Petabit Class Transmission and Switching

Ruben S. Luis[1], Benjamin J. Puttnam[1], Georg Rademacher[1], Tobias A. Eriksson[1,2], Yusuke Hirota[1], Satoshi Shinada[1], Andrew Ross-Adams[3], Simon Gross[3], Michael Withford[3], Ryo Maruyama[4], Kazuhiko Aikawa[4], Yoshinari Awaji[1], Hideaki Furukawa[1], and Naoya Wada[1]

(1) National Institute of Information and Comm. Technol. (NICT), Koganei, Japan, rluis@nict.go.jp
(2) Infinera Corp., Stockholm, Sweden, formerly NICT, Koganei, Japan
(3) MQ Photonics Research Centre, Dep. of Physics and Astronomy, Macquarie University, Australia
(4) Fujikura Ltd., 1440, Mutsuzaki, Sakura, Chiba, Japan

Abstract *We evaluate the requirements for future spatial-division multiplexing networks operating at throughput higher than 1 Pb/s and discuss possible solutions to support ultra-high capacity.*

Introduction

In recent years, the throughput of communication systems has grown exponentially, with the required throughput of optical interfaces predicted to reach 10 Tb/s within core networks operating a 1 Pb/s by 2024[1]. To date, the most likely solution to have demonstrated potential to achieve this goal is spatial division multiplexing (SDM)[2]. SDM networks make use of parallel spatial channels (SCs), which may take the form of conventional fibers in fiber bundles, modes in few or multi-mode fibers, cores in multi-core fibers (MCFs), or combinations of these. Recent examples of petabit class transmission include 10.66 Pb/s transmission over a few-mode MCF with 114 SCs[3].

With SDM transmission, increasing the SC count may improve performance, cost, and energy efficiency[1]. The same cannot be stated for SDM networking as the number and port-count of wavelength-selective switches (WSS) per network node must be multiplied by the SC count in order to support the level of flexibility achievable with conventional wavelength-division multiplexing (WDM) networks. This multiplies the cost of network nodes and increases the corresponding penalty[4]. Hence, most SDM networking solutions in the literature rely on some form of switching restriction to reduce the necessary switching resources, such as the use of spatial super channels[5]. Recently, a hierarchical SDM network architectures has been proposed[4],[6], which splits spatial and wavelength switching into dedicated SDM and WDM network layers, respectively, as shown in Fig. 1. This allows for signals carried by dedicated SCs to bypass the WDM layer, when possible. In its extreme, this approach allows eliminating WDM switching altogether and rely solely on low-loss spatial switches to direct frequency super channels (FSCs) across the network[6]. This was the approach taken in the recent demonstration of a petabit class SDM network node[7]. In this paper, we review this work and discuss the main problems and potential solutions to carry this approach from laboratory conditions to real networks. Specifically, we address the capacity requirements for the SDM transmission media, the impact of skew between the transported signals, and the switching fabric for systems targeting more than 1 Pb/s throughput.

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Fig. 1 shows a simplified diagram of a hierarchical SDM network. In this example, the optical channel (OCh) A is sent to the SDM layer, where it is directed by spatial cross-connects (SXCs) using spatial switches through some form of SDM media within a dedicated SC. It is assumed that the SDM media allows for all optical spatial demultiplexing. In these conditions, this signal can bypass the overlying WDM layer entirely, avoiding the resources that would otherwise be required to switch it and the corresponding performance penalty. When it is necessary for OChs to share a SC, then optical bypass and add drop can be performed by directing those signals to the WDM layer using conventional wavelength cross-connects (WXCs).

This approach was recently used to demonstrate a petabit class SDM node[7]. Fig. 2-a) to

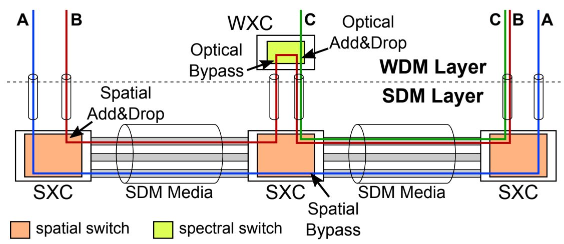

Fig. 1: Simplified diagram of a hierarchical SDM network.

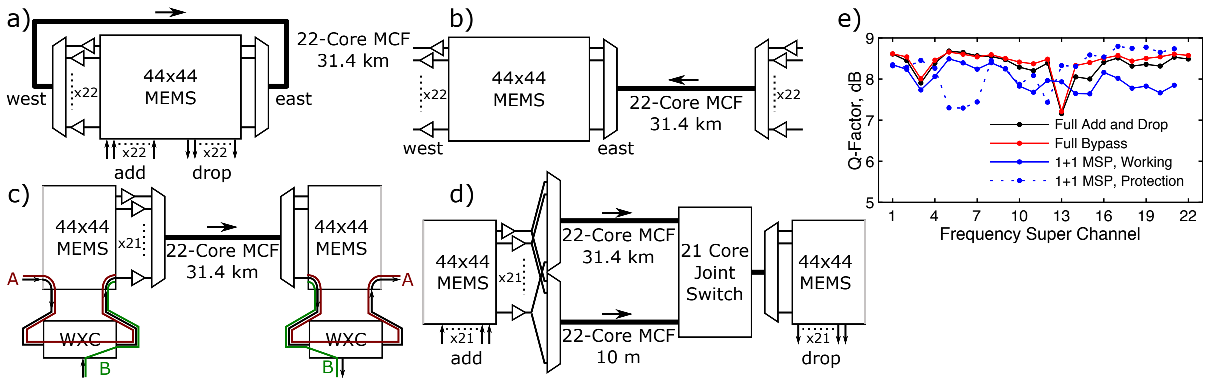

Fig. 2: Experimental setup for demonstration of a petabit class SDM network node. a) full spatial add and drop; b) full spatial bypass; c) optical add and drop and optical bypass; d) 1+1 multiplex section protection; e) performance for each scenario.

d) show simplified diagrams of 4 of the demonstrated network scenarios. The SXC consisted of a unidirectional 44×44 switch implemented using a prototype 64×64 bidirectional MEMS switch. This supported 2 line sides, each with a maximum of 22 SCs, and full add and drop. Transmission was performed on a 31.4 km, 22-core homogeneous MCF[8] with 3-D waveguide based fan-in/out devices, for spatial multiplexing. 22 independent erbium-doped fiber amplifiers (EDFAs) were used to boost the signal power. Each SC transported a FSC with 202 carriers transporting 24.5 GBd PM-64QAM signals within the C-band for an uncoded throughput of 59.38 Tb/s. The total uncoded throughput handled by the network was 1.306 Pb/s, which amounted to 1.088 Pb/s after forward error correction (FEC).

Fig. 2-c) shows the experimental setup used to demonstrate optical bypass. Two 10 Tb/s OChs, A and B, each composed of 49 carriers, were transported through the network within the same SC. Wavelength switching was performed in the WDM layer, using WXCs implemented with conventional WSSs and EDFAs for loss compensation. The OCh A was directed from the SDM layer to a WXC, where it was combined with B. Both signals where then sent back to the SDM layer and transported through the SDM network. After transmission, A and B were again directed to the WDM layer, where signal B was demultiplexed and dropped. Signal A was sent back to the SDM layer for transmission. Finally, Fig. 2-d) shows the experimental setup used to demonstrate 1+1 spatial multiplex section protection (MSP) using joint-spatial switches. The SDM signal was split after the booster EDFAs by 2×2 power splitters and multiplexed into working and protection MCFs with 31.4 km and 10 m length, respectively. Protection switching was performed at the receiver side using 3 joint spatial switches, each handling 7 SCs. As such, the system was limited to 21 SCs and a net throughput of 1.039 Pb/s. Fig. 2-e) shows the Q-factor of each of the 22 FSCs for the full add and drop, full bypass scenarios and 21 SCs of the 1+1 MSP scenario (working and protection paths). The Q-factors for OChs A and B on the optical bypass scenario (not shown in Fig. 2-e) were 9.1 dB and 8.8 dB, respectively. All considered cases presented Q-factors well above 5.7 dB, required for an FEC overhead of 20%[7].

Discussion

In order to accommodate the limitations of our laboratory, the experiment described in the previous section assumed a set of conditions that have limited applicability in real networks. From these, we highlight the physical dimensions of the MCF, which may render it unreliable for field deployment; the high FSC throughput, which would limit granularity; and the SXCs based on a single spatial switch, which would limit scalability of the node. In the following, we address these issues and potential means to solve them.

Transmission Media

A critical property of SDM transmission media is the number of supported SCs. Fig. 3 shows a theoretical estimate of the required number of SCs to support 1 Pb/s as a function of the transmission distance. It assumed 50 km spans, 50 Gbaud signals within a 50 GHz grid in the C-band, amplifiers with 5 dB noise figure and a wideband Gaussian noise model for fiber nonlinearities[9]. The throughput was computed assuming ideal FEC decoding. It is shown that even with high spectral efficiency PM-64QAM signals, the minimum number of SCs is 21, for links under 1000 km. In more realistic conditions, this is substantially higher, as shown in the previous section. For less spectrally efficient formats, such as PM-QPSK, the number of SCs

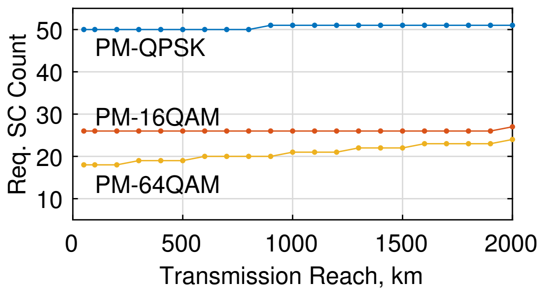

Fig. 3: Required number of spatial channels for 1 Pb/s transmission versus the transmission reach.

quickly rises above 50, which would extend to 100, if limiting FSC throughput to 10 Tb/s for the sake of granularity[6]. To date, these SC counts can only be achieved using fiber bundles or high core count few-mode MCFs[3],[10]. However, the latter require large cladding diameters to avoid inter-core crosstalk, which may reduce mechanical reliability for field deployment[11]. Furthermore, few-mode MCFs do not support all optical demultiplexing, which forces the use of spatial super channels instead of frequency super channels. Given these uncertainties, we consider that near-term petabit-class transmission will use fiber or MCF bundles, with the latter supporting 4 or 5 SCs and having the same dimensions and physical properties of standard fibers[12],[13]

Transmission Latency and Skew

Regardless of the transmission media, SDM in general requires massive serial-to-parallel-to-serial conversion in order to multiplex high-throughput data streams onto frequency or spatial super channels. As such, systematic or random varying skew between channels will require the use of buffering mechanisms at the receiver. If using spatial super channels, the skew results from the differences in propagation delay between fibers on a fiber bundle[14] or cores within an MCF[15]. In either case, the absolute skew values are difficult to predict, as they depend on the fabrication of the fiber and the environmental conditions[16]. As an example, Fig. 4 compares the relative inter-core skews of 4 spooled MCFs with 4, 7, 19, and 22 cores and cladding diameters of 125 µm, 160 µm, 200 µm, and 260 µm, respectively. The corresponding fiber lengths were 55 km, 53.7 km, 10.1 km, and 31.4 km. It is shown that the 4-core MCF has the lowest skew, under 0.2 ns/km. However, it increases up to 1.3 ns/km on the 22-core fiber. These high and hard to predict skew values discourage the use of spatial super channels in favor of FSCs. This approach has a more pre-

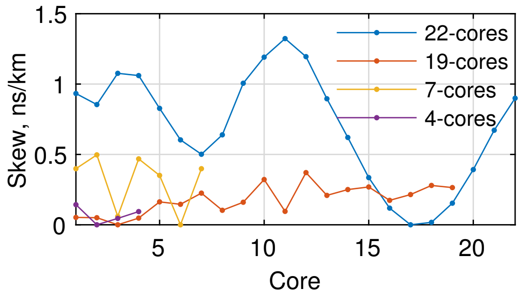

Fig. 4: Relative skew in 4, 7, 19 and 22-core MCFs.

dictable skew between channels, as it depends fundamentally on the fiber dispersion, D, WDM bandwidth, $\Delta\lambda$, and transmission distance, L, as $\Delta t \approx \Delta\lambda\, D\, L$. One may expect maximum skews around 760 ps/km when using the full C-band, regardless of the SC count. It then becomes possible to design buffers in order to accommodate transmission paths up to a given reach into commercial transceivers.

High Radix Switching

In the previous section, we used a single prototype non-blocking switch to implement an SXC. This was a straightforward implementation, with the switch port count given by $2NL$, where L is the number of line sides and N is the number of SCs. However, extending this system to support more than 2 line sides and up to 100 SCs, as previously estimated for petabit class networks, would rapidly increase the switch radix to prohibitive levels. Although current commercial switches can support 100s of ports, it is important to introduce more complex structures based on lower radix switches that allow scaling. Multiple node architectures have been proposed for this purpose[5],[6], from which we highlight the use of core selective switches (CSS). These are analogous to modern WSS for the spatial dimension by utilizing MCF ports and $N\times(L+1)$ switches[6]. Using CSS it becomes possible to implement SDM network nodes that scale with the network requirements, reducing the initial cost.

Conclusions

This paper has presented an overview of the latest achievements towards implementing petabit class optical networks. We have addressed some of the main requirements of such systems and presented some possible solutions to handle Pb/s throughput transmission, latency and switching.

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