Hybrid Optical Packet and Circuit Switching in Spatial Division Multiplexing Fiber Networks

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***Abstract*—We describe and demonstrate an approach for a hybrid optical packet switching and optical circuit switching spatial division network using homogeneous single-mode multi-core fibers. We show that this approach has potential to achieve acceptable levels of flexibility and granularity suitable for ultra high-capacity spatial division networks.**

I. Introduction

Space-division-multiplexing (SDM) technologies and networking have been widely proposed as cost-effective solutions to increase the transmission capacity in a single fiber with multiple cores and/or spatial-modes [1], [2]. In particular, the use of homogeneous single-mode multi-core fibers (MCF) enables perhaps the simplest migration path for adoption of high-capacity SDM technology in the near term [3]. They have been proposed for high-capacity and long-haul transmission [5], [4], access [6], and data-center and networking demonstrations [7], [8]. In all these cases, MCFs support the use of conventional single-wavelength optical channels, multi-wavelength super-channels (SC) and spatial super channels (SSC), as shown in Fig. 1. The latter correspond to a high-capacity data stream shared over multiple spatial channels and a given spectral occupation.

With the introduction of a new dimension (space) in optical networking comes a new set of networking challenges, including the optimization of huge bandwidth resources against the potentially limited switching resources in SDM network nodes [9]. The introduction of channel allocation maps based on spectral and spatial switching yields a potentially prohibitive demand on switching mechanisms. These will be required to assign optical signals to arbitrary sets of spatial channels and wavelengths [10], limiting the available network granularity or flexibility [11]. However, these schemes are based on the use of optical circuit-switching (OCS) extended to spatial super-channels (OCS-SSC) with quasi-static bandwidth allocation or, in the case of elastic networks, bandwidth that is flexibly assigned according to the present requirements. Recently, the use of optical packet switching (OPS) extended to spatial super channels (OPS-SSC) was proposed[8], enabled by novel optical switchining technologies, such as joint PLZT switches [12] and joint electro-absorption switches [13]. Such devices are specifically designed to share switching resources among multiple spatial channels simultaneously, enabling a joint OPS-SSC switch [8], [14]. Joint OPS-SSC switching has the potential to enable fine network granularity and energy-efficiency whilst providing both best-effort and QoS guaranteed services.

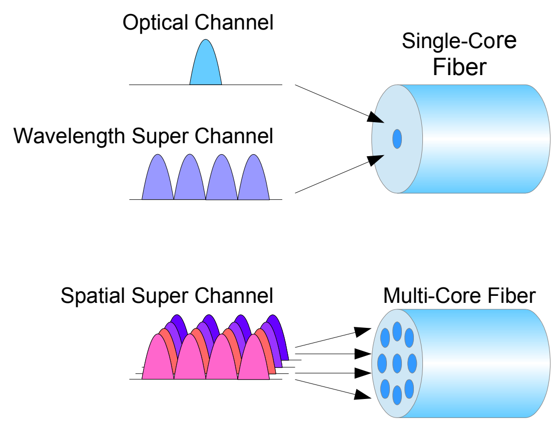

Fig. 1. Simplified structure of channel allocations for single-core/single-mode fiber networks and SDM networks.

In this work, we propose the joint usage of OPS-SSC and OCS-SSC in a hybrid SDM network. We address the advantages of this approach and provide corresponding SDM node architectures and channel allocation plans. Finally, we experimentally demonstrate an network, utilizing both OPS and OCS paths and carrying 400 Gb/s OPS-SSCs and 1 Tb/s OCS-SSCs on a 6-core configuration.

II. Integrated OPC and OCS SDM Networks

In this section, we investigate the potential for integrated OPS and OCS SDM networks. This concept was initially proposed in [14] to achieve diversification of services, adequate resource allocation, and efficient energy consumption while providing a multigranular SDM-WDM optical network. In a joint OPS/OCS SDM network, both OPS or OCS links can be flexibly established with arbitrary combinations of spatial channels and wavelengths, as shown in Fig. 2. In addition, non-data related slots may be allocated for the transmission of support signals, such as pilot-tones in the case of self-homodyne detection [11]. Joint spatial optical packet switches are used in network nodes to provide hardware efficient switching of ultra-high capacity OPS-SSC signals. Similarly, joint optical circuit switching as well as wavelength-selective switching can be used to provide hardware efficient switching of OCS-SSC. This approach is summarized in Fig. 3 where the different switching techniques can be organized into sub-switching systems within an SDM network node. Physical

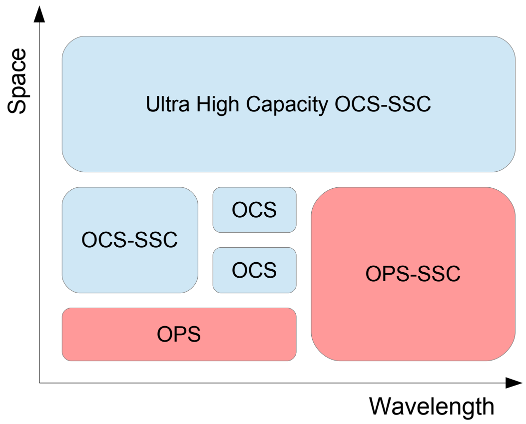

Fig. 2. Example of channel allocation for an SDM network.

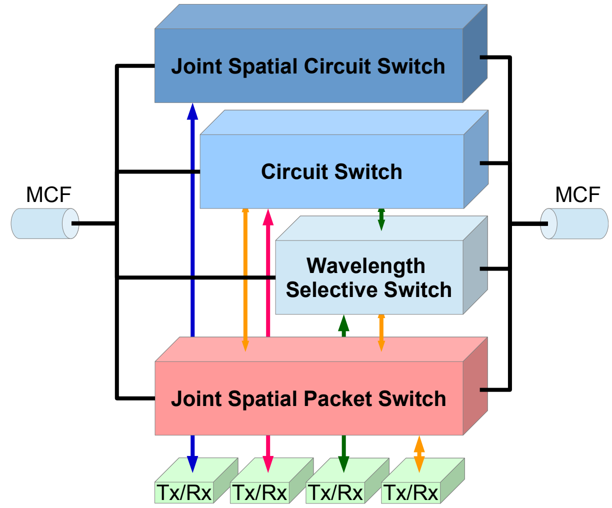

Fig. 3. Simplified diagram of a ROADM architecture for multigranular OPS and OCS SDM networks.

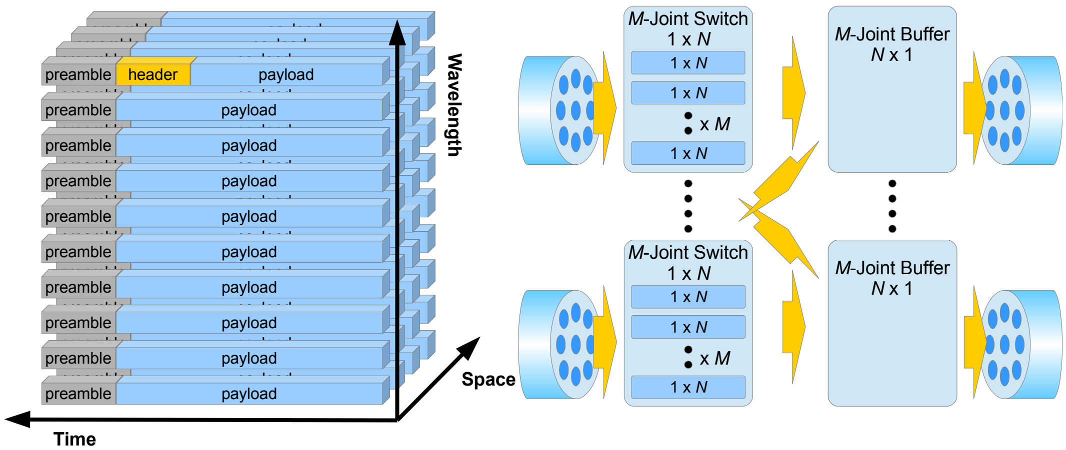

Fig. 4. Diagrams of the proposed OPS-SSC (left) and joint spatial packet switch (right).

connection to the MCFs is ensured using fan-in and fan-out devices though it may be forseable that such devices may no longer be required in the future with fully integrated spatial switching (e. g. [15]). Joint spatial circuit switching may be used to direct ultra high capacity OCS-SSCs using dedicated spatial channels whereas higher granularity OCS-SSCs sharing cores with other SSCs may be directed through combinations of circuit and wavelength selective switches. OPS-SSC signals are routed through joint optical packet switches as proposed in [8].

Fig. 4 shows the structure of the proposed OPS-SSC packets and corresponding switch, proposed in [8]. In this case, each packet consists of 10×10 Gb/s optical payloads wavelength and space division multiplexed over M spatial channels, to form an $M\times100$ Gb/s spatial channel OPS-SSC. The packet header is transmitted on only one of the spatial channels but used to jointly switch the signals on all of the spatial channels. Each 10 Gb/s signal also contains a preample for synchronization purposes. The joint switching architecture makes use of a single header processor common for all spatial channels, $1\times N$ M-joint optical switches that direct incoming spatial packets from the input MCF to $N\times1$ M-joint optical buffers. These consist of $1\times L$ switches followed by L delay lines, to control contention prior to the output MCF. A scheduler is used to coordinate operation of the switches and choice of delays. It has been shown that this architecture allows a significant reduction of the required number of switching elements, with respect to an architecture based on parallel switches [8].

III. Experimental Demonstration of a Joint OPS and OCS Network

Fig. 5 shows a simplified diagram of a joint OPC and OCS network designed to provide 400 Gb/s OPS paths and 1 Tb/s OCS paths. To reduce component cost and exploit the huge capacity provided by MCFs, it will be assumed that switching only takes place in the spatial dimension rather than

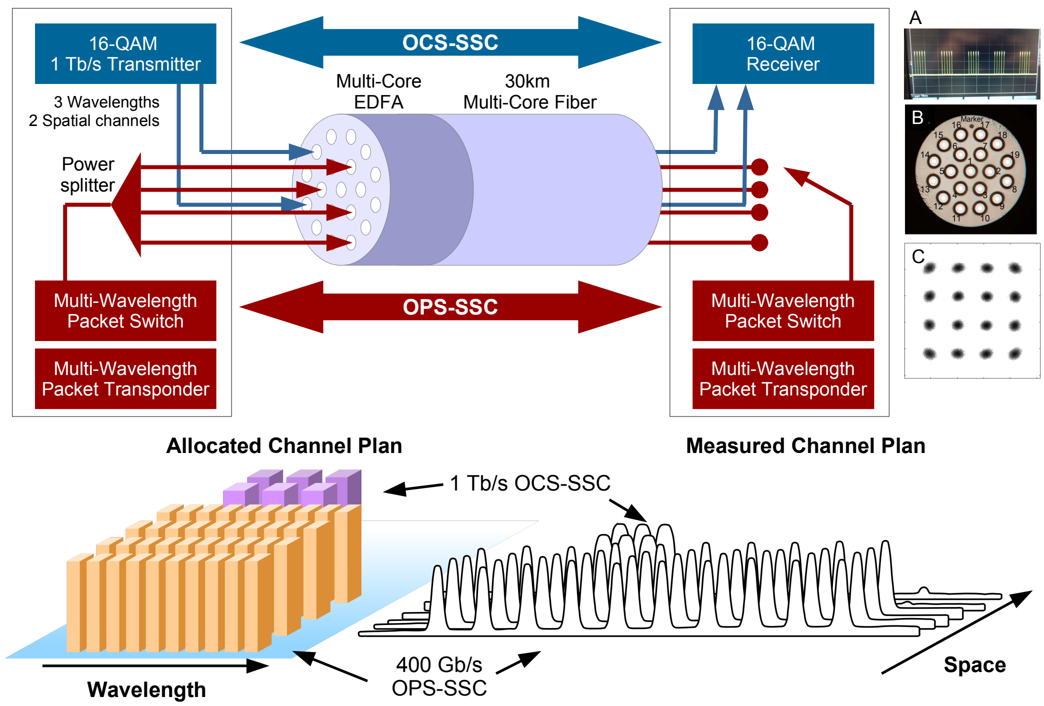

Fig. 5. Experimental setup for a joint OPC and OCS network demonstration.

the wavelength dimension in a single-core fiber network. This allows the use of spatial switching only, simplifying the SDM node requirements by providing joint spatial circuit switching as well as joint optical packet switching. We established an 1 Tb/s OCS SSC path using 2 cores and 3 wavelengths, each carrying a 24.5 Gbaud polarization-division multiplexed (PDM) 16-quadrature amplitude modulation (QAM) signals with a frequency spacing of 50 GHz for a total throughput of 1.1 Tb/s assuming 7% overhead for hard-decision forward error correction. To generate the OPS-SSC, we used a previously demonstrated optical packet transponder, which produced 100 Gb/s (10×10 Gb/s) optical packets [16]. We emulated the OPC-SSC by splitting the single-spatial channel optical packets into 4 spatial channels. Inset A of Fig. 5 shows traces of the transmitted optical packets with 7% network load.

For transmission we used a 30 km 19-core MCF preceded by a 19-core multi-core erbium-doped fiber amplifier (EDFA), both described in [17]. Inset B of Fig. 5 shows the fiber profile. Although significant additional capacity could be achieved with this fiber, due to limited laboratory resources, the experimental demonstration used only 6 of the available 19 cores. Similarly, the joint optical packet switch used after fiber transmission was emulated using a single-core switch and processing the optical packet signals on each core separately using a single-core switch with the performance estimated offline. Note however, that OPS spatial switching with this system has been previously demonstrated [14]. The optical packet switch consisted of a 2×2 electro-absorption switch, a switch controller and burst-mode EDFAs [18]. Frame error rate (FER) estimation was done by taking the individual FER of each spatial channel, FER_i and deriving the total FER as $FER \approx 1 - \prod_i (1 - FER_i)$. This approximation disregards potential error contributions from errors on the spatial channel carrying the packet header. Finally, the OCS-SSC was directed to a receiver, where the signal from each core was processed independently. We used offline digital signal processing in MATLAB and C to estimate the bit error rate (BER). The inset C of Fig. 5 shows an example constellation of the recovered PDM-16-QAM signals.

In this experiment, we considered network loads of 7% and 14% for the OPC-SSC and obtained FER values below the sensitivity limit of our measurement (1×10^{-6}). Furthermore, we have obtained error free (lower than 1×10^{-6}) 1 Tb/s 16-QAM transmission. For illustrative purposes, Fig. 5 also shows a comparison of the allocated channel plan with the optical spectra measured with an optical spectrum analyzer for each spatial channel. One may clearly distinguish between the 400 Gb/s OPS-SSC composed of 10 wavelengths and 4 spatial channels and the 1 Tb/s OCS-SSC using 3 wavelengths and 2 spatial channels.

IV. Conclusion

We describe and demonstrate the principle for a hybrid optical packet switching and optical circuit switching spatial division network. We show that this approach has potential to achieve the desired levels of flexibility, granularity and switching requirements suitable for ultra high-capacity spatial division networks.

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