Enhancing the flexibility and functionality of SCNs: demonstration of evolution toward any-core-access, nondirectional, and contentionless spatial channel cross-connects [Invited]

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A spatial channel network (SCN) was recently proposed toward the forthcoming spatial division multiplexing (SDM) era, in which the optical layer is explicitly evolved to the hierarchical SDM and wavelength division multiplexing layers, and an optical node is decoupled into a spatial cross-connect (SXC) and wavelength cross-connect to achieve an ultrahigh-capacity optical network in a highly economical manner. In this paper, we report feasibility demonstrations of an evolution scenario regarding the SCN architecture to enhance the flexibility and functionality of spatial channel networking from a simple fixed-core-access and directional spatial channel ring network to a multidegree, any-core-access, nondirectional, and core-contentionless mesh SCN. As key building blocks of SXCs, we introduce what we believe to be novel optical devices: a 1 × 2 multicore fiber (MCF) splitter, a core selector (CS), and a core and port selector (CPS). We construct free-space optics-based prototypes of these devices using five-core MCFs. Detailed performance evaluations of the prototypes in terms of the insertion loss (IL), polarization-dependent loss (PDL), and intercore cross-talk (XT) are conducted. The results show that the prototypes provide satisfactorily low levels of IL, PDL, and XT. We construct a wide variety of reconfigurable spatial add/drop multiplexers (RSADMs) and SXCs in terms of node degree, interport cross-connection architecture, and add/drop port connectivity flexibilities. Such RSADMs/SXCs include a fixed-core-access and directional RSADM using a 1 × 2 MCF splitter; an any-core-access, nondirectional SXC with core-contention using a CS; and an any-core-access, nondirectional SXC without core-contention using a CPS. Bit error rate performance measurements for SDM signals that traverse the RSADMs/SXCs confirm that there is no or a very slight optical signal-to-noise-ratio penalty from back-to-back performance. We also experimentally show that the flexibilities in the add/drop port of the SXCs allow us to recover from a single or concurrent double link failure with a wide variety of options in terms of availability and cost-effectiveness.

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1. INTRODUCTION

Space division multiplexing (SDM) technology enables simultaneous transmission of several spatially independent optical signals along optical fibers. It has gained widespread popularity due to its capability to overcome the fundamental capacity limit of a conventional single-mode fiber (SMF). A wide variety of new fiber structures is being developed worldwide that supports multiple guided spatial modes in a fiber. Such emerging SDM fibers include a nominally uncoupled multicore fiber (MCF), a few-mode fiber (FMF), a coupled-core MCF, and a few-mode MCF [1]. Optical node throughput should also be scaled in step with the increase in spatial mode counts per fiber link. There have been two approaches to addressing the optical node throughput scalability issue. The first approach is developing mixed-layer larger-scale wavelength division multiplexing (WDM)/SDM cross-connects [2–10]. Such efforts include the joint switching of spatial superchannels [2–7] and a subsystem-modular wavelength cross-connect (WXC)
architecture [8–10]. Here, it should be noted that in the optical node technologies proposed thus far, all traffic entering the node is still processed in the fine-granular wavelength domain, which may cause scalability and cost-effectiveness issues.

As another approach to offer a scalable and cost-effective optical networking solution in the future SDM era, the spatial channel network (SCN) architecture has recently been proposed [11–15]. In an SCN, the current optical layer evolves into hierarchical WDM and SDM layers. An optical node is decoupled into a spatial channel cross-connect (SXC) and a conventional WXC to form a hierarchical optical cross-connect (HOXC). This will enable us to accommodate a wide variety of traffic demands from the wavelength level to the spatial level. Adjacent SXCs are connected by an SDM link. An FMF or a coupled-core MCF could be used for such an SDM link; however, we assume that in the first-generation SCN, an SDM link would be based on a nominally uncoupled MCF or parallel SMFs, due to their higher compatibility with the current SMF-based optical transmission technology. Here, a single-mode core in an MCF or parallel SMFs are referred to as a spatial lane (SL), which is a unit of network resources of the spatial layer in the first-generation SCN. In an SCN, a spatial channel (SCh) is established by connecting unused SLs in each SDM link between SXCs on the route between the source and destination SXCs. A physical entity of an SCh is a concatenated SLs that serve as a virtual SMF, which is used to connect optical nodes in the overlying WDM layer, such as wavelength multiplexers/demultiplexers and WXCs, to form a spatial network topology in the WDM layer.

The HOXC architecture will yield two major benefits [11,15]. The first is an extension to the optical reach for optical signals that spatially bypass the overlying WDM layer through potentially low-loss SXCs. The second is a reduction in the total node cost by introducing potentially cost-effective coarse-granular spatial switching while maintaining a reasonably high spectral efficiency resulting from proper placement of WXCs in the network for spectral grooming.

The key building block in achieving scalable SXCs is a newly developed core selective switch (CSS) [11]. A CSS in SCNs plays a role similar to a conventional wavelength selective switch (WSS) in current WDM networks. A CSS has one input MCF port and \( n \) output MCF ports (\( 1 \times n \) CSS). The function of a CSS is to connect each core spatially in the input MCF to a core with the same core index in one of the \( n \) output MCFs so that all WDM signals, e.g., in the C-band, injected into any core of the input MCF can be routed to any of the \( n \) output MCF ports. It can be used in the reverse direction (\( n \times 1 \) CSS) so that for each core index, the core in only one of the \( n \) input MCFs can be connected with the core of the output MCF while cores of all other input MCFs are blocked. A CSS-based SXC does not provide the SL change (core interchange) functionality, just as a conventional WSS-based reconfigurable optical add/drop multiplexer (ROADM) does not provide the wavelength conversion functionality. Recently, a \( 1 \times 6 \) CSS that supports five-core MCFs with a standard 125 μm cladding was prototyped based on free-space optics with input and output MCFs each attached to a graded index lens, which serves as a collimator, spatial multiplexer (SMUX), spatial demultiplexer, condenser lens, and liquid-crystal-on-silicon spatial light modulator [14]. More recently, an ultrawideband (130 nm), compact (\( \sim 50 \) mm), low insertion loss (IL) (<2.7 dB), and low polarization-dependent loss (PDL) (<0.25 dB) five-core \( 1 \times 8 \) CSS employing a microlens array and a microelectromechanical systems (MEMS) mirror array was shown [16].

Figure 1 shows the basic SXC architecture with a node degree of \( D \) where ingress and egress \( 1 \times D \) CSSs are arranged in the route and select (R&S) configuration. Here, \( D - 1 \) ports in the CSSs are for passing through SChs, and the remaining one port linked to a fan-in and fan-out (FIFO) device is for terminating SChs. Since each SMF port of a FIFO device is dedicated to a particular core in a particular direction, this architecture is referred to as fixed-core-access and directional.

If we recall that WSSs were first introduced to a simple two-degree ROADM in a broadcast and select (B&S) configuration in a WDM ring network, the first practical application of CSSs might be a simple two-degree B&S reconfigurable spatial add/drop multiplexer (RSADM) in an SCh ring network. In the same way that ROADMs have evolved from two-node-degree ROADMs to multidegree ROADMs or WXCs, RSADMs should evolve to multidegree RSADMs or SXCs [9]. Furthermore, there should be a wide variety of add/drop port architectures and technologies to achieve more flexible connectivity in a CSS-based SXC at the expense of increased node complexity. So far, a wide variety of modular SXC architectures with different connection flexibilities have been proposed, and trade-off analysis between node complexity and connection flexibility has been conducted [13]. In addition, a technoeconomic analysis of SCNs comprising HOXCs showed that hierarchical spatial bypassing and spectral grooming are beneficial in terms of the required number of SLS and network-total node cost [15].

The purpose of this paper is to report feasibility demonstration of an evolution scenario regarding the SCN architecture to enhance the flexibility and functionality of SCh networking from a simple fixed-core-access and directional SCh ring network to a multidegree, any-core-access, nondirectional, and core-contentionless mesh SCN. Table 1 summarizes architectural options and associated key components in designing SXCs and SCNs. This paper is an integrated and extended version of recent conference papers [17–20] that includes more detailed experimental results and novel failure recovery
Table 1. Architectural Options and Associated Key Components in Designing SXCs and SCNs

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<th>Option B</th>
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<td>Mesh (3~8)</td>
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<td>Cross-connection architecture (key component)</td>
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functionality. Key building blocks of SXCs reported in this paper are a 1 × 2 MCF splitter, a core selector (CS), a core and port selector (CPS), and a 1 × n CSS. Since a 1 × n CSS was reported in detail in [14], details of the operating principle and performance evaluation results will be reported only for the first three components in this paper.

The rest of this paper is organized as follows. Section 2 describes an SCh ring network based on a simple two-degree RSADM equipped with a 1 × 2 MCF splitter. Section 3 describes SCh mesh networks that employ a wide variety of SXc architectures using a CS or CPS. A cost-effective and highly survivable protection scheme is also presented. Section 4 presents our conclusions.

2. SCH RING NETWORK BASED ON A B&S RSADM

A. Network and Node Architectures

Historically speaking, WSSs were first introduced to a simple two-degree ROADM in a B&S configuration in a WDM ring network. Based on this fact, the first application of CSSs might be a simple two-degree B&S RSADM in an SCh ring network, as shown in Fig. 2(a). Figure 2(b) shows the simplest RSADM architecture: a fixed-core-access directional B&S RSADM that comprises a 1 × 2 MCF splitter, two 1 × C FIFOs, and a 1 × 2 CSS per degree [16]. Here, C is the number of cores in an MCF (C = 4).

In the 1 × 2 MCF splitter, the input MCF branches into two. One MCF branch is connected to the through port of the CSS, while the other is directed to the drop-side FIFO device. The add-side FIFO is connected to the add port of the CSS. The CSS selects which core of which input port to connect to the corresponding core of the output MCF. Through this implementation, an incoming SDM signal traversing each core of the input MCF is broadcast and signals destined for this node are received by receivers attached at the corresponding port of the FIFO device while they are blocked by the CSS. Signals originating from this node are multiplexed by the add-side FIFO device onto one of the input ports of the CSS and allowed to pass to the output MCF. Since each add and drop port of the FIFOs is permanently assigned to a specific core in a specific direction, this RSADM architecture is referred to as fixed-core-access and directional.

B. Key Components

One key component for a B&S RSADM is a 1 × 2 MCF splitter. Figure 3(a) shows a possible implementation of a 1 × 2 MCF splitter using free-space optics. In the MCF 1 × 2 splitter, an input MCF, ingress collimating lens, a half-mirror, egress collimating lenses, and two output MCFs for the through and reflected light beams (referred to as the through and reflected MCF ports, respectively) are placed apart by the focal length, f, of the collimating lenses. The placement is such that each light beam from the input MCF is focused on the same point of the half-mirror with a different angle associated with the core it exits and focused again on the facet of the output MCFs. Rotational and translational alignment of the MCFs should be performed.

A 1 × 2 CSS used for a fixed-core-access RSADM has basically the same architecture as that reported in [14], but its steering mirrors may have a rotation capability on only one axis because the small number of required MCFs allows us to align an input MCF and two output MCFs in one dimension, as shown in Fig. 3(b).

C. Feasibility Demonstration Experiment

1. MCF Splitter and CSS Prototypes

We constructed a B&S RSADM using a 1 × 2 MCF splitter prototype [18] and the 1 × 6 CSS prototype reported in [14].
(two of six output MCF ports of the 1 × 6 CSS are used). They are both based on an MCF with five cores (one center core and four outer cores) in a cladding with a 125 µm diameter, as shown in Fig. 4(a). Each outer core is placed 31.2 µm apart from the center core. The mode field diameter of each core is 9 µm [21]. Figure 4(b) shows a picture of the 1 × 2 MCF splitter prototype. Figure 4(c) shows the IL and PDL of the MCF splitter prototype for two output MCFs as a function of the wavelength, including the connector loss between the 1 × 4 FIFO device and the 1 × 2 MCF splitter prototype. The IL ranges from 3.2 to 3.8 dB, and the PDL is less than 0.2 dB for all cores in the two output MCFs over the C-band. During the measurement, we used 1 × 4 FIFO devices based on a thin-cladding SMF bundle that is accessible to the outer four cores in a five-core MCF [22]. When accessing the center core, we simply use a conventional SMF.

In a 1 × 2 MCF splitter and a 1 × 2 CSS based on free-space optics, due to reflection from the mirror, the light beam from each core of the input MCF focuses on a corresponding core in the horizontally flipped position at the reflected MCF port of an MCF splitter or the output MCF ports in a CSS, as shown in Figs. 3(a) and 3(b), respectively. Here, the arrow in the insets that show core positions indicates the direction of the key of the MCF connector attached at the end of an input/output MCF. Fortunately, using the reflected MCF port in the MCF splitter for through SChs and the through MCF for locally dropped SChs, respectively, as shown in Fig. 5, the horizontal flipping in the core position that occurs in the MCF splitter is restored to the original core position at the CSS. Insets to Fig. 5 show positions of the beams observed at each indicated position in the RSADM by using a spatial beam profiler when two outer cores, C3 and C4, are illuminated. We can see that the core arrangement of the output MCF and drop MCF is the same as that for the input MCF.

2. B&S RSADM Feasibility Demonstration

Feasibility of the B&S RSADM is evaluated by routing wideband optical data streams whose spectrum occupies the entire C-band in two operation modes: through and add/drop modes. The pre-forward-error-correction (pre-FEC) bit error rate (BER) for a 100 Gb/s dual-polarization quadrature phase shift keying (DP-QPSK) optical signal in the wideband optical data stream was measured in both operation modes while changing the optical signal-to-noise ratio (OSNR) of the received signals. A wideband optical data stream was generated by combining a 100 Gb/s DP-QPSK optical signal and dummy optical signal generated by shaping an amplified spontaneous emission (ASE) spectrum using a programmable optical filter (InLC OSG20) to emulate a fully loaded SCh in the C-band. A 1 × 4 SMF splitter creates four copies of the wideband optical data stream to be used as SDM signals, and each propagates through one of four outer cores of an MCF, as shown in Fig. 6.

BER measurements for the two operation modes (through and add/drop) were conducted using the experimental configuration shown in Figs. 7(a) and 8(a), respectively. In the through operational mode experiment, SDM signals entering the RSADM were emulated by four wideband optical data streams that are spatially multiplexed by a 1 × 4 FIFO device. The optical spectrum of an input data stream is shown in Fig. 7(b). The 1 × 2 MCF splitter broadcasts the four optical data streams, and the 1 × 2 CSS passes through all of them to the MCF link; then the SDM signals are spatially demultiplexed [see Fig. 7(c)] for BER measurement. On the other hand, in the add/drop operation mode experiment, a 1 × 4 FIFO
device spatially multiplexes four optical data streams onto the add port of the $1 \times 2$ CSS. The optical spectrum of the input data stream is shown in Fig. 8(c). The CSS selects all four optical data streams and passes them to an MCF link, while it blocks all the signals from the express port. The MCF link is connected to the input of the input MCF of the RSADM. The $1 \times 2$ MCF splitter broadcasts the four optical data streams and a drop-side $1 \times 4$ FIFO device spatially demultiplexes them [see Fig. 8(b)]. We can see from the spectra of the input and output data streams that the MCF splitter and the CSS used in the experiments have almost uniform transmission over the C-band.

Because cores in some output MCFs of the CSS prototype exhibit relatively high IL and high PDL [14], we use an output MCF with a low IL ($4.2 \sim 6.2 \text{ dB}$) and a core with a low PDL (less than 0.5 dB) for BER measurement, while other outer cores in the MCF are all filled by optical data streams. Figure 9 shows the pre-FEC BER in through and add/drop operation modes for a 100 Gb/s DP-QPSK optical signal in wideband optical data transmitted through one of the outer cores that are simultaneously routed by the RSADM. We can see that there is no OSNR penalty for either the through or add/drop operation modes.

3. SCH MESH NETWORK BASED ON SXCs

There are two aspects to the evolution scenario of the SCN to enhance network flexibility and functionality. One aspect is to increase the node degree to evolve from a simple SCh ring network based on RSADMs toward an SCh mesh network based on SXCs, as shown in Fig. 10(a). This can be achieved by introducing a $1 \times n$ CSS whose number of output ports, $n$, is equal to or greater than the required node degree, $D$, and arranging them in the R&S configuration, as shown in Fig. 1. Figure 10(b) shows a possible implementation of a $1 \times n$ CSS, where an input MCF and $n$ output MCFs are arranged in two dimensions and the tilt of each mirror can be adjusted in two angular dimensions.

A $1 \times n$ MCF splitter could be employed instead of the ingress $1 \times n$ CSS; however, the R&S configuration is more preferable for two reasons. One reason is that constructing a high port count $1 \times n$ splitter for an MCF is more difficult than doing so for an SMF. A high port count $1 \times n$ splitter
for an MCF could be constructed by cascading $1 \times 2$ MCF splitters or by cascading a spatial demultiplexer, SMF-based splitters, and SMUXs; however, this could be excessively bulky. Another reason is to avoid the inherent splitting loss of a high port count $1 \times n$ MCF splitter, which will increase the IL of an RSADM/SXC and nullify the benefit regarding the optical reach expansion obtained by introducing the spatial bypass [11].

The other aspect is to enhance the connection flexibility of add/drop ports for optical signals that are generated and received at the node from simple fixed-core-access and directional to any-core-access, nondirectional, and core-contentionless. In this section, we describe flexible SXC architectures, and feasibility demonstration experiments on establishing flexible SChs and recovery from single or double link failures.

A. Flexible SXC Architectures

1. Any-Core-Access Add/Drop Architecture

The first step toward more flexible SXCs would be to introduce add/drop ports that can access any core in the add/drop MCF, which is referred to as any-core-access functionality. The any-core-access functionality corresponds to the colorless functionality in current ROADMs, which is achieved by employing a sophisticated wavelength tunable transmitter and a wavelength tunable filter or a coherent receiver. The any-core-access functionality in an SXC is achieved by replacing the FIFO devices in the fixed-core-access SXC architecture shown in Fig. 1 with client-side CSSs and introducing a novel spatial switch referred to as a CS, as shown in Fig. 11(a). A CS has an input SMF and an output MCF with $C$ cores in its cladding and provides the functionality to connect a core of the input SMF to any of $C$ cores in the output MCF [12]. Unlike the fixed-core-access add/drop ports shown in Fig. 1, any-core-access add/drop ports do not have a permanently assigned core but can select any core in the add/drop MCF.

In general, increasing the port count in a CSS is relatively easier than doing so in a conventional WSS. This is because input and output MCFs can be arranged in two dimensions if micromirrors are able to change the tilt in two angular dimensions. If higher port count CSSs are available, a much simpler SXC with lower loss for add/drop signals can be achieved by removing the client-side CSSs and connecting CSSs directly to add/drop MCFs of the line-side CSSs, as shown in Fig. 11(b).

2. Nondirectional Add/Drop with Core-Contention Architecture

In the SXC architectures shown in Fig. 11, each add/drop port is always associated with a particular direction. The next step toward more flexible SXCs would be to achieve nondirectional add/drop ports. Figure 12 shows an SXC architecture that supports nondirectional add/drop ports. A nondirectional drop port can be achieved by introducing an aggregation CSS with $D$ output ports between ingress CSSs and a client-side drop CSS in the any-core-access add/drop architecture shown in Fig. 11(a). This architecture allows us to connect a receiver equipped at any port of the drop CSS to any core of any ingress MCF unless core-contention arises in the MCF linking the aggregation CSS and the drop CSS. In the same way, a nondirectional add port can be achieved by introducing a distribution CSS with $D$ output ports between egress CSSs and a client-side add CSS where a transmitter equipped at any port of the add CSS can be connected to any core of any egress MCF unless core-contention arises. We refer to this functionality as any-core-access, nondirectional with core-contention.

With this functionality, the network operator is able to provide and alter the route of an SCh through a network management system without manual intervention. The any-core-access, nondirectional functionality also enables remote or automatic protection/restoration of failed SChs in case of a fiber cut or intermediate SXC failure, yielding more reliable optical networks.

3. Nondirectional Add/Drop without Core-Contention Architecture

One way to eliminate the core-contention constraint to achieve highly flexible and efficient end-to-end SCh provisioning is to replace the CSs with another type of novel spatial switch, which is referred to as a CPS, as shown in Fig. 13(a). Here, a CPS has an input SMF and multiple output MCFs and provides a functionality to connect any core of an input SMF to any core of any direction unless the core is used by an existing SCh.
Again, if higher port count CSSs are available, a much simpler SXC with lower loss for add/drop signals can be achieved by removing the client-side CSSs and connecting CPSs directly to add/drop MCFs of line-side CSSs, as shown in Fig. 13(b).

**B. Key Components**

A possible implementation of a CS based on free-space optics is shown in Fig. 14(a). It comprises an input SMF, an output MCF, a condenser lens, and a MEMS mirror. The SMF and MCF are placed next to each other to create an SMF/MCF bundle. The fiber bundle, the lens, and the mirror are placed apart by the focal length of the condenser lens, \( f \). The light beam exiting the input SMF focuses on the mirror and reflects so as to be coupled to one of the cores in the output MCF by adjusting the tile of the mirror. No rotational alignment of the MCF is required. A CPS can be achieved by increasing the number of output MCFs in the SMF/MCF bundle, as shown in Fig. 14(b). Again, no rotational alignment of the MCFs is required.

**C. Feasibility Demonstration Experiments**

1. **CS/CPS Prototype**

Since a CS is a subset of a CPS, we constructed a CPS prototype that comprises an SMF and six MCFs that support five cores in their cladding, a condenser lens with a 10 mm focal length, and a MEMS mirror whose tilt can be controlled in two angular dimensions [19], as shown in Fig. 15(a). The SMF and six MCFs are closely packed without core rotation alignment, as shown in Fig. 15(b). The facets of the SMF/MCF bundle are polished at 8 deg to avoid Fresnel reflection.

Figure 15(c) shows the optimum mirror angles in two angular dimensions, \( \theta_x \) and \( \theta_y \), for each core of each output MCF. By comparing this figure and the cross-section picture of the input SMF and output MCFs shown in Fig. 15(b), the 2-f system employed in the CS/CPS architecture allows us to connect a beam exiting the input SMF to any core of any output MCF, whose core positions in the rotation direction are randomly arranged with each other, by adjusting the two-dimensional mirror angles.

Figure 16 shows the IL for the connection to MCF 2 via five cores labeled C0 (center core), C1, C2, C3, and C4 (outer cores) as a function of the wavelength in the C-band. The IL includes the IL of two 1 x 4 FIFO devices attached before and after the CPS prototype for launching light from a wavelength-tunable laser diode to each outer core and for spatially demultiplexing them into SMFs. The center core C0 exhibits the lowest IL of 1.3 dB at 1560 nm, and the IL gradually increases toward shorter wavelengths up to 2.0 dB at 1530 nm. Outer cores C1 to C4 exhibit slightly higher IL ranging from 1.4 to 2.1 dB at 1565 nm, which also increases toward shorter wavelengths. Variability observed in the IL is partly due to core-to-core IL variability in the FIFO devices used for the IL measurement. The slight oscillation observed in the IL...
Fig. 17. (a) IL and (b) PDL for each core of six output MCFs.

curves may be attributed to imperfect antireflection (AR) coating of the cover glass placed at the front of the MEMS mirror. This flaw causes a slight degradation in the BER versus OSNR performance of SXCs that employ the CS/CPS prototype, as will be described in the next subsection.

Figures 17(a) and 17(b) show the IL and PDL for each core connected to eight output MCFs when using ASE from an erbium-doped fiber amplifier for the C-band as an input light. Relatively uniform low IL characteristics from 0.8 to 2.1 dB and very low PDL of less than 0.25 dB are observed for each core of the output MCFs.

In order to confirm how much intra-MCF cross talk (XT) the CS/CPS prototype has, we measured the optical transmission for target core \( \eta_t \) and adjacent cores \( \eta_{\text{adj}} \) in the same output MCF 2, which is shown in Fig. 18. The intra-MCF XT is defined by \( \eta_{\text{adj}} - \eta_t \), expressed in decibels. We can see that the CS/CPS prototype provides relatively low intra-MCF XT of less than \(-40\) dB for all target cores.

2. Feasibility Demonstration Experiment: Nondirectional Add/Drop with and without Core-Contention

Using the CSS and CS/CPS prototypes, we constructed two types of any-core-access nondirectional SXCs with and without core-contention based on the SXC architectures shown in Figs. 12 and 13(b), respectively. Due to the limited availability of free-space-optics-based CSS and CS/CPS prototypes, only some of the SXCs are equipped with the prototypes, and other CSSs and CSs/CPSs comprising the SXC are constructed using bulk optics as described in [13]. In addition, in both types of SXCs, input and output MCFs for each direction on the line side of an SXC are connected to each other (loop-back configuration) to emulate a mesh SCN. We examined the feasibility of both SXC architectures over the following networking scenarios:

(i) Establish SCh 1 heading north and then SCh 2 heading west.
(ii) In response to a fiber cut in the north, reroute SCh 1 to the preplanned and dedicated westbound detour route for failure recovery.

The experimental configuration for testing an SXC having any-core-access and nondirectional features with core-contention is shown in Fig. 19(a). The \( 1 \times 6 \) CSS prototype is used as a client-side add CSS and the \( 1 \times 6 \) CPS prototype is used as a CS (one of six output MCFs in the CPS is used). Figure 19(b) shows states of the usage of each core in the MCFs heading west and north in the SXC. We can see that SCh 2 selects a core other than C2 (C3 in this example), even when C2 in the MCF heading west is unused, in order to avoid core-contention in the add/drop stage.

Quantitative characteristics of the SXC were evaluated by establishing two SChs through a wideband optical data stream that occupies the entire C-band and by measuring the pre-FEC BER of a 100 Gb/s DP-QPSK optical signal in the data streams while changing the OSNR of the received signals. Similar equipment as was used in Fig. 6 was used to generate and receive wideband optical data streams. Figures 20(a) and 20(b) show spectra for input and output wideband optical data streams, respectively. We can see that by adding and dropping at the SXC, the wideband optical data stream experiences an almost flat loss of approximately 14 dB across the C-band. A slight OSNR penalty of \( \sim 0.4 \) dB from the back-to-back performance was observed in the BER versus OSNR curve in Fig. 20(d), which is considered to be due to the imperfect AR coating of the cover glass in the MEMS mirror in the CPS prototype. We expect that this slight penalty can be reduced by removing the cover glass of the MEMS mirror, which is unnecessary for actual products.

Next, we intentionally cut the MCF directed north. We assumed that the network management system detects the loss of signal and orders the distribution and aggregation CSSs to switch the connection from the primary route to the backup westbound route that uses C3. Figure 19(c) shows states of the usage of each core in the MCFs for the reroute state heading...
Fig. 19. Experimental configuration for testing SXC having any-core-access and nondirectional features with core-contention.

Fig. 20. Spectra for input and output wideband optical data streams and BER versus OSNR performance in SXC with core-contention.

Fig. 21. Experimental configuration for testing SXC having any-core-access and nondirectional features without core-contention.

without core-contention. In this case, the $1 \times 6$ CSS prototype is used as a north line-side egress CSS and the $1 \times 6$ CPS prototype is used as an add CPS. Figure 21(b) shows states of the usage of each core in the MCFs heading west and north in the SXC. We can see that $SCh$ 2 can select $C2$ regardless of the core assignment state of the other MCFs. In this situation, when $SCh$ 1 is rerouted to the west, $SCh$ 1 must change cores to one other than $C2$ by using the CPS due to the non-core-overlap constraint in an MCF, as shown in Fig. 21(c). Similar experiments regarding $SCh$ establishment and rerouting are conducted using wideband optical data streams, including a 100 Gb/s DP-QPSK optical signal; the results are shown in Fig. 22. We confirmed that the SXC having any-core-access and nondirectional features without core-contention achieves $SCh$ protection through the nondirectional add/drop ports without any additional performance degradation compared to that for the primary route.

3. Feasibility Demonstration Experiment for Shared $SCh$ Protection

In contrast to the dedicated $SCh$ protection described in the previous subsection, shared $SCh$ protection potentially saves spare SL resources for failure recovery by sharing the spare SLs among multiple working $SCh$s that are node and link disjointed from each other. Shared $SCh$ protection is illustrated in Figs. 23(a) and 23(b). Two working $SCh$s are established on routes A-B and E-F, respectively; each $SCh$ accommodates optical channels (OChs) 1 and 2, as shown in Fig. 23(a). Here, an optical channel is defined as a channel in the WDM layer that carries an optical signal, which is created by concatenating frequency slots in one or several $SCh$s. When a failure on either of the working $SCh$s occurs, endpoints of the failed $SCh$ and intermediate SXC-C and SXC-D on the shared detour route...
Fig. 22. Spectra for input and output wideband optical data streams and BER versus OSNR performance in SXC without core-contention.

Fig. 23. Shared SCh protection for single-failure recovery and shared SCh protection with WDM layer fallback for double-failure recovery.

are notified of the failure and are reconfigured to form the detour SCh [SCh 1b in Fig. 23(b)].

Although shared SCh protection is more spare-resource efficient than dedicated SCh protection, it is generally more vulnerable to a second link failure. That is, shared SCh protection ensures 100% recovery from an arbitrary single link failure in the network; however, if there are simultaneous failures on both working SChs, contention for the shared protection resources arises. One way to mitigate this issue is to extend the concept of capacity fallback operation, which was first proposed in an elastic optical network [23], into SDM/WDM multilayer coordinative recovery operation.

Figure 23(c) illustrates how the fallback operation improves the survivability of an SCN employing shared SCh protection from concurrent double failures. Consider that a working SCh connecting A-B and a working SCh connecting E-F share a spare SL on link C-D, and link A-B and link E-F are simultaneously cut. In this situation, the operator first reduces the frequency slot widths of OCh 1 (for example, to the low-frequency side) and OCh 2 (to the high-frequency side). Then the preplanned detour SCh for the working SCh connecting A-B, SCh 1b, in Fig. 23(b) and preplanned detour SCh for the working SCh connecting E-F, SCh 2b (not shown), are divided into three shorter SChs, respectively. OCh 1 and OCh 2 (each frequency slot width is reduced in the opposite direction) are multiplexed into SCh 5 by a WXC equipped at SXC-C and demultiplexed into SCh 6 and SCh 7 by a WXC equipped at SXC-D. In this way, both OCh 1 and OCh 2 can survive from the concurrent link failures using the shared spare SL resource at the expense of a reduced bandwidth. This may be a good compromise in the case of a catastrophic disaster, where ensuring connectivity would be the first priority. We refer to this recovery operation as shared SCh protection with WDM layer fallback.

A feasibility demonstration experiment was conducted using the experimental configuration shown in Fig. 24. Due to the limited availability of free-space optics-based CSS and CPS prototypes, only some of the SXCs are equipped with the prototypes, and other CSSs and CPSs comprising the SXC...
are constructed using bulk 1 × 4 switches. WXCs comprise an optical splitter and a 1 × 2 WSS. In addition, we emulated two 1 × 2 CSSs (in blue) using the 1 × 6 CSS prototype. This can be achieved by using two MCFs among the seven MCFs in the 1 × 6 CSS prototype as input MCFs. We first established two working SChs (indicated by blue lines) that correspond to those in Fig. 23(a), as shown in Fig. 24(a). Wideband optical data streams were generated by combining a 100 Gb/s DP-QPSK optical signal and dummy ASE spectrum to emulate a fully loaded SCh in the C-band, as shown in Fig. 25(c), and by using an experimental configuration similar to that in Fig. 6. They were launched into the working SChs (SCh 1w and SCh 2w) through the CPS prototype and a bulk 1 × 4 switch.

Next, we intentionally cut MCF A-B on the upper route to simulate a first link failure. In response to the failure, we configured the CPS prototype and CSSs including the free-space-optics-based prototype in SXC-A, SXC-C, SXC-D, and SXC-B such that they concatenate the spare SLs along A-C-D-B to establish the protection SCh, SCh 1b. Figure 25(a) shows the OSNR versus pre-FEC BER performance of the 100 Gb/s DP-QPSK optical signal in the optical data stream received at SXC-B and SXC-F. Except for a slight OSNR penalty observed for SCh 1b, which may be attributed to the CPS prototype, as discussed in the previous subsection, there is no additional degradation from the back-to-back performance.

Following the first link failure on the upper route and the recovery using the protection SCh, SCh 1b, we cut MCF E-F on the lower route to simulate a second link failure. We eliminated core-contention for the shared protection resource in MCF C-D, which arises from the simultaneous link failures in the following manner:

(i) reducing the bandwidths of optical data streams generated at SXC-A and E, to the low- and high-frequency sides, as shown in Fig. 25(d);
(ii) splitting SCh 1b into three SChs: SCh3, SCh 5, and SCh 6;
(iii) establishing SCh 4 and SCh 7 for the recovery from the second failure;
(iv) multiplexing the two optical data streams in the WDM layer by a WXC equipped at site C and launching them into SCh 5; and
(v) demultiplexing and launching them into SCh 6 and SCh 7 through a WXC equipped at site D.

Figure 25(b) shows the OSNR versus pre-FEC BER performance of the 100 Gb/s DP-QPSK optical signal in the optical data stream received at SXC-B and SXC-F. We observed no degradation from the back-to-back performance except for a slight OSNR penalty due to the CPS prototype.

4. CONCLUSIONS

We reported feasibility demonstrations of an evolution scenario regarding the SCN architecture to enhance the flexibility and functionality of SCh networking from a simple fixed-core-access and directional SCh ring network toward a multidegree, any-core-access, nondirectional, and core-contentionless mesh SCN. As key building blocks of SXC we introduced novel optical devices, a 1 × 2 MCF splitter, a CS, and a CPS. We constructed free-space-optics-based prototypes of these devices using five-core MCFs. Detailed performance evaluations of the prototypes in terms of the IL, PDL, and intercore XT were conducted. The results show that the prototypes provide satisfactorily low IL, PDL, and XT levels.

We constructed a wide variety of RSADMs/SXCs in terms of node degree, interport cross-connection architecture, and add/drop port connectivity flexibilities. Such RSADMs/SXCs include a fixed-core-access and directional RSADM using a 1 × 2 MCF splitter; an any-core-access, nondirectional SXC with core-contention using a CS; and an any-core-access, nondirectional SXC without core-contention using a CPS. Pre-FEC BER performance measurements for SDM signals that traverse the RSADMs/SXCs confirm that there is no or a very slight OSNR penalty from the back-to-back performance. The slight OSNR penalty observed for signals that traverse the CS/CPS prototype are considered to be due to the imperfect AR coating of the cover glass in the MEMS mirror in the CS/CPS prototype. We expect that this will be reduced by removing the cover glass of the MEMS mirror, which is unnecessary for actual products. We also experimentally showed that the flexibilities in the add/drop port of SXCs allow us to recover from single or concurrent double-link failures, with a wide variety of options in terms of availability and cost-effectiveness.

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