DSP-aided Telemetry in Monitoring Linear and Nonlinear Optical Transmission Impairments

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Abstract: DSP-aided telemetry within coherent receivers provide unprecedented capabilities to monitor linear and nonlinear optical transmission impairments. The recent progress of it is reviewed and discussed in the context of advanced network applications. © 2020 The Author(s)
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1. Introduction

To satisfy the ever-increasing network capacity demand, optical transmission and networking technologies have been rapidly evolving in the past decade. In particular, with the advance of digital signal processing (DSP) based coherent transceiver, the capacity of commercialized systems has approached the theoretical limit of a classical fiber channel [1]. This provides a strong incentive to build a more intelligent optical network for further reduction of cost per bit by more efficiently utilizing network resources. Meanwhile, the architecture of optical networks is being transformed to be flexible and programmable using elastic optical network (EON) [2] and software-defined network (SDN) technologies [3]. And machine learning (ML) techniques are being widely investigated to realize autonomous network control and management [4]. Real-time monitoring and collection of link status is a key building block to form a closed-loop network operation with zero-touching, self-learning and self-healing capabilities. Coherent receivers provide a new resourceful platform to measure link performance and status as the embedded digital signal processing (DSP) blocks are designed to address almost all link impairments. Further, ML algorithms can also be employed to enable or improve DSP-aid telemetry functionalities.

In this paper, we first discuss various advanced optical networking applications and the required monitoring functionalities for each, in order to reveal the necessity and requirement of the DSP-based telemetry. Then, we review the recent progress of the DSP-aided telemetry for monitoring major link impairments including amplified spontaneous emission (ASE) noise, fiber nonlinearities, linear impairments and soft failures.

2. Required Telemetry Functionalities for Advanced Optical Networking Applications

The architecture of a close-loop intelligent optical network enabled by EON, SDN and ML technologies is depicted in Fig. 1. The centralized SDN controller enables to perform global control and management of network elements in an intelligent and autonomous manner with the availability of massive data collected from the physical layer. Moreover, local analytics can also be included to balance network response latency and efficiency. Below we discuss the major network applications and the corresponding DSP-aided telemetry functionalities.

QoT estimation: The design of low margin optical networks is being actively investigated to further squeeze capacity from the current network infrastructure [5]. An accurate Quality of Transmission (QoT) estimation tool is required to minimize the *design margin* as defined in [5], which is caused by the deviation in the estimated lightpath performance. Conventionally, networks are overprovisioned to tolerate the worst case until the EoL. As networks become more intelligently adaptive, the QoT of established lightpaths might be re-evaluated in shorter periods for data rate and bandwidth reconfigurations. In both cases, performance monitoring based on coherent receivers can be adopted to facilitate building a more accurate QoT model. Specifically, the measurement in the established or probe channels can be used to calibrate both the QoT model and its inputs of the channel itself or other correlated channels [6]. BER and SNR, which represent the overall link performance, are the most useful metrics to be monitored for this purpose. Fortunately, their measurements are already feasible in most commercial coherent receivers and the accuracy is sufficiently high. Optical signal-to-noise ratio (OSNR) monitoring is also a useful feature in this application as OSNR margin is an important metric in many systems.

Physical layer optimization: Signals transmitting over a fiber channel go through complex and diverse physical effects. The proper provisioning of fiber link parameters is of paramount importance to maximize network capacity. For practical network deployments, provisioning optical launch power is one of the most challenging tasks [7]. This is because the fiber nonlinearities involve strongly-coupled interactions of a large number of WDM channels co-propagating over a single fiber. In principle, the optical power of each channel in each span should be jointly

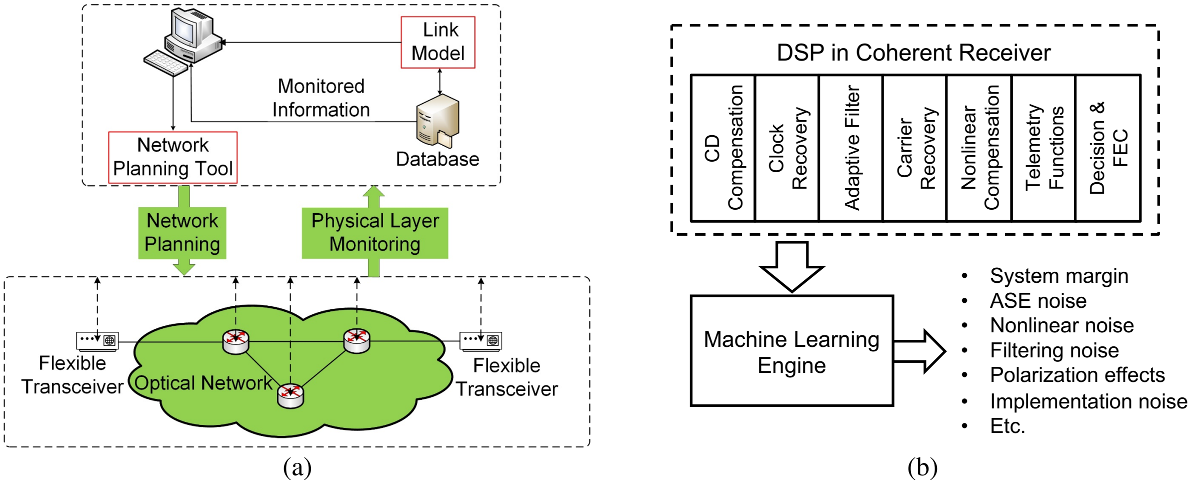

Fig. 1. (a) Architecture of intelligent optical networks. (b) DSP and ML-aided telemetry.

optimized, leading to an extremely complex problem especially for meshed elastic optical networks. The monitoring of fiber nonlinearities and ASE noise in coherent receivers is anticipated to play an important role in this optimization procedure. Further, intra-channel nonlinearity and inter-channel nonlinearity should be separately monitored to aid per-channel optimization.

Resource allocation: For EONs with mixed channel bandwidths and data rates, impairment-aware routing, modulation level, and spectrum assignment (RMSA) has become an active research topic [8, 9]. Accurate QoT estimation and monitoring are primarily needed to allocate basic resources for each lightpath. In addition, individual impairments including ASE noise, intra-/inter-channel fiber nonlinearities, optical filtering effects, in-band/inter-band crosstalk should be estimated and monitored to enable global and local optimization of resource allocations.

Failure prediction, detection and localization: To improve network reliability and robustness, proper tackle of link failures is essential. Link failure can be categorized into hard failure and soft failure [10]. The hard failure is caused by unexpected interrupting events such as fiber cut. The soft failure is caused by the deterioration of various impairments in the link including ASE noise, fiber nonlinearity, optical filtering, transceiver implementation noise, channel crosstalk, and so forth. The coherent DSP provides unprecedented capabilities to predict, detect, classify and localize the soft failure [11]. Different from the abovementioned network applications, where monitoring an exact impairment value such as OSNR and nonlinear signal-to-noise ratio (SNR) is required, the receiver telemetry for failure-related applications is designed to mainly provide alarms of link changes and monitor the anomalies of specific link impairments.

3. Progress of DSP-aided Telemetry Development

Fig. 1(b) depicts the architecture of the DSP-aided telemetry within a coherent receiver. ML has become a powerful tool to translate the data of the DSP blocks to the information of various impairments. However, extracting relevant features from DSP blocks requires deep domain knowledge, and thus is a critical step for the development. Below we review the recent progress of the DSP-aided telemetry for monitoring major link impairments.

OSNR: OSNR monitoring is one of the most explored telemetry functionalities. In current wavelength-division multiplexing (WDM) systems, the spectrum has been fully occupied, leaving no spectral gap for the direct measurement of ASE noise variance. One possible solution to realize non-intrusive OSNR measurement to use classic optical spectrum analyzers (OSA) with advanced algorithms [12]. However, it is more desirable to use coherent receivers for low cost implementation. Various OSNR monitoring schemes have been proposed based on received signals and ML [13, 14]. However, many of them ignored the interference of fiber nonlinear noise, resulting a decreasing accuracy as optical launch power increases. To address this issue, a calibration of nonlinear noise can be included in the OSNR monitoring scheme as proposed in [15].

Nonlinear noise: The monitoring of nonlinear noise has received increasing attentions more recently due to the emergence of the advanced network applications. In addition, the obtained nonlinear noise variance can be used to refine OSNR monitoring as mentioned earlier. The fiber nonlinear effects cause correlated noise due to the interaction of chromatic dispersion (CD) and the Kerr effect. However, the properties of nonlinear noise might vary significantly over different link and channel configurations, making it particularly difficult to directly measure it.

Therefore, ANN has been employed to translate the noise correlations calculated in the receiver DSP to the target nonlinear SNR [16, 17]. The training can be conducted offline by simulation thanks to the accurate modeling of the split-step Fourier method. Decent accuracy has been demonstrated in both simulations and experiments [18]. Further, the combination of nonlinear modeling and nonlinear monitoring has been proposed based on ML to achieve a higher accuracy [19].

Linear effects: Coherent systems are particularly efficient in addressing linear channel impairments such as CD, PDM/PDL/SOP, optical/electrical filtering, and so forth. Digital equalizers that are generally designed to learn optimal coefficients provide useful features to monitor the linear effects. The residual CD and polarization effects can be derived from the 2-by-2 coefficient matrix as shown in [20]. The optical filtering effect will become a severer impairment in next generation systems where the gap between adjacent channels are further reduced for higher spectral efficiency. However, few researches have been reported on the monitoring of filtering impairments.

Soft failures: Any impairment-related features used in monitoring the linear and nonlinear impairments can be reused to monitor soft failures. ML techniques have been proposed to explore these features to predict, detect, classify and localize the failure causes. For example, [11] proposed to use the signal PSD obtained from the receiver DSP together with a convolutional neural network to identify the cause of soft failures including ASE noise, nonlinearity of the fiber, optical filter shift FS and filter tightening FT.

4. Conclusion

Advanced optical network applications unprecedentedly rely on real-time monitoring of various link impairments and overall transmission performance. In this context, we review and discuss the recent progress of DSP-aided telemetry designed to provide strong and diverse monitoring capabilities at low cost with the help of ML techniques.

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