Switching in High-Capacity SDM networks

B. J. Puttnam[1], R. S. Luis[1], G. Rademacher[2], and H. Furukawa[1]

[1] NICT, 4-2-1 Nukui Kitamachi, Koganei, 184-8795 Tokyo, E-mail:ben@nict.go.jp
[2] University of Stuttgart. Pfaffenwaldring 47, 70569 Stuttgart, Germany

Abstract *We summarise switching strategies for high-capacity networks based on space-division multiplexing (SDM) fibers, including multi-mode fibers and both strongly and weakly coupled multi-core-fibers, and summarise some recent experiments in each fiber type.*

Introduction

Space division multiplexing (SDM) has been widely investigated as a means of multiplying the transmission capacity of optical fibers whilst increasing efficiency through integration and sharing of hardware and processing resources [1], [2]. The additional dimension provided by the spatial domain can also allow innovation in switching, network and control plane technologies [3, 4]. However, this opportunity comes with the challenge of how to provide the same level of flexibility as current wavelength division multiplexing (WDM) networks without also multiplying the requirement for switching resources [5]. The various approaches to spatial and wavelength switching each place some restriction in the space or frequency domain which may also have implications on approaches to integration. This is illustrated in Fig. 1, which shows how the order of multiplexing and thus integration is influenced by super-channel selection strategy, particularly considering the requirement for multiple-input multiple-output (MIMO) equalization for coupled SDM fibers.

In spectral or wavelength super channels [5], Fig. 1(a) and in particular with full spectral switching [6], each tributary is assigned a spatial channel with ROADMs performing spatial switching, giving the advantage of using only spatial switches with substantially lower loss than wavelength selective switches (WSSs) and without the need for full reconfiguration to add and drop channels [7]. This approach, often referred to as a spatial bypass [5], illustrated in Fig. 2 has been shown to allow low-loss ROADMs for long-distance transmission [8] as well as very high-capacity network nodes [9] that may also adopt wavelength switching only where higher granularity is required. This makes it naturally suited to uncoupled SDM fibers, where spatial sub-channels may be routed independently of each other such as in weakly-coupled Multi-core fibers (MCFs).

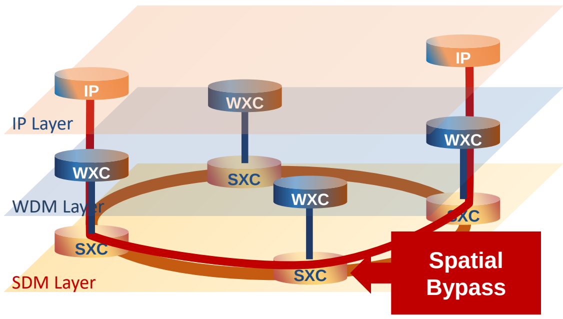

Fig. 2: Use of spatial switching can bypass WDM layer

Spatial super-channels, Fig. 1(b), group the data for a given tributary within the same frequency/wavelength band distributed across all spatial channels [10, 11]. Spatial super channels particularly lend themselves to coupled SDM fibers such as strongly coupled (SC)-MCFs [12] or few/multi-mode fibers (MMFs) [13] as it avoids the need for spatial demultiplexing at network nodes as well as naturally suiting sharing of transmitter and local oscillator lasers and potentially allowing integration of transceiver hardware compatible with MIMO processing.

Both switching approaches have been demonstrated in recent experiments, an overview of which are described in the following sections.

Spatial switching in weakly-coupled MCFs

The largest SDM switching demonstration reported to date constructed a ROADM switching node based on a 22-core MCF with petabit-per-second switching capacity. The demonstration used the hierarchical SDM architecture [5] utilizing low-loss spatial switches, summarized in

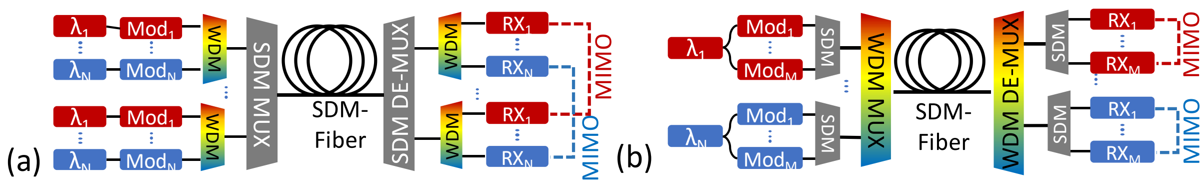

Fig. 1: Schematic diagrams of (a) multiplexing (MUX) strategy for spectral super-channel suitable for uncoupled SDM systems and (b) multiplexing strategy geared towards coupled SDMs with spatial super-channels

Fig. 3. One or multiple wavelengths or optical channels (OChs) within one or more spatial channels. (SChs) are then directed by spatial cross-connects (SXCs) through SDM transmission media, bypassing an overlying WDM layer and avoiding the corresponding penalty unless required for optical add/drop [5]. This relatively low-resource, low-loss switching approach also minimally impacts transmission quality, enabling demonstration of a high data-rate node capable of switching 22 SChs, each comprising up to 202 optical OChs. The node was integrated into a transmission test-bed using polarization-multiplexed (PM)-64-ary quadrature amplitude modulation (QAM) signals at 24.5 GBd aligned with the 25 GHz flex grid between 1527.60 nm and 1567.74 nm. The test bed was used to explore various networking, switching and transmission scenarios [4, 9], two of which, a spatial bypass scenario and optical add/drop and bypass scenario are summarised in Fig. 4.

Three of the 202 carriers were selected using a band-pass filter (BPF) for a high-quality sliding test band and performance measurement. They were split into odd and even carriers by an interleaver (IL) and modulated by a pair of dual-polarization IQ modulators (DPIQMs) driven by 4 arbitrary wavelength generators (AWGs) operating at 49 GS/s. The remaining 199 channels were generated using a DPIQM driven by an AWG with replicated and delayed output. An LCOS-based optical processor (OP) flattened the dummy band spectrum and carved a notch to accommodate the test band. The SCh, which transmitted 49 Tb/s assuming 20% FEC overhead, was amplified and split into 22 decorrelated replicas generating 22 SChs with a post-FEC throughput of 1.08 Pb/s.

The SXC was implemented using 44×44 unidirectional switch implemented with a 64×64 non-blocking bi-directional 3D MEMS switch with fiber transmission through a 22-core single-mode MCFs. The MCF cores were homogeneous trench-assisted cores arranged on a double ring

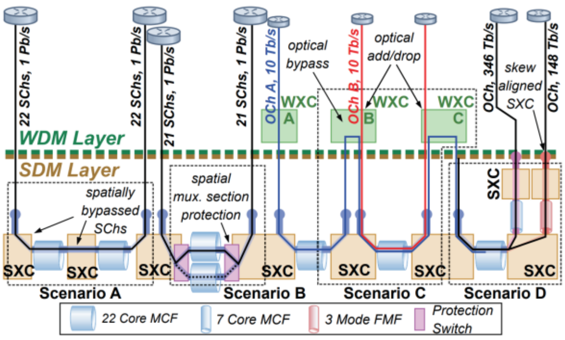

Fig. 3: Structure of WDM/SDM layered network

structure within a 260 µm cladding, as shown in the inset A of Fig. 4-a). The maximum combined fiber and fan in/out loss and crosstalk were 15 dB and -42 dB, respectively. At the receiver (RX), a switch selected the dropped SCh under analysis, which was pre-amplified by two EDFAs with a BPF used to isolate the channel under analysis. A coherent receiver (CoRX) with a local oscillator (LO) followed by a real-time digital storage oscilloscope (DSO) operating at 80 GS/s detected, sampled and stored traces for offline processing.

For the express scenario, the 22 SChs were transmitted through the MCF before switching from east to west line side of the SXC, bypassing any overlying WDM layer. Fig. 4-c) shows the estimated Q-factor values for the full add-drop and full express cases. The Q-factor was above 5.7 dB for all OChs with the wavelength profile conditioned by the EDFA gain spectrum. The SDM network node had a total data-throughput exceeding 1 Pb/s with a granularity of 10 Tb/s and shows that SDM network nodes can reach capacities comparable to the recent high throughput SDM transmission reports [2] with efficient use of switching resources.

ROADMS using coupled SDM fibers

Two notable network and switching demonstrations based on coupled SDM fibers been recently reported. Both experiments were performed at the deployed SDM fiber test-bed in

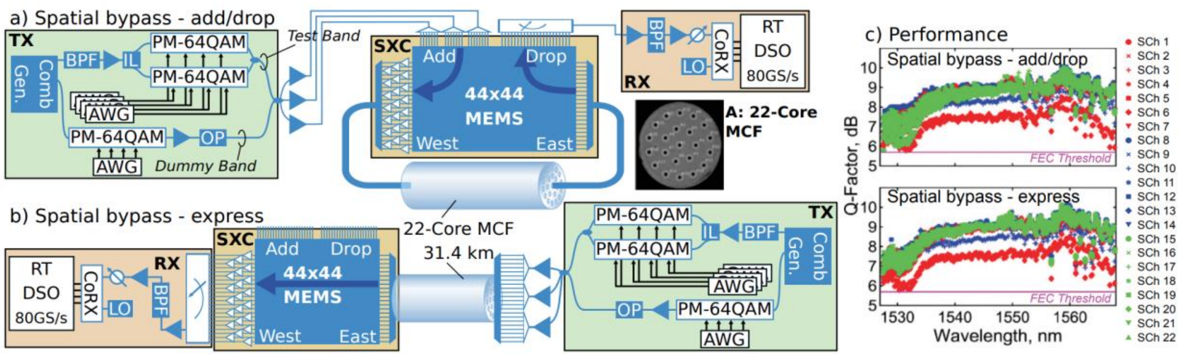

Fig. 4: Experimental setups for scenario A with full add/drop (a) and full express (b) switching. c) Q-factors estimated for all 202 OChs within each of the 22 SChs for full add/drop and express.

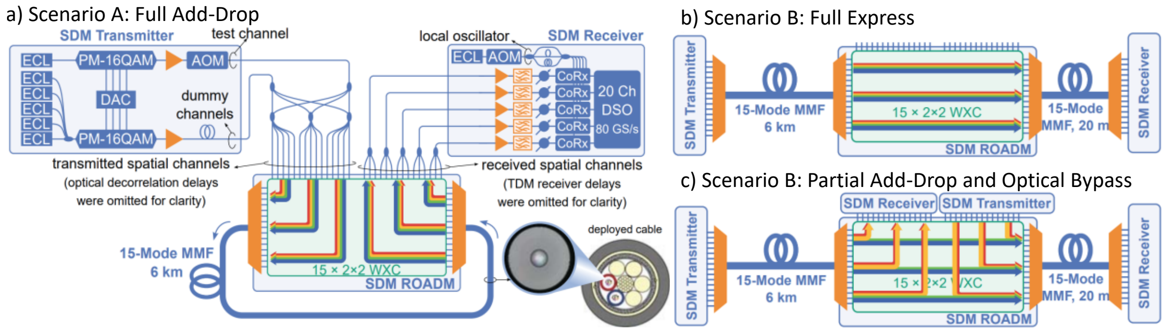

Fig. 5: Experimental setup for full add-drop (a) full express (b) and partial add-drop and bypass (c) scenarios for 15-mode ROADM demonstration.

the city of L'Aquila, Italy as part of the INCIPICT project. Both fibers, a MMF and SC-MCF, had a standard 125 µm cladding diameter making them attractive for high spatial density and compatibility with standard cabling infrastructure.

The first experiment [13] used a 15-mode fiber and reprogrammed commercial WSSs to demonstrate a high spatial spectral efficiency SDM ROADM. The network model used field-deployed 15-mode fibers and evaluated spatial super channel switching scenarios for full add-drop, full express, partial add drop, and optical bypass with a granularity of 5 Tb/s. The experimental setup for 3 of the explored scenarios is shown in Fig. 5. An SDM transmitter produced six, 75 GHz spaced, 50 GBaud PM-16QAM signals aligned with the ITU-T flex grid. A test channel and 5 dummy channels from tunable external cavity lasers (ECLs) were modulated by a pair of DPIQMs driven by four 100 GS/s digital-to-analog converters (DACs). The combined test and dummy channel spectrum was split into 15 replicas with optical decorrelation delays up to 1400 ns to emulate 15 independent SChs with an aggregated data-rate of 5 Tb/s per SSC and combined data-rate of 30 Tb/s, assuming 20% FEC overhead.

Both line sides were amplified and multiplexed using EDFAs and 15-mode multi-plane light conversion (MPLC) devices [15,16]. The transmission fiber was a 6 km span of a 15-mode graded index MMF, described in [17], and deployed in an underground cable with the structure shown in Fig.5-a. Fig. 5-b shows a simplified diagram of the full express, scenario. The SDM signals were first multiplexed and transmitted through the 15-mode MMF before reaching the SDM ROADM. There, they were directed to the other line side, and transmitted through a 20 m MMF segment. The partial add-drop and optical bypass scenario, shown in Fig. 5-c), used a similar set-up, with additional implementations of the ROADM's add and drop ports. The add port transmitter used a decorrelated copy of the primary SDM transmitter which was amplified and split into 15 replicase to act as dummy SCs shown in Fig. 5-a. The WXCs attenuation was adjusted to balance the power spectrum of the signal.

The 15-mode signals were demultiplexed and detected in a time-division multiplexing (TDM) receiver [18]. Signals from 5 groups of 3 modes were delayed and combined to be detected by 5 coherent receivers (CoRXs). To avoid time overlap and maintain phase noise consistency, the test channel and local oscillator were shuttered at a 33% duty cycle by acousto-optic modulators (AOMs). The 5 resulting signals were pre-amplified and filtered before detection and acquisition at an 80 GS/s DSO. Offline signal processing was based on a 30×30 MIMO updated using a data-aided algorithm, which switched to decision directed mode after convergence. For all scenarios, the measured Q-factor was above 5.7 dB threshold used to indicated compatibility with soft-decision FEC, demonstrating the feasibility of the 15-mode SSC transmission.

A second coupled SDM fiber experiment [12] meshed a spatial-super-channel switching SDM network using field-deployed 4-core SC-MCFs with a 3 line-side, colourless, directionless ROADM. The experimental demonstration also used reprogrammed WSS to evaluate 19 network scenarios including add-drop, bypass and grooming with 2 Tb/s granularity with BER measurements also confirming successful implementation of the investigated scenarios.

Summary

SDM switching demonstrations have shown the potential to match switching throughputs with previous high data-rate transmission experiments. Further, they offer potential for significant resource savings with required switching granularity, super-channel strategy and compatibility with coupled SDM fibers being significant design considerations.

References

[1] P. J. Winzer and D. T. Neilson, “From Scaling Disparities to Integrated Parallelism: A Decathlon for a Decade,” J. Light. Technol., vol. 35, no. 5, pp. 1099–1115, Mar. 2017, doi: 10.1109/JLT.2017.2662082.

[2] B. J. Puttnam, G. Rademacher, and R. S. Luís, “Space-division multiplexing for optical fiber communications,” Optica, vol. 8, no. 9, p. 1186, Sep. 2021, doi: 10.1364/OPTICA.427631.

[3] D. Klonidis, F. Cugini, O. Gerstel, M. Jinno, V. Lopez, E. Palkopoulou, M. Sekiya, D. Siracusa, G. Thouénon, and C. Betoule, “Spectrally and spatially flexible optical network planning and operations,” IEEE Commun. Mag., vol. 53, no. 2, pp. 69–78, Feb. 2015, doi: 10.1109/MCOM.2015.7045393.

[4] D. M. Marom and M. Blau, “Switching solutions for WDM-SDM optical networks,” IEEE Commun. Mag., vol. 53, no. 2, pp. 60–68, Feb. 2015, doi: 10.1109/MCOM.2015.7045392.

[5] M. Jinno, “Spatial Channel Network (SCN): Opportunities and Challenges of Introducing Spatial Bypass Toward the Massive SDM Era [Invited],” J. Opt. Commun. Netw., vol. 11, no. 3, p. 1, Mar. 2019, doi: 10.1364/JOCN.11.000001.

[6] A. C. Jatoba-Neto, D. A. A. Mello, C. E. Rothenberg, S. Ö. Arik, and J. M. Kahn, “Scaling SDM Optical Networks Using Full-Spectrum Spatial Switching,” J. Opt. Commun. Netw., vol. 10, no. 12, pp. 991–1004, Dec. 2018, doi: 10.1364/JOCN.10.000991.

[7] G.M. Saridis, B.J. Puttnam, R.S. Luís, W. Klaus, Y. Awaji, G. Zervas, D. Simeonidou and N. Wada, “Experimental Demonstration of a Flexible Filterless and Bidirectional SDM Optical Metro/Inter-DC Network,” Eur. Conf. Opt. Comms, vol. M.1.F.3, p. (2016).

[8] M. Jinno, T. Kodama, and T. Ishikawa, “Feasibility Demonstration of Spatial Channel Networking Using SDM/WDM Hierarchical Approach for Peta-b/s Optical Transport,” J. Light. Technol., vol. 38, no. 9, pp. 2577–2586, May 2020, doi: 10.1109/JLT.2020.2972367.

[9] R. S. Luís, B. J. Puttnam, G. Rademacher, T. A. Eriksson, Y. Hirota, S. Shinada, A. Ross-Adams, S. Gross, M. Withford, R. Maruyama, K. Aikawa, Y. Awaji, H. Furukawa, N. Wada, “Experimental Demonstration of a Petabit per Second SDM Network Node,” J. Light. Technol., vol. 38, no. 11, pp. 2886–2896, Jun. 2020, doi: 10.1109/JLT.2020.2988886.

[10] M. D. Feuer , L. E. Nelson, K. S. Abedin, X. Zhou, T. F. Taunay, J. F. Fini, B. Zhu, R. Isaac, R. Harel, and G. Cohen, “ROADM system for space division multiplexing with spatial superchannels,” in Optical Fiber Communication Conference, Optical Society of America, 2013, pp. PDP5B-8. Accessed: Jul. 25, 2014. [Online]. Available: http://www.opticsinfobase.org/abstract.cfm?uri=OFC-2013-PDP5B.8

[11] N. K. Fontaine, T. Haramaty, R. Ryf, H. Chen, L. Miron, L. Pascar, M. Blau, B. Frenkel, L. Wang, Y. Messaddeq, S. LaRochelle, R. J. Essiambre, Y. Jung, Q. Kang, J. K. Sahu, S. U. Alam, D. J. Richardson, and D. M. Marom, "Heterogeneous Space-Division Multiplexing and Joint Wavelength Switching Demonstration," in Optical Fiber Communication Conference paper Th5C.5.]

[12] R. S. Luis, G. Di Sciullo, G. Rademacher, B. J. Puttnam, A. Marotta, R. Emmerich, N. Braig-Christophersen, R. Stolte, F. Graziosi, A. Mecozzi, C. Schubert, T. Hayashi, T. Nagashima, C. Antonelli, and H. Furukawa, “Colorless and Directionless ROADM for Meshed Coupled-Core Multicore Fiber Networks,” in 2023 Optical Fiber Communications Conference and Exhibition (OFC), Mar. 2023, pp. 1–3. doi: 10.1364/OFC.2023.Th4C.3.

[13] R. S. Luis, B. J. Puttnam, G. Rademacher, T. A. Eriksson, Y. Hirota, S. Shinada, A. Ross-Adams, S. Gross, M. Withford, R. Maruyama, K. Aikawa, Y. Awaji, H. Furukawa, N. Wada., “Demonstration of a 1 PB/S spatial channel network node,” in 45th European Conference on Optical Communication (ECOC 2019), Sep. 2019, pp. 1–4. doi: 10.1049/cp.2019.1032.

[14] R. S. Luis, G. Rademacher, B. J. Puttnam, G. Di Sciullo, A. Marotta, R. Emmerich, N. Braig-Christophersen, R. Stolte, F. Graziosi, A. Mecozzi, C. Schubert, G. Ferri, F. Achten, P. Sillard, R. Ryf, L. Dallachiesa, S. Shinada, C. Antonelli, H. Furukawa “Demonstration of a Spatial Super Channel Switching SDM Network Node on a Field Deployed 15-Mode Fiber Network,” in 2022 European Conference on Optical Communication (ECOC), Sep. 2022, pp. 1–4.

[15] G. Labroille, B. Denolle, P. Jian, J.-F. Morizur, P. Genevaux, and N. Treps, “Efficient and mode selective spatial mode multiplexer based on multi-plane light conversion,” in 2014 IEEE Photonics Conference, Oct. 2014, pp. 518–519. doi: 10.1109/IPCon.2014.6995478.

[16] N. K. Fontaine, R. Ryf, H. Chen, D. T. Neilson, K. Kim, and J. Carpenter, “Laguerre-Gaussian mode sorter,” Nat. Commun., vol. 10, no. 1, Art. no. 1, Apr. 2019, doi: 10.1038/s41467-019-09840-4.

[17] P. Sillard, D. Molin, M. Bigot-Astruc, K. De Jongh, F. Achten, A. M. Velazquez-Benitez, R. Amezcua-Correa, and C. M. Okonkwo, “Low-Differential-Mode-Group-Delay 9-LP-Mode Fiber,” J. Light. Technol., vol. 34, no. 2, pp. 425–430, Jan. 2016, doi: 10.1109/JLT.2015.2463715.

[18] R. G. H. van Uden, C. M. Okonkwo, H. Chen, H. de Waardt, and A. M. J. Koonen, “Time domain multiplexed spatial division multiplexing receiver,” Opt. Express, vol. 22, no. 10, pp. 12668–12677, May 2014.