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Dynamic source aggregation of subwavelength connections in elastic optical networks

Pouria Sayyad Khodashenas · Jaume Comellas · Salvatore Spadaro · Jordi Perelló

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Abstract Elastic optical network technologies arise as promising solutions for future high-speed optical transmission, since they can provide superior flexibility and scalability in spectrum allocation toward the seamless support of diverse services along with the rapid growth of Internet traffic. In elastic optical networks, heterogeneous traffic demands are typically supported by a single type of bandwidth-variable transmitters, which is not always spectrum and cost-efficient. In light of this, the aggregation of same source but different destination subwavelength connections has been recently introduced for elastic optical networks, aiming to obtain both transmitter and spectrum usage savings. In this paper, we propose a novel algorithm for dynamic source aggregation of connections. Moreover, we introduce a novel node architecture enabling the realization of the proposed source aggregation in a cost-effective way. The obtained results demonstrate considerable improvement in the network spectrum utilization, as well as a significant reduction in the number of necessary transmitters per node.

Keywords Elastic optical network · Source aggregation · Network optimization

1 Introduction

Triggered by emerging services such as high-definition video distribution or social networking, the IP traffic volume has been exponentially increasing to date. Furthermore, the traffic growth rate will not stop here due to the day-by-day technology advances. For example, new hardware advances such as multicore processing, virtualization, and network storage will support new-generation e-Science and grid applications, requesting data flows of 10 Gb/s up to terabit level. The predictable consequence in the near future is that the network operators will require a new generation of optical transport networks to serve this huge and heterogeneous volume of traffic in a cost-effective and scalable manner [1,2]. In response to this large capacity and diverse traffic granularity need of future Internet, the elastic optical network architecture was proposed (e.g., see [3]). By breaking the fixed-grid spectrum allocation limit of conventional wavelength division multiplexing (WDM) networks, such elastic optical networks increase the flexibility of the lightpath provisioning. To do so, depending on the traffic volume, an appropriate-sized optical spectrum is allocated to a connection in elastic optical networks, that is, unlike the rigid optical channels of conventional WDM networks, an elastic optical path can expand or contract elastically to meet different traffic loads [4]. In this way, incoming traffic demands can be served in a spectrum-efficient manner. As shown in Fig. 1a, current WDM networks allocate a full wavelength capacity to a lightpath, even if the supported traffic demand is not sufficient to fill the entire wavelength capacity (subwavelength connections). This operation leads to inefficient utilization of network spectral resources. Moreover, for traffic demands greater than a wavelength capacity, multiple independent WDM channels are traditionally allocated (superwavelength connections). Note, as well, that spectral guard bands are necessary between adjacent channels for switching purposes, which further increases the spectrum overhead. To provide better spectrum utilization, as shown in Fig. 1b, elastic optical networks tightly tailor the allocated spectrum to the specific demand requirements, regardless of the total (sub- or super-wavelength) bandwidth they require.

P. Sayyad Khodashenas (✉) · J. Comellas · S. Spadaro · J. Perelló
Advanced Broadband Communications Center (CCABA),
Universitat Politècnica de Catalunya (UPC),
Jordi Girona 1-3, 08034 Barcelona, Spain
e-mail: pkhodashenas@tsc.upc.edu

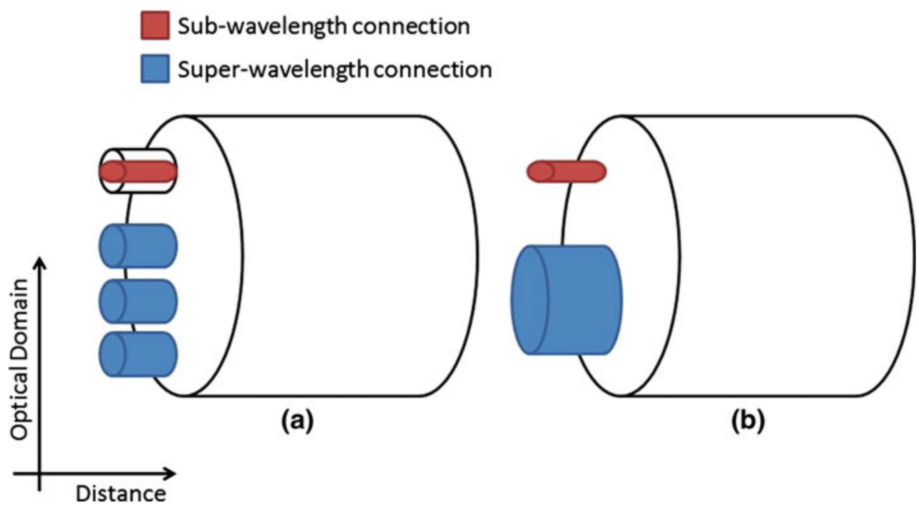

Fig. 1 Super- and subwavelength traffic over (**a**) WDM networks, (**b**) elastic optical networks

To realize an elastic optical network, several key optical technologies are used. One of the crucial components is bandwidth-variable (BV) transmitter. They should support flexible central frequency tuning and elastic spectrum allocation, which can be achieved thanks to recent technology advances [5]. To realize traffic accommodation, the bandwidth of transmitters is discretized in spectrum units (i.e., 12.5 GHz), referred as frequency slots. For example, the 50, 100, and 400 GHz transmitter's bandwidths correspond to 4, 8, and 32 slots, respectively. The spectrum variability of lightpaths is achievable by tuning the number of allocated frequency slots. The incoming traffic is mapped onto individual BV transmitters generating the appropriate-sized optical lightpaths between end nodes. However, the capacity of a transmitter may remain underutilized when the traffic demands are lower than the transmitter's full capacity. In simple words, despite the crucial role of BV transmitters in increasing the spectrum efficiency of network, their full capacity cannot be utilized efficiently. It is therefore essential to introduce a solution for maximizing the capacity utilization of BV transmitters.

This problem grabs the research community's attention. To address it, the proposal of source aggregation has appeared in the literature [6–18]. In general, this proposal tries to aggregate multiple subwavelength connections into one transmitter and serves them as a whole over the network. In this paper, we propose a novel dynamic source aggregation algorithm, aiming to improve the utilization of available spectrum resources and transmitters capacity in the network. To realize this proposal, some capability should be added to network nodes. Therefore, we also introduce cost-effective enabling node architecture. The rest of the paper is organized as follows. In Sect. 2, we initially review related work on source aggregation and then explain its principles and benefits. The proposed enabling node architecture is discussed in Sect. 3. Section 4 details the proposed dynamic source aggregation algorithm. Simulation results are presented in Sect. 5. Finally, Sect. 6 concludes the paper.

2 Source aggregation in elastic optical networks

2.1 Related work

Traffic aggregation in elastic optical networks tries to combine as much as possible traffic demands between a source–destination pair and establish a connection with an appropriate-sized spectrum between them. For example, the author in [6] introduced the concept of optical tunnel for elastic optical networks. It was shown that elastic optical networks have higher spectrum efficiency than WDM networks. However, the problem of inefficient utilization of transmitter's capacity was still unsolved.

This problem initiates a vast research on the possibility of using the residual capacity of a transmitter for establishing new connections to different destinations. In one hand, the idea of sliceable transmitter was proposed in [7–11]. Sliceable transmitters are multiflow, multirate, and multireach transmitters. Multiple connections can be provided using a single type of these transmitters, where each connection is supported by a different contiguous subset of frequency slots. To distinguish one connection from another, spectral guard bands must be placed between them. On the other hand, authors in [12–14] showed the possibility of designing and realizing cost-effective sliceable components to receive different subsets of contiguous frequency slots that correspond to one or multiple connections. These papers have shown the possibility of using the full capacity of a transmitter for establishing connections from one source to different destinations. However, using such devices will increase the cost and complexity of the network. In addition, the full capacity of a transmitter will not be used since spectral guard bands are still necessary between different connections originating from the same transmitter.

Furthermore, authors in [15] studied the possibility of traffic multicasting in elastic optical networks. They proposed point-to-multipoint connections to be provided using one transmitter and employing broadcast-and-select (B&S) switching at intermediate nodes. The saving of spectrum resources compared with the traditional WDM optical networks was demonstrated. The paper has shown the potential of sending traffic demands to multiple destinations in elastic optical networks. However, using the B&S mechanism at network nodes increases their complexity, cost, and energy consumption. Moreover, the optical signal experiences spectral penalties due to the internal optical signal splitting.

Recently, authors in [16,17] introduced a new perspective to source aggregation in elastic optical networks. They proposed aggregation of multiple connections (which may have different destinations) into a single regular bandwidth-variable transmitter and switching them as a whole over the network. Since the aggregated traffic demand is supported by a regular BV transmitter, spectral guard bands are not necessary between adjacent connections inside the resulting optical tunnel. Therefore, such a source aggregation approach can provide a simple and cost-effective way for increasing transmitter capacity utilization. However, as the connections of an optical tunnel can have different destinations, to establish an individual connection, some capability should be added to network nodes. Indeed, when a connection needs to be separated from the optical tunnel at any intermediate node, the node should be able to split the original optical tunnel into multiple tunnels. In addition, guard bands should be added in both sides of the separated optical tunnels spectrum, so that they can be switched at subsequent nodes. Same as the previous work in [15], they employed B&S switching to achieve this functionality, which unfortunately increases the cost and complexity of network nodes. Introducing less complex and more cost-effective node architectures able to provide the aforementioned functionality is one of the motivations of the current study that will be explained in the next section.

Above-mentioned studies on the benefits of the source aggregation in the planning phase of elastic optical networks show a significant improvement in terms of spectrum efficiency and number of required transmitters. However, there is no clear vision about the benefit of such a proposal in a dynamic network scenario. As a matter of fact, the random nature of connection arrivals and departures in such a scenario adds more difficulty to source aggregation. To the best of our knowledge, authors in [18] initiated this research line by proposing a new routing and spectrum assignment (RSA) algorithm that provides a spectrum reservation scheme for non-fully utilized transmitters. The pre-reserved spectrums portion of high-capacity transmitters is used for allocating possible future connections. In this way, they provided better transmitter capacity utilization. However, introducing a reservation scheme leads to inefficient use of available spectrum. In this work, we propose a novel heuristic algorithm that provides dynamic source aggregation in elastic optical networks without any spectrum pre-reservation. This algorithm is detailed in Sect. 4.

2.2 Principles and benefits

Thanks to the spectrum flexibility provided by the BV transmitters, optical signals with arbitrary spectrum bandwidth can be accommodated in elastic optical networks. In this way, such networks can provide efficient utilization of spectrum resources. To make the idea more clear, an exemplary elastic optical network is shown in Fig. 2a. In this network, enough frequency slots are allocated to incoming connection requests supported by two different BV transmitters. Note that the capacity of transmitters is not fully used if the traffic demand is lower than the transmitter capacity. In addition, as the filter characteristic of network nodes has gradual boundaries, the guard bands are necessary between adjacent connections to avoid any data mixing and information loss [19]. The typical size of single guard band is equal to one frequency slot [17]. Therefore, besides inefficient utilization of transmitter capacity, a portion of spectral resources remains unused due to the guard band necessity.

In light of the above, the basic idea of source aggregation proposals is to group multiple connections with same source into one transmitter and switch them as a whole over the network. This group of connections is called an optical tunnel. In this way, such proposals can provide better utilization of the transmitter capacity. Moreover, since guard bands are only necessary between different optical tunnels for switching purposes, better bandwidth utilization is also achievable. As highlighted in Fig. 2a, both connections 1 and 2 share a portion of their routes from source to destination. By aggregating traffic demands over this common route portion, spectrum savings as well as better transmitter capacity utilization can be achieved. Figure 2b illustrates the idea. As shown, both connections can be grouped in a single optical tunnel over the common route portion. Since the traffic demand over resulting optical tunnel is assumed less than the whole available spectrum of a transmitter, it can be established using only one transmitter instead of two transmitters as in Fig. 2a. In addition, a portion of the spectrum equal to a couple of guard bands (2 frequency slots) has been saved in this example. At the end of common route portion, each connection can be extracted from the optical tunnel and continue its way to the destination. As mentioned before, guard bands are necessary in both sides of the individual connections, once extracted from the optical tunnel. In Fig. 2b, frequency slot 4 in the optical tunnel is treated as a signal slot in connection 2 and as a guard band slot in

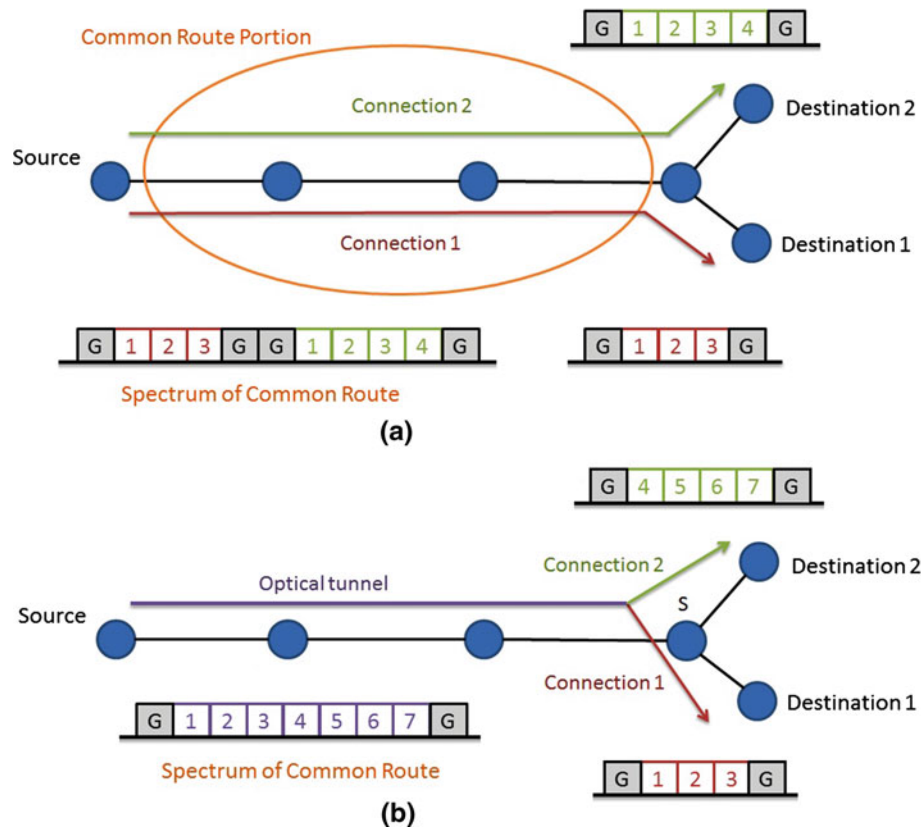

Fig. 2 Two exemplary elastic optical networks, (**a**) without source aggregation (**b**) with source aggregation

connection 1. In order to provide such functionality, special node architecture has to be employed. The proposed node architecture will be detailed in the next section.

3 Enabling node architecture

To realize the proposed source aggregation functionality, some capabilities should be added to the network nodes. An intermediate node should be able to drop a specific portion of an optical tunnel (corresponding to one or multiple connections) to an outgoing port, while continuing the remaining part of it to another outgoing port. In general, providing this functionality for a network node will increase its cost and complexity, since bandwidth-variable wavelength-selective switches (BV-WSS) should be used in the node architecture. Authors in [17] employed the B&S architecture shown in Fig. 3. In this architecture, the spectrum of the incoming optical tunnel is broadcasted to all outgoing ports and filtered by different BV-WSS to form desirable spectrums at each outgoing port. Although this is an easy architecture for an optical node, it has some drawbacks. First, this node architecture is neither scalable nor cost-effective. Second, spectrum of optical tunnels will suffer from the internal optical signal splitting. In fact, internal optical signal splitting decreases the energy level of optical signal, which may lead to difficulties in signal detection at the receiver side and worst signal-to-noise ratio [20].

To address these problems, it is desirable to reduce the number of BV-WSS in the node architecture. We propose a new architecture, named as shared splitting architecture, which is shown in Fig. 4. As illustrated, it consists of two main sections, switching section and splitting section. Bandwidth-variable optical cross-connect (BV-OXC) module switches the portions of spectrum without any signal splitting. To do so, the BV-OXC should be able to configure its spectral switching window in a continuous manner according to the spectral width of incoming optical signal. Thanks to the advancement in liquid crystals on silicon (LCoS) wavelength-selective switch (WSS) technology, BV-OXCs with these features are available nowadays [21]. In addition, the proposed node should also be able to drop a specific spectrum portion of the optical tunnel to an outgoing port, while continuing the remaining part of it to another outgoing port. As shown in Fig. 4, the splitting section of the node performs this functionality. In this section, a shared BV-WSS is employed to filter the broadcasted signals and to send the appropriated spectral bands to their desired outgoing ports. In fact, in contrast to the previously proposed architecture, no BV-WSS (which are relatively expensive devices) are placed per outgoing port in our proposal; instead, they are moved from the output ports to the splitting section. Therefore, the

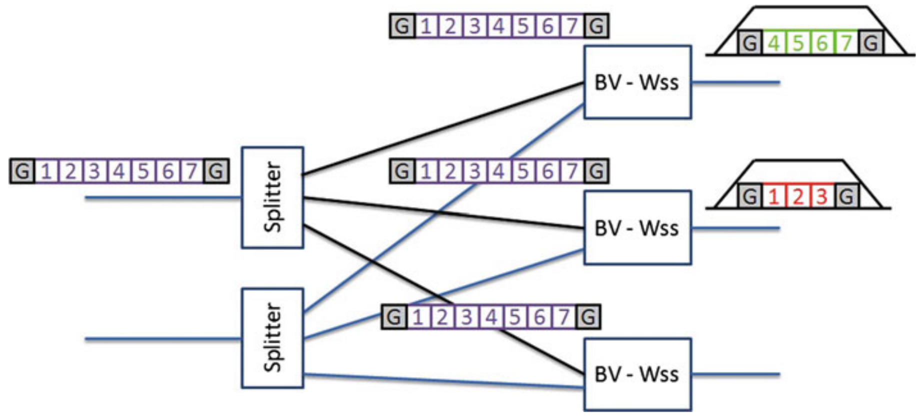

Fig. 3 Broadcast-and-select node architecture

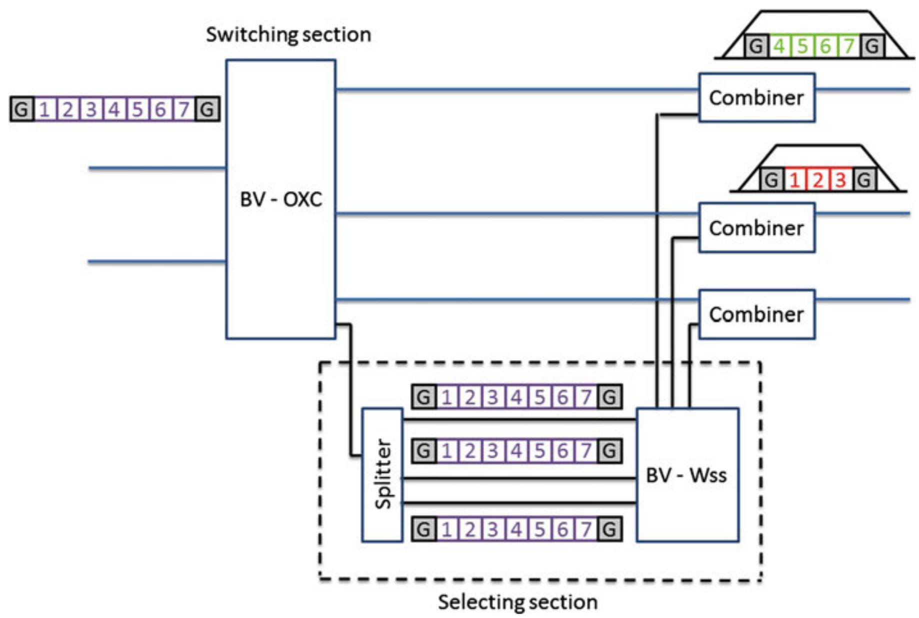

Fig. 4 Shared splitting node architecture

number of necessary BV-WSS per node is reduced significantly, which leads to considerable cost and energy savings in the network nodes. In addition, the spectral penalty due to optical signal splitting is minimized, since the shared section splits the optical signal in an on-demand fashion. Note, however, that the introduction of such a shared section in the node architecture may lead to collisions. To solve this issue, we have considered few parallel splitting sections in the node, thus allowing optical signals to be switched without experiencing any blocking. After simulation studies using different network topologies (up to 20 nodes and nodal degrees ranging from 2.5 to 3.5), we concluded that two parallel splitting sections per node are sufficient to keep the performance and cost of the node in a reasonable level. However, the detailed study about the effects of network topology on the number of necessary splitting sections in the nodes is left for future work.

4 Dynamic optical path aggregation algorithm

In this section, we propose a dynamic routing and spectrum assignment (RSA) algorithm that applies the proposed source aggregation concept, aiming to simultaneously minimizing the spectrum and transmitter usage in the network. In simple words, such an algorithm tries to aggregate incoming traffic demands with already existing connections in the network. As a matter of fact, this dynamic source aggregation adds more complexity to the RSA problems, since a single transmitter is used for establishing multiple connections. It is worth to mention that besides the contiguity and continuity constraints existent in typical RSA problem [22], aggregated traffic should use a consecutive number of frequency slots within the transmitter's spectral range. Thus, the maximum number of aggregated connections is limited by the maximum capacity of transmitters. Considering these issues, we developed the first-possible aggregating (FPA) algorithm. The FPA algorithm maximizes the transmitter capacity utilization of network by aggregating same-source subwavelength connections over their common route. Also, it improves the spectrum utilization of network by reducing the number of required guard bands between connections. These features can be easily translated to more established connections over the network and a lower number of required transmitters per node.

First-Possible Aggregating (FPA) Algorithm:

1. Calculate the shortest path for the incoming connection request. Set the calculated shortest path as the candidate route to allocate the connection request.
2. Select already existing connections in the network with the same source and following a route that shares some links with the candidate route calculated in step 1.
3. Calculate the residual capacity of the transmitters that are supporting the connections selected in step 2. Set the candidate transmitter as the first one with enough idle capacity to aggregate the incoming connection to the already allocated connection. The transmitters are supposed to be able to dynamically adjust their central frequency to the middle of the aggregated optical tunnel.
4. Check the spectrum continuity and contiguity constraints for establishing the connection using the candidate transmitter over the candidate route.
5. If the constraints satisfied, perform source aggregation and establish the connection, otherwise set the next possible transmitter with enough capacity as the candidate transmitter and go back to step 4.
6. If there is no possibility for establishing the connection over the candidate route, calculate the next disjoint shortest path. Set the calculated path as the candidate route and go back to step 2.
7. If there is no possibility for source aggregation, establish the incoming connection request without source aggregation by using a separate transmitter and employing k-shortest path routing and first-fit spectrum assignment.
8. If there is no possibility for establishing the connection at all, drop the connection request.

The aim of this work is to assess the feasibility of point-to-multipoint dynamic optical path aggregation in elastic optical networks, using a node architecture that is simpler than the previously proposed ones. More advanced aggregation algorithms are currently being developed, and preliminary simulation results have shown further improvement on the network performance.

5 Simulation results

We evaluated the performance of the proposed FPA source aggregation algorithm through extensive discrete event simulation studies and compared it with the non-aggregating scenario (i.e., a conventional elastic optical network using a k-shortest path computation algorithm with a first-fit slot assignment, starting with the shortest computed path [22]). The 14-node NSFnet (shown in Fig. 5) topology has been selected for this purpose. We assumed total optical spectrum of 1.5 THz per link and the spectrum slot size of 12.5 GHz [3]. By assuming an appropriate modulation format (e.g., DP-BPSK [23]), each spectrum slot has a capacity of 12.5 Gb/s. The full capacity of a transmitter is 100 Gb/s, which supports 8 frequency slots. The guard band size is assumed to be 2 frequency slots [17]. In addition, according to the asymmetric nature of today's Internet traffic, unidirectional connections between end nodes were considered. The traffic gener-

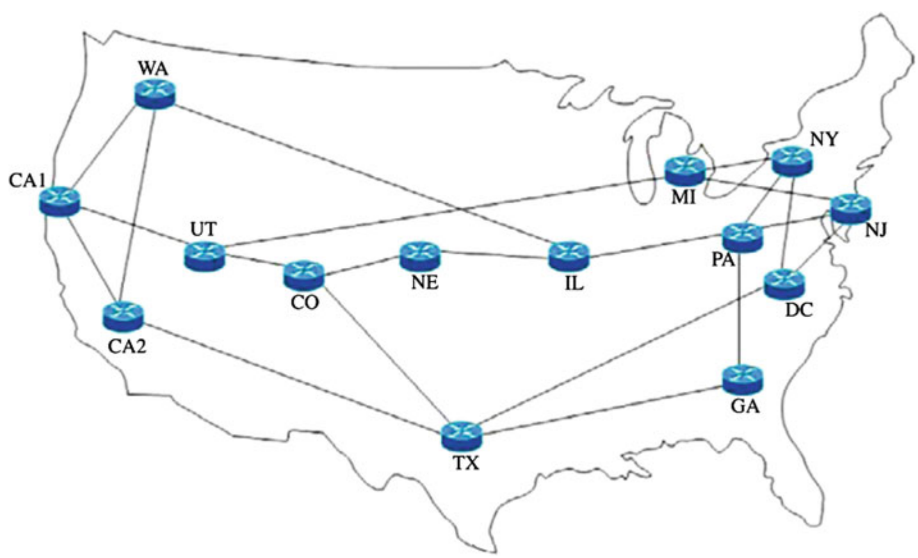

Fig. 5 The topology of NSFnet

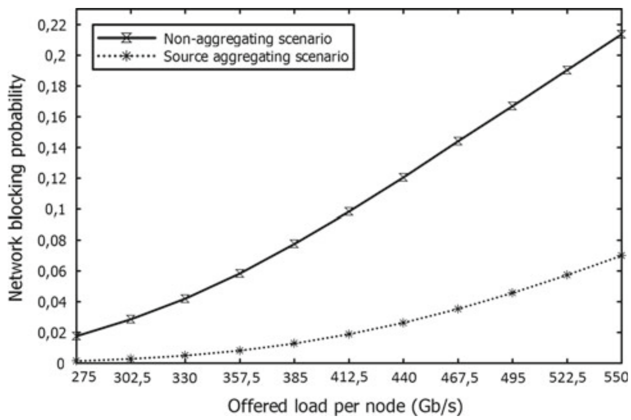

Fig. 6 Network blocking probability for different offered loads

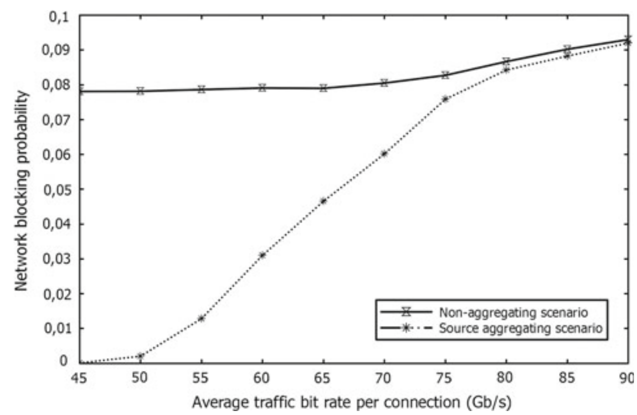

Fig. 7 Network blocking probability for different average traffic bit rates

ation follows a Poisson distribution process, so that different offered loads are obtained by keeping the mean holding time (HT) of the connections constant to 200 s, while modifying their mean inter-arrival time (IAT) accordingly (i.e., offered load = HT/IAT). Traffic demands for each source–destination pair are randomly generated by normal distribution over the range of 12.5 Gb/s (1 frequency slot) to 100 Gb/s (8 frequency slots). The average traffic demand is used to study the relationship between aggregation efficiency and service granularity.

Regarding the traffic load, we have offered from 5 up to 10 Erlang per node (total offered traffic to the network ranging from 70 to 140 Erlang). The average demand of each connection request is assumed to be 55 Gb/s. Hence, the total traffic generated per node ranges from 275 to 550 Gb/s in this study. In addition, we assumed 10 transmitters per node. As stated in Sect. 3, having enough number of parallel splitting sections in the proposed structure to avoid any collision is crucial. Considering the current topology and traffic values, and after extensive simulations, two parallel splitting sections per node are assumed. It is worth to mention that this configuration leads to significantly cheaper network nodes compared to existing node architectures, that is, by taking the average nodal degree of NSFnet topology (which is 3) into account and considering one BV-WSS per output port in a B&S node architecture, the relative cost of current network nodes is reduced by 33 % using the proposed node architecture.

Figure 6 shows the bandwidth blocking probability achieved in both source aggregating and non-aggregating scenarios. From the results, we observe that source aggregation case outperforms the non-aggregating scenario in the entire offered load range. For example, it achieves about one order of magnitude improvement for heavy loads (550 Gb/s per node) with respect to the non-aggregating scenario (the solid line). Indeed, besides increasing the transmitter capacity usage and providing more flexibility for establishing connections over the network, there is another reason for this significant improvement: the proposed algorithm can arrange aggregated connections together as much as possible, which leads to lower spectrum fragmentation [24] and thus more possibilities for establishing new connections over the network.

Figure 7 shows the effect of traffic granularity on the performance of the aforementioned scenarios for a fixed offered load per node of 7 Erlang (i.e., medium load network scenario). We observe that the source aggregating scenario achieves significant blocking probability reduction compared to non-aggregating case for small traffic demands per connection request. The reason is that finding non-fully used transmitter capacities for aggregating traffic demands is easier in this region. Previously, we stated that the number of aggregated connections in a transmitter is limited by its maximum capacity. Thus, the blocking probability of network increases as the traffic demand per connection request grows. For average bit rate requests >70 Gb/s, we observe that all results converge together. In this case, no extra spectrum savings can be achieved by the proposal, since all connections are served with separate transmitters.

Figure 8 illustrates the transmitter savings of the source aggregating scenario versus the non-aggregating scenario for total generated traffic per node ranging from 315 to 490 Gb/s (considering the same offered traffic per node of 7 Erlang as pervious case). According to the results, source aggregation can reach the same blocking probability performance as non-aggregating scenario, while it achieves 50 % transmitter savings under low traffic load (i.e., for obtaining similar blocking probability performance as non-aggregating scenario, just half the number of transmitters per node is required using the proposal). Similarly, to the previous study, this result shows that aggregating connections in one transmitter cannot provide significant benefits for high traffic loads (bit rate demands >70 Gb/s per connection).

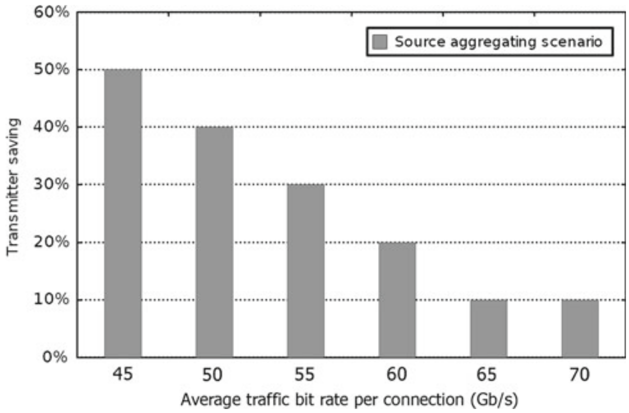

Fig. 8 Transmitter savings for different average traffic bit rates

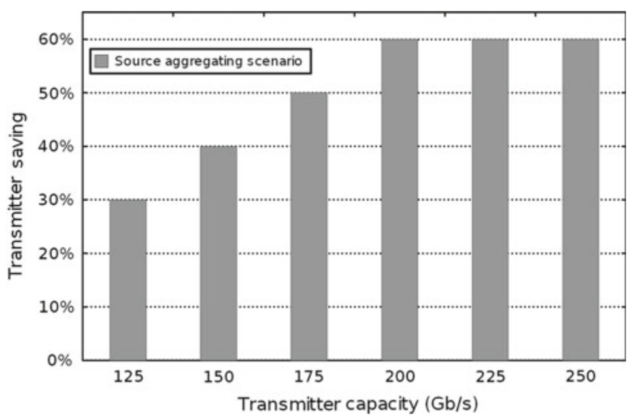

Fig. 9 Transmitter savings for different transponder capacities

Figure 9 compares the transmitter savings using source aggregating algorithm for different transmitter capacities under the fixed offered load (385 Gb/s) condition. We observe that for similar blocking probability performance, the transmitter savings grow as the transmitter capacity increases, since more traffic demands can be aggregated. However, when the transmitter capacity reaches a certain threshold, no extra savings can be achieved. This is because all the same-source connections have already been aggregated together. This result shows that selecting an appropriate capacity value of transmitters should be carefully considered during the network design.

6 Conclusion

The recently proposed elastic optical network that provides enhanced flexibility in spectrum allocation and data rate accommodation has opened up a new prospect to serve the future Internet demands more efficiently. However, providing various data rate services in a cost-effective way (especially for subwavelength traffic demands) under this network architecture still needs more research and analysis. To address the problem, the idea of source aggregation in elastic optical network has been recently proposed. In this paper, we proposed a dynamic source aggregation algorithm that supports grouping of multiple subwavelength connections with the same source into a single transmitter. We also discussed the equipment-level requirements to support the proposal in a cost-efficient manner. Performance evaluations were made to compare the spectrum usage and transmitter saving benefits of source aggregation and non-aggregating scenarios. Our results show that source aggregation achieves significant transmitter savings (10–50 %), with better or equal spectrum utilization compared to non-aggregating case.

Our future work is to derive analytical models to formally quantify the effect of the number of shared sections in proposed node architecture on the relative cost and blocking probability performance of the elastic optical network. In addition, the comparison of dynamic source aggregation and electrical grooming from energy and cost perspective is another good research possibility.

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Author Biographies

Pouria Sayyad Khodashenas received his B.Sc. degree in 2005 from the University of Guilan, Rasht, Iran, and his M.Sc. degree in 2008 from University of Tabriz, Tabriz, Iran, both in electrical engineering. Since October 2009, he has been working toward a PhD in telecommunications engineering at Universitat Politècnica de Catalunya (UPC, BarcelonaTech), Barcelona, Spain, being advised by Prof. Jaume Comellas Colome. His research interests include all-optical communication systems, all-optical switches, nonlinear optics, quantum optics, multilayer structures, and semiconductor lasers, especially VCSEL.

Jaume Comellas received the M.S. (1993) and PhD (1999) degrees in Telecommunications Engineering from Universitat Politècnica de Catalunya (UPC), Spain. His current research interests focus on IP over WDM networking topics. He has participated in many research projects funded by the Spanish government and the European Commission. He has co-authored more than 80 research articles in international journals and conferences. He is an Associate Professor at the Signal Theory and Communications Department of UPC.

Salvatore Spadaro received the M.Sc. (2000) and the PhD (2005) degrees in Telecommunications Engineering from Universitat Politècnica de Catalunya (UPC). He also received the Dr. Ing. degree in Electrical Engineering from Politecnico di Torino (2000). He is currently an Associate Professor in the Optical Communications group of the Signal Theory and Communications Dept. of UPC. Since 2000, he is a staff member of the Advanced Broadband Communications Center (CCABA) of UPC. His research interests are in the fields of all-optical networks with emphasis on network control and management, resilience and network virtualization.

Jordi Perelló received his M.Sc. and PhD degrees in telecommunications engineering in 2005 and 2009, respectively, from UPC. Currently, he is an Assistant Professor in the Computer Architecture Department (DAC) at UPC. He has participated in various IST FP-6 and FP-7 European research projects, such as FP-7 projects STRONGEST, EULER, DICONET or NoE BONE, as well as FP-6 projects NOBEL Phase 2, e-Photon/One+ or COST Action 291. He has published more than 50 articles in international journals and conferences. His research interests concern resource management, quality-of-service issues, and survivability of future optical transport networks.