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Digital-Twin of Physical-Layer as Enabler for Open and Disaggregated Optical Networks

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***Abstract*—The physical layer in optical networks is a set of transparent optical circuits — light-paths (LP)s — that has been extensively shown as reliably approximated by additive white and Gaussian noise channels. Noise sources setting the LP generalized SNR (GSNR) are the ASE noise from amplifiers, the nonlinear interference (NLI) from the Kerr effect and crosstalk from ROADMs. Coherent transceivers can be effectively modeled by the back-to-back characterization by defining the GSNR thresholds. We will describe the physics behind such approximation including the statistical impairments due the PMD, PDL and filtering penalties, and other uncertainties. Then, we will show how the physical layer digital twin (PHY-DT) that integrates the transmission impairment models can be exploited to reliably evaluate the QoT, latency and energy consumption on the topology. Finally, we will comment on the possible use of the PHY-DT as vendor neutral planning tool for disaggregated infrastructure and as on-line service within the multi-layer hierarchical controller. The optical devices controller can be separated from the optical circuit deployment, so enabling multi-vendor networks. We will also comment on the synergistic use of AI&ML techniques assisting the PHY-DT.**

***Index Terms*—Transmission Modeling, Open Optical Network Design and Control, Digital Twin, SDN**

I. Introduction

The first definition of the digital twin (DT) was proposed by the NASA as an "*integrated multi-physics, multi-scale, probabilistic simulation system that uses the best available physical models and sensor updates*" [1]. Then, the concept has been extensively used in several fields adapting the definition to each specific application [2]. In general, the DT of a system can be defined as a set of methods relying on data sensed from the system that allows an accurate simulation of the actual system functionalities. So, the DT is the core for an optimized software-defined management of a complex system.

In optical networking, the system is the physical layer (PHY), i.e., the set of components – network elements (NEs) – enabling transparent optical circuits. So, the DT of the optical transport is a set of models of the impact of each NE on the quality-of-transmission (QoT) of transparent optical circuits.

Optical networks are presently closed infrastructures in core and metro segments fast expanding in the access, inter- and intra-datacenter and 5G *x*-hauling. For an optimized exploitation and sharing such a pervasive infrastructure, disaggregation and openness must be progressively introduced in optical networking. It implies the capability to control a multi-vendor ecosystem separating the control- from the data-plane as prescribed by the software-defined networking (SDN) paradigm [3], and consequently enabling virtualized infrastructure slicing and sharing. So, open control protocols and models are needed as well as the capability of the optical network controller to dynamically optimize the data and control plane. The latter implies the need for an *entity* that is able to mimic *real-time* the effect on QoT of different HW setting: the physical-layer digital-twin (PHY-DT) . Besides the accurate physics and/or AI models for QoT impairments of NEs, the DT must include the capability to read the QoT *input data*: to this purpose, a crucial role is the availability of data from telemetry as well as from open YANG models.

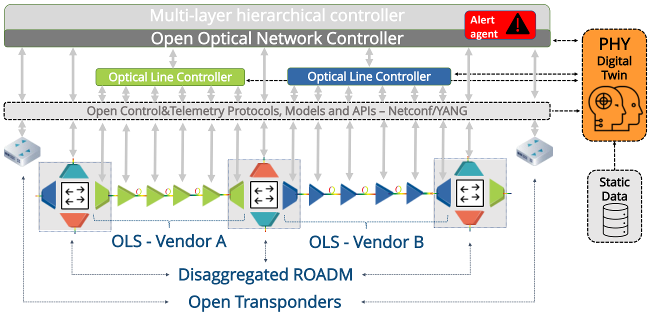

Fig. 1: Schematic description of the partially disaggregated optical network open control based on the physical layer digital twin.

We describe as the use of dual-polarization (DP) coherent optical technologies enables accurate modeling of QoT impairments referring to the open source initiative GNPy [4]. The DT can be used for design and planning multi-vendor optical network and allows the open and disaggregated optical control and ligth-path computation engine (L-PCE). We comment on how mathematical models can be integrated with machine-leaning models using telemetry data to enhance the DT core operation: the QoT estimation (QoT-E). We comment on the crucial role of common open models of network elements and on the need of scientific progress in the statistical modeling of QoT to enable minimum margin network operation.

II. Open and Disaggregated Optical Networking

The network development towards programmable systems needs the open *disaggregation* of the architectures into separate and possibly multi-vendor network elements (NEs) [5].

The fundamental optical NEs are fiber spans, optical amplifiers (OA)s, re-configurable optical add/drop multiplexers (ROADM)s and transceivers (TRX)s for the deployment of optical circuits. We consider partially-disaggregated optical

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networks as depicted in Fig. 1) where the open optical network controller (ONC) operates the optical transport within a multi-layer hierarchical controller and the amplified lines are operated as aggregated subsystems. The lines connecting ROADMs may be independent WDM optical line systems (OLS)s [6]–[8], possibly multi-vendor. These ROADMs are managed according to the disaggregated paradigm [9], [10]: each degree may be the ingress/egress of independent multi-vendor OLSs. Within the ONC, each OLS is operated by a separate optical line controller (OLC) that defines the amplifiers' working point – the PHY optical control plane. Each OLC interacts by open interfaces with the PHY-DT to provide the line description from HW YANG models and telemetry data, The PHY-DT gives back the QoT metrics to be used by the OLC to optimizing the HW for minimum OLS QoT impairment. Each OLC has *local* ROADM-to-ROADM vision and is traffic agnostic, so it must set the OLS working-point supposing the OLS full traffic load. Moreover, the OLC, thanks to the telemetry, must be able to autonomously re-compute and re-set the OLS control after hard (e.g., fiber-cut) or soft (e.g., OA degradation) failures. This operation is triggered by an *alert agent* – possibly machine-learning empowered – running within the ONC with full access to telemetry data and relying on the PHY-DT. It is worth to remark that the *alert agent*, besides performing surveillance on the network infrastructure (failure as well as malicious infrastructure intervention detection/prediction and localization) can also be exploited for environmental surveillance on mechanical stresses on the network geographical footprint (e.g., earthquake, anthropic activities, etc.)

The ONC has overarching control and evaluates and defines the light-paths, sets the switching matrices in ROADMs, and runs all control and safety operations [6], [7], [10]. The traffic is charged to the optical network by open white boxes hosting pluggable TRXs that are managed by the ONC by open interfaces [7], [8], [11], [12]. The ONC relies on the PHY-DT to compute the QoT on a given ligh-path (LP) – the light-path computation engine (L-PCE) – to compare to the TRX request and consequently set the maximum feasible rate on the available spectral slice. The L-PCE is exploited by the ONC both for new optical circuits deployment and for for quick and autonomous failure recovery.

To effectively and reliably operate, the PHY-DT needs full access to static overarching network data (e.g., topology, OA sites, fiber types and span lengths, etc.) as well as to telemetry data and HW YANG models by open interfaces to get the full set of needed input data and to follow network modifications in time due to HW aging, hard-failure recovery or HW updates.

III. TRANSMISSION MODELING

The optical data transport is a set of transparent WDM transparent circuits to be optimized and used over the network topology. So, the core of the PHY-DT is the abstraction as a single parameter defining the QoT of the digital channel of the physics of propagation over a LP. In general, it is a complex problem due to the nonlinear effects in the fiber, but the use of dual-polarization (DP) coherent optical technologies dramatically simplifies the modeling. Thanks to the TRX equalizer and because of the depolarized nature of data channels, each LP can be reliably approximated as an additive white and Gaussian noise (AWGN) channel. As shown in 2, the noise sources from LP propagation are the ASE noise from OAs, the nonlinear interference (NLI) from fiber propagation and the crosstalk (XT) from ROADMs. All these noise components are very well modeled as additive Gaussian disturbances on the equalized signal constellation. Therefore, as for all AWGN channels, a unique parameter – the signal-to-noise ratio (SNR) – identifies the QoT. In optical communications, the LP SNR is typically defined generalized SNR (GSNR) [13]–[15]:

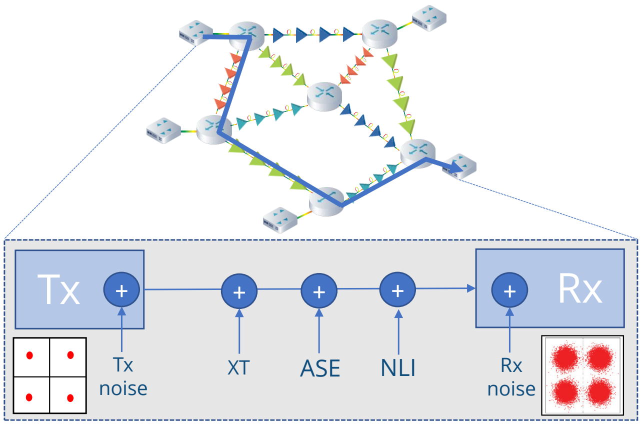

Fig. 2: Equivalent additive Gaussian noise sources from the transmission over a transparent light-path.

$$GSNR = \frac{P_{CUT}}{P_{ASE} + P_{NLI} + P_{XT}} \,, \tag{1}$$

where P_{CUT} is the power of the channel under test, P_{ASE}, P_{NLI} and P_{XT} are the accumulated ASE noise, NLI and XT in the noise bandwidth equal to the symbol rate R_s Besides the LP noise source also the TRX introduces Gaussian disturbances that must be properly considered in the TRX modeling. Besides the noise sources, significant effects impairing the QoT are the filtering penalty (FP) introduced by ROADMs, the polarization dependent loss (PDL) introduced by ROADMs and EDFA and the polarization mode dispersion (PMD) introduced by fiber spans. Moreover, the uncertainties on connectors' losses and amplifiers' gain ripples can be significant. These effects impact performance as $GSNR$ penalty, so the QoT has to refer to the effective $GSNR$ reducing the actual $GSNR$ by an overall light-path (LP) penalty LP_{pen}: $GSNR_{eff} = Pen_{LP} \cdot GSNR$ Because of the statistical nature of these effects, Pen_{LP} is a random process. So, a crucial target of research activities is an accurate statics model of penalties also exploiting data-driven machine learning techniques to enable reliable minimum margin network management. Besides the QoT, two additional metrics needed from the PHY-DT are the energy consumption and propagation latency in order to minimize the energy footprint

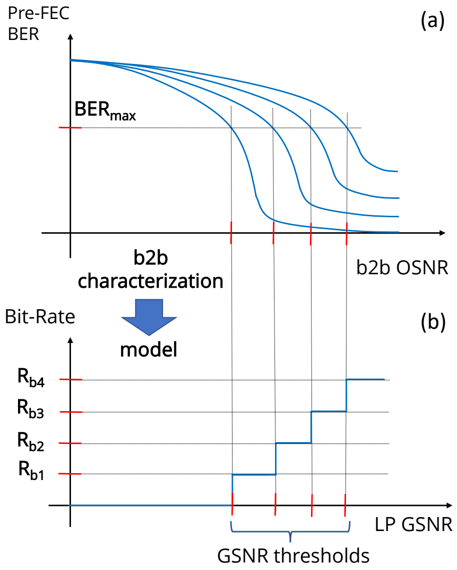

Fig. 3: Qualitative plot for the back-to-back (b2b) characterization of a flexible TRX (a) to obtain the light-path GSNR thresholds (b) for each available modulation format.

and to enable reduced latency traffic deployment as required by 5G networking.

It is worth to remark that modeling the PHY-DT as a data-driven machine-learning black-box is not a proper approach because accurate mathematical models of physics are available and it is unrealistic the availability of training datasets for all possible scenarios. Moreover, the network infrastructure is not static over its lifetime, because of many causes, starting from fiber cuts happening very frequently. While, data-driven models of some NEs (e.g., optical amplifiers) exploited in synergy with mathematical model of physics can be an excellent solution.

A. *Transceivers*

TRX for DP coherent technologies *load* data on the continuous wave by using I/Q modulators driven by DSP-shaped signals and are typically flexible, so enabling to setting different multilevel constellations with increasing data rate. The typical power spectral density is raised cosine shaped.

Considering the AWGN channel model for transparent LPs, coherent TRXs can be entirely characterized by back-to-back (b2b) setups emulating the channel impact by ASE noise loading. As an example, in Fig. 3 a qualitative plot for a four modulation formats (MF)s flexible TRX is presented. For each usable MF, in b2b setup, the pre-FEC BER can be measured versus the $OSNR$. Thus, a set of monotone decreasing curves as qualitatively shown in Fig. 3a are obtained. These curves initially follow the BER vs. OSNR given by the MF, then, for larger OSNR, the TRX noise components start to be significant inducing the typical *floor*. Note that the TRX noise is relevant, mostly for short reach scenarios [16].

Given the FEC threshold BER_{max}, a set of $GSNR$ thresholds requested for each available MF for the *in-service* operation is derived (see. 3b). According this approach to model flexible TRXs, the data needed from the network controller to compute the light-path feasibility are the symbol rate and roll-off giving the spectral occupation B_{ch}, the $GSNR$ thresholds and corresponding bit-rates. Moreover, the power consumption for each available TRX setting should be part of the model.

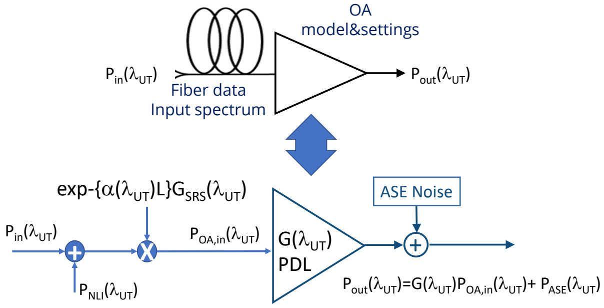

Fig. 4: Equivalent QoT model for the propagation over a fiber span followed by an optical amplifier recovering loss.

B. *Fiber propagation*

Since DSP-based receivers fully compensate for fiber propagation linear effects and apply the matched filter, different transmission mathematical models have been proposed and validated. All derivations rely on a perturbative approximation and aim at describing the nature of the residual impairments on the equalized signal [17] that is called nonlinear interference (NLI), well approximated as additive Gaussian noise [18]. These mathematical models for the NLI to be exploited in the PHY-DT need a *disaggregated* approach with the goal of the worst-case computation of the NLI separately introduced by each fiber span and modulation-format agnostic. The original disaggregated model is the well-known GN-model described in [19].

With the progressive expansion of the exploited transmission bandwidth beyond the conventional C-band [20], [21] the GN-model must be generalized by including the variation with frequency of loss [22], chromatic dispersion and effective area as well as the effect of inter-channel stimulated Raman scattering (ISRS) [23]. The generalized GN (GGN) model has been proposed [24], [25] also with a disaggregated approach [26] for faster computation. So, the impact of fiber propagation can be effectively modeled by computing the amount of NLI introduced by each fiber span using the GGN-model together with the modification of the loss $G_{SRS}(\lambda)$ induced by the ISRS, as pictorially shown in Fig.4.

C. *Optical Amplifiers*

The typical technology exploited for the amplification in the C and L bands is the Erbium-doped fiber amplification (EDFA). Technologies using other rare-earths elements are at prototype level to enable amplification beyond the C+L band for multi-band transmission.

The model of physical effects in OAs is complex and needs the complete knowledge of the internal device structure [27],

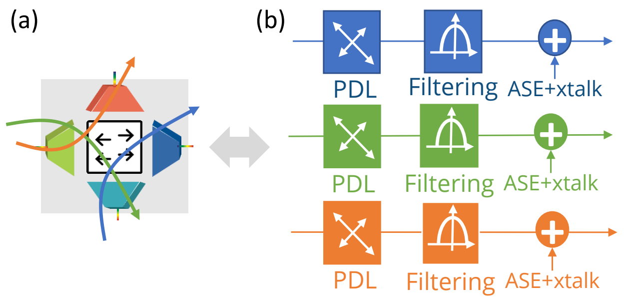

Fig. 5: Pictorial description of (a) a 4-degree disaggregated ROADM and of (b) the propagation effects on three paths.

but such details' level is not requested for transmission and networking analyses. As shown in Fig. 4, the propagation effect of OAs is conceptually simple: the gain and the amount of ASE noise degrading the $OSNR$. Thus, the ideal OA model, given the input power spectral density $P_{in}(\lambda)$ and the OA settings (gain or power mode, target gain/power and tilt) gives the gain $G(\lambda)$ and the quantity of added ASE noise $P_{ASE}(\lambda)$. The minimum and maximum wavelength within it operates is also needed. The amount of noise is consequently computed as [27]: $P_{ASE}((\lambda)) = F(\lambda)[G(\lambda) - 1]hfR_s$ where h is the Plank's constant and $f = c/\lambda$. In general, a complete model for OAs is not available, so for OAs, machine learning models can be extremely useful. These models can be provided by vendors together with the hardware as trained machine-learning agents [28] or can be trained on the installed amplified line [29]. A relevant parameter that should be included in the OA model is the introduced PDL, as OAs are source of PDL even is the most of PDL is introduced by ROADMs. Also the power consumption for different control setting should be exposed.

D. Re-configurable Optical Add/Drop Multiplexers

The networking task of re-configurable add/drop multiplexers (ROADMs) is adding/dropping optical circuits and transparent route the optical circuits: the *express* traffic. ROADMs can be described as schematically shown in Fig. 5, following a disaggregated approach. In accordance with the partially disaggregated networking paradigm, each ROADM degree can be the ingress/egress of a separate OLS. ROADMs may include a two EDFAs on each degree that are the booster- or pre-amplifier of the amplified optical line and can be modeled independently as described in Sec. III-C.

As depicted in Fig. 5(b), given the switching path, the main ROADM impairments are the filtering effect and the PDL, together with some Gaussian disturbances. These are some ASE noise from possible amplification devices in the switches, and crosstalk from side channels and residual dropped channels. The filtering effect is a GSNR penalty (FP) that accumulates over the transparent LP propagation including the contribution of each crossed filter on both signal and noise. Moreover, FP has a stochastic nature because of possible modifications of center frequencies of both TRX and filters. The cumulative FP metric introduced by ROADM is still not clear and is a needed outcome from research activities.

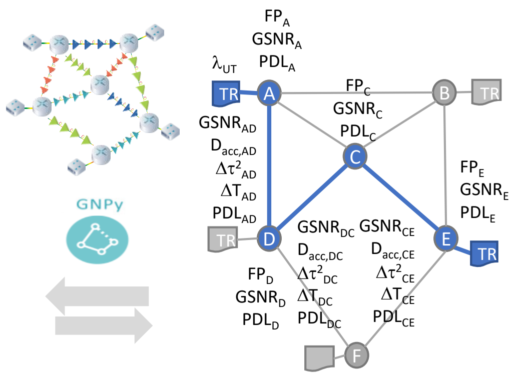

Fig. 6: Schematic description of the use of GNPy as PHY-DT.

Besides being the main source of FP, ROADMs are also the main source of PDL. Also the impact of PDL is a GSNR penalty, that has a stochastic nature given by different random origins [30], [31]. A complete ROADM model, giving the switching path and the TRX model, should provide the $GSNR$ degradation due to the XT and possible ASE noise and the I/O power spectral densities. Moreover, the model should expose the introduced PDL – possibly its statistics – and FP – possibly as transfer function.

E. Accumulated Dispersion, latency, PDL, PMD and FP

Besides the Gaussian disturbances, additional LP metrics must be available in the PHY-DT. These are the *deterministic* accumulated chromatic dispersion and latency induced by the fiber that are additive metrics introduced by each fiber span as $D_{all} = DL_{span}$ and $\Delta T = L_{span} \cdot c/n$ where c is the speed of light and n the glass refractive index. Fiber spans introduce also the polarization mode dispersion (PMD), whose statistical characteristics of its causing effect (the differential group delay, DGD) is well know as a Maxwellian distribution [32] whose variance is given by the sum of contributions of each crossed fiber span. $\Delta\tau^2 = \delta\tau^2 L_{span}$ ($\delta\tau$ is the fiber PMD parameter). So, each TRX can be characterized against the PMD and the possible penalty can be be statistically considered. The other two effects with a statistical nature accumulating over transparent LPs are the PDL and FP impairing the QoT as GSNR penalty. Regarding the PDL and FP statistical accumulation and their GSNR penalty on DP coherent technologies a definitive analyses is still missing in the scientific literature. The target is the definition of the $pen_{LP,dB}$ statistics, so to be able to set the margin μ_{dB} to be considered with respect to a maximum tolerable out-of-service probability according to the following rule: $P_{oos} = P(pen_{LP,dB} > \mu_{dB})$.

IV. USING GNPY AS OPEN PHY-DT

The WDM transmission model integrated in GNPy has been extensively validated in experimental results. In [13], GNPy was tested in the large MSFT lab network exploiting a large set of multi-vendor TRXsand in [15] the validation was extended to a full C-band mixed-fiber scenario using Raman amplification. In [33], GNPy has been validated in a production network, while in [34] multi-vendor flex-rate flex-grid validation results are presented, also for TRX exploiting shaped constellations. In [35], GNPy has been tested for Nyquist Subcarriers TRX with data rate up to 800 Gbit/s. Therefore, the GNPy modeling has been extensively validated to be reliably used as core of the PHY-DT

Fig. 6 shows the concept of digital twin of an optical network given by GNPy: a network topological graph where graph-nodes are ROADMs and graph-edges are OLS. On the graph, we can identify any route, as for instance the "ADCE" highlighted in Fig. 6 and evaluate the additive metrics at λ_{UT} over the specified route.

A. Vendor-neutral network design and planning

The primary request for the evolution of open and disaggregation networking deployment from prototype to production scenarios is for vendor-neutral design&planning tools. These tools aim at virtually test and compare multi-vendor solutions in the network design phase. The open PHY-DT is the core of such a tool to virtually test different multi-vendor and mixed vendor solutions. GNPy can be exploited as vendor-neutral optical networks design tool to virtually compare different physical layer design options [36]. A practical example has been the explotaion of GNPy in the West African backbone project [37].

Besides assisting the full network design, GNPy can be used to test possible hardware upgrades. For instance, operators may virtually verify the feasibility of novel TRX options (e.g., 400ZR) on the production network before moving-on with experimental validations.

B. Optical line control

The OLC targets the optimal working point of the OLS to minimize the QoT impairments, on each wavelength in the optical transmission spectrum, given the models of the available OAs. The OLC functions must be traffic agnostic and consider the optimization in the worst-case traffic scenario, i.e., the OLS at full WDM spectral load.

Thanks to the availability of the PHY-DT, the OLC can optimize the OAs setting to minimize the QoT impairments, i.e., maximize the GSNR over the OLS. In general, the OLS $GSNR$ depends on the frequency and on the OAs settings – the optimization space for the control algorithm – and on the needed OLS input/output power spectral density (PSD). Hence, the OLC goal is to maximize and flatten the average $GSNR$ in the transmission band. Therefore, the line optimization problem in the space of *OA settings* of each OA can be formalized as

$$\begin{cases} \max\limits_{OA\ settings} & \left\{\overline{GSNR_{OLS}}\right\} \\ \min\limits_{OA\ settings} & \left\{\left\langle \left(GSNR_{OLS}(f) - \overline{GSNR_{OLS}}\right)^2 \right\rangle\right\} \\ P_{OLS,in}(f) & = P_{ROADM,out}(f) \\ P_{OLS,out}(f) & = P_{ROADM,in}(f) \end{cases} , \tag{2}$$

where $\overline{GSNR} = \langle GSNR(f) \rangle$ and $\langle ... \rangle$ is the average vs. f.

The PHY-DT is required to provide to the line optimizer algorithm the $GSNR(f)$ at full WDM spectral load with different OA settings to be used for the optimization of Eq. 2. In [38], an experimental proof-of-concept is proposed: the OLC autonomously classifies fibers and evaluates connectors' losses from optical channel monitors, and defines the OAs working point by exploiting GNPy within a genetic algorithm optimizer.

C. Light-Path Computation Engine (L-PCE)

By exploiting the PHY-DT, the LP deployment can be entirely automatized. The ONC has a global network vision, controls TRXs and ROADMs and gets OLS models from the OLCs, and it is aware of the network loading status .

In LP deployment, first, the routing wavelength and spectral assignment (RWSA) identifies the available LP and bandwidth over a topological route. Once the RSWA has selected the LP, the L-PCE is performed relying on the PHY-DT, relying on NEs' models and the knoweldge of the OLS control strategy. The resulting $GSNR_{eff}$ is compared to the TRX GSNR threshold including the margin and the maximum feasible rate is deployed. Recently, experimental proof of concepts on the use of GNPy as L-PCE have been presented in [12], [39]–[42].

On the L-PCE also the role of uncertainties as connector and splice losses must be considered contribute to the statistics of $pen_{LP,dB}$ together with the effects of the PDL and FP. Besides the LP QoT, fundamental metrics to be considered in the L-PCE are the overall power consumption and latency.

V. CONCLUSION

We presented the concept of DT applied to the optical network and comment on how each NE can be effectively modeled within the PHY-DT to allow vendor neutral planning and the full implementation of the SDN paradigm decoupling the infrastructure control from traffic deployment.

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