

Switching Solutions for WDM-SDM Optical Networks

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ABSTRACT

Over the last few decades, network traffic has consistently grown at an exponential rate and was efficiently satisfied using WDM and more efficient coding schemes requiring coherent detection. There is no indication that the network traffic growth trend will cease anytime soon, and we are nearing the day when the capacity of the ubiquitous single-mode fiber will be fully exploited. Space-domain multiplexing (SDM) for high-capacity transmission is the promising solution with the scaling potential to meet future capacity demands. However, there is still a large technological gap between current WDM optical communication system designs and SDM network implementations. In this article we lay the foundation of switching node designs for future WDM-SDM optical networks.

INTRODUCTION TO WDM-SDM OPTICAL NETWORKS

Ubiquitous information access available to us today in multifaceted forms (laptops, tablets, smart phones, and wearable devices such as watches and glasses) has enabled us to enjoy unfettered data exchange between individuals, businesses, the cloud, and is coming soon to an appliance near you. The pervasive infrastructure supporting our information-based society is founded on optical networks traversing the globe, whether through undersea links across the oceans or in terrestrial networks spanning continents, countries, and cities, and terminating at points of business and private premises. The technology behind these optical networks has evolved considerably over the past 40 years, with each technology cycle offering an orders of magnitude capacity growth at a typically incremental cost basis. As such, we have witnessed sustained exponential network capacity growth for decades, and have reaped its benefits. However, at present we are seeing warning signs on the distant horizon that question how we can continue to evolve the infrastructure and offer continued exponential growth opportunities on an economically viable basis [1].

Optical networks are predominantly based on

the omnipresent single-mode optical fiber, which, alongside conventional Erbium-doped fiber amplifiers offers essentially 5 THz of useable bandwidth for information transmission. The available bandwidth can be efficiently exploited using wavelength-division multiplexing (WDM), allowing multiple frequency-separated channels to co-transmit, and using modulation formats that encode information over amplitude, phase, and polarization at each wavelength channel. However, when trying to encode more bits of information on every communicated symbol for even more aggressive modulation formats, a transmission distance limitation emerges due to nonlinear impairments of the fiber medium itself. Hence, higher capacities tend to lose transmission range. This implies that future higher-capacity optical transport networks might need to be constructed using either progressively aggressive modulation formats over limited ranges and then cascading networks to enable extended reach, or operating using today's modulation formats that have extended reach but lower spectral efficiency and increasing capacity by deploying additional optical networks in parallel. Barring any other development, either scenario implies that supporting future exponential capacity growth rates will be accompanied by exponentially rising costs as networks are reaching their capacity-distance limits due to the fundamental physical attributes of single-mode fibers and Erbium-based optical amplifiers. One plausible avenue of research is investigating alternative fiber dopants for enabling optical amplification in additional frequency bands to provide some relief of the capacity constraint [2], but this solution will not provide more than an order of magnitude capacity increase. The alternate research avenue is investigating different optical fiber designs that offer additional guided modes for optical communication. These new fibers are heralding a new era of space-division multiplexing (SDM), which can more significantly scale in spatial mode counts and hence capacity [3].

Optical fibers in support of SDM transmission may come in many forms (Fig. 1). Single-mode fiber (SMF) is designed to allow light guiding of a single spatial mode in the core region by tailoring the refractive index profile

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and core dimensions. Multiple cores can be placed within a single fiber cladding, forming a multi-core fiber (MCF), with each core now supporting a single spatial mode. Hence, MCF may offer a capacity multiplier equal to the core count. Alternatively, the core dimensions or refractive index contrast can be modified to support additional optically guided spatial modes. These few-mode fibers (FMFs) may offer a capacity multiplier equal to the mode count. A somewhat more exotic fiber design is that of the annular core fiber (ACF), which supports multiple spatial modes confined to the annular core region [4]. The annular structure is designed to support a single radial mode and multiple azimuthal modes. One of the key differentiating metrics between SDM supporting fibers is whether the modes remain *uncoupled* in transmission or potentially may be *coupled* due to manufacturing imperfections as well as environmental effects such as bends, stress, and temperature gradients. Coupled transmission implies that the modes intermix, but the information is maintained within the set of modes. However, coupled transmission does require that these mixed modes must remain together in order to unravel the mixing at the receiver using digital signal processing. FMF and ACF are inherently prone to mixing as the modes spatially overlap and hence are categorized as a coupled SDM transmission medium. Even though in a simple MCF the cores are distinct, they may still couple if the cores are closely packed through evanescent fields; conversely, the MCF can be specifically designed to suppress coupling to very low values and remain essentially uncoupled. One flavor of SDM purports to use an array of existing SMF (or several SMF co-packaged [5], Fig. 1a); obviously, this SDM solution can be categorized as uncoupled because the fibers are separated. The SDM fiber can also be designed to support multiple coupled spatial mode subgroups, but have no coupling between the groups. Two such examples are an FMF-MCF hybrid, where there are uncoupled multiple higher index cores and each core supports several spatial modes [6], and an MCF design with uneven spacing allowing only the closely packed cores to couple [7, 8].

Transitioning to an optical network based on high-capacity SDM fiber links is still far off and entails resolving many issues related to its implementation, such as identifying the best SDM fiber options, the optical amplification means, and efficient space multiplexing and demultiplexing methods. This article focuses on the all-optical switching operations occurring at network nodes, where information-bearing channels have to be routed toward their destinations within an optical mesh topology. Such switching can occur for the individual wavelength and space channels, or possibly performed jointly over all modes or all wavelengths, and other mixed solutions in an effort to simplify the implementation. These options are weighed in terms of their physical realization requirements, as well as routing flexibility and scaling potential. Integration is key for the economic viability of the SDM solution, and the cost of implementation of the WDM-SDM network switching nodes will be a decisive factor

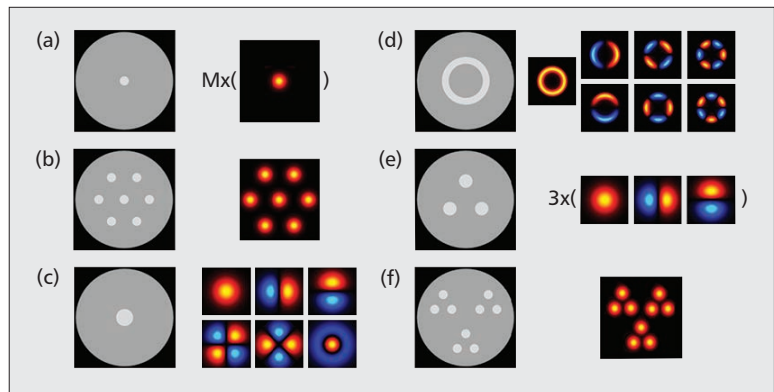


Figure 1. Different types of fibers in support of SDM, showing their geometrical form and propagating spatial mode distributions: a) single-mode fiber array; b) multi-core fiber; c) few-mode fiber; d) annular-core fiber; e) multi-core supporting few modes; f) multi-core arranged in coupled subgroups.

to be reckoned with. While this article lays the foundation for switching node designs of future WDM-SDM optical networks, their complete assessment and merit identification will likely require intense research effort by the optical networking community to identify the trade-offs and costs in advance of deployment and uptake of such networks.

WDM-SDM SWITCHING CLASSIFICATION

The adoption of new SDM-supporting fibers in the optical network potentially increases the capacity per fiber by a factor of M , the number of guided spatial modes. Considering that each fiber mode still spectrally spans the optical communication band, WDM can be applied, carrying N wavelength channels per spatial mode. Hence, the WDM-SDM fiber capacity can be defined by a two-dimensional spatial-spectral array, with wavelengths $(\lambda_1, \dots, \lambda_N)$ and spatial modes $(\sigma_1, \dots, \sigma_M)$ defining its columns and rows (Fig. 2). Before addressing the switching options available in a WDM-SDM optical network, it is first instrumental to consider the current state of switching in optical networks and emerging trends.

Today's optical networks employ wavelength-selective switches (WSSs) at network nodes to perform the switching, and are exclusively based on SMF interfaces [9]. A conventional WSS accepts a single fiber carrying WDM traffic and switches each wavelength channel to one of K possible output fiber ports. Note that each output fiber port can have any number of wavelength channels switched to it, as the switching is independently performed for each wavelength in the input port. The switch can also operate in reverse, receiving K input fibers with WDM traffic, and selecting on a wavelength channel basis which input fiber will be interconnected to the single output fiber port. Two identical wavelengths cannot be physically switched to the single output fiber in a WSS; such a network routing assignment is prohibited, and referred to as wavelength contention. In an optical mesh



Figure 2. Parsing the fiber’s SDM and WDM channels for switching, where space modes ($\sigma_1, \dots, \sigma_M$) and wavelength channels ($\lambda_1, \dots, \lambda_N$) are fully utilized: a) space-wavelength granularity (each mode/wavelength channel can be independently switched); b) space granularity (switching performed on a mode basis across all wavelengths); c) wavelength granularity (switching performed on a wavelength basis across all modes); d) fractional space-full wavelength granularity (switching performed on a wavelength basis and spatial mode sub-groups).

network node, a broadcast-and-select or route-and-select architecture can perform the switching function, with the route function performed with a $1 \times K$ WSS, and the select function with a $K \times 1$ WSS [10]. The wavelength channels of a WSS are defined by the spectral switching elements, and typically reside on a 100 GHz (supporting about 50 channels) or 50 GHz grid (supporting nearly 100 channels). The fixed WSS channel plan imparts a certain inefficiency, as guard bands are introduced between adjacent channels that reduce the bandwidth available for information encoding. Today, as data volumes grow and SMF capacity is becoming a limiting factor, flexible-grid WSSs are being introduced. In a flexible-grid WSS the spectral selection does not adhere to a fixed grid and can be provisioned as required; large contiguous spectral channel bandwidths can be defined [11]. This capability is being utilized to create spectral super-channels, which consist of closely packed subchannels that are routed through the network as one entity with few or no guard bands between the subchannels. For example, a 200 GHz wide spectral super-channel can support 1 Tb/s capacity by combining several subchannels on separate carriers. Hence, employing super-channels for transport, the number of WDM channels tends to decrease while their assigned bandwidth increases. In SDM research experiments we are witnessing a reverse trend. Initial SDM experiments were conducted with few spatial modes (e.g., three) and are gradually increasing. Hence, the WDM-SDM capacity array might have, in certain scenarios, a column count of

$\sim 100 \times 50$ GHz wide wavelength channels or maybe only $\sim 25 \times 200$ GHz spectral super-channels (or even mixed assignments); the spatial mode row count may be only a few (e.g., 6–10) modes initially, but can certainly scale to tens to 100 in the future. These expected values are important to consider when weighing the different WDM-SDM switching technologies.

While there are many SDM fiber alternatives one can consider for implementing future WDM-SDM optical networks, for mesh node switching purposes we categorize them into three general archetypes:

Uncoupled spatial modes: Spatial channels remain distinct in fiber propagation and all ancillary network equipment, as would be experienced in uncoupled MCF (Fig. 1b) or an SMF bundle (Fig. 1a). Therefore, individual spatial modes can be switched from one SDM fiber link to another, or add/drop operations applied for any spatial mode/wavelength channel combination.

Coupled spatial modes: Spatial channels mix throughout fiber transmission, as occurs in FMF (Figs. 1c, 1d) and coupled MCF (Fig. 1b), forming spatial super-channels in which multiple data streams are transported as groups of subchannels occupying the same wavelength in independent modes/cores. As a result of the channel mixing, multiple-input multiple-output (MIMO) processing is required in order to unravel the mixed information, which occurs after coherent detection of all the spatial modes at the SDM receiver. Since the information is mixed across all spatial modes, modes cannot be separated for

switching to other destinations, or information loss will be experienced. A complete MIMO receiver has to be employed in order to separate the SDM data, an operation performed at the channel destination and not desirable at every mesh network node as network transparency will be lost.

Coupled spatial subgroups: Spatial modes may mix only within subgroups of the total spatial mode count. The subgroups are defined by the SDM fiber design, and the spatial modes belonging to a subgroup must not be separated in switching operation (Figs. 1e, 1f). Subdividing the spatial modes into subgroups of smaller size eases the switching limitations with respect to full mode coupling, while not reaching the full flexibility of uncoupled modes.

At the optical network nodes, the WDM-SDM traffic on each inbound fiber link has to be either redirected to outbound fiber links as part of the network information flow, or dropped to receivers for local consumption at the node's geographical location. Additional data is typically reintroduced, or added, in its place, originating at clients associated with the node. The SDM fiber categories dictate the permissible switching operations that can transpire at the optical network nodes. We identify four alternative switching scenarios that strongly correlate to the SDM fiber categories, forming multi-dimensional switching nodes of different granularities (Fig. 2).

Independent spatial mode/wavelength channel switching (space-wavelength granularity): The WDM-SDM fiber capacity can be switched independently for every spatial mode and wavelength combination (Fig. 2a). This forms the finest switching capacity granularity, leading to the greatest flexibility at the cost of increased realization complexity. Employing independent mode/wavelength switching requires uncoupled SDM fiber.

Spatial mode switching across all wavelength channels (space granularity): The WDM-SDM fiber capacity is switched at the spatial mode level, independent of wavelengths (Fig. 2b). Hence, the entire communication band per mode is jointly switched. At low spatial mode counts, space switching granularity is coarse (all WDM channels) but simple to realize. Employing independent mode switching also requires uncoupled SDM fiber.

Wavelength switching across all spatial modes (wavelength granularity): The WDM-SDM fiber capacity is switched at the wavelength level across all spatial modes, forming spatial superchannels that are routed through the network as one entity (Fig. 2c). Since the spatial modes are not separately routed, the network topology is similar to today's SMF networks, but benefitting from the SDM capacity multiplier. Employing wavelength switching across all modes is obligatory for coupled SDM fiber, but can also be applied to uncoupled SDM fibers.

Wavelength switching across spatial mode subgroups (fractional space-full wavelength granularity): The WDM-SDM fiber capacity is switched at the wavelength level across smaller spatial mode subgroups (Fig. 2a). The switching operation is still in support of spatial superchan-

nels within each subgroup, but applied independently to the subgroup elements. Employing the fractional space and full wavelength granularity capacity switching supports coupled subgroups of SDM fiber, but can also be applied to uncoupled SDM fibers.

Routing in the WDM-SDM optical network is constrained by the employed switched capacity granularity, as the network provisioning algorithms must assign each information flow request onto a route that can be supported by the switching nodes and is contention-free. An additional degree of freedom implicit in the switching capacity granularity involving the wavelength space (options A, C, and D), is the ability to flexibly define the switched spectrum. The independent space-wavelength granularity (option A) is the smallest capacity block size and offers the greatest routing flexibility, as even single wavelength and spatial mode requests can be accommodated. The alternative solutions (options B–D) utilize larger switching capacity granularities by addressing all wavelengths (B), spatial modes (C), or spatial mode subgroups (D) as one entity. Such switching solutions may become inefficient when addressing small capacity requests, but the reduced hardware required to realize these degenerate switching solutions may be favorable implementation-wise. If using coupled SDM fiber, jointly switching all spatial modes (option C) is mandatory. The capacity granularity can be reduced by provisioning narrower spectral bands by the switching hardware, which may require some customization. For example, if the switching hardware can support minimal bandwidth provisioning of 35 GHz, a six spatial mode SDM fiber can offer enough capacity to support 1 Tb/s as the minimal switched granularity, which is a reasonable starting point for future WDM-SDM optical networks.

WDM-SDM SWITCHING SOLUTIONS

After having defined the switched capacity granularity at the WDM-SDM optical network nodes, we turn our attention to their implementation details. The switching node must complete two functions: routing traffic from an input SDM fiber to an output SDM fiber and performing channel add/drop to be terminated at optical transceivers. Each solution entails its unique switching hardware, and various levels of complexity are associated with each granularity level. However, some elements are recurring, and we briefly explain their operation. The WSS has been introduced earlier, and its flexible-grid implementation is assumed here. The WSS utilizes SMF at its input/output ports (although WSSs with direct FMF interfaces have been demonstrated [9]), and must be properly interfaced to the SDM fiber solutions. For MCF, a breakout device separates the M cores to M individual SMFs. For FMF, a mode demultiplexer converts the M modes to M individual SMFs [10, 11]. This operation does not necessarily require the modes to be mapped to individual output fibers; a unitary mode-mixing operation may be associated with the demultiplexer, which can be subsequently undone in MIMO processing at the receiver.

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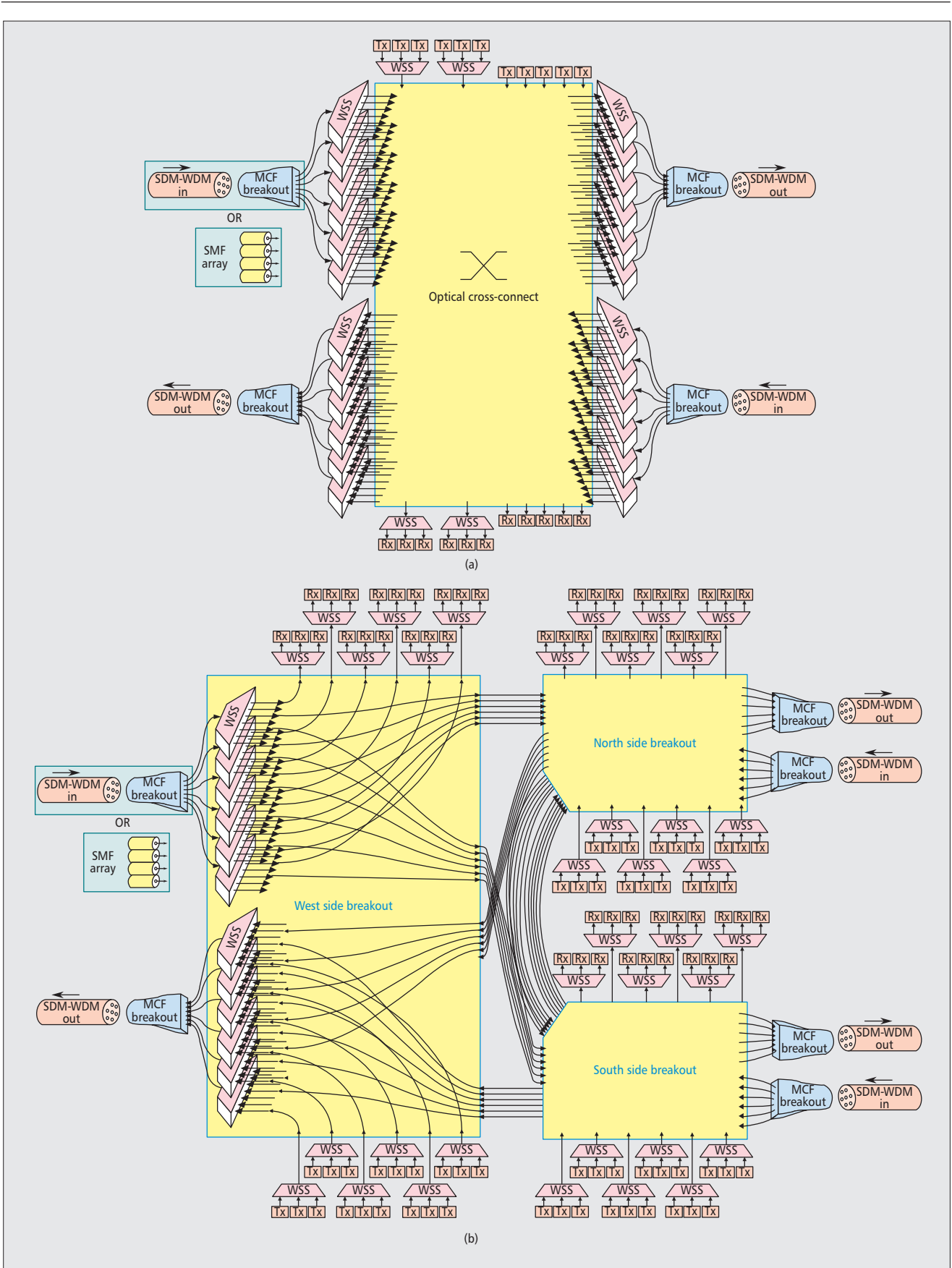


Figure 3. Implementations for independent spatial mode/wavelength channel switching: a) optical cross-connect for full connectivity (only two fiber links shown); b) route-and-select per each spatial mode. North and south side breakouts are identical to the west side breakout.

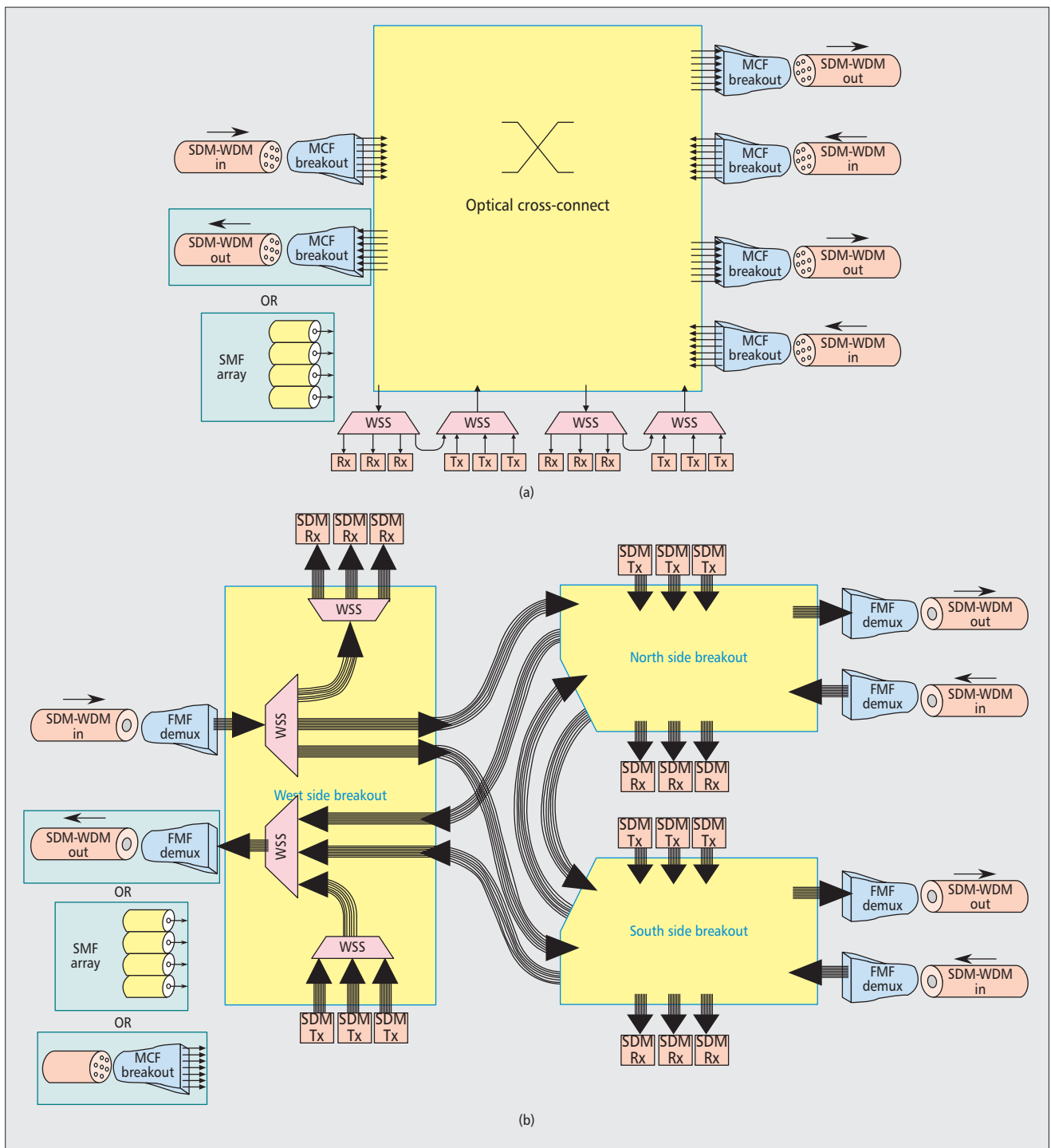


Figure 4. Switching node designs for implementing: a) space granularity, routing the entire communication band per spatial mode; b) wavelength granularity, routing all modes per wavelength.

Two possible implementations of independent spatial mode/wavelength channel switching (space-wavelength granularity) offering different levels of flexibility are shown in Fig. 3. The first implementation makes use of a large optical cross-connect (OXC). To interface between the uncoupled SDM fiber solution and the OXC, each independent spatial mode is preprocessed with a $1 \times K$ WSS. The WSS subdivides the WDM channels on each spatial mode according

to destination, whether to an output SDM fiber (on a particular spatial mode) or to a drop port. On the output side a $K \times 1$ WSS multiplexes or post-processes the channels onto a spatial mode of the SDM fiber. Single drop channels can be terminated directly at conventional receivers, and multiple drop channels can be further separated with another WSS. This architecture provides full routing flexibility thanks to the OXC, especially wavelength contention by enabling

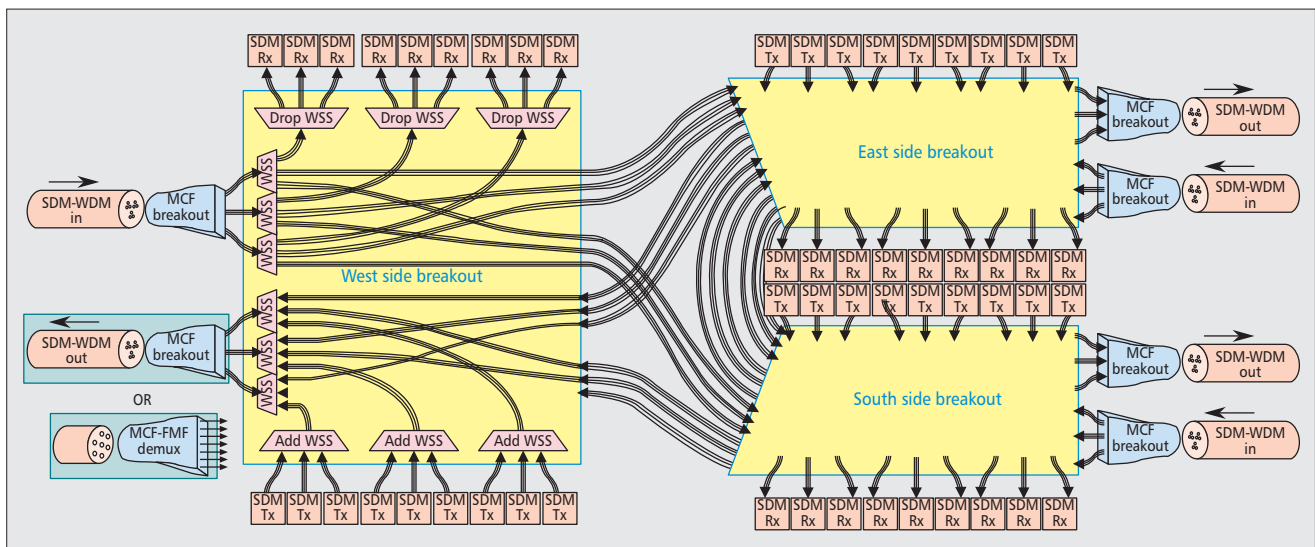


Figure 5. Switching node design for implementing hybrid fractional space-full wavelength switching granularity, routing spatial super-channels spanning spatial subgroups.

SDM “lane changes” or routing of a wavelength channel from one spatial channel to another instead of the much harder wavelength conversion solutions proposed for SMF networks. Additionally, the transceiver elements are accessible to all fiber directions (and are further colorless and contentionless), resolving the directional limitation in route-and-select solutions. Having WSS pre- and post-process WDM channels enables flexible bandwidth allocation, and also conserves OXC fiber ports as WDM channels destined to the same direction and able to be routed jointly.

The alternative independent spatial mode/wavelength switching solution eliminates the OXC, which is a costly element and a single point of failure threat. Here, route-and-select switching is performed for each spatial mode independently. Each independent spatial mode is subdivided by a $1 \times K$ WSS and routed to output fiber destinations (mapped to the same mode on the output fiber, eliminating SDM lane change operation), or to a set of receivers associated with the spatial mode (i.e., directional in both the fiber and mode senses). Hence, eliminating the OXC results in routing constraints.

The biggest disadvantage of the independent space-wavelength granular switching node designs is the amount of hardware required to implement them. Essentially, this entails scaling the WSS count M -fold, the same as the capacity increase. Hence, the mesh node cost scales linearly with the capacity gain, which is counter to the value proposition of SDM. We are seeking a sublinear cost increase with capacity to maintain network economics by way of better device and sub-system integration. With independent space-wavelength granular switching this requirement is not met.

Eliminating the WDM switching elements and realizing a space-granular capacity switching design significantly reduces the node hardware and cost (Fig. 4a). An OXC receives all spatial modes along its input ports and switches each

mode to an output SDM fiber, thereby completing the routing of the entire optical communication band (all WDM channels carried on a spatial mode) to the output destinations. For the add/drop operation, the OXC can switch the dropped spatial mode to a port where a WSS separates the channels to be detected, and the remaining channels are fed through to a second WSS that combines these channels with additional channels added back into the OXC for output fiber assignment. The WSS count in the node depends on the number of spatial modes allowed to be dropped, with a minimum of one spatial mode per fiber. However, as this number increases, which is required to offer reasonable routing flexibility in a multi-node network, the WSS count can again become prohibitively high.

Alternatively, the wavelength-granular capacity switching design utilizes a recently introduced WSS modification specifically designed for routing of spatial super-channels [12, 13]. The WSS is based on a conventional (SMF-based) high-port-count WSS, and is made to operate with all the spatial modes of the input SDM fiber feeding a first subset of the WSS ports. The internal wavelength switching mechanism of the WSS (based on beam steering) steers the set of input ports onto a second subset of the WSS ports. When the ports are arranged in a linear equi-spaced array, the fiber ports are imaged from the first subset onto the second, switching in parallel all the fibers and hence the entire spatial mode set. This joint-switching WSS can be used to construct the conventional route-and-select architecture of SMF networks, with the M -fold parallelism applied across all modes with a single switching module. The routed spatial super-channels traverse a first $M \times (1 \times K)$ for destination selection and a second $M \times (K \times 1)$ for combining the wavelength channels to the output SDM fiber. The dropped spatial super-channels are interfaced to SDM transceiver elements where MIMO processing is performed for information extraction in the case where the modes

	Space-wavelength granularity	Space granularity	Wavelength granularity	Fractional space-full wavelength granularity
Minimum switching granularity	Bandwidth of a single WDM channel present at a single spatial mode.	Bandwidth of entire optical communication band carried on a single spatial mode.	Bandwidth of a single WDM channel spanning over all spatial modes.	Bandwidth of a single WDM channel over a subset of spatial modes.
Realization	<i>With OXC:</i> High-port count OXC and at least $2M$ conventional WSSs per I/O fiber link. <i>Without OXC:</i> $2M$ conventional WSSs per I/O fiber link. $4M$ if WSSs placed on add/drop.	Moderate port count OXC, and 2 WSSs per mode selected for WDM channel add/drop.	4 joint switching WSSs per I/O fiber link in route-and-select topology applied to all spatial modes in parallel.	$4 \times M/P$ joint switching WSS modules per I/O fiber link.
Flexibility	<i>With OXC:</i> Each mode/WDM channel independent provisioned and routed. Supports SDM lane change. Single point of failure. <i>Without OXC:</i> Each mode/WDM channel independently provisioned and routed. Spatial mode maintained. Prone to wavelength contention.	The complete optical communication band is routed across network. Coarse granularity. If WDM channels need to be extracted from many modes, WSS count quickly escalates.	Each spatial super-channel provisioned across all modes. Susceptible to wavelength contention. Add/drop bound to direction.	Compromise solution using small SDM groups. More efficient when provisioning low-capacity demands.
Scaling	<i>With OXC:</i> Can quickly escalate to very large port counts. Switching node cost linearly scales with capacity, no price benefit to SDM.	Conventional OXC can support foreseeable mode and fiber counts. OXC is a single point of failure. Pricing favorable but with greater add/drop require more WSS modules.	Cost roughly independent of SDM count. Inefficient for low-capacity connections due to minimum BW provisioned across SDM. Large SDM Rx/Tx are an integration and DSP challenge.	Cost scales as group count. Groups can be turned on as capacity grows, offering a pay-as-you-go alternative. Maintaining small group sizes facilitates MIMO processing at Rx.

Table 1. Comparison of WDM-SDM switching alternatives.

are mixed due to mode coupling from the SDM fiber. The scalability of this wavelength-granular solution to high mode counts (tens of modes) is presently undetermined, as joint switching WSSs have limited fiber port counts.

The final variant is a space and wavelength hybrid design, which offers fractional space and full wavelength granular capacity switching (Fig. 5). This switching scenario is matched to an SDM fiber solution offering M spatial modes, where the modes can be divided to M/P independent subgroups, where modes are coupled within the individual subgroups having P modes. Each mode group must be switched jointly due to the inherent intra-coupling, but the groups can be switched independent of one another. The switching solution is the basic route-and-select topology applied to each subgroup using modified WSSs that support the joint-switching concept for groups of size P . The solution is replicated M/P times, matching the subgroup count. This hybrid solution offers finer granularity than switching all modes (wavelength granularity) at a price of increased switching hardware; however, the cost is a fraction ($1/P$) of the capacity gain. While the fractional space-full wavelength solution requires specific forms of SDM fiber, it can also be applied to uncoupled SDM fiber. This switching solution can more effectively

address SDM fibers with very high spatial mode counts, provided they are designed according to coupling within grouped modes.

CONCLUDING REMARKS ON WDM-SDM OPTICAL NETWORKING

SDM transmission is a promising solution to the capacity limitation of SMF, but addressing the physical SDM elements of novel fiber types, supporting optical amplifiers, and mode multiplexers, without careful attention to optical networking implications misses an important element of the entire value proposition. In this article we highlight some of the implications of designing a WDM-SDM optical mesh network, concentrating on the switching node designs by which information flows need to be provisioned. We identify four categories of capacity granularities to be provisioned, applied across the space and wavelength domains. Each category can be realized with different optical switching gear at the network node, affecting the realization complexity and cost, flexibility, and scalability. These findings are summarized in Table 1.

It is premature at this early stage to deduce if there is an optimal solution to the WDM-SDM optical network. This has to be assessed for spe-

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cific network layouts and traffic patterns. Different networking applications are likely to have divergent conclusions. Assessment of the complete optical network must take into account the physical layer attributes, the expected information flow scales and churn, how efficiently they can be met given the minimum capacity granularity that is routed by the network, blocking probabilities due to contention for the provisioning of information flows, and cost of implementation, amongst other. WDM-SDM mesh node switching solutions, the focus of this article and a key factor in network operation and cost, can be assessed with a routing power metric, borrowed over from reconfigurable wavelength add-drop node designs [14, 15]. The routing power metric can provide a measure of the number of connection states for the switching node, and will decrease for larger switching granularity, but this loss of flexibility is favorably accompanied by lower implementation costs. As such, a complete analysis involves the contributions from different skillsets and it will likely require the concerted effort of many researchers in the field to analyze the performance level and benefits offered by WDM-SDM optical networks.

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BIOGRAPHIES

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