Network-Wide SNR-based Channel Power Optimization

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Abstract *We propose a per-channel power allocation to maximize worst service's SNR network-wide. The technique, rooted in the Gaussian noise model but accounting for all transmission effects, is validated on a testbed with commercial, real-time equipment; a gain of 0.5 dB margin improvement is experimentally demonstrated.*

Introduction

Quality of Transmission (QoT) of a signal is explicitly related to the Signal-to-Noise Ratio (SNR). SNR of a signal depends on many parameters, including its power and the power of all the other signals. Equalization consists in setting the launch power of each channel on each network segment through the per-channel attenuation of the Wavelength Selective Switch (WSS) located at the start of each Optical Multiplex Section (OMS). We propose a network-wide algorithm to select the power of each channel, on each OMS, to improve the worst SNR margin (the difference between a signal's SNR and its Forward Error Correction (FEC) limit SNR_{FEC}) among all the established services, thereby improving the network's robustness, e.g., caused by ageing.

The Local-Optimum Global-Optimum (LOGO) strategy[1] optimizes the SNR of the worst channel on a given OMS through balancing linear and nonlinear noises (computed e.g. through the Gaussian Noise (GN) model[1]) while assuming flat amplifier gain, flat fiber attenuation, and no Stimulated Raman Scattering (SRS). LOGO results in flat power allocation. Similarly, convex optimization was proposed in[2] to optimize either system capacity or worst margin, again assuming flat parameters (SRS only is addressed in[3]). Moreover, heuristics were proposed in[4] in the context of submarine links with EDFA power constraints to optimize capacity, and in[5] for more general systems without EDFA power constraints for robustness optimization and without Raman effect.

Real networks exhibit strong wavelength dependence e.g. through amplifier ripples, fiber attenuation and SRS. This paper relaxes flatness assumptions, accounts for power amplifier constraints and optimizes the SNR of the worst channel network-wide; although we leverage the GN model to determine the powers (P), we also account for any physical impairment that can be modeled by an SNR estimator. We evaluate the strategy, first through simulations, and then in a network environment using real-time, commercial equipment. We demonstrate a gain of 0.5 dB for the worst channel's SNR margin for a mixed modulation format network scenario.

Heuristic algorithms

Assuming flatness of amplifier gains and fiber attenuation, and neglecting SRS, LOGO dictates that the SNR of the worst channel is maximized when ratio $\rho=P_{ASE}/P_{NLI}$ between the amplifiers spontaneous emission (ASE) noise power P_{ASE} and the nonlinear noise power P_{NLI} is 3dB (Non Linear Threshold, NLT). In those conditions, we have $d\rho/dP=3$, while, in the linear regime, $dSNR/dP=1$ (all quantities in dB). We use those rules of thumb as an approximation within our optimization process in the more general case where the system is not flat and SRS is present; however, while optimizing, we leverage a more general QoT (SNR) computation tool that accounts for non-flatness and SRS, such that system SNR margin is indeed maximized.

Margin maximization results from power re-allocation across services; re-allocating power from high margin services to low-margin services may result in a large SNR margin drop (hence capacity loss) for some services while only marginally improving the SNR margin of other services, resulting overall in an average network capacity loss with little gain in worst channel SNR margin. The proposed heuristic accounts for this trade-off between capacity and robustness.

S*ingle OMS heuristic: OMS_Optimize*

The heuristic algorithm "OMS_Optimize" is depicted in Fig. 1(a) for a single OMS.

Initialization Set launch power $P_0(\lambda)$ to be in highly linear regime by subtracting 3 dB from the optimal total output power (P_{opt}) obtained using LOGO. If needed, we clamp P_{opt} to the maximum total output power of the first amplifier (P_{max}).

Step 1 identifies the worst performing channels by computing the SNR margins $M(\lambda)$ using

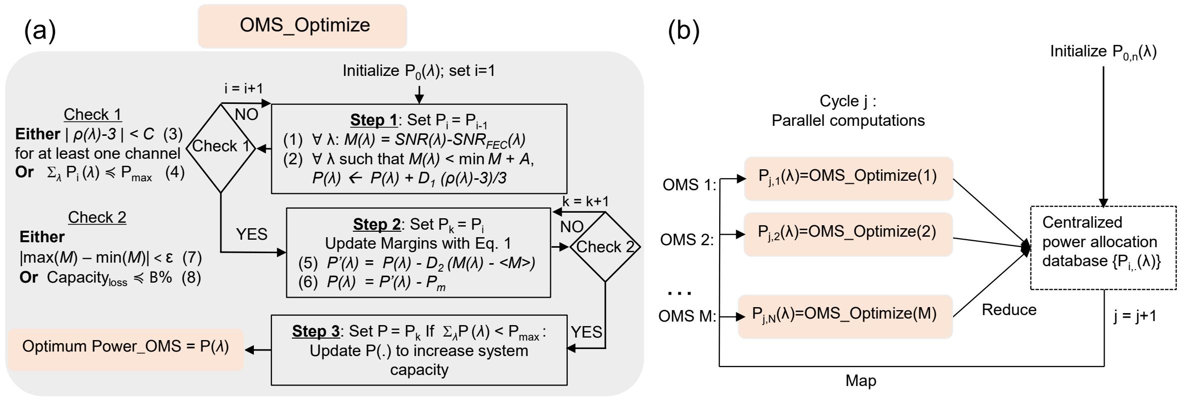


Fig. 1: (a) Single OMS power optimization algorithm "OMS_Optimize"; (b) Network-wide power equalization algorithm.

Eqs. (1)-(2). Parameter '*A*' affects the number of worst performing services being selected and avoids local minima. Eq. (2) updates the powers of these services close to NLT using a damping factor D_1(<1) to avoid oscillations. Step 1 is repeated until either one of the service reaches NLT (Eq. 3) or the amplifier power constraint is met (Eq. 4). Parameter '*C*' defines the lower and upper bounds that can be accepted as closeness to NLT as a stopping criterion.

Step 2 Try to equalize margins for all the services in the OMS by updating margins by varying the power values obtained at Step 1: reallocate the powers of each service such that their margins are closer to their average <M> using damping factor $D_2<1$ (Eq. (5)). Normalize powers obtained in this step to have the same total output power P_m as in Step 1 (Eq. (6)). Step 2 is repeated iteratively until one of the breaking conditions is met in Check 2. In Eq. (7), ε defines the desired margins flatness and 'B' defines the trade-off between capacity and margins, i.e., capacity cannot decrease by more than B% while trying to improve the worst service margin.

Step 3 At this point the worst margin is maximized; any left-over power is used to increase the system capacity by driving the system closer to NLT using Eq. (1).

The proposed algorithm can be also used to maximize the system capacity without optimizing the worst-channel SNR, by running Step 3 only.

Network heuristic

We extend the single-OMS method to the more generic meshed network case (see Fig. 1(b)). The iterative method relies on cycles indexed by *j*, each cycle consisting of a "map" and a "reduce" step, as in distributing computing. $P_{j,n}(\lambda)$ is the power at Cycle *j* for the *n*-th OMS on the service going though channel λ; $P_{0,n}$ is initialized using LOGO for each OMS. A centralized database contains all power allocation $P_{j,n}(\lambda)$. In the "map" step, each OMS is optimized using OMS_Optimize, independently of the other OMS: each OMS is optimized in parallel, assuming that the data from other OMS are known (from the global database) so that the margins of all the services going through a given OMS can be computed. After this step, the power allocation for each OMS is known. Then, in the "reduce" step, each OMS shares its power allocation with all the other OMS through the global database. Cycles are iterated until convergence of the desired metric, e.g., SNR margin. If a single cycle is run, the optimization is OMS-local as each OMS can compute its power allocation independently by simply assuming that all other OMS use the LOGO procedure; when several cycles are run, instead, the optimization is global as the OMS exchange information through the centralized database.

Experimental Setup

The proposed algorithm is validated using the experimental 3-OMS tandem network with heterogeneous spans shown in Fig. 2. 38 400G 16QAM (dropped after OMS1) and 38 200G QPSK (dropped after OMS3) modulated services are allocated over a 75GHz fixed grid using a commercial 68GBaud 200 Gb/s QPSK / 400 Gb/s

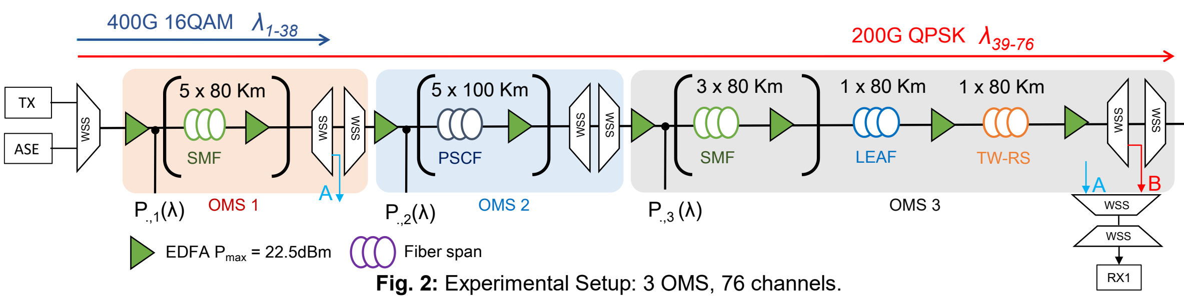
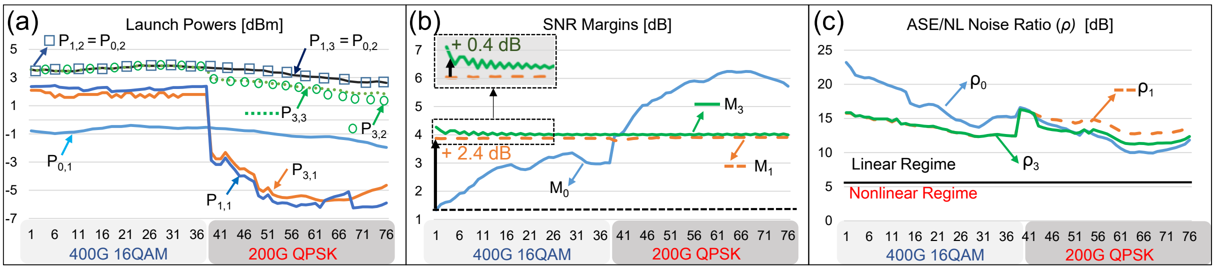


Fig. 2: Experimental Setup: 3 OMS, 76 channels.



(a) Launch power $P_{j,n}$ for all services on the n^{th} OMS at Cycle j. (b) SNR margins M_j for all services at Cycle j. (c) Ratio ρ_j for all services at Cycle j.

Fig. 3: Simulations: equalization of a 3-OMS network.

16QAM transponder. Lower wavelengths carry the 400G channels. All the amplifiers gain, noise figure are experimentally measured and mapped into the QoT tool for the SNR calculation. The ASE noise has been loaded along the line to fill the empty portion of the spectrum for OMS2 and OMS3. We sweep all the channels with a single transponder to measure the SNR for all channels. The setup has been, first simulated and then experimentally validated.

Results

Simulation: In the network described above, we constrain the total output powers (P_{max}) on OMS1, OMS2 and OMS3 to 18 dBm, 22.5 dBm and 22.5 dBm, respectively. We use a large back-to-back SNR ceiling (SNR_{B2B}) for illustration. Tab. 1 reports capacity, margin and running time (expressed in calls of the QoT tool) for each cycle. In Fig. 3(a), we observe that OMS2 and 3 are not optimized in Cycle 1 because all the 16QAM services are dropped after OMS1: the algorithm ensures that the launch powers remain at LOGO ($P_{0,\cdot}(\lambda) = P_{1,\cdot}(\lambda)$). Fig. 3(b) shows that Cycle 1 flattens the SNR margins M_1 on OMS1 (the large SNR_{B2B} allows the poorly performing 16QAM services to improve their SNR by re-allocating power from the QPSK services). In Cycle 2, both the 16QAM and QPSK services are now treated as worst performing since margins are flattened. Launch powers on OMS1 do not change since the other OMS have not yet been optimized, while OMS2 and 3 improve the margins of the QPSK services. Then, in Cycle 3 this gives the possibility to further optimize the low-performing 16QAM services for OMS1. Results reported in Fig. 3(b) show that, compared with LOGO, the algorithm improves the minimum margin by 2.8 dB (2.4 dB in Cycle 1 and 0.4 dB in Cycle 3) using a total of 24 QoT tool calls.

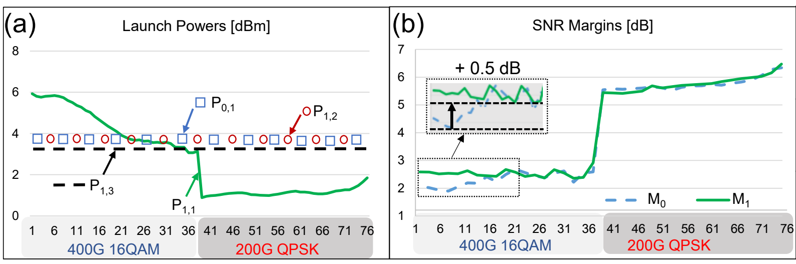
Tab. 1: Simulation – cycles description.

Cycles	OMS 1	OMS2	OMS3	Capacity (average) [bps/Hz]	Margins (min,max) [dB]	#Calls of QoT Tool (Step 1+ Step2 + Step 3)
LOGO	-	-	-	8.5	1.3, 6.2	N/A
Cycle 1	Improve margins	✖	✖	8.4	3.7, 3.9	14 (6+8+0)
Cycle 2	✖	Improve margins	Improve margins	8.5	3.8, 5.0	4 (2+2+0)
Cycle 3	Improve margins	✖	✖	8.5	4.1 4.2	6 (2+4+0)

Experiment: the power constraint on OMS1 is set to 22.5dBm, transponders have a finite SNR_{B2B}. Fig. 4(b) shows that after Cycle 1 we have improved the worst channel margin by 0.5 dB; margins cannot be flattened in Step 2 of Cycle 1 for OMS 1 because the 16QAM services are limited by the transponder SNR_{B2B} and the algorithm stops (Fig. 4(c)). Further cycles would indeed re-allocate power to the B2B limited 16QAM services without any margin improvement, thereby degrading overall capacity for no robustness gain. Also, from Fig. 4(a), we can observe that the launch powers of OMS2 and OMS3 remain at LOGO because the worst performing channels are dropped after OMS1.

Conclusions

We have proposed and experimentally demonstrated a network-wide power allocation algorithm, and improved the SNR of the worst channel by 0.5 dB on a testbed using commercial equipment.



(c)

Cycles	OMS 1	OMS2	OMS3	Capacity (average) [bps/Hz]	Margins (min,max) [dB]	#Calls of QoT Tool
LOGO	-	-	-	8.7	1.9, 6.4	N/A
Cycle 1	Improve margins	✖	✖	8.7	2.4, 6.4	9 (7+0+2)

Fig. 4: Experiment: (a) launch powers $P_{j,n}$ for all services on n^{th} OMS at Cycle j; Margins M_j at Cycle j; (c) Cycles.

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