Impact of WSS Passband Narrowing Effect on the Capacity of the Flexible-spectrum Networks

Haining Yang[1], Rui Wang[1,2], Paul Wright[3], Abhijit Mitra[3,4], Brian Robertson[1], Peter Wilkinson[1,2], Subrat Kar[4], Andrew Lord[3], Daping Chu[1,2]

1. Roadmap Systems Ltd, St John's Innovation Centre, Cowley Road, Cambridge CB4 0WS, UK
2. Department of Engineering, University of Cambridge, 9 JJ Thomson Avenue, Cambridge CB3 0FA, UK
3. British Telecom Laboratories, Polaris House, BT Adastral Park, Martlesham Heath, Ipswich IP5 3RE, UK
4. Department of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India
Author e-mail address: daping.chu@roadmapsystems.co.uk

Abstract: We show that the WSS passband shape needs to be optimized to the 3.6th and 3.2th Super-Gaussian orders in BT-UK and PAN-Europe networks, respectively, for realizing the 30% capacity increase promised by the flexible-spectrum standard.

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1. Introduction

The adoption of a flexible-spectrum network standard [1] has demonstrated significant bandwidth savings in point-to-point (P2P) data transmission. Such bandwidth saving could be further translated into gains in the total network capacity [2,3], depending on the network characteristics [4]. The network capacity model used in these studies has taken into account the noise impairment in the physical layer due to the optical amplifications and the non-linear effects associated with the optical fibers. However, the high spectral efficiency of the advanced modulation formats employed by the flexible-spectrum networks, e.g. the higher M-ary quadrature amplitude modulation (QAM), also makes it, at the same time, more susceptible to the passband narrowing effect (PNE) of the wavelength selective switches (WSSs) [5]. The penalty on optical signal noise ratio (OSNR) introduced by such PNE may have a further impact on the total capacity of the network, especially when signals are cascaded through multiple WSSs.

In this paper, we incorporate the effect of OSNR penalty due to the cascaded WSSs into the network capacity model, along with the impairments due to the optical amplification and fiber non-linearity. We compare the capacities between networks operating on fixed and flexible spectrum regimes, and further explore the benefit of the optimized WSS passbands in these scenarios. Simulations are carried out over both BT-UK and PAN-Europe networks in order to investigate the impact from different network characteristics.

2. Network capacity model

The network capacity is simulated over both BT-UK [6] and Pan-Europe [7] networks, respectively. The BT-UK network in this simulation has 22 nodes and 35 edges between them. The edge distance ranges from 2 km to 439 km with an average value of 135.6 km. The PAN-Europe network has 16 nodes and 23 edges, whose distance ranges from 218 km to 783 km with an average value of 486.5 km. Each network node employs a reconfigurable optical add/drop multiplexer (ROADM) to route the optical signal. The ROADMs are built on the 'route-and-select' architecture, i.e. transit signals will pass through two WSSs and experience -18 dB loss, which will be compensated by erbium-doped fiber amplifiers (EDFAs). Fibers are assumed to have a loss of -0.25 dB/km, which is compensated by in-line EDFAs placed for every 80 km. Tab. 1 lists the modulation formats available in both networks and their corresponding characteristics. The OSNR threshold for each modulation format was calculated according to [2].

Table. 1 Characteristics of the modulation formats available

Modulation Format	Data rate (Gb/s)	Baud rate (GBaud)	OSNR threshold (dB)	Channel bandwidth (GHz)
QPSK	100	27.75	12.8	37.5
8-QAM	150	27.75	17.5	37.5
16-QAM	200	27.75	19.6	37.5

In the elastic optical networks (EONs), WSSs need to meet the most stringent passband requirement when they have to route independent channels instead of Super-channels. The WSS passband need to have a flattened top and a sharp roll-off so that independent channels carrying individual traffic loads will not experience excessive OSNR penalties. Therefore, independent channels are necessary to demonstrate the worst case scenario. In this paper we have considered a cumulative traffic of 1 Tb/s between random node pairs and used the light path OSNR estimation model in [4] to choose a modulation format. This could be met either using 5 16QAM, 7 8-QAM or 10 QPSK independent channels to demonstrate the worst case. Demands were routed by using one of the 8 shortest paths and at the highest QAM rate possible. A total of 100 randomly generated traffic matrices, each with up to 1000 demands of 1 Tb/s (cumulative) between random node pairs, over both the networks before and after the adoption of flexible -

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spectrum standard have been simulated. The total capacity of a network for a specific traffic matrix is measured as the amount of the routed traffic when a cumulative blocking probability reaches 10%. Finally, the capacity values for the 100 traffic matrices are averaged to give the representative result for the network.

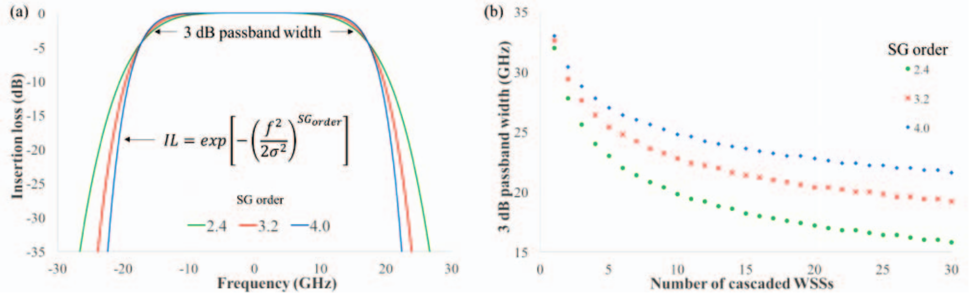

Fig. 1. (a) Passband shapes defined by super Gaussian orders; (b) cascaded 3 dB passband widths for WSSs with different passband shapes.

The OSNR level of a path is contributed by the amplified spontaneous emission (ASE) from the EDFAs, non-linear impairments (NLI) from the fibers and penalties introduced by WSSs. Our previous work [3] has detailed the calculation of ASE and NLI noises in optical networks. The passband shape of a WSS can be described by the Super-Gaussian (SG) function while the cascaded passband can be characterized by the 3 dB passband width. Fig. 1(a) gives examples of passbands with SG orders of 2.4, 3.2 and 4.0 for a 37.5 GHz slot. Despite of their similarities, the corresponding cascaded 3 dB passband widths differ significantly, as illustrated in Fig. 1(b). The relationship between the OSNR penalty and the 3 dB passband width of cascaded WSSs has been studied in [5] for each modulation format listed in Tab. 1. Based on this relationship, we further calculated the OSNR penalties of cascaded WSSs with different passband shapes. The results are plotted in Fig. 2 for both the fixed and a flexible-spectrum networks. The OSNR penalties are significantly lower in the fixed-spectrum network than in the flexible-spectrum network. This is because the extra spectrum a channel has in the fixed-spectrum network make it more tolerant to the PNE. Modulation formats with higher spectral efficiencies are more sensitive to the PNE of cascaded WSSs. The higher OSNR penalties may prevent the bandwidth savings in the P2P transmission to be translated into a capacity increase in a multi-node network. In addition, OSNR penalties can be reduced by using WSSs with higher SG orders. Our network capacity simulation tested 9 types of WSSs, whose SG orders increase from the standard value of 2.4 to 4.0 in a step of 0.2.

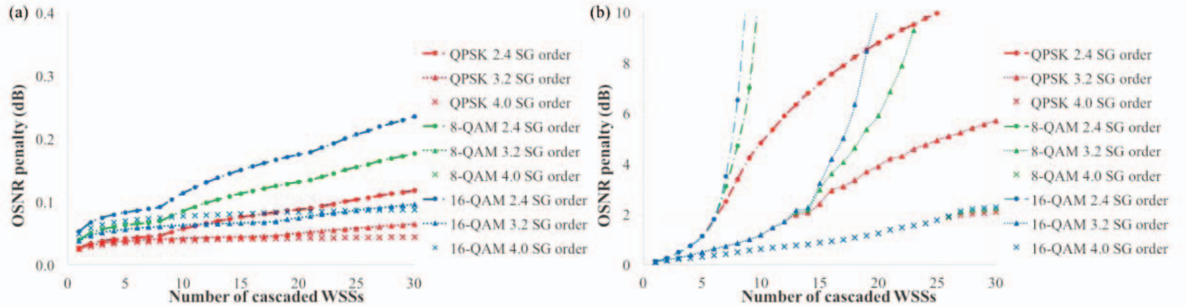

Fig. 2. OSNR penalties to the signals in(a) a fixed-spectrum network and (b)a flexible-spectrum network, respectively.

3. Results and discussions

The network capacity for the fixed-spectrum network was simulated first and the results are plotted in Fig. 3(a).The total capacities of the BT-UK and the PAN-Europe networks are ~220 Tb/s and ~150 Tb/s, respectively. The optimization of the WSS passband beyond 2.4th SG order did not increase capacity. This is not surprising considering the small OSNR penalties due to the PNE from the cascaded WSSs in the fixed-spectrum networks. These capacity values for each network will be used as a benchmark in the following analysis on the impact of WSS passband shapes in the flexible-spectrum networks. Fig. 3(b) compares the capacity of the flexible-spectrum network employing the WSSs of different passband shapes with the benchmark capacity value for each network. It can be seen that the capacity actually dropped in both networks if they changed to the flexible-spectrum standard without upgrading the WSS passband shape. Fig. 4(a) compares the number of modulation formats used by routed demands in these scenarios. It shows that the higher number of demands were routed by the 16-QAM format when the networks operated under the fixed-spectrum standard. It is not difficult to imagine a scenario in which a 1Tb/s demand could be routed by 5 16-QAM channels (250 GHz bandwidth) in a fixed-spectrum network whereas it could only be routed by either 7 8-QAM (262.5 GHz) or 10 QPSK channels (375 GHz) in a flexible-spectrum network due to the higher OSNR penalty introduced by WSSs with low SG order passband. In this case, the demand would be routed more efficiently in the fixed-spectrum network. However, Fig. 3(b)also shows that the network capacity did increase in both networks as the SG order of the WSS passband shape increases. This was also reflected by the higher number of demands routed with the 16-QAM format shown in Fig. 4(b) and(c). It was predicted that the BT-UK network would have a ~33% capacity increase when SG order of the WSS reached 3.6 while the PAN-Europe network a ~28% increase with the SG order 3.2. The higher SG requirement in the BT-UK network is because routed signals on average passed through more nodes and therefore were more affected by WSSs. Fig.4(c) also reveals that only ~33% of the demands can be routed by the 16-QAM format in the larger PAN-Europe network due to high ASE and NLI noises in the long paths. Under this circumstance, the capacity is not limited by WSSs passband and therefore further optimization will not yield improvement.

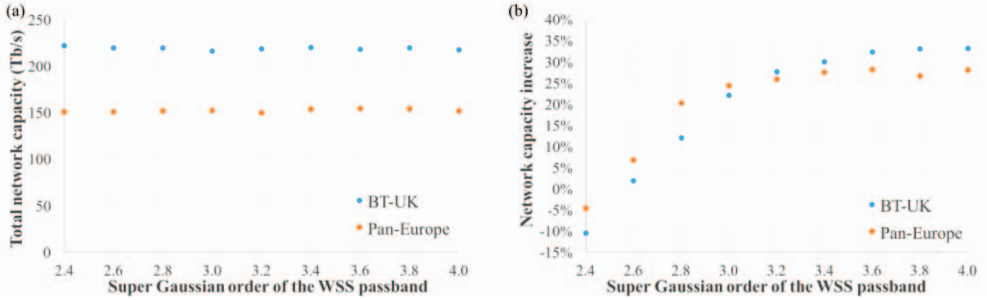

Fig. 3. (a) the network capacities of BT-UK and PAN-Europe networks operating under the fixed-spectrum standard; (b) the network capacity changes due to the adoption of a flexible-spectrum standard for BT-UK and Pan-Europe networks.

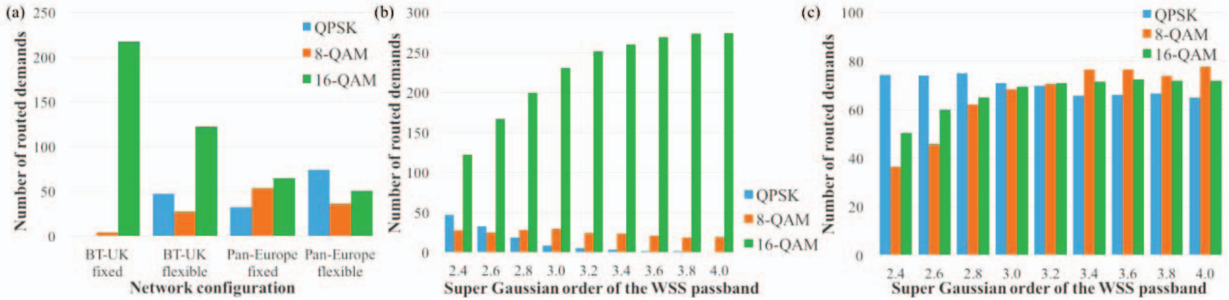

Fig. 4. The number of demands routed through (a) the BT-UK and PAN-Europe networks using WSSs with a 2.4th SG order passband shape; (b) the BT-UK network and c) PAN-Europe network under flexible-spectrum regime using WSSs with passband shapes of different SG orders.

4. Conclusion

A network capacity model was used to analyze the impact of the adoption of the flexible-spectrum standard in both the BT-UK and PAN-Europe networks. The model comprehensively considered impairments in the physical layer, including the ASE noises from EDFAs, NLI from the fibers and PNE from cascaded WSSs. It was shown that the bandwidth saving in the P2P transmission enabled by the flexible-spectrum standard could only be translated into the network capacity increase if the passband shapes of WSSs deployed in the network were optimized higher than the standard 2.4th SG order. In the BT-UK network, a 33% network capacity increase could be achieved by optimizing the WSS passband into the 3.6th SG order. However, further optimization on the passband will not lead to additional increase of the network capacity. In the PAN-Europe network, where routed signals pass through fewer network nodes, the WSS passband only needs to be optimized into the 3.2th SG order for a 28% increase in the network capacity. These results are useful for network operators in deciding their equipment upgrade strategies.

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