Cross-layer optimization: network cost vs. physical layer margins

P. Soumplis[1], P. Pananikolaou[1], K. Christodoulopoulos[1], N. Argyris[2], C. Spatharakis[2], S. Dris[2], H. Avramopoulos[2], and E. Varvarigos[1]

[1]*Department of Computer Engineering and Informatics, University of Patras, Greece and Computer Technology Institute and Press – Diophantus, Patra, Greece,*
[2]*National Technical University of Athens, Zografou, Greece*
email: soumplis@ceid.upatras.gr

ABSTRACT
Transmissions in optical networks are typically over-provisioned with respect to their capacity but also their physical layer performance: to account for physical layer interference and aging effects, worst-case assumptions and gross margins are used, resulting in low network efficiency and high network cost. Using realistic assumptions we evaluate the network cost gains that can be obtained by establishing connections with just enough physical layer performance on the first day of a flexible network operation.
Keywords: flexible optical networks, optical signal-to-noise-ratio (OSNR), non-linear interference, Routing and Spectrum Allocation (RSA).

1. INTRODUCTION

Flexible optical networks appear to be a promising technology for meeting the requirements of next generation networks, able to offer increased granularity and better spectrum utilization. These networks are built using bandwidth variable flex-grid switches that are configured to create appropriately sized end-to-end optical paths (lightpaths) of sufficient spectrum slots. Bandwidth variable switches operate in a transparent manner for transit (bypassing) traffic that is switched while remaining in the optical domain. The support of variable spectrum connections increases spectral efficiency, supports future transmission rates, and reduces capital costs. Flexible transceivers envisioned, also referred to as bandwidth variable transceivers (BVTs) allow multiple choices when serving a demand: they can decide the modulation format, baud-rate, spectrum or even the FEC, and choose those that give sufficient performance to reach the required distance. Thus, the flexible transceivers can offer configurations that fit better to the heterogeneous reach and capacity demands, reducing the *unallocated margins* experienced by fixed transceivers [1].

Digital coherent transceivers play a crucial role in the development of next generation optical networks. Novel technologies for optical components and devices along with high-speed electronics and sophisticated Digital Signal Processing (DSP) techniques, achieve an unprecedented increase in the capacity and spectral efficiency of the optical network. In addition, the emergence of the flex-grid technology relaxes the rigid bandwidth requirements, provides novel approaches for the system architecture design and improves utilization of the available resources. Coherent receivers employing DSP are able to compensate several physical layer impairments which accumulate during signal propagation (mainly dispersion effects), but still the physical layer plays a major role in current and future systems. In fact, the traversed optical path, the existence, and the characteristics of neighboring connections (interference impairments such as crosstalk, cross-phase modulation, and four-wave-mixing) affect an optical connection. These parameters vary as time passes because of component aging and the establishment of new or the modification of existing connections in the network. Taking a worst-case assumption for the physical layer impairments and in particular for interference related ones and aging effects reduce the feasible transmission reach.

However, in reality, the network is not fully congested and a relaxation in the worst-case assumptions and consequently in the margins taken into consideration can improve its performance [2]. Many efforts focus on the design of algorithms whose goal is to grant the lowest possible margins by configuring various parameters. The authors in [3] improve the network throughput by taking under consideration the nonlinear interference during the routing and spectrum allocation decisions optimizing the individual transmission parameters and spectral channel allocation. In [1] three different flexibility parameters of the BVT transceivers are examined, the baud rate, the modulation format and the channel spacing adjustment, presenting the trade-off between these parameters and the selected network margins. In [4] the authors examine the benefits of avoiding considering future losses and consequently reducing the margins due to forecast losses, examining the advantages that arise in the spectrum usage and capacity on the first day of the network operation. The approach presented in [5] minimizes the launch power to the minimum required value, while [6] is focused on the optimization of routing, spectrum assignment and launch power to reduce the overall effect of the nonlinear interference parameters in the network.

Thus, controlling interference related impairments seems a crucial factor for improving the efficiency of the system. Instead of considering margins calculated under a worst-case approach where all adjacent connections are active, the network can operate with the actual margins required to make feasible the transmission of each connection. An interesting approach in this direction is to use spectrum guardbands as a way to control and reduce interference and increase the reach of certain connections, trading off spectrum utilization for reach. Intuitively, such approach increases the number of available transmission options, and thus can reduce the transceivers' unallocated margins. To harvest the use of spectrum as a guardband, appropriate Impairment Aware Routing and Spectrum Allocation (IA-RSA) algorithms have to be used [7]. Using such an algorithm, in this paper we evaluate the gains that we can obtain by establishing connections with just enough physical layer performance on the first day of a flexible network operation.

2. QUALITY OF TRANSMISSION EVALUATION

In order to evaluate the performance of such a flexible optical network we created a simple transmitter-channel-receiver setup in the simulation engine of the VPI TransmissionMaker [8], appropriately parameterized in all stages of the topology. The Quality-of-Transmission (QoT), based on the calculation of the BER performance of a multi-format (M-QAM), multi-rate (28 and 32 GBaud) signal, considering both single and multi-channel transmission cases was assessed, while the maximum reach and optimum launch power of the system's transceivers estimated.

Specifically, at the transmitter side, IQ modulators generated a dual polarization QPSK/M-QAM signal at 28 and 32 GBaud whith Nyquist pulse shaping filters (Root-raised-cosine response with roll-off factor 10%) to maximize the bandwidth efficiency. To select carrier frequencies and bandwidth spacing of the transmitted signals, we adopted the Flexible DWDM Grid [9]. In particular, the bandwidth of the transmitted signals was set to 37.5GHz, while the spacing of the carrier frequencies were set to minimum, following the Flex-Grid recommendation.

To explore the transmission limitations of a flexible coherent system, the fiber channel model accounted for all the major linear and non-linear impairments induced by an optical fiber (such as Chromatic Dispersion, Polarization Mode Dispersion, Self-phase Modulation, Cross-phase Modulation). Note that for impairments related to the inter-channel interference in case of multi-channel transmission, all the neighboring channels were modulated with the same modulation format and at the same symbol rate. To point out the upgrade capability of the links' inline components (e.g. EDFAs, optical filters) we modelled them with characteristics similar to those of a legacy network.

Finally, typical coherent receiver architecture and standard DSP algorithms were employed for recovering the received information. In particular, Analog-to-Digital emulators fed DSP units for signal normalization and resampling, followed by CMA algorithm for polarization de-multiplexing and equalization. Prior to symbol estimation and detection we also employed algorithms for carrier phase recovery dependent on the examined modulation formats.

A standard span length of 80 km was considered and the maximum transmission reach was evaluated for both hard-FEC (BER ~ $1 \cdot 10^{-3}$, overhead 7%) and soft-FEC (BER ~ $1.9 \cdot 10^{-2}$, overhead 20%) limits [10], [11]. Finally, transmission at different launch power values was simulated in order to examine the correlation of fiber impairments and the launch power. Our simulations resulted to the following transmission scenarios. As we can see, when there is at least one neighbor close the transmission reach is significantly decreased, while higher FEC can be used to transmit over longer distances.

Modulation format: DP –QPSK	*FEC=7%, Symbol rate: 28 Gbaud*		*FEC=20%, Symbol rate: 32 Gbaud*	
# neighboring channels	Launch power: 0 dBm	Launch power: 1.5 dBm	Launch power: 0 dBm	Launch power: 1.5 dBm
0 (single channel)	19x80 = 1520km	16x80 = 1280km	21x80 = 1680km	20x80 = 1600km
1	17x80 = 1360km	14x80 = 1120km	17x80 = 1360km	16x80 = 1280km
2	17x80 = 1360km	14x80 = 1120km	16x80 = 1280km	13x80 = 1040km

Table 1. Transmission reach for the DP–QPSK 100 Gbps transponder

Modulation format: DP - 16QAM	*FEC=7%, Symbol rate: 28 Gbaud*		*FEC=20%, Symbol rate: 32 Gbaud*	
# neighboring channels	Launch power: 0 dBm	Launch power: 1.5 dBm	Launch power: 0 dBm	Launch power: 1.5 dBm
0 (single channel)	6x80 = 480km	5x80 = 400km	8x80 = 640km	8x80 = 640km
1	5x80 = 400km	3x80 = 240km	7x80 = 560km	6x80 = 480km
2	4x80 = 320km	3x80 = 240km	5x80 = 400km	6x80 = 480km

Table 2. Transmission reach for the DP–16QAM 200 Gbps transponder

In our performance experiments except for the aforementioned configurations we also assumed a 40 Gbps transmission with transmission reach of 3000 Km when no neighbors exist, decreased by 300Km for each neighboring connection, to account on interference. We also assumed a 400Gbps transmission, consisting of two 200 Gbps carries using DP-16QAM, with corresponding reach that of the 200 Gbps case.

3. PERFORMANCE RESULTS

Using the transmission evaluation results presented in the previous section, we conducted evaluation simulations for network level performance. In particular, we examined three network scenarios: (i) the spectrum

a.

b.

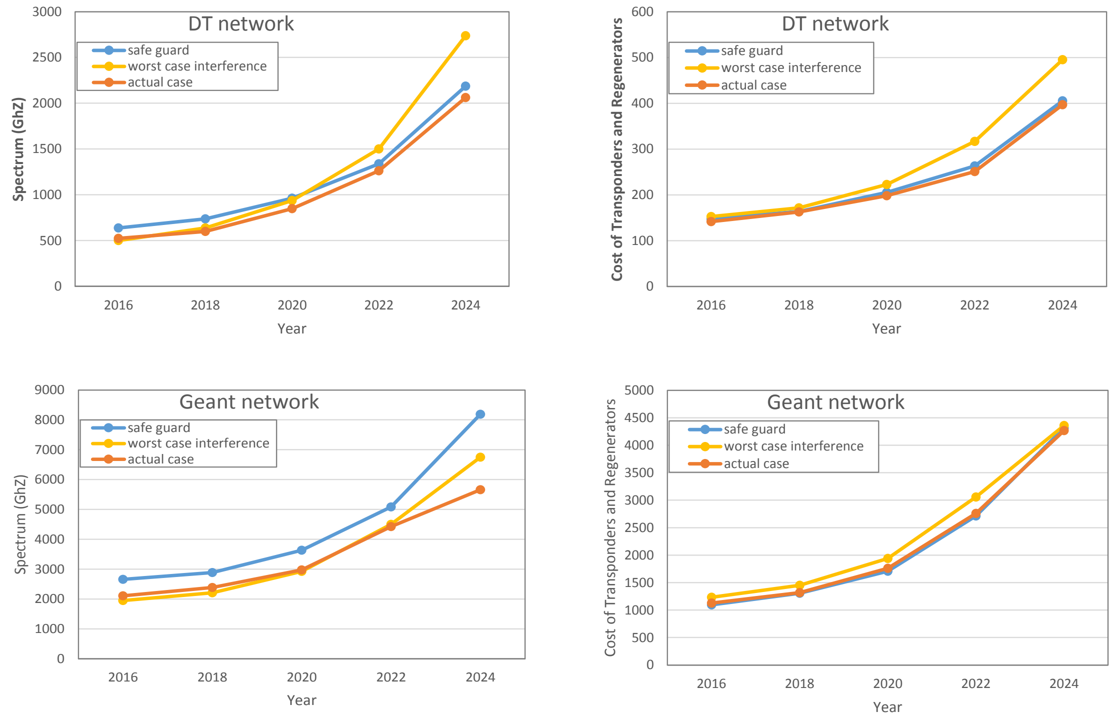

Figure 1 Spectrum utilization and cost for transponders and regenerators for (a) DT network and (b) Geant network for the different transmission scenarios.

safe-guard, (ii) the worst case interference and (iii) the actual case. The spectrum safe-guard scenario assumes the existence of one guardband slot at each side of each connection. In this way, we prohibit the establishment of connections close enough to the connection under study, eliminating in that way the corresponding interference and increasing the reach, as shown in the previous section. The worst-case interference scenario permits the establishment of neighboring connection directly adjacent to each connection, resulting in lower spectrum usage but also lower transmission reach. Obviously, these two scenarios represent a tradeoff between the spectrum and the transmission reach. The third scenario, the actual case scenario, has all transmission options available: it can choose to use guardband slots to increase the transmission reach or to emit them to save in spectrum utilization. It can also harvest intermediate cases, where only one neighboring connection is established.

In our experiments, we examined the performance of the aforementioned scenarios for the 14-node DT and the GEANT network topologies. Starting with realistic traffic matrices, we scaled them up assuming a uniform increase of 34% per year to obtained matrices for years 2016 to 2024 for both networks. The IA-RSA algorithm used is the one presented in [7], using a weighting coefficient *w*=95% for the maximum spectrum utilization and the remainder for the relative cost of transceivers and regenerators. To compute the relative cost of the transceivers and regenerators we assumed that the cost of a regenerator equals 0.8 times that of the corresponding transceiver. Note that at each year examined we assumed that we plan the whole network from scratch, without considering the previous or next state and solutions. Note also that the presented results correspond on the first day of a flexible network operation, meaning that traffic is exactly as given in the traffic matrix, no additional connections that could cause interference are established, and that equipment are brand new and no ageing effects have deteriorated the transmission performance.

As one would expect, the actual case scenario performs better in all cases regarding both the spectrum utilization and the combined cost of transceivers and regenerators. The worst-case interference scenario follows second when the traffic load offered in the network is low (years 2016-2018), while the spectrum safe-guard scenario comes second when the traffic load is high (years 2022-2024). Regarding the relative cost of transceivers and regenerators again the actual case scenario exhibits the best performance for all examined years. The spectrum safe-guard scenario comes closely second, while the worst case interference scenario is the worst.

In the DT network until year 2020 the worst-case interference scenario that permits the establishment of connections directly adjacent to each other has almost the same spectrum and cost performance as the actual case. This happens because the network traffic is low, mainly served by 40 and 100 Gbps connections. At such transmission rates the reach is longer than all network paths, and thus the reach reduction due to interference has none effect on the performance. Interference and reach becomes an issue only for 400 Gbps connection, which are scarce at low loads. As expected, the spectrum safe-guard scenario performs worst in means of spectrum slots, but has good performance in means of transceivers and regenerators. The use of extra guardband slots between the connections reduces interference and offers the capability to the flexible transceivers to transmit with acceptable QoT over longer reaches, thus reducing both the number of transceivers and regenerators used.

For intermediate traffic and specifically at the year 2020, the performance of the three scenarios converges in means of spectrum slots and number of transceivers. This point can be perceived as a turning point, after which the performance of the worst-case interference deteriorates severely, due to the high demand for 400Gbps connections. As load increases, more than one transceiver is needed to serve some source-destination pairs, and the higher number of transceivers and regenerators used in the worst-case interference scenario results also in an substantial increase of the spectrum utilization. Therefore, after year 2020, the worst-case interference scenario starts to exhibit worse spectrum utilization performance than the spectrum safe-guard scenario.

The GEANT network is characterized by longer link distances and lower demands compared to the DT network. In this topology, the gains obtained are less significant. The worst-case interference scenario manages to keep the number of transceivers and regenerators low and close to the other two solutions, without a sudden increase as was the case in DT network (might happen latter than the examined period). This is the reason the spectrum utilization of the worst-case interference scenario remained lower than the related spectrum utilization of the spectrum safe-guard scenario. The actual case scenario kejeps always the lowest cost, sacrificing some spectrum at early years and experiencing slightly higher spectrum utilization than the worst-case interference scenario.

4. CONCLUSIONS

Currently deployed optical networks are over-provisioned with respect to their capacity but also their physical layer performance. Based on worst-case network state and not on the actual state, they use higher than needed margins to ensure the proper transmission. Our performance experiments show that the worst-case scenario results in much higher network cost at least on the first day of the network operation, and that significant gains can be achieved both in spectrum utilization and network cost (transponders and regenerators) using algorithms that consider the actual case of the network and just enough physical layer margins.

ACKNOWLEDGEMENTS

This work was supported by the EC through the Horizon 2020 ORCHESTRA project (grant agreement: 645360).

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