OCATA Optical Time-Domain Digital Twin: Continuous Model Tuning with Signal-Domain Fidelity Assessment

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ABSTRACT
This paper focuses on the continuous tuning of OCATA Optical Time-Domain Digital Twin models for multiband transmission using telemetry data collected from the optical transceivers. Models' performance is evaluated before and after tuning using pre-FEC BER prediction error. In addition, signal-domain fidelity is assessed by comparing measured and modelled statistical distributions using divergence measures across constellation points. In addition, signal-domain fidelity is assessed by comparing measured and modelled statistical distributions using Kullback–Leibler (KL) divergence measures across constellation points. Results show that tuning the pre-trained OCATA models based on the collected telemetry samples, reduces KL divergence across all S, C, and L bands and all constellation point and follows the actual behaviour of lighpaths.

Keywords: Optical digital twin, Multiband Optical transmission, model tuning.

1. INTRODUCTION

Multiband (MB) optical transmission has emerged as a leading solution to extend the capacity of deployed fiber infrastructure by exploiting the S, C, and L bands simultaneously. However, the inter-channel stimulated Raman scattering (ISRS) which causes optical power transmission across the wide MB spectrum, beside a channel-dependent nonlinear impairment (NLI) profile, due the fiber-nonlinearity, complicates quality of transmission (QoT) estimation [1], [2]. To address the need for fast and accurate physical-layer awareness, OCATA was proposed as a time-domain optical digital twin (DT) built on deep neural networks (DNNs) that propagate in-phase (I) and quadrature (Q) optical constellation features through individual fiber spans [3], enabling fast pre-FEC BER estimation, NLI mitigation, and failure management [4]. The OCATA-MB which is introduced in [3], extends the OCATA DT to MB C+L+S scenario. Since the impact of nonlinearities is highly channel dependent in C+L+S systems, directly modelling every channel would require an excessively large number of models. To overcome this issue, OCATA-MB considers a reduced set of reference channels (RChs) across different bands, while the features of arbitrary target channels are obtained through feature composition from adjacent references. OCATA-MB enables lightpath provisioning and receiver-side nonlinear mitigation, and showed that accurate channel-aware QoT estimation can be achieved with manageable model complexity in multiband optical networks [5]

Pre-trained span models inevitably introduce mismatch with the operational network due to span-length differences, channel allocation between RChs, and device aging [6]. While modest at provisioning time, this mismatch degrades model fidelity for operational tasks such as degradation detection, motivating periodic tuning with collected telemetry data. The importance of model tuning has been recently confirmed experimentally where the authors in [7] proposed a complete lightpath operation workflow and validated on a distributed testbed connecting HHI, UPC, and CTTC, where OCATA was used for provisioning-time QoT estimation and subsequently tuned using telemetry collected after lightpath setup. Results showed that the tuned model enables significantly earlier degradation detection compared to the original concatenated model, directly reducing operational costs.

The authors in [4] showed that failure management procedure is highly dependent not only on the QoT of the lightpath, but also on the fitted bivariate Gaussian distribution around each constellation point. Considering this matter and to complement our previous work in [6], in this paper we are assessing model tuning performance and its quality at the level of individual constellation-point distributions using the KL divergence between model-predicted and telemetry-fitted bivariate Gaussian distributions. We use per-CP KL analysis to show in higher precision the effectiveness model tuning procedure across the S, C, and L bands under multiple span configurations, where the simulation results show that even a small amount of telemetry improves model fidelity.

2. SYSTEM MODEL AND OCATA-MB CONTINUOUS TUNING FRAMEWORK

Fig. 1(a) presents the architecture for MB optical network operation. A Software-Defined Networking (SDN) controller is responsible for lightpath provisioning and telemetry data collection [7], and runs beside the OCATA Digital Twin, which serves as the intelligent assistance layer. The OCATA DT internally comprises a Telemetry/Model database storing pre-trained span DNN models and collected telemetry, a Sandbox Domain where model tuning is executed to tune the lightpath model based on the algorithms presented in [6], and is responsible for checking, tuning, and storing lightpath models.

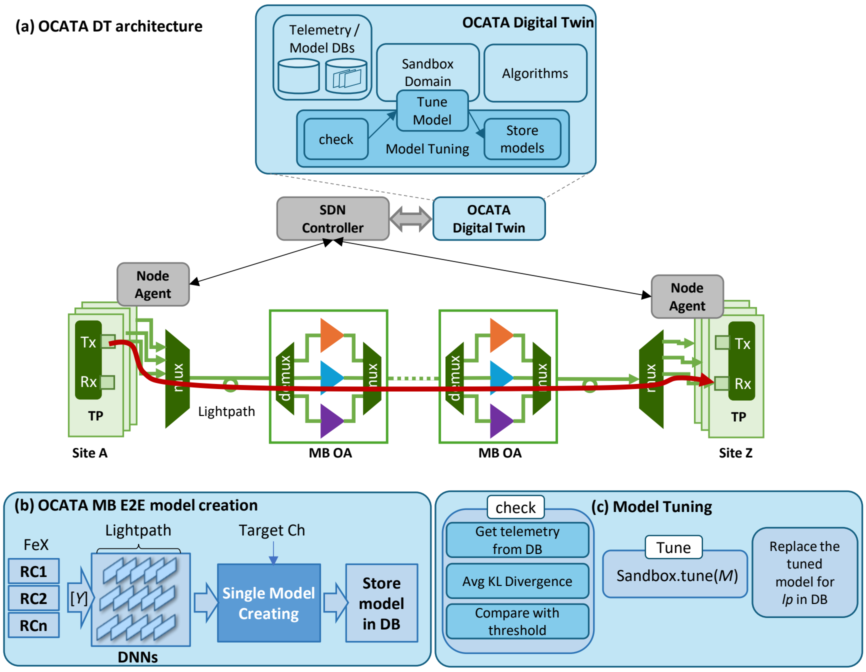

Fig. 1 (a) OCATA DT architecture, (b) OCATA MB E2E model creation, (c) Model tuning procedure.

Fig. 1 (b) details the OCATA-MB end-to-end (E2E) model creation procedure, which takes place when a lightpath is provisioned. Since the ISRS effect causes the noise profile experienced by each channel to differ significantly across the S, C, and L bands, it is impractical to pre-train DNN span models exhaustively for all 337 channels in the C+L+S system. Instead, a small set of reference channels (RCh1, RCh2, …, RCh*n*) is selected to represent the spectral diversity of the three bands [5]. OCATA MB then creates one single model from span models of RCh closest to the selected target channel and stores the model DB.

Rather than operating on raw symbols, OCATA condenses the received constellation into a compact set of features Y through a features extraction (FeX) module based on Gaussian mixture model (GMM) fitting [3]. Consequently, the vector $Y^i=[\mu^I,\mu^Q,\sigma^I,\sigma^Q,\sigma^{IQ}]$ represents the distribution of symbols around each CP i for I and Q position mean (μ), variance and symmetric covariance terms (σ).

Fig. 1(c) represents the tuning procedure where it first checks whether the model tuning is required. It receives set of telemetry from the telemetry DB and compute features for the collected data, generate the bivariate Gaussian distribution, $P_i^{(T)}=\mathcal{N}(\mu_i^{(T)}, \Sigma_i^{(T)})$, and at the same time, generates the expected features using the store model lightpath, $P_i^{(M)}=\mathcal{N}(\mu_i^{(M)}, \Sigma_i^{(M)})$. After generating the related distributions, to quantify the discrepancy between telemetry and model for each CP i, we apply the forward Kullback-Leibler (KL) divergence as:

$$D_{KL}\left(P_i^{(T)} \parallel P_i^{(M)}\right) = \frac{1}{2}\left[tr\left(\left(\Sigma_i^{(m)}\right)^{-1}\Sigma_i^{(t)}\right) + \left(\mu_i^{(m)} - \mu_i^{(t)}\right)^T\left(\Sigma_i^{(m)}\right)^{-1}\left(\mu_i^{(m)} - \mu_i^{(t)}\right) - 2 + \ln\left(\frac{\det \Sigma_i^{(m)}}{\det \Sigma_i^{(t)}}\right)\right], \tag{1}$$

where the three terms measure: (*i*) variance/covariance shape mismatch via the trace term, (*ii*) mean position mismatch via the Mahalanobis distance, and (*iii*) overall noise volume ratio via the log-determinant. KL(.||.) divergence is asymmetric by design, placing telemetry in the first argument penalizes the operationally critical case where the model has mismatch to the performance of actual signal. The average KL across all CPs gives an overall fidelity score:

$$KL_{avg} = \frac{1}{m}\sum_{i} D_{KL}\left(P_i^{(t)} \parallel P_i^{(m)}\right), \tag{2}$$

where m is the order of modulation format.

3. SYSTEM MODEL AND OCATA-MB CONTINUOUS TUNING FRAMEWORK

The OCATA-MB dataset was generated with the MATLAB-based multiband optical simulator of [7], which solves the nonlinear Schrödinger equation using an adaptive-step Runge-Kutta method. We consider 16-QAM signals at 32 GBaud, shaped with a root-raised-cosine filter with 0.06 roll-off, launched at 0 dBm on a 50 GHz grid spanning 337 channels over the S, C, and L bands. Gain-flattening filters compensate ISRS-induced power tilt, and ideal chromatic-dispersion compensation and phase recovery are applied at the receiver before collecting IQ constellations. Span models are pre-trained for 80 km spans on seven reference channels selected across the three bands [5], while evaluation is performed on 50 km-span lightpaths using three non-reference channels, namely ch 75, ch 170, and ch 245, under 3-, 6-, and 9-span configurations. This 80 km/50 km mismatch is the main source of model-reality discrepancy analyzed in this work. Tuning uses telemetry samples with $K \in \{5, 50, 100, 200, 500, 1000\}$, from which per-CP features are extracted through GMM fitting. KL divergence is then computed between the telemetry-fitted distribution and the model-predicted distribution before and after tuning.

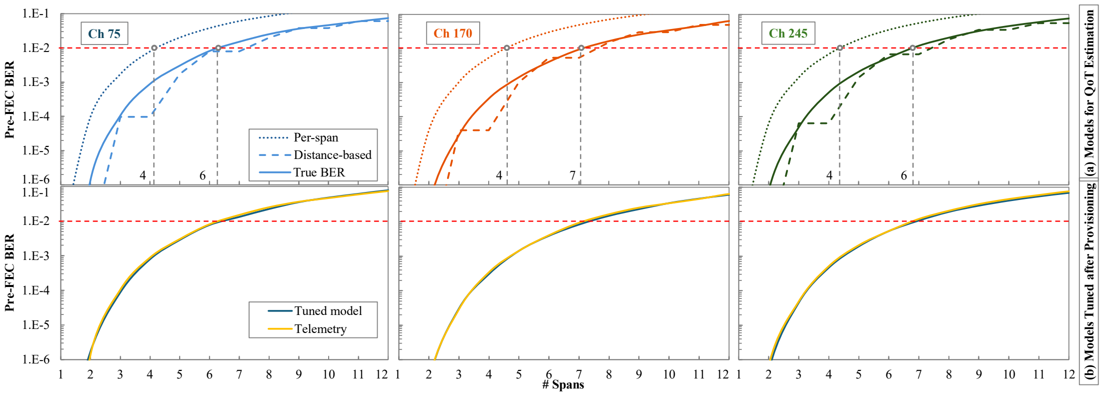

Fig. 2 Pre-FEC BER vs # of spans (50 km) before (a) and after tuning (b); adapted from our previous work [6].

Fig. 2 is reproduced from our previous paper [6] and is included here to recall the impact of model tuning on pre-FEC BER estimation. The figure shows that, before tuning, both model composition methods estimate deviate from the True BER, with the per-span method being more conservative than the distance-based one. After tuning, the estimated BER closely matches telemetry for all three channels, highlighting the effectiveness of model adaptation.

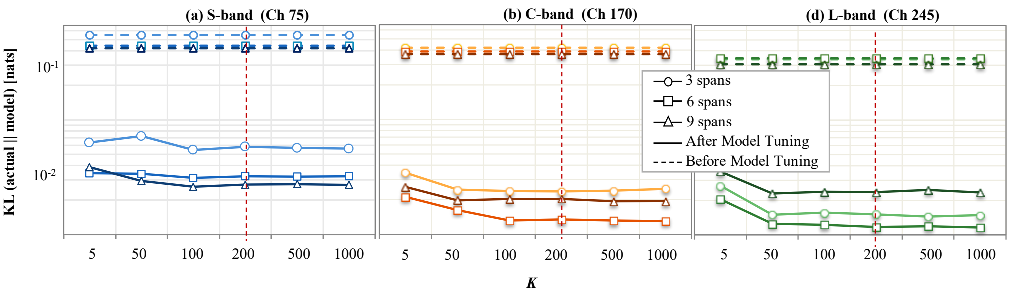

Fig. 3 Average of KL divergence over CPs before and after model tuning for channel in (a) S-, (b) C-, and (c) L-band.

Fig. 3 shows the average KL divergence KL_{avg} (Eq. (2)) as a function of the number of collected telemetry repetitions K, for each band and span configuration. Horizontal dashed lines indicate the pre-tuning KL baseline (before any telemetry is used). As can be concluded from the results, K=200 is enough to have accurate tuning for the model. The main mismatch between initial model (i.e., model before tuning) and the actual performance of lightpath in this scenario, is span length mismatch. The length mismatch affects the NLI noise as $L_{eff}=(1/\alpha)(1-e^{-\alpha L})$, and affects the amplified spontaneous emission (ASE) noise as $e^{\alpha L}$ (which is translated into optical amplifier gain), where α is the fiber attenuation and L is fiber length; thus we can conclude that in a scenario which higher portion of total noise is ASE compare to NLI, we have higher KL divergence between model and actual performance of lightpath. This conclusion can be understood from the results in Fig. 3 where the KL divergence before tuning model is higher for the channel in S-band than C-band and than L-band. It should be noted that NLI noise power is lower for S-band compare to C-, and L-band due to the ISRS effect. The same discussion is applied to compare scenarios with 3, 6, and 9 spans where the NLI is increasing by number of spans

Fig. 4 (a) shows the heatmap for per-CP KL divergence of the 16-QAM constellation points, for 9 spans and K=200, comparing the pre-tuning and actual performance of lightpath using collected telemetry samples for all three bands.

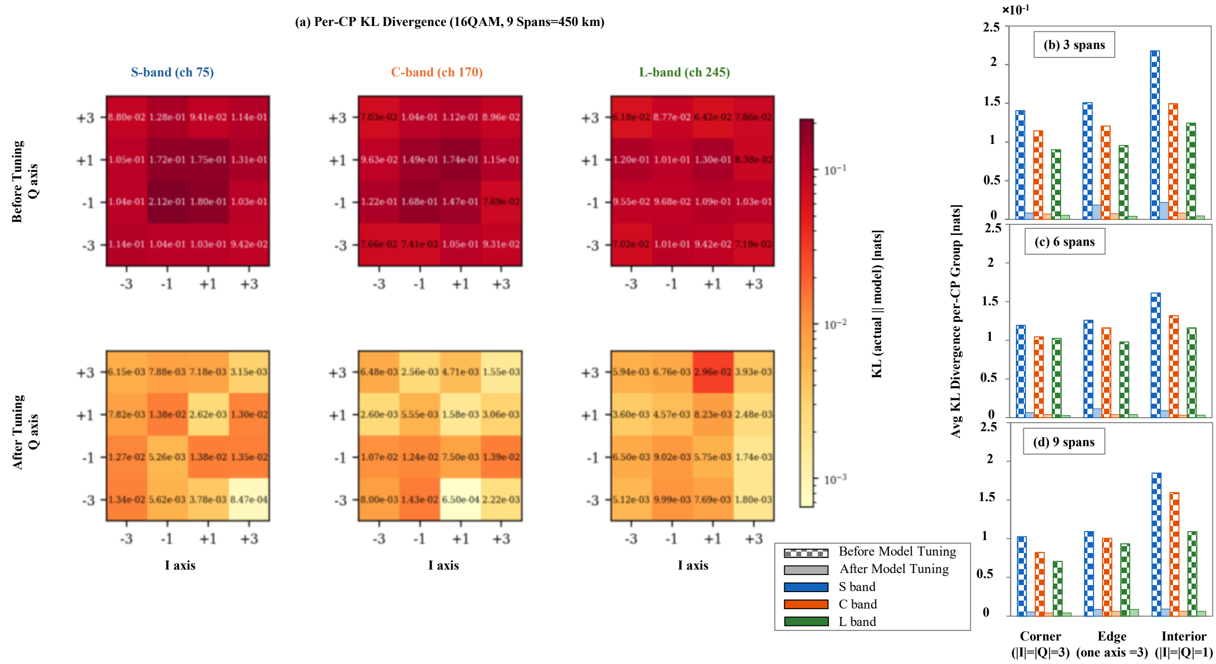

Fig. 4 Per-CP KL divergence for 9 spans lightpath configuration (a), average KL divergence for interior, corner and edge CPs for 3 spans(b), 6 spans(c), 9 spans, (d) lightpath configuration.

From this heatmap it also can be concluded that the KL divergence for each constellation point in different considered configuration is reduced after tuning the lightpath model. Furthermore, it can be pointed that interior (|I| = |Q| = 1) exhibit we have higher KL divergence than corner CPs (|I| = |Q| = 3) before tuning the lightpath model. This is also shown in Fig. 4 (b)-(d) that the average of KL divergence for interior CPs is higher than corner and edge (one axis =3) CPs in different scenarios across C, L, S-bands.

Conclusion

This paper showed that telemetry-assisted continuous lightpath model tuning effectively improves OCATA-MB model accuracy in multiband optical transmission by reducing the mismatch between pre-trained models that used for lightpath provisioning and actual lightpath behaviour. The results confirmed consistent reduction of pre-FEC BER error and KL divergence across the S, C, and L bands after tuning. In addition, about K=200 telemetry repetitions were sufficient to achieve accurate tuning in all the assessed scenarios.

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