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Quality of Transmission Estimator Enabling the Transparency Paradigm in Legacy IMDD Networks

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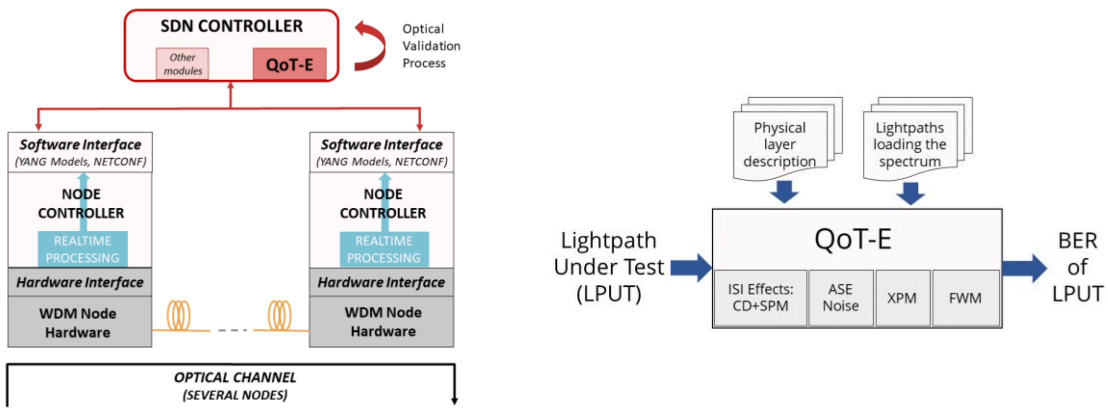
ABSTRACT

Optical transmission based on IMDD modulation and dispersion-managed links is still of interest for the community because of its low-cost. Although the optical technologies deployed for this networking scenario are well-consolidated, operators are still requiring software-based orchestration capabilities. To this purpose, the line system and in general the network management software need to rely on a Quality-of-Transmission Estimator (QoT-E) enabling a quick evaluation of lightpath performance for the optical feasibility and network optimization. In this work, we propose a QoT-E considering the joint effect of SPM, XPM and FWM.

Keywords: QoT-E, network disaggregation, multi vendor networks, IMDD, 10G, dispersion managed.

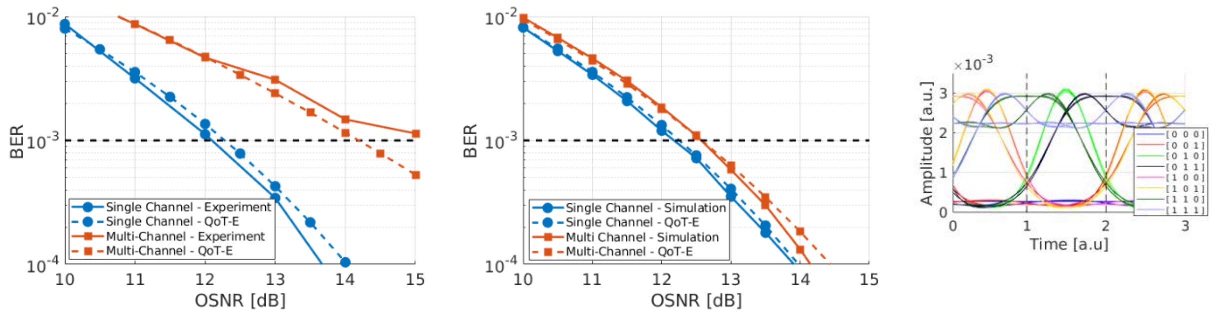
1. INTRODUCTION

Recent research activities are putting a lot of effort in the optimization of the optical networks moving from the hardware-centric and implementation-specific to the service-centric and multi-vendor paradigm [1]-[2]. In this disaggregated network scenario, it is necessary to provide an abstraction of the network elements from the implementation details of the physical layer. To this aim, NETCONF/YANG models are gaining momentum as configuration protocols and interfaces between the physical characteristics of optical nodes, cards and channels enabling multi-layer autonomous network operations, managed by network controllers and orchestrators [3]-[6].
Nevertheless, the peculiar properties of signal propagation in optical fibers cannot be overlooked. For example, the simple availability of a fiber path between two nodes does not imply channel compliance with the required Quality of Service (QoS). A Quality of Transmission Estimator (QoT-E) module within the network controller is thus needed to calculate the actual propagation performances exploiting the relevant data available by means of YANG data structures. This allows physical layer aware management of optical channels routing and configuration. QoT-Es already exist for multilevel modulation formats over uncompensated fiber links with coherent receivers for 100G and beyond data rates [1]. Such optical technologies dominate the long-haul Wavelength Division Multiplexing (WDM) market for back-bone networks. However, the Metro segment is still often operated by 10G transceivers based on the Intensity Modulation Direct Detection (IMDD) over Dispersion Managed (DM) links, because of the large CAPEX saving. In particular, simpler WDM architectures represent a large market potential as upgrade of legacy but still widespread Synchronous Digital Hierarchy (SDH) networks, since the expensive coherent technology would not be effective from a cost/advantage point of view. For these reasons, the extension of Service Validation models to the legacy 10G technology has a definite appeal for network design and management. Still, QoT-Es developed to this purpose are not available for IMDD over DM networks deploying legacy 10G IMDD channels. However, thanks to the lower Optical Signal to Noise Ratio (OSNR) requirement allowed by the high-gain FECs currently in use, the extensive transmission modelling available for these channels can be used to provide reliable signal quality estimation. In this scenario, much more Amplified



(a) *(b)*

Figure 1. (a) Interfacing between network elements. (b) Block diagram for QoT-E architecture.



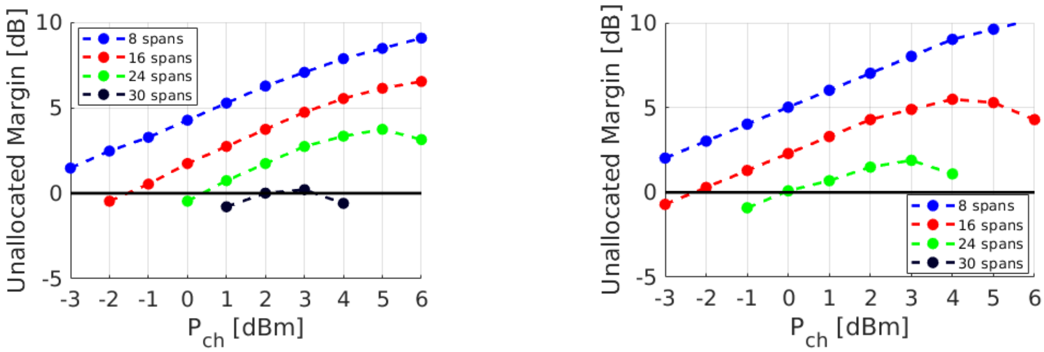
(a) (b) (c)

Figure 2. QoT-E vs experiment (a) and simulation (b) validation at $D_{RES,IL}$ = 0 ps/nm (a) and at $D_{RES,IL}$ = 20 ps/nm (b). Black dashed line sets the pre-FEC target BER. (c) ISI-distorted signal eye-diagram. Each color refers to one of the 8 patterns of $M = 3$ bit.

Spontaneous Emission (ASE) noise can be tolerated. Thus, the Gaussian assumption for the overall interference on the photo-detected signal is always a reliable approximation, with benefits for bit-error rate (BER) prediction methods. At the heyday of 10G, on the contrary, the required OSNR was so high that the optimal working region was between the tails of the error distributions, where the Gaussian approximation of ASE noise could lead to significant errors in BER estimation. DM 10G-based networks are harder to flexibly manage and have long been treated with rigid constraints derived from offline calculations. Such an approach is not well-matched to the flexibility and reconfigurability requirements of modern network architectures. So, the aim of this work is the development of a QoT-E module for such a scenario. Its characteristics in terms of speed and reliability are such for it to be included in a centralized Optical Domain Controller (ODN), or in general in a SDN controller, for real time validation. For each optical node, the ODN acts as collector and enabler of the hardware-specific implementation (Fig. 1 (a)). The QoT-E module can also operate as an offline Design Tool, guaranteeing consistency of results between design and real-time management.

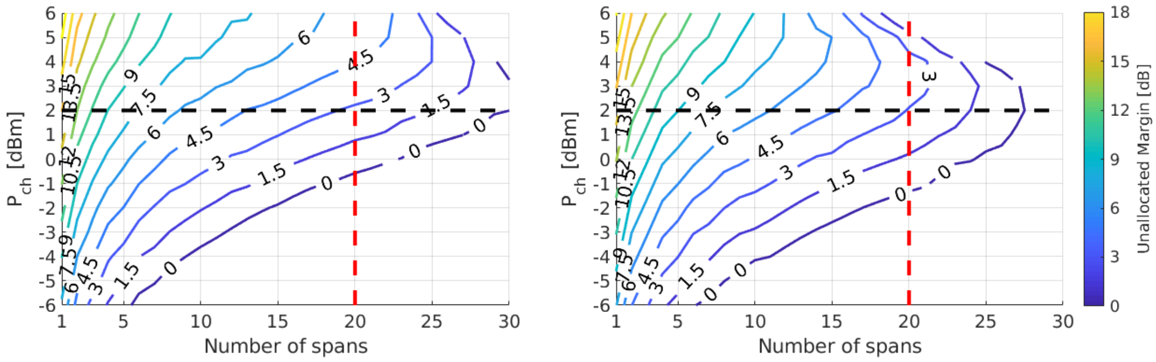
2. QoT-E DESCRIPTION AND VALIDATION

The QoT-E software layer enables flexible network management and orchestration evaluating the feasibility of the optical path. An optical path is composed by fiber spans, each one followed by an optical amplifier (EDFA) and dispersion compensating unit (DCU) which compensates for the Chromatic Dispersion (CD) introduced along the fiber [1]. The feasibility is evaluated by estimating the BER at for the optical path as quality metric. This requires the description of the optical elements along the path together with the knowledge of the WDM channel planning, as illustrated in Fig. 1 (b). The performance evaluation for the Lightpath Under Test (LPUT) relies on modelling linear phenomena (CD) and non-linear phenomena impairing the propagating signal together with the ASE noise: Self Phase Modulation (SPM), Cross Phase Modulation (XPM), Four-Wave Mixing (FWM) [7]. XPM and FWM (when considerable) are multi-channel effects and are evaluated by implementing the well-known models [8]-[9]. Here, a novel approach - to the best of our knowledge - is used to account for the Intersymbol Interference (ISI) [10] introduced by CD and SPM, which are single-channel effects. The QoT-E estimates the ISI-affected zeros and ones average levels of the propagated signals by looking at symbols of M bits rather than bit by bit, being M the memory introduced by the ISI. From our investigations, $M = 3$ is adequate to including the whole ISI effect (Fig. 2 (c)). The distorted signal is obtained by means of a Fast Split-Step method-based API embedded in the QoT-E and optimized for single channel, noise free propagation which runs in less than one second on a general-purpose CPU at moderate power levels. The overall ASE noise is considered at the receiver (Rx) and its amount is determined by the OSNR. The QoT-E results have been extensively validated by comparing the QoT-E outcomes to full split-step simulations and with experiments. We considered fiber spans of 50 km of average length since real installed links are not strictly periodical. This makes the residual dispersion at the end of each span $D_{RES,IL}$ slightly different from the target value, providing a more reliable estimation of the non-linear impairments. This becomes important when assessing optical performances in the context of network flexibility and reconfigurability rather than a simple system planning and leans towards the prediction of optimal/sub-optimal power levels for network optimization in 10G networks. Fig. 2 displays BER vs OSNR at Rx from experiments and simulations. The curves refer to a 16 spans optical path, P_{ch} = 1 dBm launch power. 11 channels at R_b = 11.3 Gbps filled the spectrum on the Δf = 50 GHz WDM grid. The center channel was probed while neighboring channels were pumping multichannel phenomena. We used only 10 pumps as we investigated via simulation that XPM generation saturated vs the total WDM bandwidth when around 10 channels on the 50 GHz WDM grid were present on the fiber. Fig. 2 (a) shows the QoT-E outcome with respect to an experiment for an optical path with $D_{RES,IL}$ = 0 ps/nm while Fig. 2 (b) compares the QoT-E to simulations with $D_{RES,IL}$ = 20 ps/nm path. Results confirm a good agreement of the QoT-E evaluation with both experiments and simulations.



(a) (b)

Figure 3. Unallocated Margin vs Channel power vs Number of spans for (a) SMF network, (b) LEAF fiber network at Δf = 37.5 GHz. The black continuous line sets the zero-margin threshold below which the lightpath is out of service.



(a) (b)

Figure 4. Unallocated Margin mask for (a) SMF network, (b) LEAF fiber network at Δf = 37.5 GHz. Black dashed line is the $P_{ch,max}$ constrained to EDFA total power of 22 dBm and 107 WDM channels. Red dashed line sets the maximum number of spans a path in the network. The color scale refers to both plots.

3. QoT-E NETWORK MANAGEMENT

Previous section showed that QoT-E delivers a fast yet accurate estimation of the required OSNR at the Rx, enabling a quick test of the lightpath feasibility. The Unallocated OSNR Margin (UM) [11] can thus be considered as a quality metric intended to perform physical layer aware network design and orchestration. As an application example, we considered DM meshed networks deployed using SMF and LEAF fibers. 50 km spans are assumed with typical $D_{RES,IL}$ = 50 ps/nm. The available OSNR at the Rx - $OSNR_{RX}$ - has been calculated assuming EDFA noise figure of 5.5 dB, 8 dB of additional system and design margin [11] and, for each span, 6 dB of lumped loss due to patch panels, as typically for metro network scenarios. Note that $OSNR_{RX}$ is the quality metric for the ASE noise accumulation only. So, the UM is computed as the difference between $OSNR_{RX}$ and the OSNR at Rx $OSNR_{req}$ provided by the QoT-E. $OSNR_{req}$ is the minimum value required to support error-free transmission (pre-FEC BER = 10^{-3}) considering all the propagation effects, including CD and non-linear impairments. The UM has been calculated for P_{ch} between -6 and 6 dBm, varying the span count from 1 to 30 and on both the Δf = 37.5 GHz and 50 GHz WDM grid, populating the C-Band with 107 and 81 channels, respectively. The span count defines the extension of the longest allowed path in the meshed network. Fig. 3 shows how the UM varies with channel power P_{ch} and increasing the path length of both the SMF and LEAF networks at the 37.5 GHz spacing. When the optical path is short, the UM increases almost linearly with P_{ch}, so that performance is limited only by optical amplifiers. As the span count increases the non-linear impairments become predominant at moderate to large powers, so that is possible to obtain an optimal power delivering the largest margin. This is more evident on LEAF network due to its stronger non-linear effects, limiting the maximum reach to less than 30 spans. Finally, at lower powers and longer paths, the optical feasibility is limited by the accumulation of CD, and the corresponding tolerance of the transceiver. Fig. 4 shows the extended set of results arranged on a margin mask, which is a set of iso-UM curves vs channel power and number of spans. Here, the network dimension is set as the maximum span count an optical path may include. The maximum $P_{ch,max}$ is set by the EDFA total output power. By jointly satisfying these two constraints, we can identify the region where the system may operate. For both SMF (Fig. 4

(a)) and LEAF (Fig. 4 (b)), the $P_{ch,max}$ of 2 dBm guarantees nearly 3 dB of UM for the entire routing space. Also, lower power levels are feasible at the cost of decreased margin, for possible energy saving management.

By cutting the margin mask at the $P_{ch,max}$ supported by the EDFA, we observed the UM vs the number of spans at both the considered WDM spacings (Fig. 5), leading to $P_{ch,max}$ = 2 dBm at Δf = 37.5 GHz and $P_{ch,max}$ = 3 dBm at Δf = 50 GHz. This allows us to make some interesting considerations. Assuming a path length of 700 km (14 spans) both spacings deliver nearly the same 5 dB margin. In case of link failure, this permits to recover the same lightpath by routing it along a much longer path still providing enough margin.

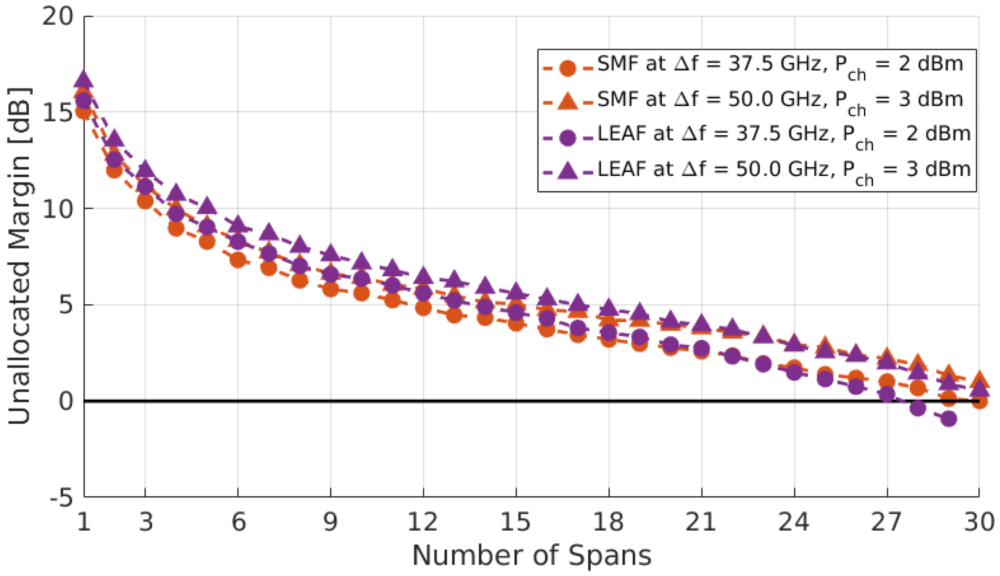


Figure 5. Unallocated Margin vs Number of spans with channel power constrained to WDM spacing and Total EDFA output power of 22 dBm. Orange (Purple) curves refer to SMF (LEAF) networks. Circle (Triangle) curves refer to 37.5 GHz (50 GHz) spaced networks allowing 107 (81) channels at 2 (3) dBm each one. Black continuous line sets the zero-margin threshold below which the lightpath is out of service.

4. CONCLUSIONS

We have developed a QoT-E enabling physical layer aware networking on IMDD over DM networks. The reliable estimation of the UM allows to evaluating real-time path feasibility together with the definition software-defined power management strategies both for minimization of power consumption minimization and margin optimization.

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