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Resource Allocation for Space Division Multiplexing: Optical White Box vs. Optical Black Box Networking

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Abstract—Elastic optical networking (EON) with space division multiplexing (SDM) is the only evident long-term solution to the capacity needs of the future networks. The introduction of space via spatial fibers, such as multi-core fibers (MCF) to EON provides an additional dimension as well as challenges to the network planning and resource optimization problem. There are various types of technologies for SDM transmission medium, switching, and amplification; each of them induces different capabilities and constraints on the network. For example, employing MCF as the transmission medium for SDM mitigates the spectrum continuity constraint of the routing and spectrum allocation (RSA) problem for EON. In fact, cores can be switched freely on different links during routing of the network traffic. On the other hand, inter-core crosstalk should be taken into account while solving the resource allocation problem. In the framework of switching for elastic SDM network, the programmable architecture on demand (AoD) node (optical white box) can provide a more scalable solution with respect to the hard-wired reconfigurable optical add/drop multiplexers (ROADMs) (optical black box). This study looks into the routing, modulation, spectrum and core allocation (RMSCA) problem for weakly-coupled MCF based elastic SDM networks implemented through AoDs and static ROADMs. The proposed RMSCA strategies integrate the spectrum resource allocation, switching resource deployment, and physical layer impairment in terms of inter-core crosstalk through a multi-objective cost function. The presented strategies perform a cross-layer optimization between the network and physical layers to compute the actual inter-core crosstalk for the candidate resource solutions and are specifically tailored to fit the type of optical node deployed in the network. The aim of all these strategies is to jointly optimize the switching and spectrum resource efficiency when provisioning demands with diverse capacity requirements. Extensive simulation results demonstrate that 1) by exploiting the dense intra-nodal connectivity of the ROADM-based SDM network, resource efficiency and provisioned traffic volume improve significantly related to AoD-based solution, 2) the inter-core crosstalk aware strategies improve substantially the provisioned traffic volume for AoD-based SDM network, and 3) the switching modules grows very gently for the network designed with AoD nodes related to the one with ROADMs as the traffic increases, qualifying AoD as a scalable and cost-efficient choice for future SDM networks.

Index Terms—Architecture on demand; Network planning; space division multiplexing; multi-core fiber; inter-core crosstalk; quasi-static traffic.

I. INTRODUCTION

The sustained exponential growth of Internet traffic demands spectrum-efficient, performance-adaptive and scalable

infrastructure for future networks. Recently, elastic optical networking (EON) has emerged as a worthwhile solution for spectrum-efficient and flexible networking. In the EON paradigm, the frequency spectrum is sliced into a number of small spectrum slots that are allocated to match as close as possible to the bandwidth requirement of each user demand. Moreover, in such networks, a specific number of transmission parameters, such as optical data rate, modulation format, and spectrum spacing between optical channels are made tunable. The typical architecture of EON mainly comprises of bandwidth-variable transponders (BVTs) [1], bandwidth-variable optical cross-connects (BV-OXCs), and flexible spectrum grid. These elements facilitate the implementation of a spectral superchannel, which is a networking entity with variable but adjacent spectral resources able to transport a flexible capacity demand over an end-to-end path in the network. The BVT adjusts the transmission bit rate and bandwidth by varying the number of slots (subcarriers), modulation format, and baud-rate. The BV-OXC assigns an appropriately sized cross-connection as per requirement to support an elastic optical connection. Thus, a BV-OXC needs to configure its switching window in a flexible way corresponding to the spectral width of the incoming optical signal. Spectrum selective switch (SSS) is considered as an enabling module for BV-OXC, and there are some SSS-based optical node designs that support the flexibility of EON. For example, “spectrum routing” *reconfigurable optical add-drop multiplexer* (ROADM) architecture in which both switching and filtering functionalities are controlled by the SSSs as shown in Fig. 1. However, the switching modules at the input and output ports are hard-wired, which restrict the upgradeability, limit the support for new functionalities, and curb the capability of adapting the architecture to the network requirements. Due to these limitations such hard-wired design can be conceived as an *optical black box*.

Another alternative solution is the *architecture on demand* (AoD) [1], [2]. The AoD consists of an optical backplane (based on beam-steering or 3D-MEMS) that interconnects inputs, outputs, adds, drops, single device building modules (e.g., MUX, coupler, SSS) and composed building modules (e.g., EDFA plus splitter) as shown in Fig. 2. With this architecture, different compositions of inputs, modules, and outputs can be created by setting up appropriate cross connections in

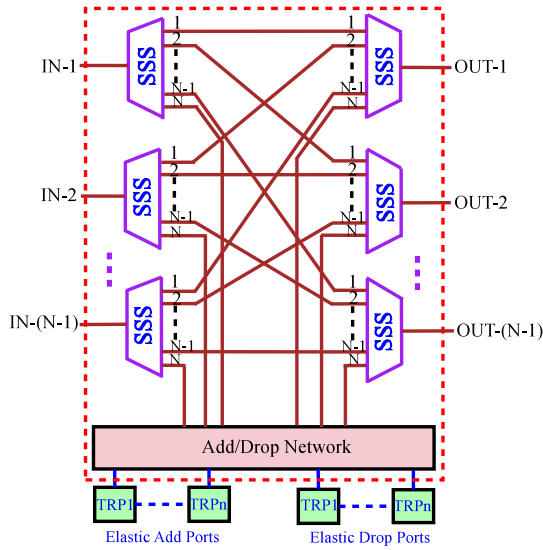


Figure 1. Node architecture of spectrum routing ROADM.

the optical backplane. AoD provides greater flexibility than hard-wired ROADM configuration as the modules used for optical processing, e.g., SSS, power splitters, and other functional modules are not hard-wired but can be interconnected together in an arbitrary manner. In fact, it is possible to provide programmable *synthetic* architectures according to the needs of the network traffic, and can be viewed as the first proposed *optical white box*.

The finite transport capacity of the single mode fiber core [3] and the limited gain bandwidth of optical amplifiers [4], necessitate other technological developments apart from efficient utilization of spectrum resources through flexible networking, in order to expand the capacity needed for future networks. The adoption of the *spatial* dimension via space division multiplexing (SDM) is identified as a promising solution for the capacity expansion of future networks. The SDM can be supported by various transmission media, such as multi-mode fiber (MMF), multi-core fiber (MCF), few-mode fiber (FMF), few-mode multi-core fiber (FM-MCF), or even single-mode fiber (SMF) bundles [5]. The MMF employs the propagation of few independent modes within a single core. The number of modes supported by a fiber depends on the core size and the refractive index of the fiber. On the other hand, MCF has several single mode cores embedded in the fiber cladding. SDM networks provide an extra degree of freedom in the form of the spatial domain. Spatial resources can be flexibly allocated to different traffic demands, hence, increasing the employed degrees of flexibility, and the planning and optimization capabilities of the network. For example, the concept of superchannel can be employed in the spatial domain, i.e., spatial superchannel [6], [7], by carrying an elastic capacity demand over a number of cores or modes in MCFs or MMFs, respectively. Furthermore, the spatial-spectral superchannel networking entity utilizes the spectrum allocation flexibility in both spectrum and spatial domains. Hereafter, the term demand is used interchangeably with superchannel.

As the spectrally and spatially flexible optical network has

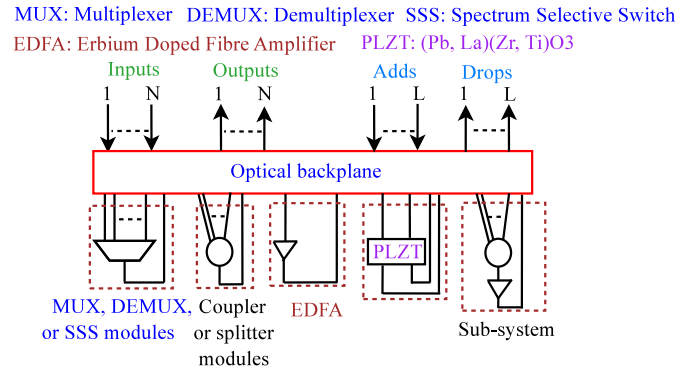


Figure 2. Architecture on demand (AoD) implementation.

been widely acknowledged as the next generation high capacity transport system, the research community has focused on its architecture and network resource allocation (transponders, spectrum, etc.) techniques. The recent articles [8], [9] laid the foundation of switching node designs for future elastic SDM networks. The proposed spatial-spectral switching models are the extension of the optical black box solutions for spectrally flexible networks [10]–[13]. A more flexible and scalable architecture for multi-dimensional switching node can be accomplished using optical white box (AoD) [14]. In the context of network planning and operation, the advent of spatial multiplexing introduces an additional degree of freedom and new issue, such as inter-core crosstalk, which is incorporated in the proposed resource allocation strategies [15]–[19]. These schemes target specific objectives for static [15], [16] and dynamic [17]–[19] traffic, without analyzing the impact of network parameters (e.g., traffic growth, adaptive modulation, optical node solutions) on the network capital and operational expenditures.

This paper investigates the planning and dimensioning of MCF-based SDM networks considering the quasi-static traffic model (which is the norm on current and future operational metro/core networks). To this end, the paper focuses on distance-adaptive resource allocation for elastic SDM networks implemented by using optical white boxes (AoDs) and optical black boxes (ROADMs). In particular, the work addresses the routing, modulation, spectrum and core allocation (RMSCA) problem with multi-objective optimization criteria that exploit the benefits offered by each type of the optical node solution. The proposed strategies perform a cross-layer optimization between the network and physical layers to estimate the actual inter-core crosstalk for the candidate resource solutions to improve the network provisioning capability. At the same time, the strategies aim to make use of the already deployed switching resources as much as possible to minimize the overall switching modules for the network nodes. Furthermore, the proposed strategies reconfigure the network (resources) to optimize the resource consumption whenever the network traffic alters. Cross-layer optimization approach is not a new concept in the optical networking paradigm. It has been studied in the context of network planning and operation [20], [21] for its performance benefits.

The rest of the paper is structured as follows. A brief

overview of the related work and motivation for RMSCA are presented in section II. Section III introduces the assumptions for SDM network and general framework for resource allocation strategies. Proposed inter-core crosstalk aware algorithms for RMSCA problem are presented in section IV. Numerical results are shown in section V, and, finally some concluding remarks are made in section VI.

II. RELATED WORK

The SDM technology has been intensively researched for the last few years owing to the looming optical networks capacity crunch [3], [22]. Several transmission media, such as MMF, FMF, MCF, and FM-MCF can be utilized for the deployment of SDM. However, from the system design perspective, two categories of SDM have been predominately studied. The two classes are differentiated whether crosstalk among parallel spatial paths is treated as an uncompensated impairment at the receiver or being effectively managed through multiple-input-multiple-output (MIMO) coherent digital signal processing (DSP). Similarly, the fibers designed for SDM can be divided into three classes depending on how the deleterious effects of crosstalk are eliminated. In the first type (denoted as weakly-coupled), crosstalk is minimized by reducing the overlap between the electrical fields of the two cores/modes so that each SDM channel is separately detected without employing MIMO. Most MCFs belong to the weakly-coupled class, whereas, the FMFs fit to the second type (denoted as strongly-coupled). In the strongly-coupled class, the differential group delays among all the SDM channels are minimized so that they can be concurrently detected at the receiver while the MIMO can efficiently unravel the mixed information due to crosstalk. Finally, in the hybrid type, strongly-coupled SDM channels are arranged in weakly-coupled groups. MC-FMFs preferably belong to this class, i.e., strongly-coupled modes inside weakly-coupled cores.

The amount of crosstalk between different spatial modes and the requirement for MIMO processing will affect not only the physical layer performance but also the way superchannels are created and routed. Note that a superchannel is a group of aggregated spectrum slots that are transmitted, routed and received as a unit [23]. For a MIMO relying SDM system, it is essential to create a superchannel in the spatial domain (spatial superchannel) with an end-to-end signal that holds all of the spatial modes for a given spectral slot. Since the information is mixed across all spatial modes, modes cannot be separated for switching to other destinations; otherwise information loss will occur. Such constraint (on the formation of spatial superchannels) limits the flexibility to switch, add, and drop single SDM channels. However, at the same time it facilitates the network control by confining the fragmentation issue only to the spectrum domain. In addition, the spatial superchannel can benefit from the availability of integrated FMF amplifiers [5]. On the other hand, SDM system not depending on MIMO, the formulation of superchannels and resource utilization would be more flexible. However, the system will need sophisticated fiber and a different amplification stage for each core/mode. Finally, a spatial superchannel is less spectrally efficient than

a spectral superchannel of the same capacity as it needs guard band on every spatial dimension.

Spectral superchannels have been extensively investigated [24]–[26] for their benefits, such as high-throughput transmission [27], [28], system component integration [29], and reduction in the number of switching devices [30]. Spatial superchannels have recently gained interest [5], [31], and their advantages for enhancing throughput [32] (per fiber) and enabling system component integration, such as replacing several single-mode amplifiers by one multi-mode amplifier [33]. Moreover, the potential of spatial superchannels to reduce the switching complexity at the link level and network level have been illustrated in [33] and [34], respectively.

Most of the works above considered point-to-point systems while the spatial dimension in optical networking still needs to be explored. This in turn requires novel optical node and network architectures that can support the increased number of the spatial channels per fiber and yet able to switch traffic at diverse granularities. The study in [14] reports the first demonstration of an elastic MCF-based SDM network capable of switching the traffic in spatial, spectral, and time domains. The networking demonstration employed four programmable AoD nodes with a range of bandwidth granularity of over 6000-fold. Similarly, [35] presents the utilization of software-defined networking (SDN) for the control and management of programmable MCF-based SDM networks. A couple of articles [8], [36], [37] outlined the hard-wired switching approaches for SDM node with different levels of switching granularity. The proposed designs in [8], [36] switch the entire spatial domain for a spectral granularity (i.e., spatial superchannel), which require less hardware at the expense of losing the provisioning spatial degree of freedom. Besides, it will be more challenging to implement such designs for higher nodal degree nodes due to the port number limitation of the SSS/WSS. On the other hand, the reported architectures in [37] are customized for specific capacity request scenarios ranging from a spectrum slot to a fractional-spatial-full-spectral superchannel, hence, offer different degrees of flexibility, scalability, cost, and design complexity. However, a thorough analysis of their performance and benefits yet need to be studied, which is beyond the scope of this work.

For the SDM network planning and operation, there exist limited work on resource allocation strategies that use the additional flexibility offered by the spatial domain [15], [16], [18], [19], [38], [39]. For example, the optimal planning for MCF based SDM networks with the objective to minimize the required spectral resources is investigated in [15]. The study in [16] extends the planning problem to networks implemented through programmable AoDs with the aim to reduce the network switching resources. References [18], [19] solve the resource allocation problem for dynamic SDM networks with the objective to minimize the network blocking probability. Similarly, the routing, wavelength and mode assignment problem for dynamic networks with FMF is examined in [38]. The work in [39] solves the resource allocation problem for dynamic spatially-spectrally flexible networks, by presenting several heuristic policies that are limited to employ only spatial or spectral superchannel but not a mix of these two domains.

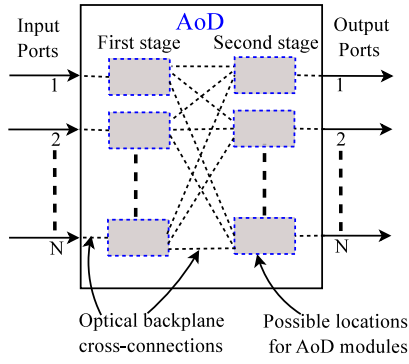


Figure 3. Two stage AoD logical model.

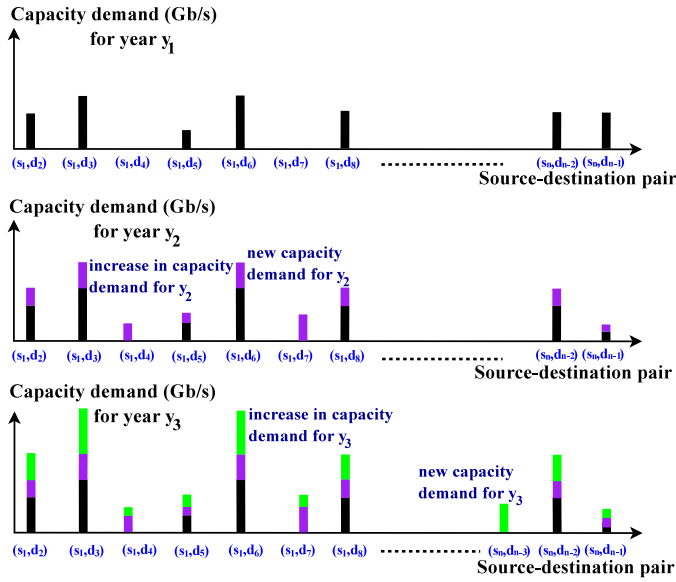


Figure 4. Quasi-static traffic model.

Notice that these last two studies are not taking into account the crosstalk issue, which is critical for the deployment of weakly-coupled MCF-based SDM system.

The possibility to exploit the spatial domain effectively inflicts new challenges on the optical control plane, which are discussed in [35], [40]. For instance, the control plane needs to differentiate between links with multiple fibers and multiple cores in a MCF as they exhibit different physical characteristics. The control plane should be able to consider the new switching features and constraints for routing and spectrum allocation algorithms, particularly for the dynamic node architecture (AoD node) swift reconfiguration in response to varying network traffic needs to be performed. The SDN seems to be a convenient choice for the control of SDM networks as advocated in [8], [35], [40]. In fact, the work in [35] experimentally demonstrates the automatic bandwidth and quality of transport (QoT) provisioning, AoD node configuration, and spatial superchannel slicing over the SDM infrastructure using the SDN controllers.

On the fiber fabrication level, inter-core crosstalk (XT) suppression has been a prime concern in MCF research [41]–[46] for enabling long distance transmissions. Most of these

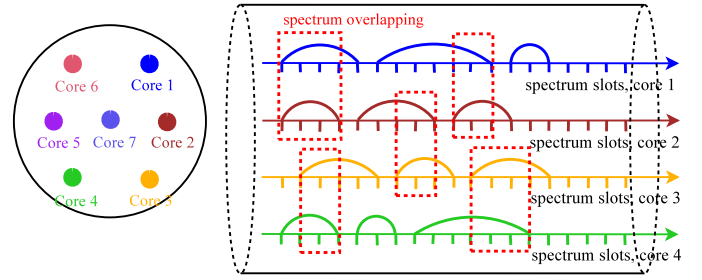


Figure 5. XT unaware spectrum allocation.

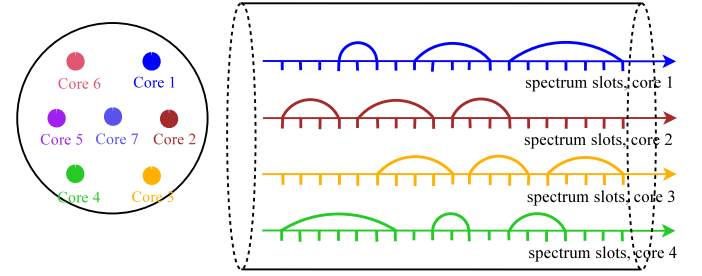


Figure 6. XT aware spectrum allocation.

studies ([43], [44], [46]) reported the design and fabrication of MCF having low XT and low attenuation. For MCF design with low XT, it is essential to reduce the overlap between the electric fields of the nearby cores. For this purpose, the step and trench assisted profiles have been considered [45]–[47]. References [45], [46] also derive an approximation model for estimating crosstalk and measure the crosstalk dependence on the bending radius of the MCF. The presented model relates the crosstalk as a function of fiber parameters, such as bending radius, fiber length, core pitch, etc.

To the best of the authors' knowledge, there is no prior work on investigating the distance-adaptive modulation, nor the cross-layer optimization approach to handling the XT in weakly-coupled MCF for large-scale network planning and operation. Moreover, the scalability and cost-effectiveness issues for SDM networks implemented through AoD nodes and ROADMs as well as their performance comparison are yet to be investigated. The aim of this study is to examine these matters by presenting novel heuristic strategies for solving RMSCA problem with customized multi-objective cost function to suit each type of optical node solution. The proposed cost function blends the spectrum resource assignment, switching resource deployment (and allocation), and physical layer impairment issue in order to achieve an advantageous trade-off between switching and spectrum resource efficiency.

III. INTER-CORE CROSSTALK (XT) AWARE RESOURCE ALLOCATION FOR SDM NETWORKS

This section presents the assumptions used to model the elastic SDM network under consideration, and the general framework for the XT aware resource allocation strategies. The adoption of the spatial dimension along with the spectrum could potentially lead to different options for flexible optical networking, some of which are described in Section II. However, this work exploits the spatial dimension for enhancing

the system capacity and employ only spectral superchannel to fulfill the users capacity demand. This approach seems the natural evolution of today's transmission systems toward higher-capacity systems. It is assumed that the network consists of BVTs, weakly-coupled MCFs, flexible optical nodes and operates without MIMO DSP technique for unraveling the XT. The BVT adapts the client data signal to be transmitted to and received from the optical network and assigns just enough spectrum resources based on the transmission path characteristic. It is considered that the functionalities of BVT are realized through advanced modulation formats and multi-carrier technique, such as coherent optical orthogonal division multiplexing (OFDM). The coherent optical OFDM transponder integrates multiple contiguous single-carrier (sub-carrier), modulated with the same format to form a spectral superchannel and serve a given bit rate. The number of sub-carriers depends on the requested capacity and the modulation level. The employed modulation formats are binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), and x-quadrature amplitude modulation (x-QAM), where x belongs to $\{8, 16, 32, 64\}$. Also, the polarization division multiplexing (PDM) is used to double the spectral efficiency. The transmission rate of a subcarrier, T_{sub} , is characterized by its spectral width (B) and selected modulation level (M), i.e., $T_{sub} = B \cdot \log_2(M)$. A spectrum width of 12.5 GHz for the subcarrier is adopted in this study, and consequently there are 320 spectrum slots for the C-band (4 THz bandwidth). Setting 12.5 GHz as the spectrum width means that the transmission rate of the subcarrier can be 25, 50, 75, 100, 125, 150 Gb/s for PDM BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM and 64-QAM modulation format, respectively [48]. For the selection of the modulation level, this work makes use of the empirical model for OFDM transmission presented in [49]. The model estimates the transmission reach of OFDM transponder as a function of the chosen modulation format and the requested bit rate.

For the optical node, both hard-wired derived solution (ROADM) and AoD-based design are considered. For the ROADM architecture, this work focuses on spectrum routing design with colorless, directionless and contentionless features [11], [12] while a two-stage composition (Fig. 3) is considered for the AoD implementation. Note that the use of a switching module by an optical signal is viewed as an AoD stage. The number of AoD stages depends on the required functionalities and more details on this topic can be found in [50].

The SDM network is modeled as a graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where \mathcal{V} represents the set of nodes, and \mathcal{E} the set of unidirectional links. Each link is characterized by two parameters, that is the set of cores \mathcal{C} , and the set of spectrum slots \mathcal{S} . Demands are assumed to be quasi-static, i.e., once routed in the network they stay virtually permanent. However, the capacity need of the prior established connection grows with time in addition to the new generation of demands as illustrated in Fig. 4. In the proposed RMSCA solution, the routing and MSCA (i.e., modulation, spectrum and core allocation) sub-problems are treated separately. Pre-computed k -shortest path paths between each source-destination pair are considered for routing. More-

over, the spectrum and core selection made for a connection demand affects and is influenced by the spectrum and core decision made for the other demands, due to the XT effect. The XT effect strengthens when signals are transferred between next/neighbor cores with the same frequency spectrum as shown in Fig. 5. However, this study adopts the strategy of assigning spectrum resources in such a way to minimize the spectrum overlapping for signals on the adjacent cores of the fibers (Fig. 6). Besides, such XT aware approach estimates the actual interference among superchannels with same frequencies and adjacent cores. To estimate the XT in MCF, this work utilizes the model developed in [46]. The model is based on the coupled-mode theory and measures the crosstalk as the function of fiber parameters. The crosstalk of a particular core is the ratio of power (in that specific core) originating from the rest of fiber cores to the power that emanates from that specific core [46]. For weakly-coupled MCF with cores arranged in a hexagonal array, the mean XT for any core can be calculated by using the following formula:

$$XT = \frac{n - n \cdot \exp(-(n+1) \cdot 2 \frac{\kappa^2}{\beta} \frac{R}{\Lambda} L)}{1 + n \cdot \exp(-(n+1) \cdot 2 \frac{\kappa^2}{\beta} \frac{R}{\Lambda} L)} \quad (1)$$

where n is the number of adjacent cores. For seven cores MCF, the value of n is equal to six for the center core while it is equal to three for all the other cores (excluding the center core). More details about the fiber parameters and their values used for calculating XT are given in Table I (Section V).

The network planning and resource optimization algorithms presented in this paper broadly follow three phases as depicted in Fig. 7. In the first phase, the required spectral resources for all the demands of each routing path are calculated based on the transmission model described in [49]. The second phase arranges the traffic demands in descending form, according to their values for the ordering function, which is equal to the product of needed slots for setting-up demand on the first (shortest) path and the fiber length of that path. It is worth noting that several variations of the proposed ordering function are investigated, which result in worse performance (in terms of established demands) specifically for high traffic volume. Finally, the third phase aims to assign contiguous resources to demands such that to maximize the objective function while satisfying the XT threshold for the assigned modulation format to each demand. It is worth mentioning that different modulation formats can tolerate a different amount of XT. The signal robustness to XT decreases as the modulation order increases [51]. For example, QPSK can tolerate a high level of XT compared to 16-QAM. On the other hand, a low-level modulation scheme consumes more spectrum slots for provisioning a capacity demand, which in turn increases its chances of interference with other neighbor superchannels having the same frequencies.

In general, the objective is to establish the maximum possible number of demands for a given network spectrum resources in a cost-efficient way. The cost of the network can be reduced by minimizing the switching modules (SSSs) for the optical nodes. For ROADM, this can be achieved by gradually

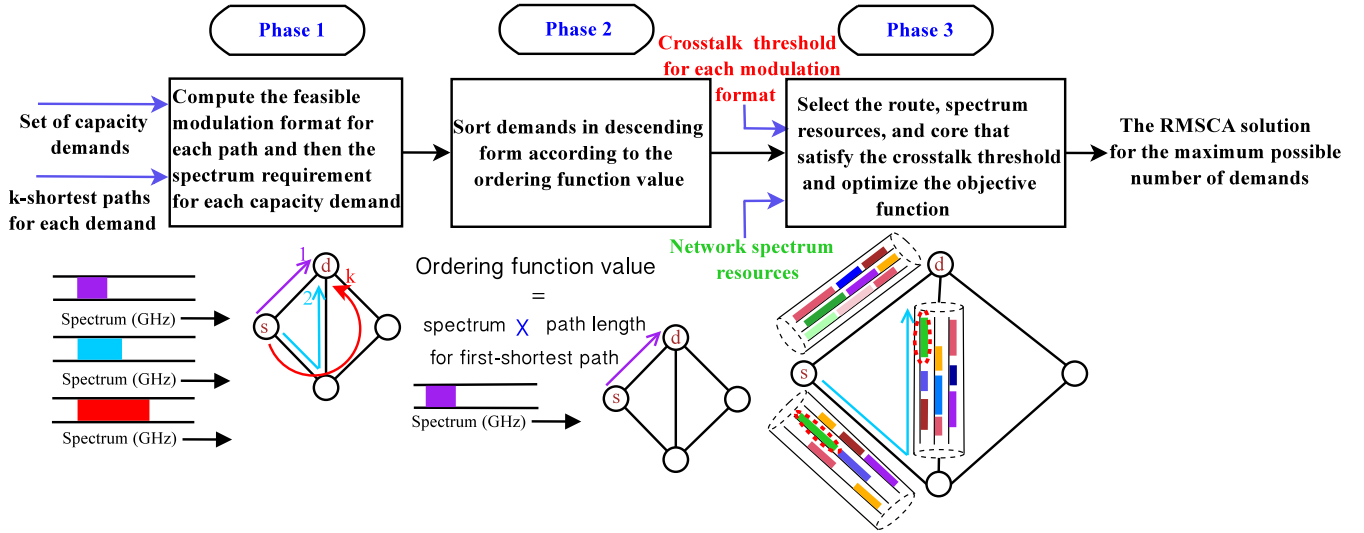


Figure 7. Block diagram of the resource allocation algorithms.

lighting up the essential number of fiber cores needed to carry the network traffic and scaling the ROADM size with network traffic demand. On the other hand, the flexible structure of AoD facilitates to remove redundant switching modules in nodes when and where they are not needed. Furthermore, AoD nodes support the switching of optical signals from an input port directly to their targeted output port through the optical backplane without utilizing any (de)multiplexing modules. Such an operation (denoted as fiber switching) can be enhanced to design cost-efficient networks. More details about cost-efficient network planning using AoD nodes can be found in [52]. To attain this goal of maximizing the provisioned demands while keeping the network switching resources lower, a multi-objective cost function is formulated for each type of SDM node, which is described in the following section.

IV. PROPOSED STRATEGIES FOR ROUTING, MODULATION, SPECTRUM, AND CORE ALLOCATION (RMSCA) PROBLEM

The resource allocation problem for elastic SDM networks can be solved by considering all parameters, such as the number of paths, highest attainable modulation format for each path, XT threshold for each modulation format, available spectrum slots, and the number of cores per fiber. Moreover, the additional factor of core-switching on different links of the path must be taken into account along with the physical layer impairment between neighbor cores in the form of XT. To solve the RMSCA problem, this work proposes different algorithms, which can be divided based on whether the modulation levels for demands computed in Phase 1 (Fig. 7) are alleviated in Phase 3 (Fig. 7) to enhance the signal robustness to XT. These algorithms are further subdivided based on their cost function objective, which is tailored to fit each type of optical node solution for SDM networks.

Algorithm 1 consolidates the common tasks/operations of the algorithms. The demands, which are arranged in descending form (according to the ordering function value), the available spectrum slots, and the XT thresholds for the modulation formats serve as the input parameters. The spectrum resource

availability (for a demand) on a given path $\hat{\pi}$ can be searched for all the viable core combinations set $\aleph_{\hat{\pi}}$ whose sum (i.e., $|\aleph_{\hat{\pi}}|$) is equal to the product of the numbers of unexhausted cores on the path links. The size of $\aleph_{\hat{\pi}}$ depends on the state of the network, i.e., the amount of traffic set-up in the network. Initially, when the traffic volume is low the size of $\aleph_{\hat{\pi}}$ is large, however, the size starts diminishing as the amount of provisioned traffic increases. The algorithm first determines the exact location (beginning) of the free contiguous spectrum slots ($\Lambda_{l_c^{\hat{\pi}^d}}$) on each $l_c^{\hat{\pi}^d} \in \aleph_{\hat{\pi}^d}$ for $\hat{\pi}^d \in \pi^d$ for each demand d . Then the algorithm examines the feasibility of each resource option by computing the level of XT inflicted by the established superchannels if the spectrum resource is availed for routing demand d . Also, the XT impairment effect of these resources on the provisioned superchannels is calculated. Note that the required spectrum and the XT threshold for each demand (in Algorithm 1) correspond to the estimated highest achievable modulation format for the pre-computed candidate paths in Phase 1 (Fig. 7). If the level of XT for d and all affected superchannels is below the threshold then the triplet $\hat{\pi}^d$, $l_c^{\hat{\pi}^d}$, and $\Lambda_{l_c^{\hat{\pi}^d}}$ is a feasible solution and the value of $Ct_{\hat{\pi}^d, l_c^{\hat{\pi}^d}, \Lambda_{l_c^{\hat{\pi}^d}}}$ is computed. If a feasible solution is not found either due to network layer constraint (spectrum unavailability) or physical layer constraint (high level of XT), then the demand d is rejected.

A. Algorithm Modulation Format Fixed (MFF)

The modulation format fixed (MFF) algorithm always employs the pre-computed most spectral efficient modulation format based on the transmission model described in [49]. Thus, a demand is rejected if it cannot attain the XT threshold for the chosen modulation format, or its provisioning will exacerbate the XT level of the prior established superchannels above the threshold.

Algorithm 1 XT Aware RMSCA

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1:  $\mathcal{G}(\mathcal{V}, \mathcal{E})$ : network topology;
2:  $\mathcal{C}$ : set cores;
3:  $\mathcal{S}$ : set available spectrum slots;
4:  $\mathcal{D}$ : set demands sorted for ordering function;
5:  $\mathcal{P}$ : path matrix;  $\pi^d \in \mathcal{P}$  set candidate paths for  $d \in \mathcal{D}$ ;
6:  $\mathcal{M}$ : set modulation levels;  $m_{\hat{\pi}^d} \in \mathcal{M}$  highest attainable level for  $d$  on path  $\hat{\pi}^d \in \pi^d$ ;
7:  $\mathcal{N}_{\hat{\pi}}$ : set link core combinations for path  $\hat{\pi}$ ;
8:  $\Omega$ : set computed spectrum slots;  $\omega_{\hat{\pi}^d} \in \Omega$  slots needed for  $d$  on path  $\hat{\pi}^d$  using modulation level  $m_{\hat{\pi}^d}$ ;
9:  $\mathcal{XT}$ : set crosstalk thresholds;  $xt_m \in \mathcal{XT}$  crosstalk threshold for modulation format  $m$ ;

10: Initialization:  $\tilde{C} = -1$ ;
11: for each demand  $d \in \mathcal{D}$  do
12:   Initialization:  $\tilde{M} = |\mathcal{XT}|$ ;
13:   Initialization:  $\tilde{S} = 0$ ;
14:   for each path  $\hat{\pi}^d \in \pi^d$  do
15:     for each  $l_c^{\hat{\pi}^d} \in \mathcal{N}_{\hat{\pi}^d}$  do
16:       Let  $\Lambda_{l_c^{\hat{\pi}^d}}$  be set of free contiguous slots for  $l_c^{\hat{\pi}^d}$ ;
17:       if  $\omega_{\hat{\pi}^d} \leq \Lambda_{l_c^{\hat{\pi}^d}}$  then
18:         Increment  $\tilde{S}$  by 1;
19:         Compute xt for  $d$  and those prior established super-channels that are inflicted by  $\Lambda_{l_c^{\hat{\pi}^d}}$ ;
20:         if  $xt \leq xt_m$  for  $d$  and all the affected superchannels then
21:           Compute cost function  $Ct_{\hat{\pi}^d, l_c^{\hat{\pi}^d}, \Lambda_{l_c^{\hat{\pi}^d}}}$ ;
22:         end if
23:       end if
24:     end for
25:   end for
26:   if  $\tilde{S} \neq 0$  then
27:     Try_subroutine_xxx;
28:   else
29:     Reject  $d$ ;
30:   end if
31: end for

Try_subroutine_MFF
  Select  $\hat{\pi}^d$ ,  $l_c^{\hat{\pi}^d}$ , and  $\Lambda_{l_c^{\hat{\pi}^d}}$  with  $\tilde{C} = \min\{Ct_{\hat{\pi}^d, l_c^{\hat{\pi}^d}, \Lambda_{l_c^{\hat{\pi}^d}}}\}$ ;

  if  $\tilde{C} \neq -1$  then
    Return  $\hat{\pi}^d$ ,  $m_{\hat{\pi}^d}$ ,  $l_c^{\hat{\pi}^d}$ , and  $\Lambda_{l_c^{\hat{\pi}^d}}$ ;
  else
    Reject  $d$ ;
  end if

Try_subroutine_MFS
  Select  $\hat{\pi}^d$ ,  $l_c^{\hat{\pi}^d}$ , and  $\Lambda_{l_c^{\hat{\pi}^d}}$  with  $\tilde{C} = \min\{Ct_{\hat{\pi}^d, l_c^{\hat{\pi}^d}, \Lambda_{l_c^{\hat{\pi}^d}}}\}$ ;

  if  $\tilde{C} \neq -1$  then
    Return  $\hat{\pi}^d$ ,  $m_{\hat{\pi}^d}$ ,  $l_c^{\hat{\pi}^d}$ , and  $\Lambda_{l_c^{\hat{\pi}^d}}$ ;
  else
    Decrement  $\tilde{M}$  by 1;
    Downgrade the modulation for  $d$  by one level and compute new values for  $\Omega$ ;
    if  $\tilde{M} \neq 0$  then
      Repeat Steps 13-23;
    else
      Reject  $d$ ;
    end if
  end if

```

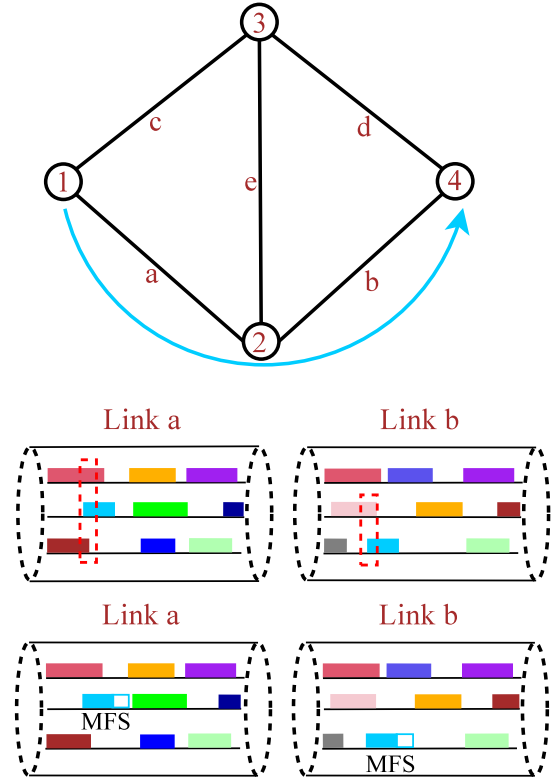


Figure 8. Switching the modulation to lower level by expanding the superchannel bandwidth.

B. Algorithm Modulation Format Switching (MFS)

The modulation format switching (MFS) downgrades/lowers the modulation level from the most spectral efficient to the feasible whenever a demand cannot be provisioned due to the physical layer constraint. MFS enhances the signal robustness to physical layer impairment (i.e., XT) at the expense of expanding the spectrum bandwidth of the impaired demand. Fig. 8 illustrates the concept of MFS, where the most spectral efficient but less tolerable (to XT) modulation format on path 1-2-4 for a demand fails to attain the targeted XT threshold. Since, there is some vacant spectrum on the path links, the MFS scheme can switch the modulation to a less spectral efficient but more XT tolerable level to provision the demand. However, modulation format switching is not possible for every impaired demand as there might not be always free spectrum on the path links to expand the bandwidth. Note that the MFS rejects a demand either due to the unavailability of additional spectrum resources or exhausting the list of possible modulation switching without satisfying the physical layer constraint.

C. Cost Function for ROADM-based SDM Network

The cost function, Ct for the ROADM-based SDM network is a linear combination of the following two terms: (i) the number of new link cores lit by the candidate resources; and (ii) the estimated XT value (for d) while employing the candidate resources. The avoidance to light new link cores by making use of the remaining spectrum resources on the lit cores diminishes the size of ROADM for routing the traffic and

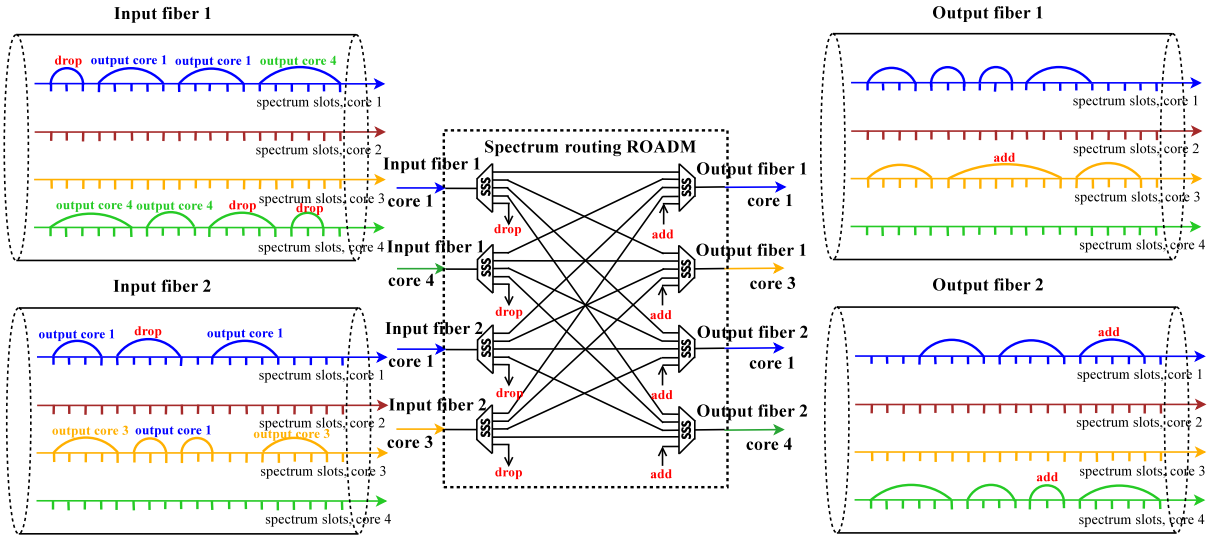


Figure 9. ROADM for MCF-based SDM networks.

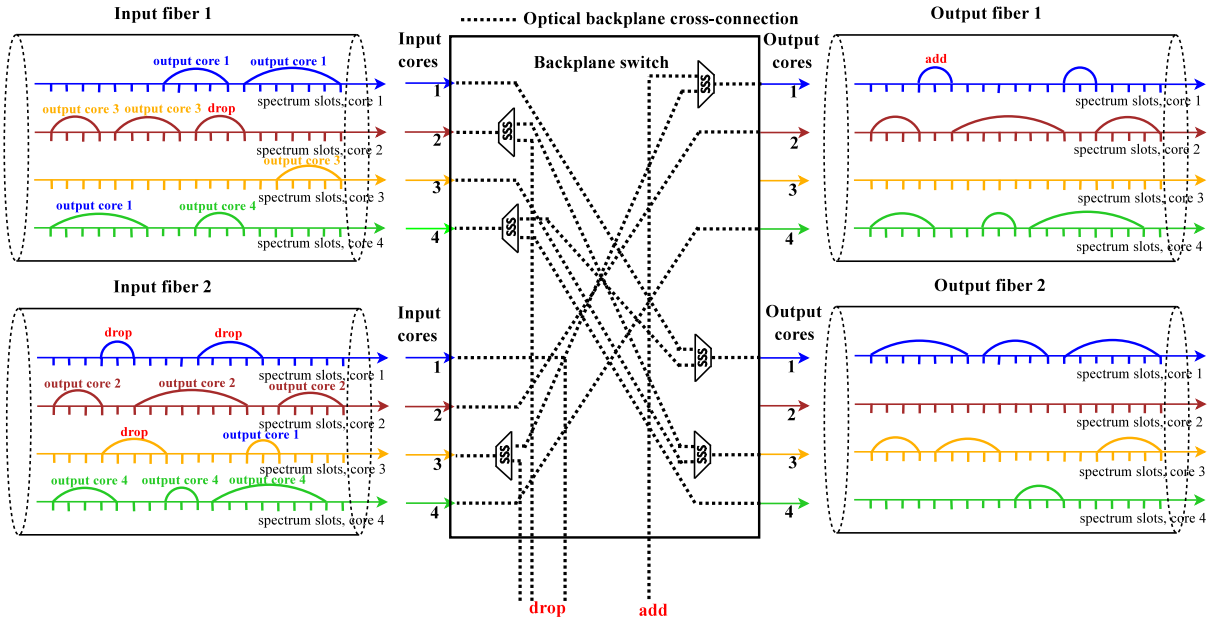


Figure 10. AoD for MCF-based SDM networks.

hence decreases the cost of the network. On the other hand, a low XT value provides more margin to d to be impaired by subsequent connections provisioning. Selecting the solutions with minimum C_t values enable the algorithms (MFF and MFS) to reduce the number of lit link cores required to carry the network traffic and scale the ROADM size with traffic volume. Fig. 9 depicts an example where resources to demands are allocated in such a way to employ a smaller size ROADM for switching purposes.

D. Cost Function for AoD-based SDM Network

For AoD-based SDM network, the cost function C_t is a linear combination of the following two terms: (i) the number of additional (i.e., not prior deployed for established superchannels) switching modules needed to set-up d using

the candidate resources; and (ii) the computed XT value (for d) while utilizing the candidate resources. As mentioned in Section III, the AoD nodes support fiber switching, and augmenting such operation through proper allocation of spectrum resources can reduce the number of switching modules. This approach may lead to lighting more link cores with spectrum resources partially occupied. The aim of the second term (in C_t) is to assign resources to demands in a way that minimizes the spectrum overlapping between the neighbor link cores. Fig. 10 shows a scenario where spectrum resources are allocated to demands such that to reduce XT and to cut down the total switching modules.

Table I
PARAMETERS AND THEIR VALUES

Parameter	Value
Number of cores (C)	7
Total Bandwidth of C-band	4 THz
Spectrum slots per core	320
Number of shortest paths (k)	3
Capacity limit of BV-T	400 Gb/s
Bending radius (R)	0.05 m
Propagation constant (β)	4×10^6 1/m
Coupling coefficient (κ)	4×10^{-4}
Core pitch (Λ)	4.0×10^{-5} m
Amp. inter span spacing	60 km
DP-BPSK crosstalk threshold	-14 dB
DP-QPSK crosstalk threshold	-18.5 dB
DP-8QAM crosstalk threshold	-21 dB
DP-16QAM crosstalk threshold	-25 dB
DP-32QAM crosstalk threshold	-27 dB
DP-64QAM crosstalk threshold	-34 dB

E. Computational Complexity Analysis of RMSCA Algorithms

The computational complexity of MFF for ROADM-based (MFF-ROADM) and AoD-based (MFF-AoD) SDM networks is $O[|D||\pi^d||C|^{|\mathcal{V}|+1}|S|^2|\mathcal{V}|^2]$. Similarly, the complexity of MFS for ROADM-based (MFS-ROADM) and AoD-based (MFS-AoD) networks is $O[|D||\pi^d||\mathcal{X}\mathcal{T}||C|^{|\mathcal{V}|+1}|S|^2|\mathcal{V}|^2]$. It can be observed that the number of cores (i.e., $|C|$) is the dominant parameter in the complexity due to core-switching aspect of the presented algorithms.

V. NUMERICAL RESULTS

The performance of the proposed XT aware RMSCA algorithms is evaluated with a custom-built discrete-event-driven simulator. The assessment is carried out on the BT topology (Fig. 11) with 22 nodes and 70 unidirectional links. Set of demands and their capacity requirements are generated by uniformly selecting the source and destination nodes and values from 10 Gb/s to 500 Gb/s, respectively. These capacity values are increased by 30% besides the arrival of new demands (randomly) at every next epoch. Results are collected until a confidence interval of 5% or less is reached with a confidence level of 95%. Moreover, a single spectrum slot is introduced for the guard band between neighboring superchannels. Table I presents the list of physical parameters and their values used in this study.

The performance of XT aware strategies is determined in terms of successful network traffic volume, and the number of network switching modules needed to route the demands. For the benchmarking purpose, the proposed algorithms are compared with the basic approaches, i.e., no cross-layer optimization between the network and physical layers. The benchmark scheme for both ROADM and AoD-based networks is a modified version of Algorithm 1 that excludes Steps 17 and 18 and verify the feasibility of resources after selection.

A. Performance Comparison in Terms of Provisioned Traffic

Fig. 12 exhibits the successful traffic volume values for all the proposed strategies, which are normalized to the value of total network traffic for all load levels. To analyze the trade-off

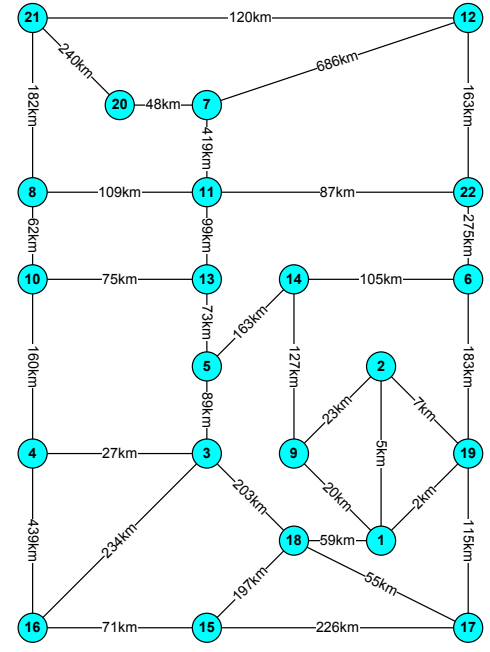


Figure 11. British telecom (BT) topology.

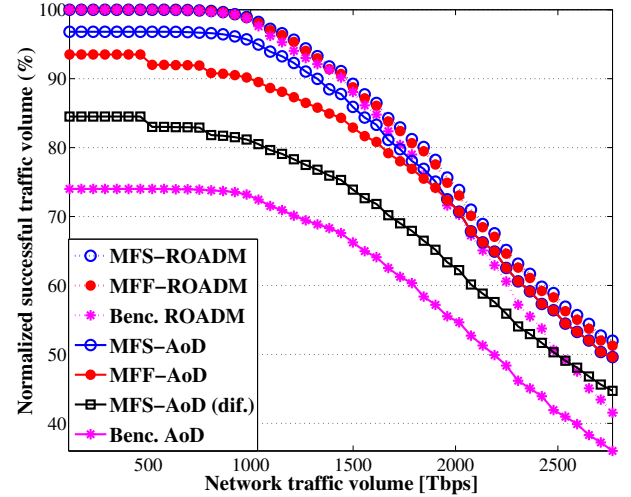


Figure 12. Normalized provisioned traffic volume vs. total traffic volume.

between switching modules and the level of impairment (due to XT) a third strategy for the AoD-based network (i.e., MFS-AoD (dif.)) is also presented. In this later strategy, a three times higher weighting for the first term in the cost function (i.e., the number of additional switching modules) is employed compared to the second term (i.e., estimated XT value term). Several observations can be made from the results shown in Fig. 12. First, by incorporating the XT impairment values while computing the candidate resource solutions through cross-layer optimization techniques the network provisioning capability is improved especially for the AoD-based network. Second, the proposed algorithms for networks with ROADM show slightly better performance compared to the ones for the AoD-based network. These algorithms (ROADM case) first seek the spectrum resources on the non-adjacent cores of the network links by exploiting the dense intra-node connectivity

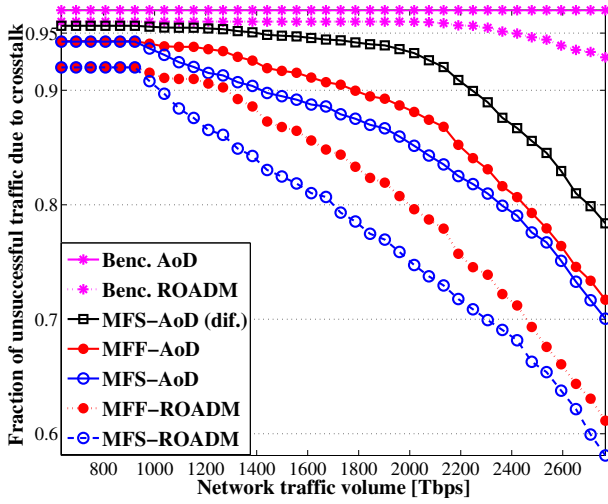


Figure 13. Fraction of total unsuccessful traffic due to XT vs. total traffic volume.

of the ROADMs. Once the spectrum resources on the non-adjacent cores are used up (due to increasing network traffic), the strategies reconfigure the allocated resources to demands so that to minimize the level of impairment due to XT. On the other hand, the algorithms for the AoD case occupy resources on different link cores instead of first exhausting spectrum on non-adjacent cores to maximize the fiber switching. Though the algorithms search for spectrum slots that are disjoint (in frequencies) from the allocated resources on the adjacent cores, the chances of the spectrum overlapping with neighbor cores are still higher compared to the approach adopted for ROADM case. Third, MFS-AoD demonstrates better performance compared to MFF-AoD, particularly for low network traffic. However, their performance is more or less the same for the ROADM-based network since for AoD case, XT impairment is the prime issue and thus enhancing signals resistance by lowering the modulation levels elevate the provisioned traffic volume. Finally, prioritizing the cost function to diminish the deployment of new switching modules (MFS-AoD (dif.)) results in exacerbating the successful traffic volume.

To obtain insight into the unprovisioned traffic, Fig. 13 displays the fraction of the total unsuccessful traffic volume that fails to satisfy the physical layer constraint, i.e., higher XT than the threshold. It can be seen from Fig. 13 that most of the rejection (traffic volume) occurs due to XT, particularly for AoD case. However, as the network traffic volume increases, the impact of the other factor, i.e., network resource unavailability starts to militate the total unsuccessful traffic volume. Finally, to assess the feasibility of the proposed strategies in terms of network scalability, Fig. 14 exhibits the ratio of computational time for both MFS and MFF compared to the benchmark approach. At lower loads when the network resources are relatively less occupied, the computational time for MFS is higher compared to MFF. However, the computational time gap between these two approaches shrinks at higher loads owing to a diminished search space for finding additional free resources to downgrade the modulation format.

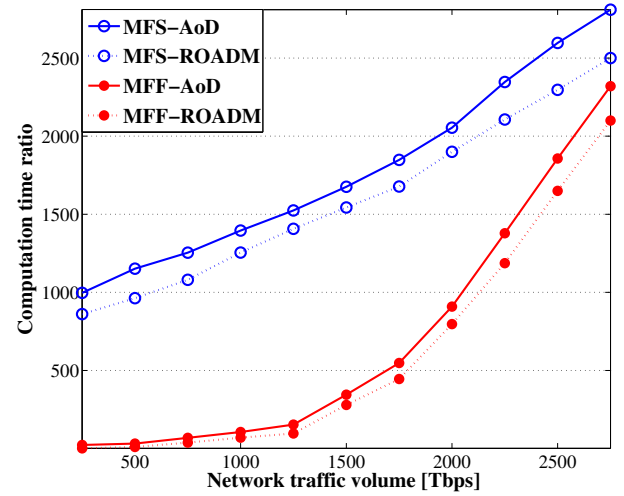


Figure 14. Computation time rate vs. total traffic volume.

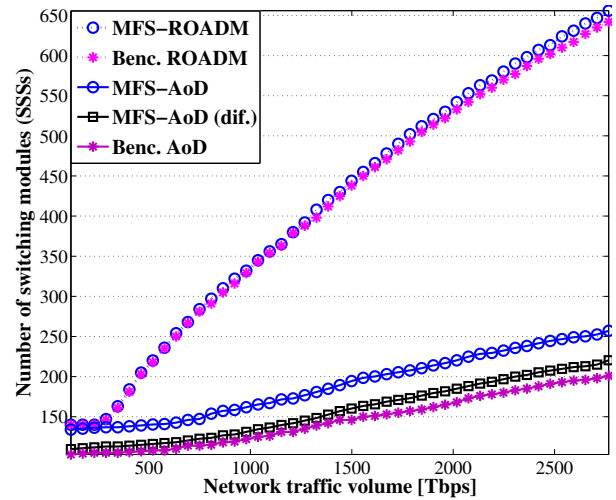


Figure 15. Number of switching modules vs. total traffic volume.

B. Performance Comparison in Terms of Required Switching Modules and Amplifiers

Fig. 15 shows the sum of switching modules needed in the network for routing the traffic volume. It can be seen from the results (Fig. 15) that the performance of MFS-ROADM is approximately the same as that for of the benchmark strategy since both the strategies (MFS and benchmark) employ the same criteria, i.e., to use up the spectrum resources of a core before lighting the other cores. The required modules for ROADM based networks depend on the number of lit cores; hence, the two strategies attain the same performance. To verify this point (i.e., avoiding to light up a new fiber core) Table II reports the number of lit-up fiber cores for ROADM-MFS at different network traffic volumes. These values confirm that by incorporating the number of new link cores lit by the candidate resources in the optimization function, the number of lit-up fiber cores can be curbed. This leads to diminishing the size of ROADM for routing the network traffic.

On the other hand, the algorithms for AoD-based network

Table II
NUMBER OF LIT-UP FIBER CORES VS. NETWORK TRAFFIC VOLUME FOR MFS-ROADM

Number of lit-up fiber core	1	3	4	5	7
Network traffic vol. [Tbps]	350	700	1400	1800	2600

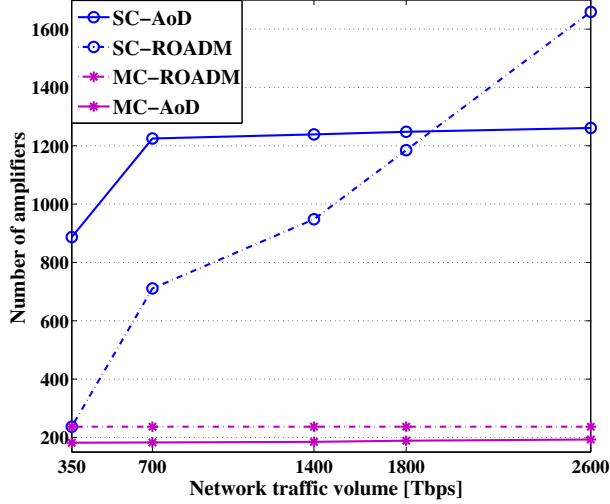


Figure 16. Total number of single-core (SC) and multi-core (MC) amplifiers for ROADM and AoD based networks.

employ a significantly lower number of switching modules (Fig. 15) compared to ROADM case, thanks to the adaptability inherent in AoD. These algorithms reconfigure the network and exploit the AoD flexibility to minimize the deployment of new switching modules as the network traffic increases. This minimization is achieved by enhancing fiber switching and relocating the prior installed modules in the nodes. Due to these factors the required switching modules grow slowly (compared to ROADM case) as the traffic volume increases. At low load, the strategies for AoD save up to 20% of modules compared to schemes for ROADMs, and this savings jumps to 60% at high loads. It is worthwhile to mention that AoD requires an additional switch for the optical backplane. However, the market price of a large-size (96 x 96) switch is just 20% higher than the cost of a 1 x 16 SSS [53]. Thus, even incorporating the cost of a large-size switch (as an optical backplane), the cost reduction of the network design with AoD nodes is substantially higher compared to the ROADM case. Besides, a cost comparison of the AoD with conventional black box solutions at the node level also confirms the cost-effectiveness of AoD [50]. Finally, the strategy (AoD-MFS (Dif.)) with the cost function that aims at minimizing the number of new switching modules as the primary objective and the XT as the secondary objective further diminishes the required modules with respect to AoD-MFS.

Fig. 16 exhibits the number of amplifiers deployed in the ROADM and AoD based networks at different traffic volumes. For the single-core (SC) amplifier class, the number of amplifiers for ROADM based network is equal to the sum of inline amplifiers (for the light up fiber cores) plus the ones for compensating the ROADMs internal losses. For the AoD based network, the fiber switching operation alleviates

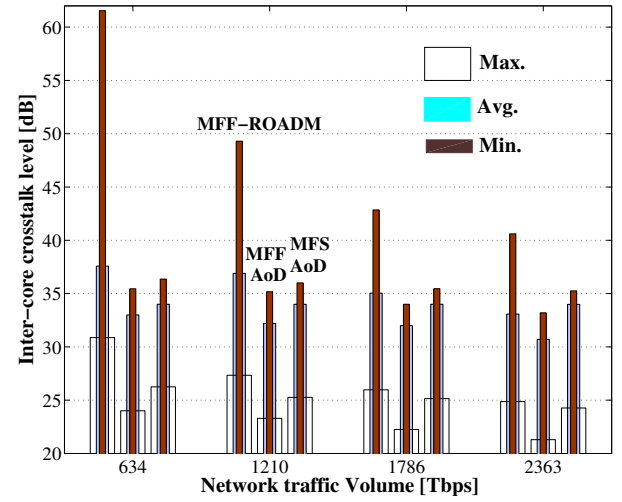


Figure 17. XT for different provisioning strategies at different network loads.

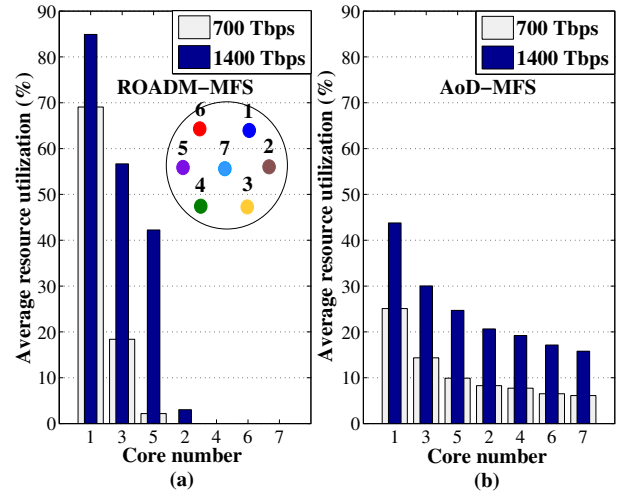


Figure 18. Average spectrum resource utilization on different cores for MFS.

the compensatory amplifiers for switching losses but raises the number of inline amplifiers considerably (for lower traffic volumes) compared to the ROADM case. However, for higher network traffic the AoD case needs less amplifiers than the ROADM since most of the fiber cores are lit up to establish the demands. On the other hand, for the multi-core (MC) amplifier class where each amplifier can serve multiple cores (assuming seven cores in this study), the number of inline amplifiers becomes independent of the lit up fiber cores, thus, enabling the AoD based networks to reduce the employed amplifiers for switching losses (through fiber switching) related to ROADM case.

C. Analysis of XT Intensity and Spectrum Resource Utilization

To investigate the presented algorithms for the XT intensity, Fig. 17 depicts the XT values at different network loads. Note that these values are calculated for the set-up superchannels without taking into account the values for demands rejected due to XT. As expected the strategies for the AoD-based network, in general, and the MFF-AoD, in particular, have

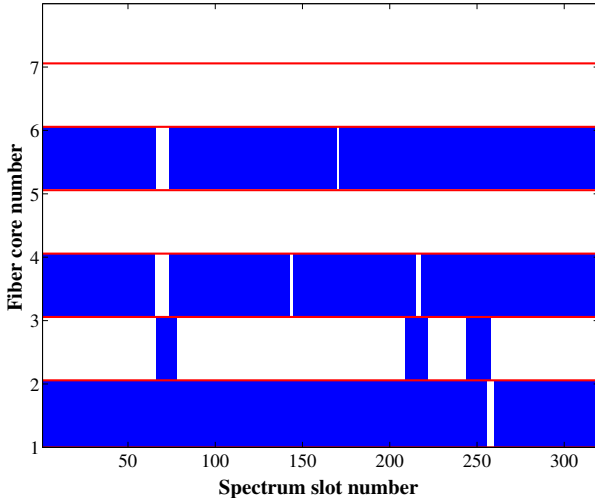


Figure 19. Spectrum resource occupancy for link from node 22 to node 6 for traffic volume of 1400 Tbps.

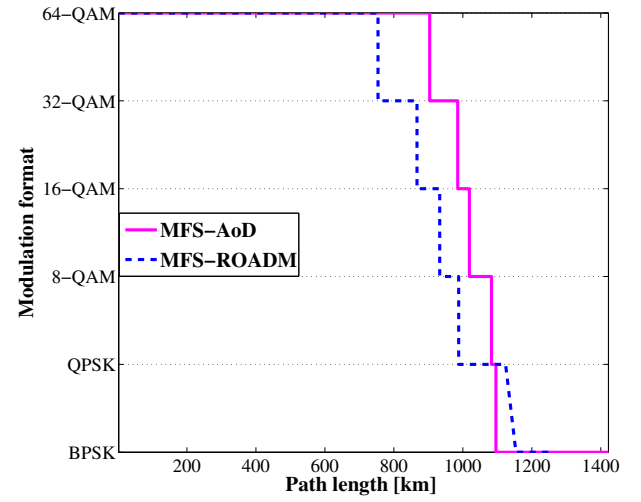


Figure 21. Modulation format vs. path length.

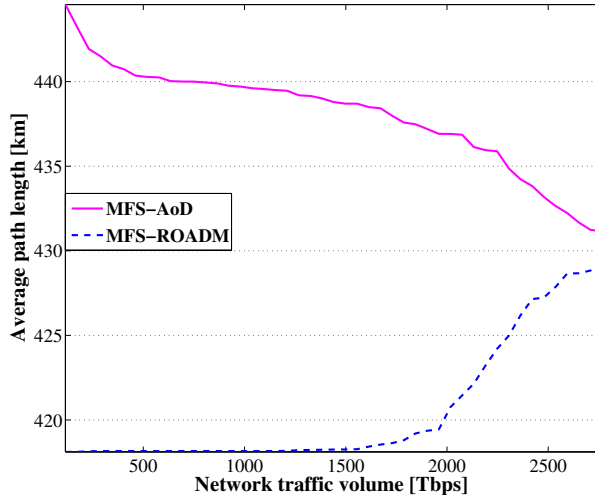


Figure 20. Average path length vs. total traffic volume.

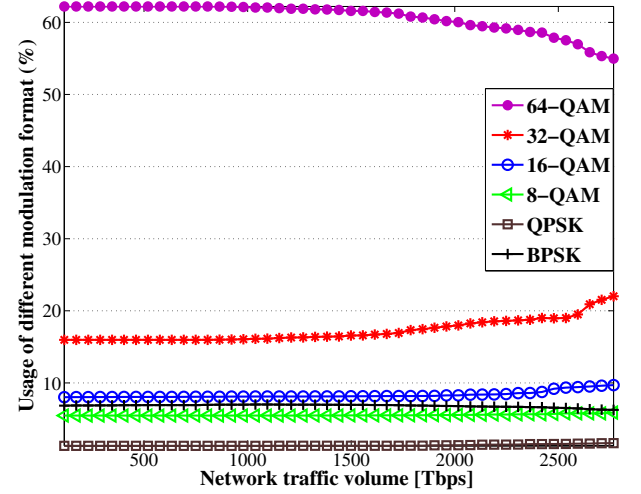


Figure 22. Percentage usage of different modulation format vs. total traffic volume for MFS-AoD.

a higher level of XT (smaller value of dB on the plot) with respect to the scheme for the ROADM-based network. Furthermore, the feature of modulation switching (to lower levels) enables MFS-AoD to alleviate the level of XT compared to AoD-MFF.

Fig. 18 highlights the average spectrum resource utilization per core for MFS at low and medium network traffic volumes. The resource utilization values for MFF strategy are slightly lower than MFS, which are not shown in Fig. 18. As anticipated, the MFF-ROADM (Fig. 18.(a)) lights up a subset of cores in order to reduce the switching modules, which grows with the increase in network traffic volume. Furthermore, MFS-ROADM utilizes most of the resources on the non-adjacent cores of the fiber so that to minimize the impact of XT. On the other hand, the MFS-AoD (Fig. 18.(b)) makes use of partial resources on all the cores (with minimum spectrum overlapping among neighbor cores) to maximize the fiber switching. The spectrum resource consumption trend for MFS-ROADM is further analyzed in Fig. 19. It is worth mentioning that the link from node 22 to node 6 is identified as

a bottleneck link for the given topology. Augmenting spectrum resources on this link can improve the traffic provisioning, which is beyond the scope of this work. Fig. 19 confirms that the proposed XT aware scheme assign spectrum resources to superchannels in such a way to mitigate the impairment owing to neighbor cores crosstalk.

D. Analysis of Path Length and Modulation Level Selection

Fig. 20 shows the average path length for MFS as a function of network traffic volume. For MFS-AoD, the switching resources (and consequently the intra-nodal connectivity) grow with the increase in traffic volume. The more intra-connected nodes improve the chances of finding spectrum resources on shorter paths. Thus, the path length for MFS-AoD drops with the rise in network traffic. On the other hand, the average path length for MFS-ROADM goes up with the increase in network traffic volume. The reason is that the cost function forces the selection of shorter paths (i.e., to achieve low XT) when the network spectrum resources are partly occupied. As the network traffic increases, the candidate solution space shrinks,

which leads to the selection of spectrum resources on longer paths.

The relation between routed path length and selected modulation level for network traffic demands is examined in Fig. 21. Notice that the selection of modulation level (for MFS strategy) not only depends on the path length but also on the XT intensity. The ratio of provisioned traffic for MFS-ROADM (Fig. 12) is higher than for MFS-AoD, which indicates more likelihood of signal interference on longer routes for MFS-ROADM. Thus, the signal robustness to XT is enhanced by employing a relatively lower level of modulation compared to MFS-AoD. Finally, Fig. 22 illustrates the usage of different modulation formats for MFS-AoD as a function of network traffic. The figure reveals that the 64-QAM is the prominent scheme used for all traffic values. This is because the links (and hence paths) of the used network topology (Fig. 11) are relatively short, which facilitates the selection of the most spectral efficient modulation format. Such high spectral efficient scheme (64-QAM) occupies only a few spectrum slots for establishing traffic demands, which in turn alleviates the possibility of XT. A similar pattern for the selection of different modulation format is also observed for MFS-ROADM.

VI. CONCLUSION

The paper has studied the routing, modulation, spectrum, and core allocation (RMSCA) problem for quasi-static elastic SDM networks. For the switching purposes, the study considered both optical white box (repurposable and evolvable AoD) and optical black box (hard-wired ROADM) solutions. Different resource allocation strategies are presented that are particularly tailored to fit the type of optical node deployed in the network with a hybrid cost function objective to minimize the unprovisioned traffic volume and the total switching modules. The proposed heuristic algorithms exploit the flexibility offered by multi-core fiber (MCF) in the form of switching cores on different links during provisioning of traffic demands but are limited to employing only spectral superchannels. Moreover, the algorithms take into account the inter-core crosstalk (XT) stems from the multi-cores embedded in the fiber cladding by adopting the cross-layer optimization approach to calculate the actual XT for the candidate resource solutions. As a result, the proposed strategies improve the amount of provisioned traffic significantly with respect to the technique that compute the resource feasibility once it is assigned to a demand.

Among the proposed algorithms, the ones based on the modulation format switching (i.e., MFS) show better performance in terms of successful traffic volume, at the expense of increased computational complexity and marginal increment in switching modules (notably for the AoD-based network). Furthermore, the inherent flexibility of AoD capacitates the proposed strategies (for the AoD-based network) to achieve a substantial savings (up to 60%) in switching modules at the cost of slight exacerbation in provisioning performance compared to hard-wired ROADM case. In conclusion, these results indicate that AoD is the scalable and cost-efficient solution for future generation elastic SDM networks.

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