cores, core arrangement, outer cladding thickness, and cladding diameter in terms of optical and mechanical properties. Fiber design is required based on the application because desirable features differ. SMFs currently have a single fiber core surrounded by 125 mm cladding and coated. Greater cores with the same cladding or larger core diameters allow for more fiber capacity [12]. Adding cores to the

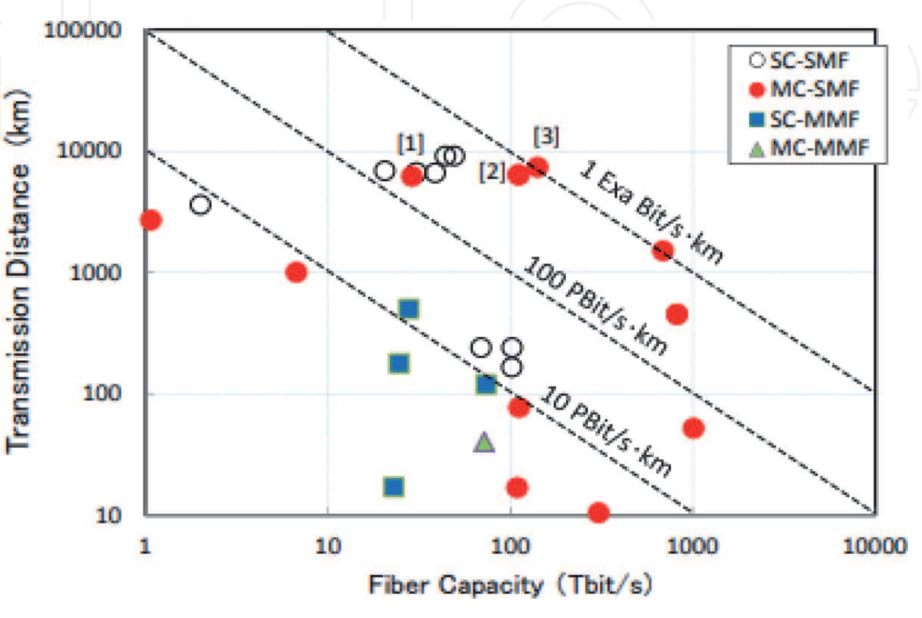

Figure 4.
Recent reports on high capacity transmission [19].

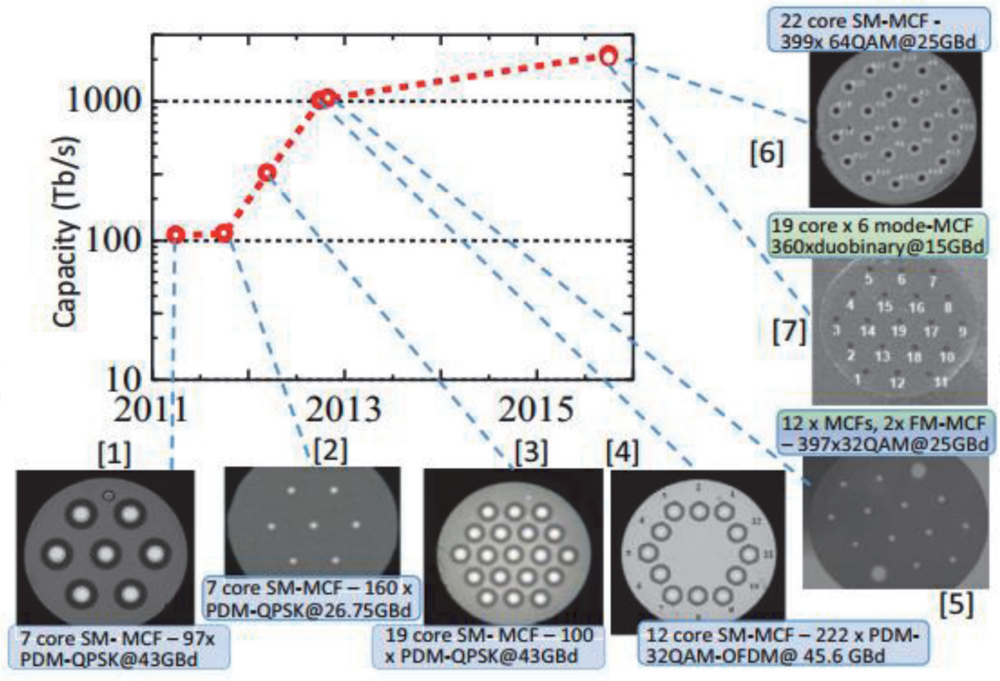

Figure 5.
High-capacity transmission experiments using SM and FM-MCF [12].

cladding may improve capacity, but it may need changes to the transmission system architecture.

SM–MCF transmission experiments on FMFs have shown fibers with as many as 32 and as little as 45 modes. Adding multi-core fibers that enable a few-mode core to join the fibers results in an additional 100 optical channels in each transmission and throughputs of more than 10 Pb/s [30]. The high-capacity experimental transmission utilizing SM and FM-MCF is shown in **Figure 5**.

A random coupled MCF is one that is MCF if XT is compensated by MIMO DSP. Even though the core is simple, the paired MCF is denser. Furthermore, random coupling in the connected MCF prevents the emergence of nonlinearity impairment, SMD, and mode-dependent loss/gain. In long-distance point-to-point communication, coupled MCF is utilized. Nokia Bell Labs, Sumitomo Electric, and Sumitomo Corporation collaborated to develop and launch new fibers [31].

Few-mode (FM) MCF fiber is a kind of uncoupled MCF (MCF with fiber coupled together) designed for mode-multiplexed transmission. KDDI Research, Inc. received a prototype 36-core fiber created in cooperation with NICT and Yokohama National University. The most recent accomplishments include a 19-core fiber that can be used in the whole C + L bands (1530–1625 nm) for long-distance communications [37]. This fiber achieved 10 Pbit/s per optical fiber in an experiment performed by KDDI Research [30].

The MCF has the potential to enhance data and power transmission for high-power devices. PoF, on the other hand, need MCF due to its nonlinear aberrations. Inside MCF, an eye-catching power transmission capacity was recently discovered. The placement of the cores has an impact on the MCF's performance.

Multi-core fiber architectures such as triangle, ring, square, rectangle, and hexagon were developed after analyzing the number of cores, pitch, and power spectrum. Many people are interested in the MCF fiber-optic structure and the question is how it allows the transmission of powerful signals. One-mode fiber has a lower limit imposed by the MCF and is currently limited by MCF analysis and picture processing. The placement of the cores influences the performance of the MCF.

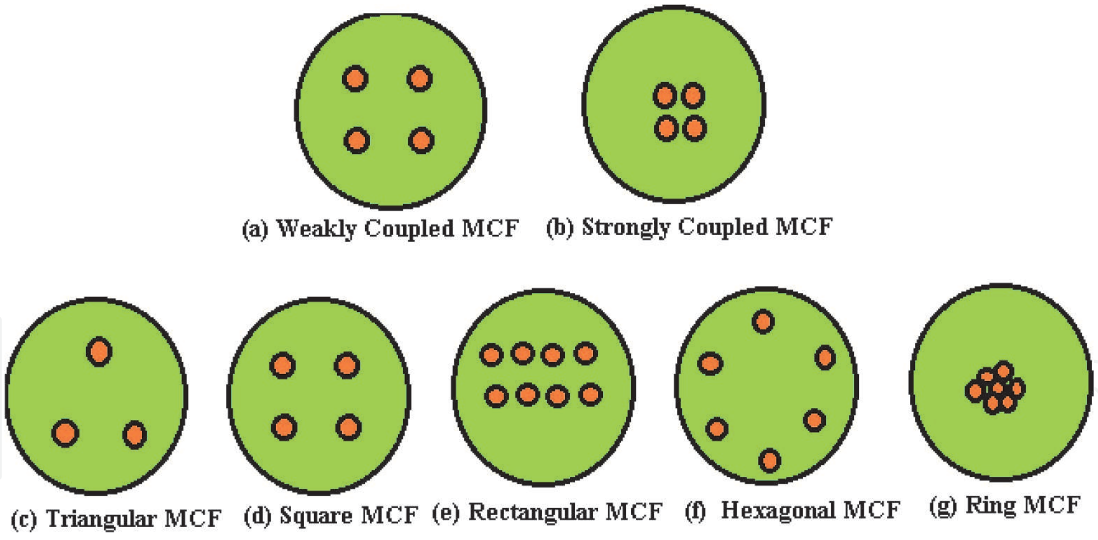

Figure 6.
Structure of multicore fiber with coupling region and with different pattern [17].

For MCF, strong and weak coupling are illustrated in **Figure 6**. Strongly linked MCF has the smallest core-to-core distance, whereas weakly coupled MCF has the most core-to-core distance. The size of the core may vary with the pitch of the core. The effective area (A_{eff}) relies on the number of cores (as shown in **Figure 6**), and their configuration influence the output receiving power. MCF contains several cores with enlarged effective areas, resulting in minimal dispersion and bending losses. The suggested solution to fiber bending losses included four air core MCF. **Figure 6** shows the five distinct MCF structures.

To provide long-distance reliable signal transmission, the XT must be less than -30 dB/100 Km [32]. To get ultra-low XT levels, make changes to MCF structures, such as trenching around the cores. Essentially, trenches are refractive index profiles with lower refractive index than the core and cladding. Trench-assisted method is one of the noteworthy techniques that lowers the coupling between the adjacent cores, therefore helping to minimize existing crosstalk.

With an MCF, if the number of cores in a restricted cladding area grows, crosstalk suppression becomes a problem. XT in MCFs is decreased by decreasing the coupling coefficient between cores. The underlying design, with strong containment of modes is critical to suppressing the mode coupling coefficient. For a higher A_{eff} and lower nonlinear noise, you may choose for a higher-index core with a smaller diameter.

It has three important geometrical features, as shown in **Figure 7**. The outer cladding thickness (OCT) is the distance between the outer core's center and the cladding's perimeter. Optical fiber mechanical reliability is strongly linked to cladding diameter D. A higher D value increases MCF deformations before collapse. Inter-core XT may be reduced by adjusting core and rod radius, cladding and rod relative refractive index differences, and core-to-core distance.

3.2 Application

The MCF technologies have been gradually increasing, and now we can see feasible commercial uses for the technologies. Practical use of MCFs will likely occur in near future due to continuous MCF development [28]. **Figure 8** illustrates the whole growth stages of MCF technology. Larger applications in the network such as metro and core may provide challenges to MCF implementation, because they need a complete suite of network components other than the MCF and cable

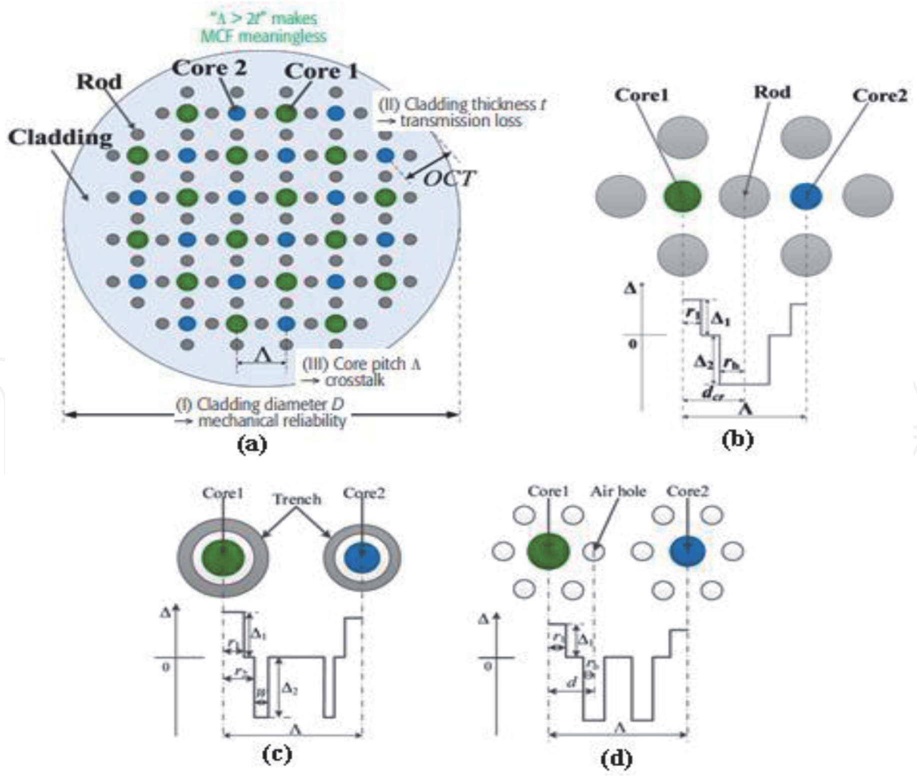

Figure 7.
(a) A 32 core schematic structure shows three key geometrical parameters in MCF. Schematic diagrams of (b) core index profile of heterogeneous rod rod-assisted 32-core fiber (c) trench-assisted (TA) profile, (d) hole-assisted (HA) profile [33].

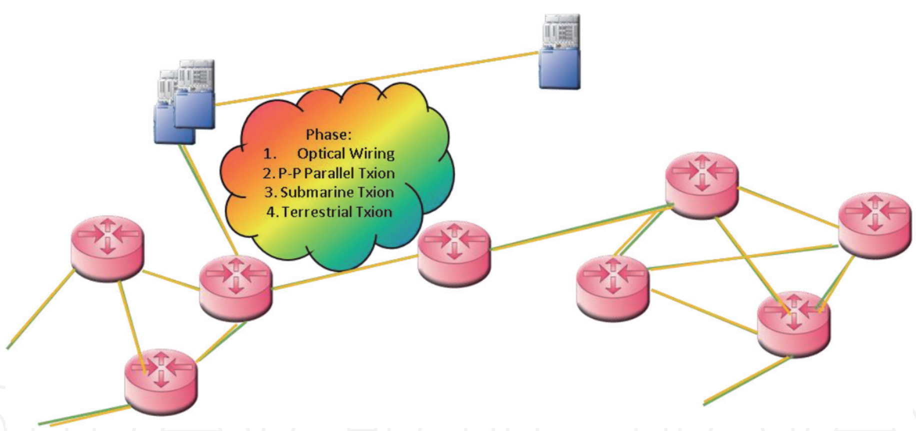

Figure 8.
Schematic image of expansion phases of MCF technology [24].

(e.g., optical amplifier, and node management technologies). To a large extent, central offices and/or data centres are the primary target for MCF technology since they are maintained and/or optimized separately by experienced operators, making it simpler to upgrade current network components. Here, compatibility with traditional SMF is very essential, especially for connection. Then, in the second deployment phase, we use MCF P2P and/or parallel transmission technology. MCF requires a flexible connection to the optical subsystems. Submarine transmission systems may offer more promise because of their use of the newest technology, and SDM might possibly achieve a power-efficient transmission system [34]. We have finally achieved flexible and dependable SDM nodes [24].

A FORECAST predicts that data center network traffic would increase at a 25% CAGR, with most traffic (about 70%) staying within the data center [35]. Modern data centers utilize dense non-blocking topologies with point-to-point optical transponder connections. Either on end servers or in slots of electronic switching devices, data is electrically switched. This resource-intensive paradigm may cause future data center scaling problems. Modern data center networks are increasingly relying on optical technologies like hybrid electrical-optical switching (HEOS). Recent demonstrations of a time-slotted pSSC and core-joint SDM optical switching system for edge applications [36].

SDM may improve network capacity by multiplexing SMF strands, multicore fiber cores, or even each mode of a few-mode fiber using MIMO digital signal processing [38]. Spatial Division Multiplexing-Elastic Optical Networks will then be the future of optical transport and data center networks (SDM-EON) [39]. MCF front haul multiplexes MIMO signals onto a single cable, enabling multiple optical data streams to be transmitted simultaneously. The MCF may also provide a single optical data signal to each antenna element, with varying delays and phases. Multi-antenna systems need MIMO and beamforming. The MCF front haul uses MIMO signals to transmit multiple optical data streams at the same wavelength. The MCF also uses optical data transmissions with variable phase or time delays to each antenna element. 5G systems need MIMO and beamforming capabilities. **Figure 9** shows a multi-antenna MCF-based RRH-to-remote-site connection with optical beamforming and/or digital MIMO capabilities. These methods enhance system performance.

The system capacity and accessible user bitrate may be enhanced by multiplexing MIMO data streams. A 22 MIMO LTE-A transmission using MCF technology was evaluated early. This research adds 44 MIMO transmission supported by a 4-core fiber capable of feeding four AEs concurrently. The M(22) arrays allow 5G systems to control multiple groups of four AEs. MCF may be used to reduce the size and complexity of beamforming systems. A same data signal is supplied by four separate AEs with varying delays, as shown in **Figure 9**. MCF aligns all optical lines in the beamforming system, simplifying the network [40].

In [36], Making fiber bundles revealed a 19-core MCF. A 7-core MCF Micro-lens array (MLA) claims 47.8 dB return loss and 0.87 dB insertion loss. Tapers were made, then cut apart to make fused fiber. Non-mode-selective, in which the modes spin on the device itself, and mode-selective, with minimal unitary rotation between modes. The most common components were lamps, phase plates, PLCs, and then mode selective PLCs. Ultrafast laser inscription can produce low loss 3D waveguides in conventional optical glass for MCFs. 3 mode FM-MCF fiber with average IL 0.92 and homogeneity 0.1.

SDM enthusiast offered considerable flexibility in fiber light mixing, integrated sensors and controllers. MCF technology has also been used to construct optical fiber sensors, which make them excellent for industrial applications. High

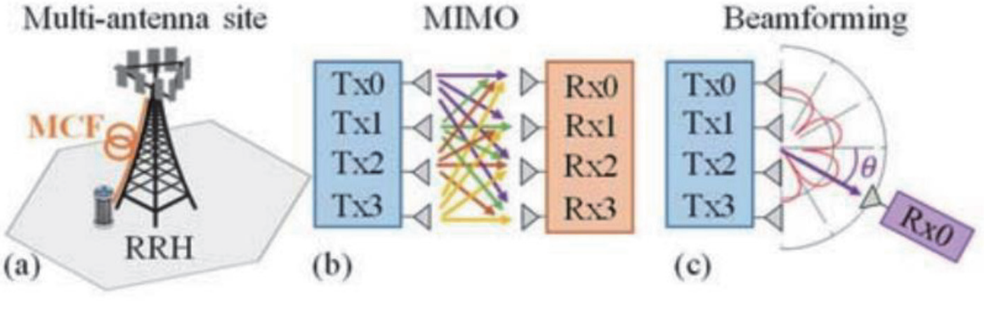

Figure 9.
(a) A multi-antenna site application scenario in which the RRH is linked to the antenna components through MCF. Examples of four-antenna systems with (b) spatial multiplexing using 44 MIMO (4 distinct data streams coded in 4 layers) and (c) 41 beam forming (4 antennas transmitting the same data with different delays) [40].

temperature sensing to 1000°C using MCF optical sensors with a typical temperature sensitivity of 170 pm/°C Mach–Zehnder (MZ) interferometers may be fabricated by employing MCFs since the slopes of the resultant interference peaks are steeper. Until quite recently, many MCF optical sensors used inefficient methods to throw light into the multi-arm MZ, causing substantial losses for QI processing [41] use novel tapering methods to construct the multi-arm MZ directly into a specially built MCF.

4. Key functional building blocks for next generation optical communication

Aspects of future network and technology MCF also requires FI/FO devices, connections, amplifiers, and integration technologies. This section covers the optical network equipment relevant to this research.

4.1 Space division multiplexer/demultiplexer

MCF technology uses SDM MUX/DEMUX. There are now numerous options, each with its own footprint, cost, capabilities, multi-mode affinity, etc. An SDM multiplexer or demultiplexer effectively links light between SMF fibers and SDM fiber modes or cores. Spatial MUXs are needed for SDM studies and may be used to link SMF and SDM networks in the future. This connection has been suggested in many creative ways. Direct and indirect coupling methods are widely classified. The optical signal is fully confined inside a waveguide during connection. **Figure 10** shows two typical layouts. As illustrated in **Figure 10**, the SMF cladding diameter is tapered to splice a bundle of SMFs to the SDM fiber. A photonic lantern is made by compressing MCF or SMF cores into an FMF. Alternatively, an unneeded

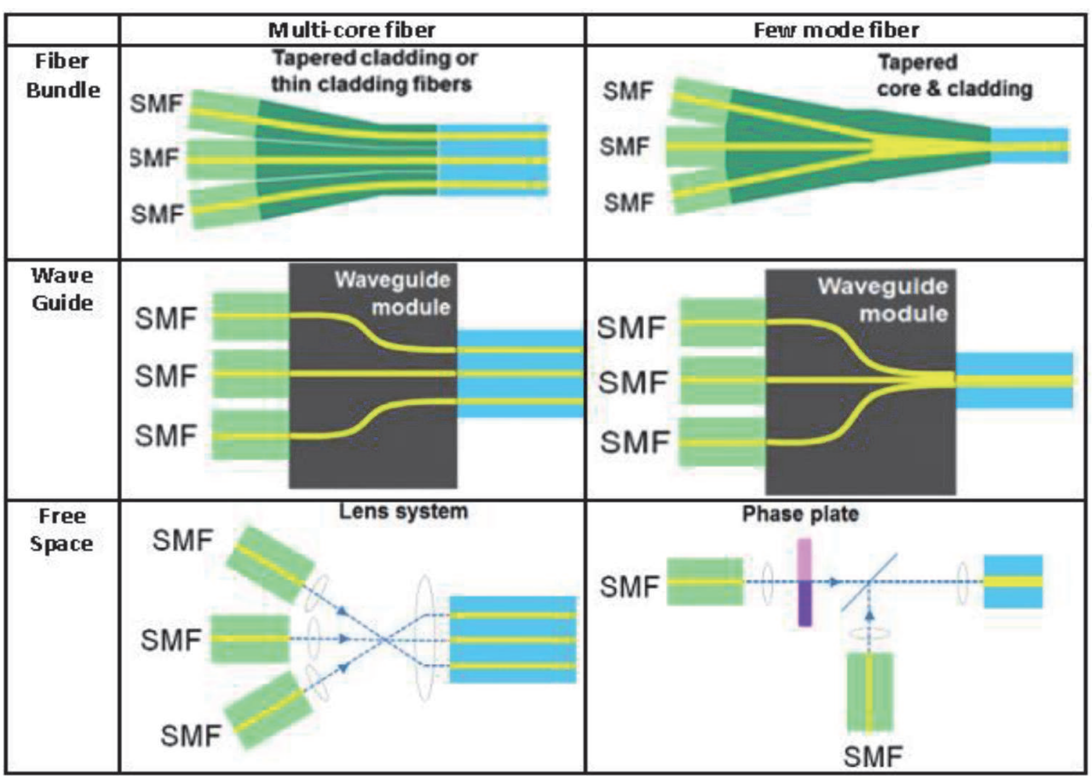

Figure 10.
Fiber bundle, waveguide and free space MUX for MCF and FMF respectively [12].

waveguide may be used. Inscribed light-guiding cores on a tiny glass block form the waveguide [12].

Figure 10 shows the inscribed cores in the waveguide output plane separated by the MCF core separation. Input and output SMF arrays are connected using UV-cured glue. In addition to fiber producers, Chiral Photonics uses the fiber bundle technique often. Optoscribe's commercialized 3D waveguide technology is easy to incorporate with photonic integrated circuits (PICs). Indirect coupling uses bulk optics like lenses and prisms [12].

4.2 Transceiver

Transceivers are devices that combine the operations of a transmitter and a receiver into a single unit. They connect the network to a computer module in both directions. Their duty is to generate optical signals and then convert them to electronic data. Aside from the form factor and connectors, the optical and electrical properties are significant factors to consider throughout the selection process. The transmitter determines the wave properties of the transmission. The wavelength, spectral breadth, and transmission power are all critical parameters. Other transmitter characteristics include wave modes, reflections, and so on. To receive an optical signal, the receiver must be set to the proper wavelength. Furthermore, the signal's polarization and power must be compatible. Photo-diodes and other light-sensitive semiconductors transform optical impulses into electrical signals that may be monitored for data extraction. The received power must be within the detector's permitted range. If the power is too low, it is impossible to differentiate between signal and thermal noise, resulting in a poor signal-to-noise ratio. The detector gets overwhelmed if the received power is too high. Modulations of the luminous flux are not detectable. Overloading may permanently harm the detector and should therefore be avoided [42].

4.3 Connectors

Connectors are devices that connect optical wires. Connectors are required for SDM systems such as fusion splicing in terrestrial and submarine trunk networks. For a variety of cable types and transmission methods, many connection types have been created. Due to the fiber break, the link transmission is lossy. Lenses, end polishing, and forms are utilized to decrease attenuation. M-type connections were used for 7-core MCFs with an IL of 0.13 dB and a 500-fold improvement in MTBF. A multi-fiber MPO connection with over 40 dB return loss and 0.85 dB IL. A 7-core MCF connection with a return loss of 45 dB and an MPO connector for four 7-core fibers with a return loss of 0.3 dB are also shown in the study.

4.4 Amplifiers

Erbium-doped MCF amplifiers may be constructed utilizing separate pump lasers. Sharing pumps across multiple cores enhances power efficiency. Another approach is to pump the MCF's cladding, which is outfitted with multi-mode lasers. To achieve greater efficiency than an array of SSMF EDFAs, more power must be injected [43].

4.5 Switches

A network's heart is comprised of switches. Switches manage signal paths between nodes. In traditional copper networks, this routing is based on data packet IDs. Routing in optical networks, on the other hand, may be based on physical

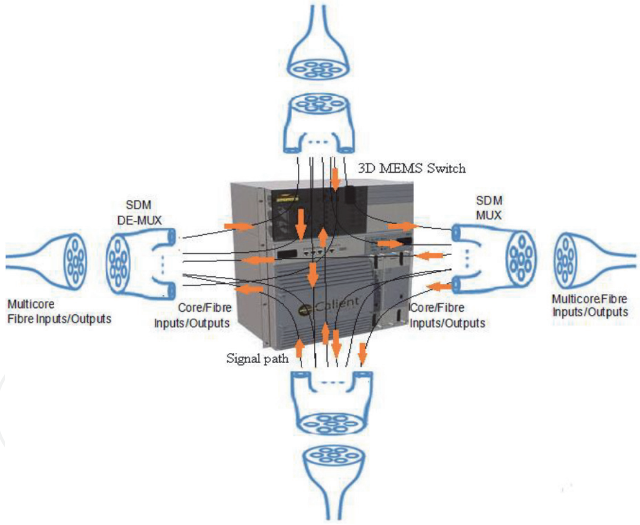

Figure 11.
Core switching with spectrum contiguity within an optical network that uses multi-core fiber transmission.

signal properties. This may be the wavelength in WDM or the core in multi-core fiber transmission, for example.

Figure 11 is an example of a signal route in a switch. All the linked wires has seven cores. Every signal has its own core. When routing a signal, it may be done dynamically or statically. The physical routing technique is switch-dependent, which means that different switch types will have different methodologies. Due to physical coupling effects between the various cores, the range of multi-core fiber technology is limited to km. The limited flexibility of single-core fibers is distinct from that of multi-core fibers [44].

Low-speed SDM optical switches are already promising technologies, and preliminary work on SDM optical switches based on MEMS or LCoS technologies has been done. This will benefit WAN networks that need high-layer packets to be routed directly into the optical domain. Optical fast-switching networks have never achieved broad adoption owing to building difficulties, quicker signal degradation, and lower-cost electronics.

These switching granularities arise from the spatial component of SDM networks: Space granularity (joint switching) is needed when all modes intermix. Fibers like FMFs have full wavelength granularity in fractional space. Recently, several papers on SDM optical switches have appeared. In [36], a heterogeneous WSS switches spatial channels in an FMF, SSMF array, and SC-MCF. [36] claims a three-port four-core MCF WSS for SDM with 34 dB crosstalk and IL under 2.2 dB. Reference depicts a silicon PIC with a 7 7 switching matrix (MZIs) with an insertion loss of [4.5, 7.0] dB. Acoustic-optical crystals may also be used to create SDM optical switches. **Figure 12** depicts a CJ-AOM switch for 7 spatial channels. A 10 second switching time with an insertion loss of 10 dB.

There are spectrum resources in each core in SDM-EONs. All Spectrum slots are created equal. Following the spectrum contiguity requirement implies the whole service must utilize the same spectrum slots along the lightpath. To keep spectrum continuity constraint in a fiber, service spectrum slots must be continuous in the spectral dimension. The OFDM method should be used for each core to enhance spectrum efficiency. Spatially and spectrally resolved optical switching fibers are made as shown in **Figure 13**. In the optical switching fabric, core, fiber, and spectrum switching may be accomplished, which enables flexible channel addition, removal, and wavelength-level granularity channel switching. A transceiver pool supplies the necessary sub-transceivers for the different communication

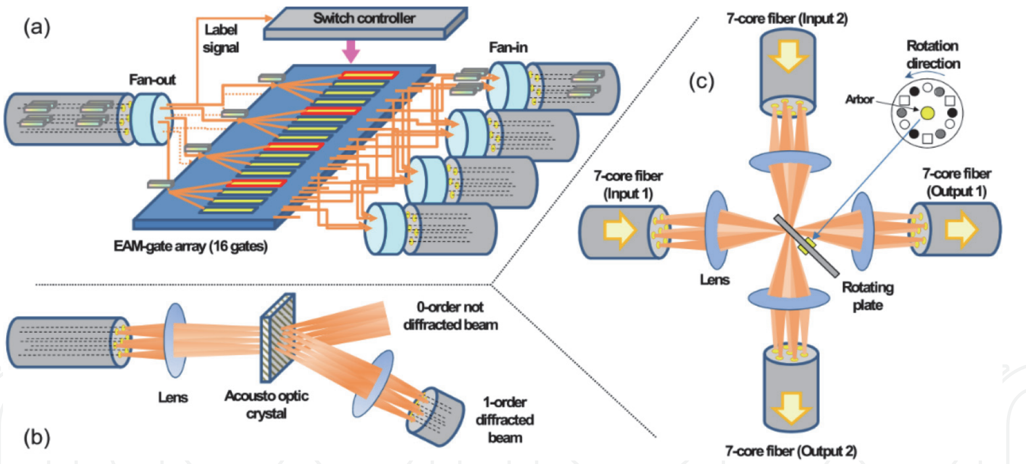

Figure 12.
(a) Core-joint electro-absorption switch diagram, (b) core-joint acousto-optical modulator switch diagram, and (c) core-joint mirror switch diagram [36].

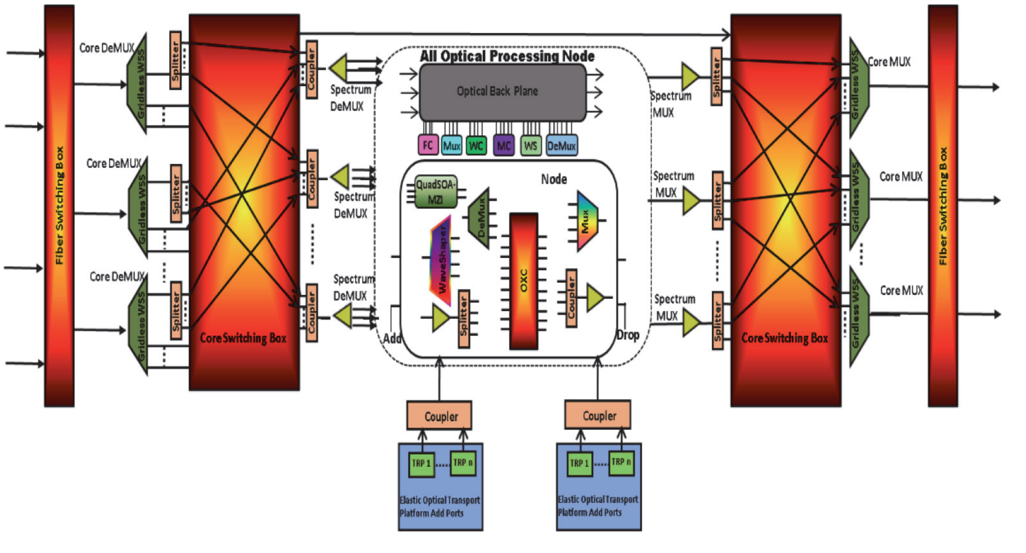

Figure 13.
Spatially and spectrally resolved optical switching fabric.

requirements. To overcome the spectrum contiguity restriction, spectrum slots in the switch fabric may be swapped between various cores. To summarize, it is possible to flexibly move signal cores without losing spectrum.

5. Limitation

Researchers all around the globe are working to reduce problems in order to attain ultra-low signal distortions in fiber optic technology [45]. However, high-capacity transmission systems place extra importance on network reliability [46]. It has gotten a lot of attention as a promising technique for dealing with the capacity limitations that are associated with single-core SMFs and cable size limitations like in datacenter networks and Passive Optical Networks (PONs) (which require high fiber count and high-density). Also, MCFs provide redundant signal lines and primary signal lines, which enable them to construct extremely dependable networks [47].

5.1 Cross talk

MCF is currently actively researched for SDM. SDM-based long-haul transmission requires low-crosstalk (XT) architecture. MCF transmission presents an

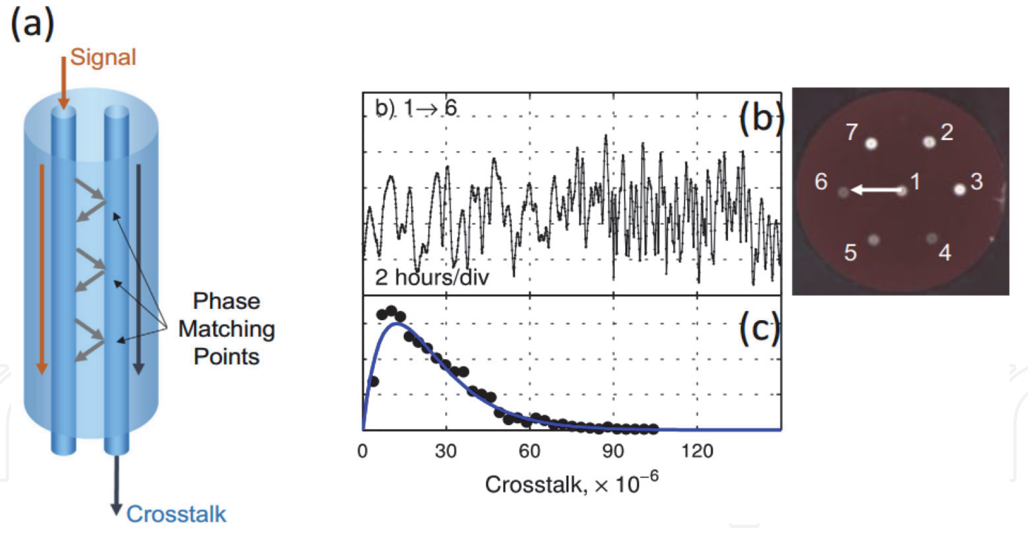

Figure 14.
(a) Mechanism of inter-core crosstalk, (b) time evolution of XT, (c) histogram of XT [12].

immense difficulty because to crosstalk, which may decrease the quality of optical data, caused by unintentional coupling between cores running in the same direction and wavelength, as shown in **Figure 14**.

Transmission is hampered by crosstalk in an MCF-based optical network, which may be reduced via power and mode coupling. So cladding widths vary. The cladding's strength decreases with increasing diameter. Each of these parameters must be changed. The MCF inter-core crosstalk is now calculated using coupled-mode and coupled power theories. First, MCF systems must agree on allowable crosstalk per length. Modern coherent optical communication systems have MCF crosstalk requirements regardless of transmission distance. Tolerable crosstalk has penalties for capacity, reach, universality transponder installation, and system link implementation [48, 49].

Ratio-reach trade-off of optical transponders capable of fine-tuning their modulation format to the channel circumstances through methods like probabilistic constellation shaping (PCS) for Nyquist pulses,

$$SE = 2.\log_2\left[1 + \frac{1}{\eta_{TRX}}\frac{P_S}{\left(\eta_L P_{ASE} + \chi P_S^3 + kP_s\right)}\right] \quad (1)$$

where $\text{SNR} = \frac{P_S}{\left(\eta_L P_{ASE} + \chi P_S^3 + kP_s\right)}$.

Ps is the per-channel (dual-polarization) signal launch power, and PASE is the per-channel (dual-polarization) amplified spontaneous emission power. For example, non-perfect amplification causes noise enhancement, beginning with PASE as the ASE from ideal distributed amplification. The parameter represents nonlinear interference noise (NLIN) and is calculated utilizing [50] formalisms. It indicates the average XT power due to other signals co-propagating at the same wavelength in different MCF cores. In the low coupling regime studied here, XT may be represented as AWGN, k increases linearly with distance, and interactions between XT and fiber nonlinearities can be disregarded.

MCF optical network crosstalk research for spectrum and fiber core allocations are many. As a consequence, to reduce crosstalk, all of the methods suggested reduced network capacity. A nearby core is already transmitting data on the same wavelength, therefore they do not send data on it. Recent work in [51] shows that optical signal counter-propagation across MCF cores may decrease crosstalk.

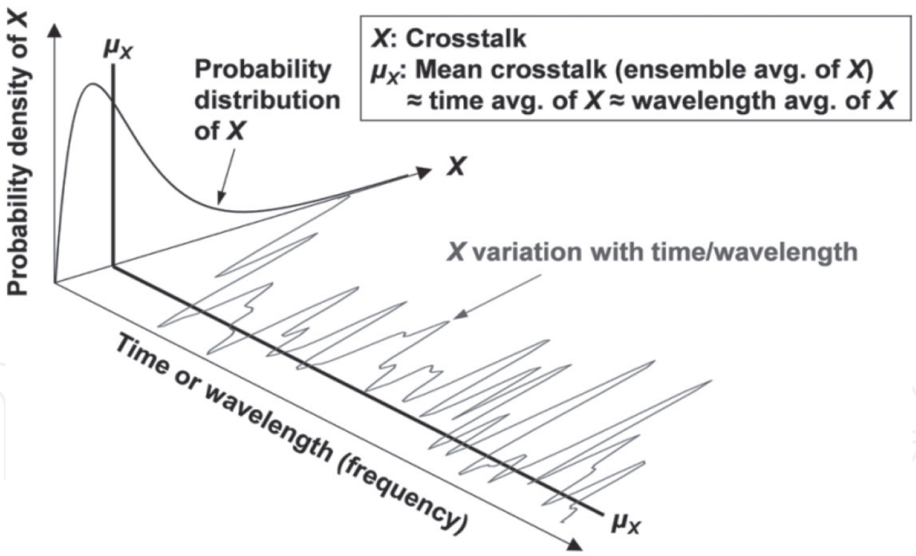

Figure 15.
Schematic diagram explaining stochastic behaviors and statistical parameters of XT in MCF [28].

Figure 15 shows XT's stochastic nature. The ensemble average X is characterized by the unpredictability of its behavior. The values of X are present in the MCF literature, but not explicitly stated. The instantaneous frequency of light is constant while the spectrum of the signal light is flat. Components of XT components that are sufficiently broad act as Gaussian noise, also called ASE noise, or nonlinear interference noise.

5.2 Non linearity

As a result of the numerous nonlinear distortions, the traditional single mode fiber properties are harmed. Many kinds of SDM fibers have been proposed. In all optical transmission and network scenarios, no single SDM fiber seems to be better than parallel SMF or ribbon fiber. To mention a few, connected core MCFs (CC-MCFs) have shown to be more resistant to non-linearity, resulting in a longer transmission distance as well as processing and amplification benefits. However, FMFs or FM-MCFs have more spatial channels per cladding diameter, making them more suited for short-distance, high-capacity connections [12, 17].

5.2.1 Self phase modulation (SPM)

The intensity dependence of the refractive index is the main source of SPM (i.e. optical Kerr effect). The change in refractive index as the signal passes through the fiber. Positive and negative refractive index gradients have leading and trailing edges. The total load at the user end of a PoF connection is dictated by the PV cell's conversion efficiency (detector). Eq. (2) states the mathematical connection, Eq. (3).

$$P_{load} = P_{in} * \eta_{pv} \tag{2}$$

$$P_{in} = \frac{P_{load}}{\eta_{pv}} \tag{3}$$

The nonlinear phase change due the SPM is given by the Eq. (**4**).

$$\varphi_{nl} = k_{nl} * P_{in} * L_{eff} \tag{4}$$

Where k_{nl} denotes the nonlinear component of the propagation constant and L_{eff} denotes the effective length. The following phase equation may be recast in terms of P_{load}, demonstrating that the nonlinear phase distortion in Eq is caused by load power (5).

$$\varphi_{nl} = k_{nl} * \frac{P_{load}}{\eta_{pv}} * L_{eff} \tag{5}$$

5.2.2 Cross phase modulation (XPM)

It is a nonlinear optical phenomenon produced by intensity changes in refractive index. XPM is guided by SPM since both rely on the refractive index and intensity of separate transmission pulses. Asymmetric spectrum broadening and signal distortion are caused by power and refractive index changes. The effective refractive index is given by Eq. (6).

$$\eta eff = \eta\,\mathrm{l} + \eta\mathrm{nl}\left(\frac{P_{in}}{A_{eff}}\right) \tag{6}$$

This is the linear component of the refractive index profile. Similarly, as seen in Eq., the propagating constant is defined as linear and nonlinear (7)

$$k_{eff} = k_l + k_{nl} * A_{eff} \tag{7}$$

The effective refractive index and propagation constant are proportional to the effective area. It is possible that the number of cores required for high power applications has a substantial effect on the link's nonlinear distortion. Also in Eq., the core multiplicity factor [21] and N-number of core and D-cladding diameters define the A_{eff} (8)

$$A_{eff} = \left[CMF * \left(\frac{D}{2}\right)^2 * \pi\right]/N \tag{8}$$

Thus the Eq. (7) can be re written

$$\eta_{eff} = \eta_l + \eta_{nl}\frac{N}{CMF * (D/2)^2 * \pi} \tag{9}$$

According to Eq. (9), the effective refractive index (cause of XPM) is likewise affected by the number of cores in MCF.

5.2.3 Stimulated Raman scattering (SRS)

MCF has a large doped area where several optical beams may propagate. SRS is created when nonlinear acoustic vibrations interact with optical photons. The overlapping of the signal and pump electric fields at different excitation settings determines SRS efficacy. The effect of SRS for MCF for PoF connection has not been investigated. Because A_{eff} and L_{eff} influence threshold power, the number of cores, cladding diameter, and input pump power impact output power. Long-distance transmission weakens power signals, and optical beams' frequency changes downstream, producing signal loss [52].

5.2.4 Stimulated Brillouin scattering (SBS)

The performance of every optical link is affected by scattering. The number of cores improves the fiber's high power transmission capacity while decreasing the back scattered photon power, which influences the medium's nonlinearity and the acoustic photon. Within the core region, both weakly and strongly connected cores may be linear, triangular, rectangular matrix, tightly spaced hexagonal, or any other symmetric or asymmetric structure. The small core pitch type fiber has the greatest crosstalk and possible photo interaction. A PoF connection's maximal optical power transmission is limited by this interaction. Since the large numerical aperture (NA) is responsible for beam diffraction, the number of cores determines the SBS threshold. SBS changes depending on the medium's characteristics (homogeneous or birefringent) and the optical source. The thermally generated photon field affects the spectral breadth. The temperature of the fiber and its surroundings induce heat dispersion. The strain produced by internal heat may damage the fiber, reducing the output optical power. SBS has a lower effect on MCF than single mode fiber [53].

5.2.5 Optical pulse compression

MCF uses pulse compression and combination extensively. All MCF cores combine the injected optical signal. Structure and density determine signal compression. The MCF's nonlinearity produces self-focusing, anomalous dispersion, and wave collapse at high power levels. Due to the constant distance between MCF cores, the spatial non-uniformity of coupling is very important. The coupling coefficient, which determines Gaussian statistics, fluctuates with distance. Inhomogeneity in coupling causes phase mismatches and pulse delays that require special care [54].

5.2.6 Capacity wastage

If network capacity is bidirectional, overusing data centers wastes considerable capacity. To minimize MCF network effects, we asymmetrically distribute the fiber cores. It minimizes inter-core interference and allows for varying the amount of fiber cores on each side of a fiber connection. This minimizes network capacity wastage owing to mismatched bidirectional traffic demand. The suggested approach is tested on the MCF optical network's routing, spectrum, and core assignment (RSCA) problems. Two ILP models and a graph-based heuristic method are suggested to improve network spectrum usage [51].

6. Conclusion and future direction

Over the last decade, it has become apparent that MCF technologies are the only viable solution to the optical network's "capacity crunch" and other issues. Due to fiber nonlinearity, which limits growing transmission power and amplifier bandwidth. MCF should be operating by 2025. SDM's endurance and demand for telecommunications services must be shown. MCF just exceeded SSMF's maximum capacity. Increased capacity, dependability, and cost-effectiveness are required to allow broad use. New possibilities in multi-mode, spatial coding, and efficient DSP are anticipated to improve the performance of next-generation optical communication systems. This chapter examines the realities of multi-core fiber-based SDM optical wiring. The most common SDM fiber is the UC-MCF. SDM fibers use MIMO DSP to cope with modal XT.

Bidirectional traffic demand asymmetry is growing, leading to substantial capacity waste while building and running an optical transport network. Asymmetric and counter-propagating MCF fiber core allocation is advised for MCF optical networks. Assigning a flexible number of fiber cores in opposing directions to reduce network capacity waste owing to asymmetric traffic demand.

Inter-core crosstalk and traffic demand imbalance are significant factors in MCF optical network design. This network's design reduces inter-core crosstalk and capacity waste owing to bidirectional traffic demand imbalance.

Assemblies and PIC fabrication procedures are all part of SDM. When light couples the fibers, the cores converge and link the PICs. It includes extending the cores and attaching them to the PIC entrances through photonic wire bonding. Complicated handling and fusing are needed, but time-control introduces propagation delays.

Power over fiber technique uses multicore fiber structures. This chapter examined various MCF variations. The hexagonal MCF form is recommended for high power applications. Our MCF losses were also addressed. Nonlinear distortions in MCF act differently than in SMF. Some nonlinearity compensating methods, such pre-distortion, may also help reduce the impact of such distortions. The fiber cores, modes, or a mix of both provide new difficulties and possibilities for future research.

Acknowledgements

We thank Dr. Muneer Azam for assistance with particular for comments that greatly improved the manuscript.

Author details

Muhammad Irfan Anis* and Hamdan Ali
High Performance Research Group, FEST, Iqra University, Karachi, Pakistan

*Address all correspondence to: mirfananis@iqra.edu.pk

References

[1] H. Furukawa and R. S. Luis, "Petabit-class Optical Networks Based on Spatial-Division Multiplexing Technologies," *2020 24th Int. Conf. Opt. Netw. Des. Model. ONDM 2020*, pp. 21–23, 2020, doi: 10.23919/ONDM48393.2020.9132998.

[2] Mansour A, Mesleh R, Abaza M. New challenges in wireless and free space optical communications. Opt. Lasers Eng. 2016;**89**:95-108. DOI: 10.1016/j.optlaseng.2016.03.027

[3] Al-zubaidi FMA. *Towards High Bandwidth Communication Systems : From Multi-Gbit / s over SI-POF in Home Scenarios to 5G Cellular Networks over SMF by*, no. May. 2021

[4] Y. Sagae, T. Matsui, T. Sakamoto, and K. Nakajima, "Ultra-Low Crosstalk Multi-Core Fiber with Standard 125-$µ$m Cladding Diameter for 10,000 km-Class Long-Haul Transmission," *IEICE Trans. Commun.*, p. 2019OBI0001, 2020.

[5] T. Matsui *et al.*, "Multi-Core Fiber with Standard Cladding Diameter," pp. 4–5.

[6] Matsui T, Sagae Y, Sakamoto T, Nakajima K. Design and applicability of multi-core fibers with standard cladding diameter. J. Light. Technol. 2020;**38**(21):6065-6070. DOI: 10.1109/JLT.2020.3004824

[7] Zhao Y, Hu L, Zhu R, Yu X, Wang X, Zhang J. Crosstalk-Aware Spectrum Defragmentation Based on Spectrum Compactness in Space Division Multiplexing Enabled Elastic Optical Networks with Multicore Fiber. IEEE Access. 2018;**6**(4):15346-15355. DOI: 10.1109/ACCESS.2018.2795102

[8] Kitayama KI, Diamantopoulos NP. Few-Mode Optical Fibers: Original Motivation and Recent Progress. IEEE Commun. Mag. 2017;**55**(8):163-169. DOI: 10.1109/MCOM.2017.1600876

[9] Kareem FQ et al. A Survey of Optical Fiber Communications: Challenges and Processing Time Influences. Asian J. Res. Comput. Sci. 2021;7(4):48-58. DOI: 10.9734/ajrcos/2021/v7i430188

[10] Van Weerdenburg J et al. 138-Tb/s Mode- and Wavelength-Multiplexed Transmission over Six-Mode Graded-Index Fiber. J. Light. Technol. 2018;**36**(6):1369-1374. DOI: 10.1109/JLT.2018.2791100

[11] Y. Awaji, "Review of space-division multiplexing technologies in optical communications," *IEICE Trans. Commun.*, no. 1, 2019, doi: 10.1587/transcom.2017EBI0002.

[12] Awaji Y et al. High-capacity transmission over multi-core fibers. Opt. Fiber Technol. 2017;**35**:100-107. DOI: 10.1016/j.yofte.2016.09.008

[13] Y. Xie, L. Pei, J. Sun, J. Zheng, T. Ning, and J. Li, "Optimal design of a bend-insensitive heterogeneous MCF with differential inner-cladding structure and identical cores," *Opt. Fiber Technol.*, vol. 53, no. March, p. 102001, 2019, doi: 10.1016/j.yofte.2019.102001.

[14] Y. Xie, L. Pei, J. Zheng, Q. Zhao, T. Ning, and J. Li, "Low-DMD and low-crosstalk few-mode multi-core fiber with air-trench/holes assisted graded-index profile," *Opt. Commun.*, vol. 474, no. June, p. 126155, 2020, doi: 10.1016/j.optcom.2020.126155.

[15] C. Antonelli, G. Riccardi, T. Hayashi, and A. Mecozzi, "Role of polarization-mode coupling in the crosstalk between cores of weakly-coupled multi-core fibers," *Opt. Express*, vol. 28, no. 9, p. 12847, 2020, doi: 10.1364/oe.391092.

[16] H. Yuan *et al.*, "Experimental Analysis on Variations and Accuracy of Crosstalk in Trench-Assisted Multi-core Fibers," pp. 1–14, 2020, [Online]. Available: http://arxiv.org/abs/2008.08034.

[17] A. K. Vyas, "Analysis of different structure and nonlinear distortion of multicore fiber for power over fiber applications," *Optik (Stuttg).*, vol. 168, pp. 184–191, 2018, doi: 10.1016/j.ijleo.2018.04.106.

[18] Shibahara K, Mizuno T, Lee D, Miyamoto Y. Advanced MIMO Signal Processing Techniques Enabling Long-Haul Dense SDM Transmissions. J. Light. Technol. 2018;**36**(2):336-348. DOI: 10.1109/JLT.2017.2764928

[19] I. Morita, K. Igarashi, H. Takahashi, T. Tsuritani, and M. Suzuki, "Trans-oceanic class ultra-long-haul transmission using multi-core fiber," *Opt. Express*, vol. 22, no. 26, p. 31761, 2014, doi: 10.1364/oe.22.031761.

[20] Mendinueta JMD, Shinada S, Hirota Y, Luis RS, Furukawa H, Wada N. Converged inter/intradata center optical network with packet super-channels and 83.33 Tb/s/port. J. Light. Technol. 2019;**37**(2):571-578. DOI: 10.1109/JLT.2018.2877815

[21] M. Jiang, C. Chen, B. Zhu, and F. Hu, "MIMO-free WDM–MDM bidirectional transmission over OM3 MMF," *Opt. Commun.*, vol. 473, no. April, p. 125988, 2020, doi: 10.1016/j.optcom.2020.125988.

[22] K. Nakajima, T. Matsui, K. Saito, T. Sakamoto, and N. Araki, "Space division multiplexing technology: Next generation optical communication strategy," in *2016 ITU Kaleidoscope: ICTs for a Sustainable World (ITU WT)*, 2016, pp. 1–7.

[23] Kaur G, Kaur G, Sharma S. Performance optimization of broadband communication system using hybrid parametric amplifier. Int. J. Appl. Eng. Res. 2017;**12**(14):4484-4490

[24] Nakajima K, Matsui T, Saito K, Sakamoto T, Araki N. Multi-core fiber technology: next generation optical communication strategy. IEEE Commun. Stand. Mag. 2017;**1**(3):38-45

[25] Sakamoto T et al. Spatial Density and Splicing Characteristic Optimized Few-Mode Multi-Core Fiber. J. Light. Technol. 2020;**38**(16):4490-4496. DOI: 10.1109/JLT.2020.2987351

[26] T. Hayashi *et al.*, "Field-Deployed Multi-Core Fiber Testbed," *OECC/PSC 2019 - 24th Optoelectron. Commun. Conf. Conf. Photonics Switch. Comput. 2019*, pp. 1–3, 2019, doi: 10.23919/PS.2019.8818058.

[27] B. J. Puttnam *et al.*, "Characteristics of homogeneous multi-core fibers for SDM transmission," *APL Photonics*, vol. 4, no. 2, 2019, doi: 10.1063/1.5048537.

[28] T. Hayashi and T. Nakanishi, "Multi-core optical fibers for the next-generation communications," *SEI Tech. Rev.*, no. 86, pp. 23–28, 2018.

[29] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Uncoupled multi-core fiber enhancing signal-to-noise ratio," *Opt. Express*, vol. 20, no. 26, p. B94, 2012, doi: 10.1364/oe.20.000b94.

[30] Puttnam BJ et al. 0.61 Pb/s S, C, and L-Band Transmission in a 125μm Diameter 4-Core Fiber Using a Single Wideband Comb Source. J. Light. Technol. 2021;**39**(4):1027-1032. DOI: 10.1109/JLT.2020.2990987

[31] Cho J et al. Trans-Atlantic Field Trial Using High Spectral Efficiency Probabilistically Shaped 64-QAM and Single-Carrier Real-Time 250-Gb/s 16-QAM. J. Light. Technol. 2018;**36**(1):103-113. DOI: 10.1109/JLT.2017.2776840

[32] Peng G-D. *Handbook of Optical Fibers*. Springer; 2019

[33] Xie X, Tu J, Zhou X, Long K, Saitoh K. Design and optimization of 32-core rod/trench assisted square-lattice structured single-mode multi-core fiber. Opt. Express. 2017;**25**(5):5119-5132

[34] A. Turukhin *et al.*, "105.1 Tb/s power-efficient transmission over 14,350 km using a 12-core fiber," *2016 Opt. Fiber Commun. Conf. Exhib. OFC 2016*, pp. 105–107, 2016, doi: 10.1364/ofc.2016.th4c.1.

[35] Z. Luo, S. Yin, L. Jiang, L. Zhao, and S. Huang, "Routing, Spectrum and Core Assignment based on Auxiliary Matrix in the Intra Data Center Networks using Multi-Core Fibers with Super Channel," in *Asia Communications and Photonics Conference/International Conference on Information Photonics and Optical Communications 2020 (ACP/IPOC)*, 2020, p. M4A.279, doi: 10.1364/ACPC.2020.M4A.279.

[36] J. M. D. Mendinueta, S. Shinada, Y. Hirota, H. Furukawa, and N. Wada, "High-Capacity Super-Channel-Enabled Multi-Core Fiber Optical Switching System for Converged Inter/Intra Data Center and Edge Optical Networks," *IEEE J. Sel. Top. Quantum Electron.*, vol. 26, no. 4, 2020, doi: 10.1109/JSTQE.2020.2969558.

[37] V. N. Korshunov, I. A. Ovchinnikova, S. S. Shavrin, N. A. Shishova, and A. Y. Tsym, "Spectral Efficiency and Information Transfer Rate over Optical Fibers in Spatial Parallelism," 2020 Syst. Signals Gener. Process. F. Board Commun., vol. 4, no. 1, pp. 0–3, 2020, doi: 10.1109/IEEECONF48371.2020.9078609.

[38] García Cortijo S. Distributed radiofrequency signal processing based on space-division multiplexing fibers. Valencia (Spain): Universitat Politècnica de València; 2020

[39] Tang F, Li Y, Shen G, Rouskas GN. Minimizing inter-core crosstalk jointly in spatial, frequency, and time domains for scheduled lightpath demands in multi-core fiber-based elastic optical network. J. Light. Technol. 2020;**38**(20): 5595-5607

[40] M. Morant, A. M. Trinidad, E. Tangdiongga, and R. Llorente, "Multi-core Fiber Technology supporting MIMO and Photonic Beamforming in 5G Multi-Antenna Systems : (Invited paper)," *2019 IEEE Int. Top. Meet. Microw. Photonics, MWP 2019*, pp. 1–4, 2019, doi: 10.1109/MWP.2019.8892041.

[41] J. Cariñe *et al.*, "Multi-core fiber integrated multi-port beam splitters for quantum information processing," *Optica*, vol. 7, no. 5, p. 542, 2020, doi: 10.1364/optica.388912.

[42] B. Annighoefer, A. Zeyher, and J. Reinhart, "Multi-core Fiber and Power-limited Optical Network Topology Optimization with MILP," 2021, [Online]. Available: http://arxiv.org/abs/2103.16981.

[43] Lee SH. Experimental study. Sch. Res. Music. 2017:81-88. DOI: 10.4324/9781315458090

[44] A. Samir, J. Ratkoceri, and B. Batagelj, "Multi-core optical fiber in a passive optical local area network," in *2018 International Conference on Innovative Trends in Computer Engineering (ITCE)*, 2018, pp. 77–82.

[45] D. Kumar and R. Ranjan, "Crosstalk Suppression using Trench-assisted Technique in 9-core Homogeneous Multi Core Fiber," *2017 14th IEEE India Counc.* Int. Conf. INDICON *2017*, pp. 6–9, 2018, doi: 10.1109/INDICON.2017.8487586.

[46] Rademacher G et al. High Capacity Transmission in a Coupled-Core Three-Core Multi-Core Fiber. J. Light. Technol. 2021;**39**(3):757-762. DOI: 10.1109/JLT.2020.3013966

[47] Lee Y, Tanaka K, Hiruma K, Nomoto E, Sugawara T, Arimoto H. Experimental demonstration of a highly reliable multicore-fiber-based optical network. IEEE Photonics Technol. Lett. 2014;**26**(6):538-540. DOI: 10.1109/LPT.2013.2296100

[48] A. Macho Ortiz, "Multi-Core Fiber and Optical Supersymmetry: Theory and Applications," 2019.

[49] Gene JM, Winzer PJ. A universal specification for multicore fiber crosstalk. IEEE Photonics Technol. Lett. 2019;**31**(9):673-676. DOI: 10.1109/LPT.2019.2903717

[50] C. Antonelli, O. Golani, M. Shtaif, and A. Mecozzi, "Nonlinear interference noise in space-division multiplexed transmission through optical fibers," *Opt. Express*, vol. 25, no. 12, p. 13055, 2017, doi: 10.1364/oe.25.013055.

[51] Tang F, Yan Y, Peng L, Bose SK, Shen G. Crosstalk-Aware counter-propagating core assignment to reduce inter-core crosstalk and capacity wastage in multi-core fiber optical networks. J. Light. Technol. 2019; **37**(19):5010-5027. DOI: 10.1109/JLT.2019.2927025

[52] Ceballos-Herrera DE, Gutierrez-Castrejon R, Alvarez-Chavez JA. Stimulated raman scattering and four-wave mixing effects on crosstalk of multicore fibers. IEEE Photonics Technol. Lett. 2018;**30**(1):63-66. DOI: 10.1109/LPT.2017.2774501

[53] Z. Zhao, M. A. Soto, M. Tang, and L. Thévenaz, "Demonstration of distributed shape sensing based on Brillouin scattering in multi-core fibers," *25th Int.* Conf. Opt. Fiber Sensors, vol. 10323, p. 1032393, 2017, doi: 10.1117/12.2267486.

[54] A. M. Rubenchik, I. S. Chekhovskoy, M. P. Fedoruk, O. V. Shtyrina, and S. K. Turitsyn, "Nonlinear pulse combining and pulse compression in multi-core fibers," *Opt. Lett.*, vol. 40, no. 5, p. 721, 2015, doi: 10.1364/ol.40.000721.