Optics Communications 413 (2018) 80–86

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Allocation of spectral and spatial modes in multidimensional metro-access optical networks

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ARTICLE INFO

Keywords:
All optical network
Optical access network
Resource allocation
Spatial division multiplexing

ABSTRACT

Introduction of spatial division multiplexing (SDM) has added a new dimension in an effort to increase optical fiber channel capacity. At the same time, it can also be explored as an advanced optical networking tool. In this paper, we have investigated the resource allocation to end-users in multidimensional networking structure with plurality of spectral and spatial modes actively deployed in different networking segments. This presents a more comprehensive method as compared to the common practice where the segments of optical network are analyzed independently since the interaction between network hierarchies is included into consideration. We explored the possible transparency from the metro/core network to the optical access network, analyzed the potential bottlenecks from the network architecture perspective, and identified an optimized network structure. In our considerations, the viability of optical grooming through the entire hierarchical all-optical network is investigated by evaluating the effective utilization and spectral efficiency of the network architecture.

1. Introduction

As we know, introducing plurality of spectral components (DWDM and/or OFDM channels) has contributed to both the network throughput increase and dynamic/elastic operation of optical networks [1,2]. In parallel, introduction of spatial modes propagating in few mode fibers (FMF) and multicore fibers (MCF) as spatial division multiplexing (SDM) has provided a base for a substantial increase in channel capacity [3–5]. It was also proposed that spatial modes can also be used to perform networking functions mainly through interworking between spatial and spectral modes [6,7]. In parallel, the routing and resource allocation in the SDM-based networks become a meaningful research topic in dynamic and elastic networking scenarios. In order to maximize the network throughput and optimize the usage of network resources in SDM-based networks, a comprehensive network design should be put in place, which deals with dynamic and flexible-grid-based arrangement of spectral components carried over specific spatial modes, adaptive adjustment of the spectral efficiency (SE) through dynamic change of the constellation size and coding strength in applied modulation formats, and advanced software defined network (SDN) control.

In this respect, some important works have been presented in [8–16], where novel algorithms have been considered and so-called RMSCA (routing, modulation, spectrum, core assignment) problem has been defined.

When considering multidimensional networking in SDM-based architectures, some important aspects, such as the impacts of spatial mode crosstalk and structure of spectral slots with respect to modulation formats and achievable spectral efficiency have been analyzed in our recent work [16]. Namely, in our investigation of RMSCA, we introduced the first fit/least loaded dynamic routing method in SDM-based metro/core optical networks and generated algorithms to analyze interworking between spectral and spatial modes, the impact of spatial mode crosstalk, and selection of modulation formats.

We should mention that consideration of spectral–spatial arrangement for networking is not limited to metro/core networking segments, but extends to optical access networks as well [14,15]. This goes along with the effort to accommodate future traffic demands in optical access networks and save on both CAPEX and OPEX.

In multidimensional network environment with plurality of spectral and spatial components, we can assume that transparency and 'blurring' of the boundaries between different optical network segments become more meaningful. As an example, we can say that the long-reach PON (LR-PON) architecture [17], in which the metro network is absorbed in the access network, can be considered as a reference that network performance can be enhanced by the employment of spatial modes.

In this paper, we will take a comprehensive approach with respect to optical transparency extension to the network edge and access, while

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https://doi.org/10.1016/j.optcom.2017.12.042
Received 2 October 2017; Received in revised form 14 December 2017; Accepted 15 December 2017

taking into account the result that we obtained in [16]. In that respect, we have proposed a multidimensional access network architecture with different levels of spectral–spatial interworking while considering its connection to metro/core networking segment through an edge node. We have considered the impact of the optical grooming on the spectrum utilization in an access network and bottlenecks in the dynamic bandwidth distribution. As a result, optimized network scenarios have been identified with respect to established design constraints.

2. Structure of elastic transparent network

In the basic concept of elastic network [1], the allocation of the spectrum slices is flexible and depends on the capacity requirements for each connection. With finer granularity in spectrum assignment, the utilization of the available optical spectrum is improved. We can assume that spectral slices can be increased/decreased by specified granularity (i.e. by changing the number of subcarriers within the slice). At the same time, different modulation formats may be applied according to the performance requirements and available spectral slots [18]. If the transmission distance is short enough, modulation formats with high spectral efficiency, such as 64-quadrature amplitude modulation (QAM), can be selected to reduce the bandwidth of the required spectral slot. To generate and switch/route flexible spectrum slots in an elastic network, bandwidth variable transceivers (BVT) and bandwidth variable wavelength selective switches (BV-WSS) are required. Accordingly, as compared with conventional network, there is an additional 'contiguity' constraint in the bandwidth routing process. Namely, at the source side, several spectrum slots can be bundled together to convey a signal whose bandwidth is wider than a single spectral slot and these slots need to stay contiguous until they reach the destination side.

We should also have in mind that, during a dynamic routing process in an elastic network configuration, establishing and releasing connections with mixed-sized bandwidth will break the spectrum into fragments, and hence reduce the utilization of the network resources. To successfully transmit data flow with given spectral efficiency and modulation/coding format from source to destination, the signal to noise ratio (SNR), as a benchmark, is required to stay above the threshold corresponding to that specific modulation/coding format. Adding spatial degree of freedom opens a new avenue in the elastic network design and optimization.

The hierarchical structure of an elastic optical network that we study is shown in Fig. 1. As we know, the network infrastructure is shared by fewer numbers of users when moving to the edge of the network, which makes the access network much more price-sensitive. Similarly, with fewer users, the fluctuation of the traffic has more significant effect.

We assume that spatial modes are present in all networking segments shown in Fig. 1. Accordingly, it is a challenging task to investigate the benefits brought by the network flexibility having in mind various switching and routing options. Our goal is to identify and optimize this active network structure from Fig. 1, and investigate extension of the optical transparency from the core network segment further down to access while studying the resource allocation problem associated with it. Since optical access is in essence a point-to-multipoint architecture corresponding to the tree topology, some kind of power splitter (PS) is used between central office (CO) and optical networking units (ONU) to reach a number of ONUs in a cost-effective way. The signals for each ONU should belong to independent and orthogonal basis functions from time–frequency–space volume. With that respect, passive splitting, switching in frequency and space domains, and demultiplexing in time and frequency domains can be associated with specific functions placed at different access network stages shown in Fig. 1. Therefore, by using this approach, we consider the operation of access network in conjunction with the metro/core segments, which helps to identify the problems in an elastic and dynamic scenario and propose possible optimized solutions.

3. Opaque central office

Let us examine several possible scenarios with different transparency levels when considering dynamic and elastic bandwidth distribution from metro/core to access and end-users. In this section, we assume that the central office (edge node) is opaque in nature, while the connection between the access and metro/core network segments with transparent edge nodes is studied in Section 4.

3.1. Network model

For this network model, cf. Fig. 1b/c, the optical signals for each ONU went through $O/E/O$ regeneration in the CO, which means that the connection between metro and access network segments is not transparent. With spatial dimension introduced, and to provide a wider bandwidth that will be split among related ONUs, we can assume that N_{core} spatial channels (or modes) are originating from optical line terminal (OLT) in question and that each spatial mode can support N_{ss} spectral slots (in our model to save on computation time we used $N_{core} = 3$ and $N_{ss} = 30$). Next, to achieve finer granularity and more flexibility, we assume that subwavelengths are also used to occupy spectral slots. In our considerations, orthogonal frequency division multiplexing (OFDM) format is adopted with assumption that a single spectral slot equals n_{sc} subcarriers ($n_{sc} = 40$). Accordingly, the total number of subcarriers for each core is 1200.

For each independent channel, there is a wavelength switch and each switch output port is connected to a power splitter (PS). We should mention that "wavelength switch" has a broader meaning in this context, which means that different elements (such as WDM demultiplexer or wavelength selective switch-WSS) can play this role as explained below. We can also assume that there are N_{ps} power splitters/output ports per one wavelength switch ($N_{ps} = 5$), but, of course, these numbers can vary. The signals from one power splitter will be broadcasted to all ONUs (here we assume 8 ONUs per power splitter connected to it), which means that these units will share the wavelength/spectral slots assigned from the wavelength switch. If the bandwidth is assigned uniformly to each power splitter, they will have 6 slots (240 SCs) per PS, and each ONU will have 30 SCs in average. To better illustrate this architecture, simplified traffic assumption is adopted. In our model, the traffic required by each ONU follows the Gaussian distribution, measured by the number of subcarriers. The mean value and standard deviation of SCs per demand are assumed to be 25 and 12, respectively. Meanwhile, the duration of each traffic demand obeys the exponential distribution as common practice.

3.2. Resource allocation strategies and results

Now, different strategies may be used to assign resources (or bandwidth) per traffic demands from each ONU. Let us investigate the following possible scenarios: (1) All components are passive, (2) Spectrum slots can be freely switched within one PS group, and (3) Spectrum slots can be switched between spatial channels.

-Case #1: *All components are passive:* In this case the wavelength switch is just a WDM demultiplexer, and the spectrum slots assigned to power splitters are fixed. Fig. 2a shows the assignment of 90 slots (3×30) for all 15 power splitters. The upper left red rectangular in Fig. 2a means that the slots for the power splitters 1–5 are only from the first spatial channel (slots 1–30), and it is similar for the other two (as in Fig. 3a). The red square corresponds to the blue ellipse in Fig. 1b. Level "1" means that the slots are occupied, zero means it is empty.

Although everything is fixed at the optical switch level, the subcarriers for ONUs can still be adaptively adjusted based on the traffic demands. Namely, OFDMA–TDMA approach can be implemented in DSP with MAC layer protocols [19]. Fig. 2b illustrates one realization of subcarrier (SC) assignment within one power splitter (as we will see, 240 SCs in Fig. 2b/c equal 6 slots in Fig. 2a, that is the red block). The