Quantifying Resource Savings from Low-Margin Design in Optical Networks with Probabilistic Constellation Shaping

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Abstract *We estimate resource savings from low-margin optical-network design considering (i) different transmission modes (including PCS), (ii) full vs. actual load for interference modelling and (iii) greedy heuristic vs. evolutionary metaheuristic for routing. Numerical results, mimicking multi-year-traffic evolution, allow to quantify extent of these savings.*

Introduction

Operators are always seeking new techniques to most-effectively utilize spectrum resources in optical networks. This attempt is often referred to as "low-margin design" (LMD)[1], implying that Signal to Noise Ratio (SNR) margins by which optical paths are operated must be reduced as much as possible, with the aim of carrying the highest possible amount of traffic in the network. LMD can be achieved using (a combination of) different technical directions, e.g.: i) using advanced transmission modes, as those based on multiple modulation formats (MFs) and Forward Error Correction (FEC) codes, to increase spectral efficiency and maximize lightpaths' data rate[2] (in particular, in this work we consider also the recently-proposed Probabilistic Constellation Shaping (PCS), that offers finer data rate adaptation capabilities to achieve LMD[3]); ii) using accurate Quality of Transmission (QoT) modeling[4] achieved, e.g., by lifting full-load assumption[5] and accounting for the actual non-linear interference (NLI) during planning; iii) using advanced network optimization techniques (e.g., bio-inspired metaheuristics as genetic algorithms) to achieve quasi-optimal resource allocation over large instances, instead of using simplistic greedy heuristics.

Existing studies tend to examine in isolation these three technical directions, and a systematic comparison of the extent of resource savings achieved by each (or a combination) of them cannot be found in literature. Moreover, the only previous study quantifying network-wide savings of PCS is[3], and no previous work has considered different configurations of PCS. So, in this study, we systematically quantify the resource savings achieved using (jointly, or in isolation) advanced transmission modes (including PCS), accurate interference modeling, and advanced RSA algorithm. We quantify resource savings in terms of spectrum occupation, number of required transponders and maximum wavelength index for a continental, a national and a metro network topology. This quantification allows us to gain insight into the extent of resource savings enabled by these technical directions for LMD.

Physical Layer Modelling

To investigate the effect of different transmission modes on resource utilization, we consider five scenarios with different combinations of baud rate, MF and FEC (see Fig. 1). *Single MF* mode, our baseline scenario, uses a fixed baud rate and modulation format (PM-QPSK), so that a lightpath can only carry 200 Gb/s. *Multiple MF* mode introduces additional MFs (from PM-16QAM to PM-64QAM) with uniform distribution of constellation points. This allows to expand the range of data rates to 800 Gb/s (with 100 Gb/s step) at a cost of using multiple baud rates and two different channel spacings. In *Multiple MF - Multiple FEC* mode, a second code rate is introduced to reduce data rate granularity to 50 Gb/s and increase channel capacity utilization. *PCS - 2 baud rates* uses PM-64QAM with Maxwell-Boltzman distribution of constellation points and two different baud rates: this scenario also enables 50 Gb/s granularity, but with a single FEC code rate, as data rate adaptation is brought by probabilistic modulation. In *PCS - 1 baud rate* only the highest baud rate is used. This allows us to use only one hardware configuration, paying off a higher spectrum occupation (nb: minimal data rate increases to 300 Gbit/s).

To estimate the required SNR for each data rate

Transmission mode	MF	Code rate	Baud rate, Gbaud	Spacing, GHz
Single MF	PM-QPSK	0.8	62.5	75
Multiple MF	PM-QPSK-PM-64QAM	0.8	62.5, 84, 87.5	75, 100
Multiple MF - Multiple FEC	PM-QPSK-PM-64QAM	0.74, 0.8	56, 60, 62.5, 84, 85, 87.5	75, 100
PCS - 2 baud rates	PM-64QAM	0.8	62.5, 87.5	75, 100
PCS - 1 baud rate	PM-64QAM	0.8	87.5	100

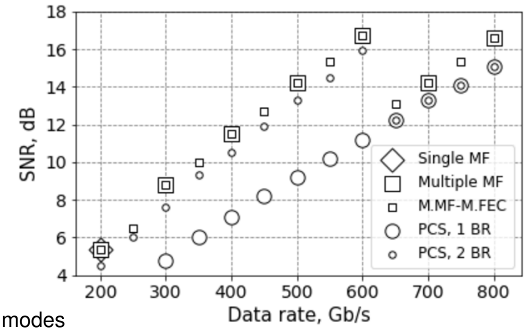

Fig. 1: Transmission modes

and transmission mode (see Fig. 1), we follow the approach in[6], using the concept of mutual information. Setting parameters of PCS according to[7], we obtain (0.7-1) dB lower SNR with *PCS - 2 baud rates* for the same data rate w.r.t. transmission modes with uniform distribution of constellation points, while, for *PCS - 1 baud rate*, we obtain (3-4) dB lower SNR for data rates below 600 Gb/s, as less information per symbol must be transmitted with the higher rate of symbols, and thus, more noise can be tolerated. We add a 2 dB system margin to account for quickly varying parameters, like polarization-dependent loss.

We consider an optical network operating across 6 THz in C-band, resulting in 480 frequency slots, 12.5 GHz each. Non-linear interference is estimated using Incoherent Gaussian Noise model[8]. Power optimization is done according to Locally-Optimized Globally-Optimized (LOGO) strategy[8]. Erbium-Doped Fiber Amplifiers (EDFA) are placed every 80 km to compensate propagation losses and have flat and deterministic gain profile.

Routing and Spectrum Assignment

We assume that an aggregate request R between two optical nodes can be split into separate lightpaths, possibly going across different routes.

Routing. An enhanced version of the Genetic Algorithm (GA) in[9] is used to select lightpath routing among k shortest paths (SP), with the objective of minimizing the number of occupied frequency slots in the network. As GA must be given as an input the number of lightpaths N_R, needed to provision the request R between a pair of nodes, we estimate N_R by assuming the longest option is used as a route for every lightpath, and fibers are fully loaded. Note that this N_R represents an upper bound, and RSA can provision request R using less lightpaths.

Spectrum Assignment. If full-load assumption on interference is considered, spectrum assignment (SA) is performed in a First Fit (FF) manner, after the requests have been ordered, starting with the ones with the highest number of slots occupied in the worst-case routing described above. For every request, among the N_R paths, chosen by the GA, we assign spectrum, starting from paths having the best SNR and capable of carrying the most traffic. Otherwise, if interference is computed based on actual load, spectrum allocation is performed using a modified First-Fit policy that ensures that SNR of previously established lightpaths does not drop below the threshold of the currently used MF when a new request is routed, even if this means leaving gaps in spectrum. Baud rate, modulation format and FEC are selected for the lightpath to minimize the number of occupied slots, given the SNR.

Case Studies and Results

We perform our evaluations on three topologies: a 19-node European optical networks (EU19) and a 17-node German network[10], both in actual scale (GE17) and scaled down by 75% to represent a metro network (ME17). Main metrics for the three topologies are shown in Tab. 1.

Tab. 1: Network parameters

Metric	ME17	GE17	EU19
Av. link length, km	36	147	576
Av. SP length, km	103	415	1441
Av. node degree	3.06	3.06	4

Results are averaged considering 20 instances of a full-mesh traffic matrix with different data rate requests randomly distributed within 200 Gb/s and 1000 Gb/s with 50 Gb/s step. Each data rate in range (200-400) Gb/s can be chosen with 10% probability, (450-650) Gb/s - with 5%, (700-800) Gb/s - with 2.5% and (850-1000) Gb/s - with 1% probability. For the remaining 15% probability, no traffic is transmitted between a node pair. With this traffic distribution, transmission modes starting from *Multiple MF* reach about 50% spectrum utilization on average on network links. We then consider a yearly traffic growth of 10% per year, for 5 years, for all the transmission modes, except *Single MF*, as in that case some fibers are already

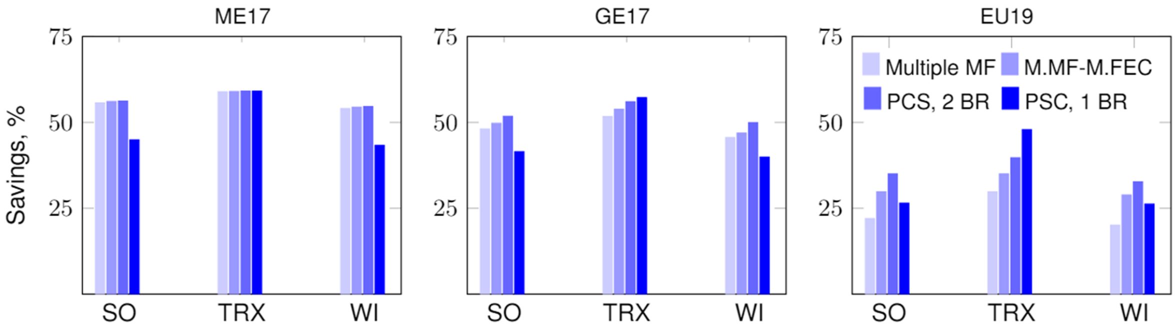

Fig. 2: Savings w.r.t. Single MF, Year 0, %

fully occupied. Routes are chosen among 9 pre-computed shortest paths.

Savings for different transmission modes. In Fig. 2 we report savings in spectrum occupation (SO), number of required transponders (TRX) and Wavelength Index (WI, the highest occupied frequency slot across the network) that come from advanced transmission modes, using GA for routing and full-load assumption. In this scenario we have not observed significant changes with incremental traffic growth, so only savings at Year 0 are presented. For all three networks, *PCS - 2 baud rates* achieves highest savings in SO: 56% less spectrum is used in ME17, 52% in GE17 and 35% in EU19. On the other hand, due to its lower SNR requirements, *PCS - 1 baud rate* provides highest savings in TRX: 59% for ME17, 57% for GE17 and 48% for EU19. *PCS - 1 baud rate* allows to save 8% in TRX over *PCS - 2 baud rates* in EU19 network, due to its longer paths, as opposed to 1% savings in GE17 and 0% in ME17. WI decreases along with spectrum occupation.

Actual load vs. Full load. From now on we focus only on *PCS, 2 baud rates*, as it provides highest SO savings among transmission modes. We first analyze the effect of accurate interference modeling, namely, actual-load vs. full-load assumption. Tab. 2 shows the results for the 3 topologies (using GA-based routing).

Tab. 2: Actual- vs. full-load savings, Year 0 (Year 5), %
PCS, 2 baud rates

	SO	TRX	WI
ME17	0.0 (0.0)	0.0 (0.0)	-2.3 (-2.0)
GE17	1.3 (2.5)	1.3 (2.1)	-12.0 (-12.0)
EU19	4.1 (5.1)	3.5 (4.6)	2.9 (-1.7)

As expected, actual-load assumption enables small, yet perceptible, savings in EU19, i.e., 4.1% and 3.5% in terms of SO and TRX, respectively, at Year 0. Savings increase by Year 5, as established lightpaths have higher excess capacity to accommodate new traffic. Savings decrease with the network size, and no savings are achieved in ME17 network, as, due to shorter paths, even with full-load assumption all the requests are provisioned with a single transponder. WI gets worse for actual load, as spectrum gaps are left to avoid disruption of previously established lightpaths.

GA Routing vs. kSP. Finally, we investigate the impact of optimized routing, comparing GA-based and k-Shortest Paths routing, and considering full-load assumption for both cases. Tab. 3 shows the results for the 3 topologies.

Tab. 3: GA Routing vs. kSP savings, Year 0 (Year 5), %
PCS, 2 baud rates

	SO	TRX	WI
ME17	5.1 (5.0)	0.0 (0.0)	23.2 (24.5)
GE17	4.9 (2.0)	2.0 (-2.0)	16.6 (13.3)
EU19	11.2 (10.8)	2.0 (1.4)	25.1 (24.4)

Wavelength Index is the metric that experiences largest reduction, up to 24%, as, to minimize SO, GA balances the load, leaving more space for future requests. EU19 benefits most from the GA-based routing algorithm, providing savings of 11% in SO and 2% in TRX at Year 0. Savings reduce by Year 5, as longer routes utilized to distribute the load reduce excess capacity of the established lightpaths, so that more lightpaths must be added to support traffic growth w.r.t. kSP routing. In GE17 this factor even leads to 2% losses in TRX.

Conclusion

In summary, considering an accurate physical layer modeling, and three realistic network topologies, we jointly quantified the resource savings obtained applying three technical directions for LMD: (i) with advanced transmission modes (up to 56% savings in spectrum or 59% in transponders in case of PCS), (ii) using a actual load assumption on interference modeling ((2-5)% of spectrum), and (iii) using advanced network-level optimization (5-11)% of spectrum w.r.t. to greedy approaches). These quantifications will be used to set our expectations on the extent of savings achievable using Machine Learning based tools for LMD.

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