Dimensioning Flex-Grid Optical Nodes: Correlation with Network Topological Parameters

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ABSTRACT

As optical traffic scales, the hardware complexity of modern flex-grid architectures has emerged as a critical cost driver. This work investigates the correlation between network graph metrics and the dimensioning requirements of switching nodes in Elastic Optical Networks. Through a systematic analysis of diverse mesh topologies, we quantify the relationship between topological features and the bypass capacity of ROADM nodes. Results demonstrate that betweenness centrality is a good predictor of node bypass requirements compared to traditional metrics such as nodal degree, closeness, or eigenvector centrality. In particular, we show that switching capacity scales near-linearly with a node's transit pressure, enabling accurate hardware dimensioning even without prior knowledge of the traffic load. This approach allows network architects to optimize resource allocation and hardware investment in next-generation optical backbones.

Keywords: Elastic Optical Networks, ROADM dimensioning, network topology, graph centrality, optical switching.

1. INTRODUCTION

The rapid growth of bandwidth-hungry applications and cloud services is pushing legacy fixed-grid WDM networks to their spectral and architectural limits. Elastic Optical Networks (EONs) [1, 2] built on flex-grid ROADMs address this challenge by slicing the optical spectrum into fine-granularity frequency slots (FS) and assigning them according to bit-rate, modulation format, and path length of the connection requests. This flexibility enables higher spectral efficiency and more agile use of fiber capacity, but it also increases node-level hardware complexity, particularly in large mesh backbones. In flex-grid architectures, the amount of switching fabric and associated transceivers installed at each node has become a major cost and power driver [3-5]. Over-dimensioning nodes wastes expensive hardware, whereas under-dimensioning leads to elevated connections blocking probability (BP) values under peak load. Existing planning approaches often focus on link spectrum while treating node resources as uniformly provisioned, which is inefficient in partial mesh topologies where many nodes mainly relay transit traffic. This motivates the search for simple, topology-aware rules that predict the required bypass and switching capacity at each node, even without detailed traffic forecasts.

This paper investigates the correlation between network-level graph metrics and the dimensioning of flex-grid optical nodes. Using an ad-hoc EON simulator, we evaluate how nodal degree, closeness, eigenvector, and betweenness centrality network parameters [6] relate to the transit traffic handled by ROADMs in several realistic backbone topologies. Our results show that betweenness centrality is a significantly better predictor of required switching capacity than traditional local metrics such as nodal degree, enabling a near-linear relationship between a node's "transit pressure" and its optimal number of optical switching units. This yields a simple predictive framework that minimizes total switching hardware while keeping node utilization balanced and blocking probability low.

EONs extend fixed-grid WDM by dividing the fibers available spectrum into narrow frequency slots that can be aggregated into variable-bandwidth optical channels. Bandwidth-variable transceivers (BVTs) select modulation formats and occupied bandwidth as a function of bit rate and end-to-end reach, trading spectral efficiency against robustness [7]. For example, higher-order modulation such as 16-QAM provides high spectral efficiency but limited reach, whereas BPSK sacrifices spectral efficiency to enable very long paths. The underlying flex-grid ROADM architecture and bandwidth-variable wavelength cross-connects (BV-WXCs) establish end-to-end lightpaths by allocating contiguous FS along a route, subject to continuity and contiguity constraints. This architectural flexibility improves spectrum utilization and allows the optical layer to adapt to heterogeneous and time-varying traffic demands. However, it also requires careful dimensioning of transceivers, receivers, and fine-granularity switching elements at each node. Flexible node architectures and photonic switching fabrics have been widely studied [5], but most works assume either uniform node capacities or rely on traffic-matrix-driven sizing. Because EON backbones are typically deployed in partial mesh topologies, a substantial share of the carried traffic is transit traffic that bypasses intermediate nodes. The amount of such bypass load is strongly influenced by the structural role of each node in the topology. Graph-theoretic centrality measures [6] provide a convenient way to quantify this role. Degree centrality counts incident links (i.e. local connectivity). Closeness centrality reflects average distance to all other nodes, and eigenvector centrality emphasizes nodes connected to other important nodes. Betweenness centrality, in contrast, measures how many shortest paths between node pairs traverse a given node, directly reflecting its importance as an intermediate relay. Intuitively, nodes with high betweenness centrality are expected to carry more transit traffic and therefore require greater switching and bypass capacity to avoid congestion. Prior works used centrality to analyze robustness and traffic flow in networks, but its explicit use as a design-time predictor for hardware dimensioning in flex-grid ROADMs has received limited attention.

Blocking in an EON occurs when a connection request cannot be served due to the lack of a feasible spectrum-continuous path, limited transceiver resources, or insufficient switching capacity at intermediate nodes. Classical design approaches typically focus on routing, modulation format and spectrum assignment (RMSA) under link-capacity constraints, often assuming that node hardware is over-provisioned. More recent work explores machine-learning-based RMSA [8] and graph-neural-network modelling of network performance [9], but still under fixed node capacities. Our work complements these efforts by explicitly modelling the consumption of transmitters, receivers, and switching units at source, intermediate, and destination nodes. We show that a simple betweenness-driven allocation rule can dimension node switching hardware efficiently and robustly.

2. NETWORK AND NODE MODEL

We consider an EON where each fiber link is modeled as a collection of 320 FS, corresponding to the usable C-band. Wavelength continuity and contiguity constraints must be satisfied for all established connections. Link length is considered during the routing phase for modulation-format (MF) assignment. The simulator considers three bit-rates (100, 200, 400 Gb/s) and three modulation formats (BPSK, QPSK, 16-QAM) with the parameters shown in Table 1, including bandwidth, maximum reach, number of FS used, and spectral efficiency in bit/s/Hz.

Table 1. Modulation formats.

BitRate (Gbit/s)	ModFormat	BW (GHz)	MaxReach (km)	FS	SE (Bit/s/Hz)
100	BPSK	50	12000	5	1.60
100	QPSK	25	3000	3	2.67
100	16QAM	15	600	2	4.00
200	BPSK	95	12000	8	2.00
200	QPSK	45	3000	4	4.00
200	16QAM	25	600	3	5.33
400	BPSK	160	12000	14	2.29
400	QPSK	72.5	3000	7	4.57
400	16QAM	45	600	4	8.00

The MF is chosen according to the end-to-end path length and the required bit rate. Once the MF is decided, the FS width of the connection is set, and the RMSA reserves contiguous slots on each traversed link. Each network node i is characterized by three resource pools, all measured in FS units: Number of Transmitters (TX_i), Number of Receivers (RX_i) and Number of Optical Switching Units (OXC_i). The node consists of a central optical backplane which interconnects input and output fibers, and local transceivers (TX/RX).

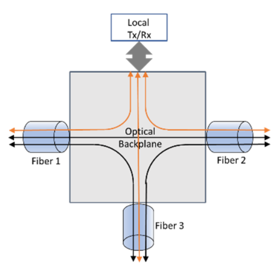

Figure 1. Structure of the network nodes considered throughout this work. An optical backplane connecting input and output fibers (ND=3 in the example shown, and local transceivers where traffic flows start/end.

While TX and RX are equal for all nodes (uniformly distributed source-destination pairs are assumed), the OXC is different for each node depending on their centrality. This is the key parameter explored in this work. The switching capacity required at any node is determined by 2 components, which are the connections starting/ending at the node plus the traffic bypassing the node (i.e. those connections whose selected path crosses that node). When analyzing this, it is found that the former term is equal for all the network nodes as the generated traffic is uniformly distributed from any to any nodes. Obviously, in a scenario where some nodes were more likely to send/receive information, this term would be increased (as would increase the required number of transmitters and receivers). As for the bypassing traffic, extensive simulations have been run with the aim of finding the appropriate value which minimizes the total number of switches in the network. For every tested network topology, the different centrality parameters [6] (NodalDegree (ND), ClosenessCentrality (CC), BetweenessCentrality (BC) and EigenvectorCentrality (EV)) are calculated and then applied to the simulator. Assuming a total number of switching units (OXC_{TOTAL}),

$$OXC_{TOTAL} = \sum_{i=1}^{num\_nodes} OXC_i \tag{1}$$

the different centrality metrics are used during the simulations to minimize OXC_{TOTAL} while satisfying certain network performance parameters. These centrality parameters as well as a network representation are shown in Figure 2 for the 17 nodes and 26 links German network topology [10].

NODE	ND	ND (Norm)	CC	BC	EV
1	2	0.038	0.046	0.000	0.037
2	3	0.058	0.053	0.016	0.070
3	2	0.038	0.066	0.028	0.024
4	**4**	**0.077**	**0.067**	**0.096**	0.069
5	2	0.038	**0.067**	0.032	0.021
6	3	0.058	**0.069**	**0.112**	0.054
7	3	0.058	0.050	0.000	**0.081**
8	**6**	**0.115**	0.066	**0.135**	**0.143**
9	3	0.058	0.046	0.000	**0.090**
10	**4**	**0.077**	0.056	0.052	**0.112**
11	**5**	**0.096**	**0.076**	**0.191**	**0.111**
12	2	0.038	**0.067**	**0.116**	0.034
13	2	0.038	0.062	0.084	0.017
14	3	0.058	0.058	0.068	0.028
15	2	0.038	0.050	0.012	0.014
16	2	0.038	0.044	0.000	0.023
17	**4**	**0.077**	0.057	0.060	0.073

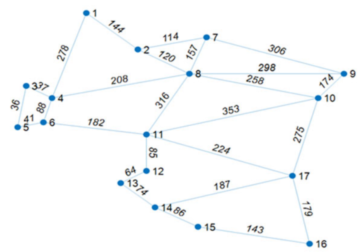

Figure 2. Centrality parameters (left) and network representation of the Germany backbone network (right).

Some interesting details can be obtained from Figure 2 observation. Node 8 is the most connected node in the network (ND=6) but node 11 is clearly more important when BC is considered. To figure out how centrality parameters impact on the network performance, simulations have been carried out using these different parameters. When analyzing a stablished connection, the number of nodes traversed equals the number of hops (NH) plus 1. As explained earlier each connection will use OXC at the source and destination nodes as well as at the intermediate nodes, so the number of used switching units for a connection whose size is B (FS) will be

$$B \cdot OXC_{source} + B \cdot (NH-1)\ OXC_{intermed} + B \cdot OXC_{dest} \tag{2}$$

When averaging a huge number of connections the number of OXC used will be $B \cdot (2+NH_{AVG})$, where NH_{AVG} is the network average number of hops. Therefore, in the network planning/design phase, the quantity of switches assigned to each node is calculated as

$$OXC_i = OXC_{TOTAL} * (Factor1 + Factor2_i) \tag{3}$$

where

$$Factor1 = \frac{2}{[(NH_{AVG}+1)*N]} \tag{4}$$

accounts for the traffic starting/finishing at every node (identical for all of them), and

$$Factor2i = XC_i * \frac{NH_{AVG}-1}{NH_{AVG}+1} \tag{5}$$

N is the number of nodes and XC_i is the centrality parameter (ND, CC, BC or EV) according to Fig. 2 table.

3. SIMULATION RESULTS AND DISCUSSION

The main objective during simulations is minimizing the total quantity of optical switches in the network (OXC_{TOTAL}). If OXC_i values are far from optimal there are nodes whose switches are underutilized while other nodes switches are very loaded. To capture this effect, the ratio of used switches at each node is monitored and recorded. To study carefully this issue, we have simulated the following sequence: **1)** Simulate network performance assuming fiber links are the only limiting factor (unlimited TX, RX, OXC in all the network nodes). This way we find a reference load which leads to some BP point (1% is the value considered during simulations). **2)** Start reducing the TX, RX and OXC_i values to find the load where total BP is kept about 1% but all of the factors (TX+RX+OXC_i in addition to fiber links) are contributing to BP. The values of OXC_{TOTAL} are calculated according to equations (3-5) above. Results when using the different centrality parameters (ND, CC, BC and EV) are shown in Figure 3.

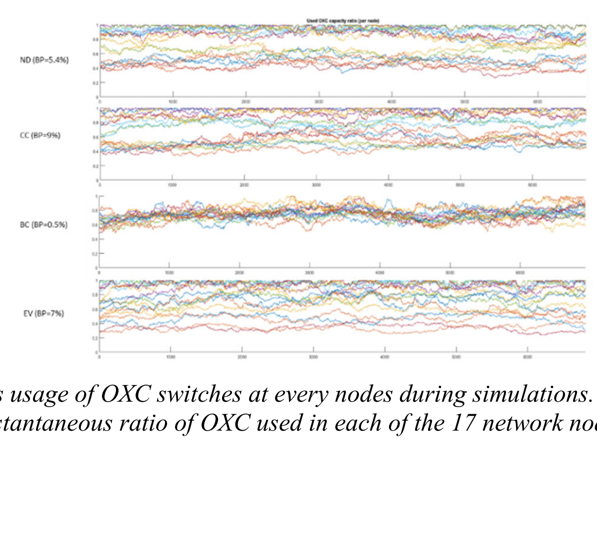

Figure 3. Instantaneous usage of OXC switches at every nodes during simulations. Each line represents the instantaneous ratio of OXC used in each of the 17 network nodes.

A sequence of 8000 connection requests are generated during each simulation run with a mix of 40% 100G, 40% 200G and 20% 400G, and observing the restrictions given in Table 1. It is easily seen how choosing betweenness (BC) as the centrality parameter clearly improves network behaviour. While in the remaining draws the OXC consumption shows a high variance, in the BC plot the different nodes show a very compact OXC usage, always close to 70%.

To better understand the importance of assigning a proper number of switches to every node, Table 2 shows the normalized usage (averaged during a complete simulation) for each node, as well as the Mean, STD, Maximum and Minimum values. It is observed how while average usage takes almost the same values for any of the used centrality metrics, the STD value for BC is much smaller. This pattern was already seen in Fig. 3 where all the plots keep grouped together during the whole simulation for BC. Although nodal degree (ND) has been traditionally considered as the key topological parameter for network planning and evaluation, BC fits much better under realistic random traffic load values.

Table 2. OXC usage values during simulations.

XC\NODEi	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	AVG	STD	Max	Min
ND	0.49	0.49	0.66	0.88	0.63	0.94	0.40	0.90	0.43	0.83	0.98	0.97	0.91	0.86	0.53	0.51	0.88	0.72	0.20	0.98	0.40
CC	0.56	0.62	0.52	0.92	0.49	0.80	0.54	0.98	0.57	0.93	0.98	0.80	0.79	0.89	0.47	0.45	0.94	0.72	0.19	0.98	0.45
BC	0.78	0.71	0.69	0.75	0.68	0.76	0.73	0.73	0.71	0.78	0.77	0.74	0.72	0.73	0.72	0.81	0.83	0.74	0.04	0.83	0.68
EV	0.47	0.49	0.75	0.87	0.74	0.95	0.34	0.79	0.33	0.60	0.95	0.97	0.96	0.95	0.69	0.65	0.91	0.73	0.21	0.97	0.33

Highlighted cells in Table 2 correspond to nodes which are overprovisioned (yellow), so the average ratio of switches used during simulation is below 50%, or underprovisioned (blue) which implies usage ratio greater than 90%. It is observed that there are no highlighted cells in BC row. Indeed, BP in this case is minimum so the actual network load is about 5% higher. By using the same OXC_{TOTAL} value, it is found that the average BP rises from 0.2% in BC case to 5-9% when other centrality metrics are used. We repeated the same procedure for the NSF (14 nodes, 21 links), USBackbone (24 nodes, 43 links), and DT20 (12 nodes, 20 links) networks and a consistent pattern holds: at equal OXC_{TOTAL}, using BC translates into lower blocking and improved robustness to traffic random fluctuations compared to the other centrality metrics.

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