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Survey of resource allocation schemes and algorithms in spectrally-spatially flexible optical networking

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ABSTRACT

Space division multiplexing (SDM) is a promising optical network solution with the scaling potential to overcome the possible capacity crunch problem in backbone networks. In SDM optical networks, optical signals are transmitted in parallel through spatial modes co-propagating in suitably designed optical fibers. The combination of SDM with wavelength division multiplexing technologies, based on either fixed or flexible frequency grids, allows for a significant increase in the transmission system capacity and improves network flexibility through the joint management of spectral and spatial resources. The goal of this tutorial paper is to survey the resource allocation schemes and algorithms that aim at efficient and optimized use of transmission resources in spectrally and spatially flexible optical networks. There are several flavors of SDM, which results from available optical fiber and switching technologies; hence, we begin from classifying SDM optical network scenarios. As some SDM solutions have specific limitations, for instance, due to coupling of spatial modes, we discuss related constraints and their impact on resource allocation schemes. Along with defining possible SDM scenarios, we survey the proposed in the literature resource allocation algorithms and classify them according to diverse criteria. This study allows us to overview the state-of-the-art solutions in the scope of planning and operating SDM optical networks in a systematic way as well as to identify some open issues that lack solutions and need to be addressed.

1. Introduction

The overall Internet traffic grows quickly due to continuously increasing popularity of various network services. According to the recent Visual Networking Index report published by Cisco, the IP traffic will grow at a compound annual growth rate (CAGR) of 22% from 2015 to 2020. These trends lead to incremental exhaustion of available capacity in optical transport networks [1]. The currently deployed wavelength division multiplexing (WDM) optical communication systems rely on single-mode fibers (SMFs), in which optical signals are transmitted in parallel through non-overlapping, fixed-spaced channels in the frequency domain [2]. The refractive index profile and core dimension of an SMF is adequately tailored so that to allow for light guiding of a single *spatial mode* in the core region.

For efficient utilization of scarce spectrum resources in SMFs, the concept of spectrally flexible (elastic) optical networking was developed in recent years [3]. The key features of elastic optical networks (EONs) are adaptive use of various modulation formats [4], which differ in spectral efficiency and transmission reach, and multiplexing of wavelengths (also called frequency slots or spectrum channels) of suitably tailored width within a flexible frequency grid, which extends the idea of fixed-grid WDM optical networks. EONs enable multi-carrier (i.e., super-channel, abbreviated as SCh) transmission, where a high-capacity SCh transmitted over the network consists of a number of optical carriers (OCs) [5]. The carriers are generated/terminated using transceiver devices, each making use of a certain modulation format and carrying a fraction of aggregated traffic. Although flexible-grid EONs support high bit-rate traffic demands more efficiently than conventional fixed-grid WDM optical networks, still their transmission capacity is approaching its upper bound due to the nonlinear Shannon limit of the conventional SMF [1].

SDM is a forthcoming optical network technology going beyond the capabilities of WDM/EON systems by enabling parallel transmission of several co-propagating spatial modes [6–9]. SDM operates with suitably designed fibers in which the modes are guided either through multiple cores placed within a single fiber cladding or in a single core of enlarged dimension and modified refractive index contrast [10]. SDM, when combined with WDM/EON, brings many benefits including

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enormous increase in transmission capacity, extended flexibility in resource management due to the introduction of the spatial domain, as well as potential cost savings thanks to the sharing of resources and the use of integrated devices, such as switches [11], amplifiers [12], or transponders [13]. Nevertheless, it poses also many challenges, with the main concerning development of practical, reliable, and cost-effective hardware for long-haul transmission systems, capable of competing with current optical network solutions. General discussion on SDM can be found in [1,11,14–17], and for extensive overview of SDM enabling technologies refer to [8,18].

The main concern in optical networking is provisioning of lightpath connections for transmitted signals. A lightpath is an optical path established between a pair of source-destination nodes. In spectrally flexible optical networks, the lightpaths carrying SChs are routed through the network over SMF links in appropriately assigned spectrum channels, which are switched in network nodes with the aim of wavelength selective switches (WSSs). Having a set of traffic demands, the routing of lightpaths requires a contention-free allocation of spectrum resources on each link belonging to the routing path of each connection realizing a demand. It translates into the problem of routing and spectrum allocation (RSA), which consists of finding lightpath connections, tailored to the actual width of transmitted signals (i.e., SChs), for end-to end demands that compete for spectrum resources [19]. The RSA problem is present both in the phase of network planning and during its operation.

The introduction of the spatial dimension (through the availability of parallel spatial modes in SDM) allows for carrying the OCs of SChs using not only continuous frequency slots in the frequency domain (as in EONs), but also to distribute them over different spatial modes. In spectrally-spatially flexible optical networking, RSA converts into the problem of routing, spatial mode, and spectrum allocation (abbreviated as RSSA), which adds new decision variables related to the selection of spatial modes in network links by means of which the optical signals will be transmitted. The handling of a much larger number of spatial modes than in WDM/EON optical networks increases dramatically the complexity of both hardware and control functions in SDM networks. It results in a large set of decision variables in network optimization, which makes RSSA more complex than the RSA problem. Moreover, as discussed in next sections, some SDM scenarios may have specific requirements, for instance, certain groups of modes may need to be transmitted and switched together due to mode coupling. Consequently, new dedicated resource allocation schemes and algorithms are required in such networks.

1.1. Motivations and contributions

The main motivation behind this work is the lack of a comprehensive literature survey on spectral and spatial resource allocation schemes and RSSA algorithms in SDM networks. There is a need for such a survey and particular motivations are the following. First of all, the SDM technology is still in its infancy and there are many technological options considered for realization of SDM transmission in optical networks, each having specific properties, for instance, due to coupling of spatial modes. Since it is not clear which solution (or solutions) will be finally deployed, we try to identify the most promising SDM network scenarios based on the analysis of research works that appeared in the literature. Secondly, we aim at classifying SDM technologies according to their characteristics, which are reflected in proper resource allocation schemes to be applied when establishing/provisioning optical connections in the network. Such classification will help to understand the differences between particular solutions and their impact on network operation. In this scope, we also briefly summarize the so far performed comparative studies concerning different SDM scenarios. Eventually, although the research work in SDM network optimization is in its initial phase and efficient algorithmic solutions for more complex networking problem are yet to come, in the literature there have been proposed different approaches for solving specific network planning and operation problems that arise in SDM optical networks. Before developing new and more efficient algorithms as well as before addressing the RSSA optimization problems and the SDM optical network scenarios that lack solutions, the state-of-the-art methods presented in related works should be recognized, which is our another goal.

The result of our study is compiled and reported in this work, which is to the best of our knowledge the only comprehensive literature survey for studies related to the RSSA problem. More specifically, the major contributions of the survey are as follows: (a) an overview of SDM technologies with identification of their main properties that have impact on network operation and spectral-spatial resource allocation process, (b) a classification of SDM network scenarios considered in the literature using diverse classification criteria allowing for identification of the most relevant ones, (c) a review of the studies that compare different SDM scenarios, (d) a comprehensive survey of the state-of-the-art RSSA-related algorithms in spectrally-spatially flexible optical networks, (e) the identification of the research gaps and the unanswered questions in the scope of planning and operating SDM optical networks.

In this survey, our main focus is on optical backbone networks, and other applications of SDM, for instance, such as short-distance data center networks [20] or access networks [21], are left for further studies. Also, we do not include into analysis some older works, such as [22–25], which although address multi-fiber optical network scenarios, still do not fully exploit spectral and spatial flexibility offered by the SDM transmission and switching technologies that are discussed in this paper. Finally, we do not cover the issues strictly related to the control plane which, however, is responsible for performing connection setups/teardowns and thus for applying the discussed resource allocation schemes in the network, it may have different implementations, such as for instance based on the software defined network (SDN) concept [26,27], which analysis is out of scope of this paper.

In order to report the state-of-the-art and current proposals, we collected more than 40 recent papers, and considering a variety of classification criteria we reviewed the related papers. In each case where there existed some doubts how to classify given work with respect to specific criteria, for instance, if required information was not provided in the article or it was not clearly stated, then such work was not included in this specific classification.

The rest of this survey paper is organized into six sections. In its first part, which spans from Sections 2–5, we aim at classifying the surveyed solutions according to particular SDM optical network scenarios. Namely, in Sections 2 and 3, we focus on SDM suitable optical fibers and switching paradigms, respectively. Since all the considered options for realization of SDM are widely discussed in the literature (e.g., see [8,18]), including their pros and cons, we skip their detailed description and address specific technology-related constraints that influence the functioning of resource allocation schemes and algorithms. In Section 4, we classify different types of SChs supported by SDM optical networks, which lead to different spectral-spatial resource allocation schemes. As a summary, in Section 5, we distinguish several complete network scenarios that assume jointly specific technological options. Next, in Section 6, which is the largest and consists of several subsections, we classify and discuss particular algorithmic approaches the are presented in the surveyed papers. Among others, we focus on the addressed network planning and operation problems, applied optimization methods, solving the RSSA problem, integer linear programming (ILP) modeling of RSSA, dealing with crosstalk, resource fragmentation, and considered performance/optimization metrics. Finally, in Section 7, we conclude our work and point out some possible directions for future research.