Network Nervous System: When Multilayer Telemetry Meets AI-assisted Service Provisioning

(*Invited Paper*)

Jiawei Kong, Bin Niu, Shaofei Tang, Yingcong Li, Hongqiang Fang, Wei Lu, Zuqing Zhu
University of Science and Technology of China, Hefei, Anhui 230027, China, Email: zqzhu@ieee.org

***Abstract*—We present a network nervous system (NNS) that leverages hybrid centralized/distributed processing to achieve automatic and effective network control and management (NC&M) for realizing artificial intelligence (AI) assisted service provisioning in IP over elastic optical networks (IPoEONs).**

***Index Terms*—Artificial intelligence (AI), Multilayer in-band network telemetry (ML-INT), Elastic optical networks (EONs), Performance monitoring and troubleshooting.**

I. Introduction

Recently, to adapt to the fast development of emerging network services (*e.g.*, data analytics, network function virtualization (NFV), and 5G-based network slicing) [1–6], the infrastructure of optical backbone networks are undergoing dramatic changes [7]. Therefore, research efforts have been focused on developing flexible network architectures that support dynamic lightpath establishment in the optical layer with high spectral efficiency, for delivering highly dynamic and bursty IP traffic. Consequently, flexible-grid elastic optical networks (EONs) have attracted intensive research interests [8–13], and composing IP-over-EONs (IPoEONs) becomes appealing as they can seamlessly integrate the advantages of IP and EON technologies [14–17]. Meanwhile, the enhanced flexibility provided by IPoEONs would make it more challenging to design an effective and automatic network control and management (NC&M) scheme. More importantly, the various network services running in an IPoEON would require the NC&M scheme to make intelligent and timely decisions such that IP flows belonging to different services can be groomed and routed over the underlying lightpaths cost-effectively, to ensure not only high bandwidth utilization but also high quality-of-service (QoS) [18]. However, how to realize such an NC&M scheme is still an open question and both the academia and industry are working on it.

The centralized NC&M provided by software-defined networking (SDN) [19, 20] can greatly improve the programmability and flexibility of IPoEONs [21]. Nevertheless, how to efficiently manage the IP and EON layers in an software-defined IPoEON (SD-IPoEON) and respond proactively to network status changes for guaranteeing stringent QoS requirements from network services, still needs further exploration. In this paper, we explain our design of a network nervous system (NNS) that can not only perform fine-grained performance monitoring and troubleshooting to visualize an IPoEON in realtime but also leverage the monitoring results to address network status changes and specific needs of network services proactively. Specifically, the NNS is mainly based on two innovations: 1) a flexible multilayer in-band network telemetry (ML-INT) scheme to monitor an IPoEON in realtime, and 2) an AI-assisted NC&M framework that utilizes hybrid centralized/distributed processing to analyze the telemetry data for achieving application-aware service provisioning.

The rest of the paper is organized as follows. Section II explains the operation principle of the ML-INT scheme. The design of the AI-assisted NC&M framework is described in Section III. Finally, Section IV summarizes the paper.

II. Multilayer In-Band Network Telemetry

Our ML-INT scheme [22] utilizes the idea of in-band network telemetry (INT) [23], and is developed based on the programmable data-plane (PDP) that uses programming protocol-independent packet processor (P4) [24]. To facilitate distributed, programmable, realtime and end-to-end flow monitoring and troubleshooting in an SD-IPoEON, the ML-INT scheme is designed to have the system architecture shown in Fig. 1(a). Here, the IP layer consists of P4-based PDP switches and application hosts. The PDP switches have been implemented the packet processing pipelines in Fig. 1(b) to realize ML-INT on the IP flows that are routed through them. More specifically, the ML-INT works as follows.

If an IP flow is selected for being monitored, the ingress and subsequent PDP switches on its routing path will select a portion of its packets to insert the collected telemetry data as INT fields [22]. Note that, an INT field stores a performance metric of a network element (NE) (*i.e.*, either an electrical one in the IP layer or an optical one in the EON layer) on the flow's routing path. For instance, an INT field can contain the packet processing latency in a PDP switch or the input power-level of a lightpath. We design the ML-INT scheme such that after aggregating all the INT fields encoded in the flow's packets, a complete and realtime view of all the concerned NEs on its routing path can be got. At the egress PDP switch, all the INT fields are removed from the packets and sent to the data analyzer for data aggregation, analysis and storage.

Although the INT fields are encoded by the PDP switches in the IP layer, the ML-INT scheme covers the monitoring on the NEs in the EON layer too. This is because the PDP switches are interconnected by the lightpaths established in the EON layer, and their optical ports can be utilized

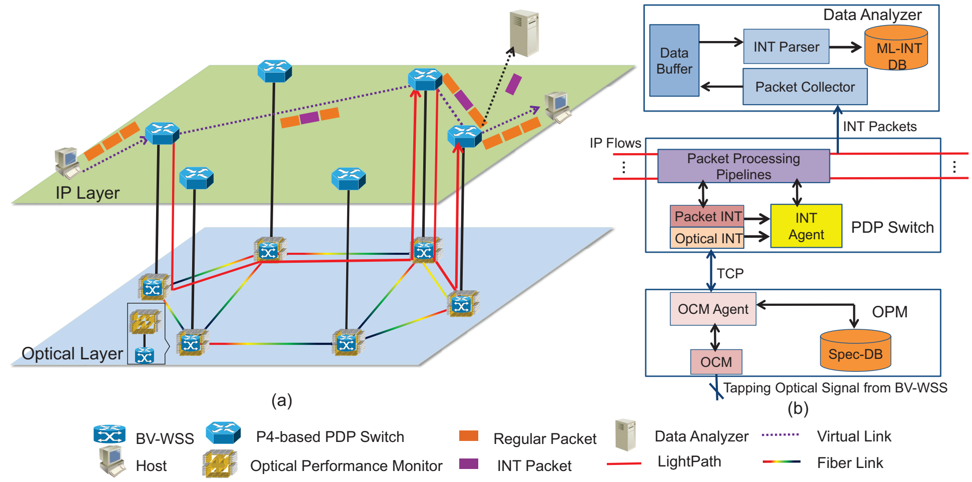

Fig. 1. System architecture of our flexible ML-INT system, ML-INT DB: multilayer INT database, Spec-DB: optical spectrum database (adapted from [22]).

to achieve optical monitoring and troubleshooting [25, 26]. Specifically, we insert an optical performance monitor (OPM) on each bandwidth-variable wavelength selective switch (BV-WSS) to collect performance metrics regarding the lightpaths switched by it. Here, the OPM collects optical spectra from the optical ports on the BV-WSS and analyzes them to get the lightpaths' performance metrics such as optical signal-to-noise ratio (OSNR), central wavelength, and input power-level. The PDP switch directly connected to the BV-WSS can poll the OPM on it in realtime and specify one or more lightpaths for performance monitoring. Fig. 1(b) explains the interactions among the data analyzer, PDP switch, and OPM.

III. AI-Assisted Service Provisioning

Our AI-assisted NC&M framework is designed to avoid flooding the control plane with huge volumes of telemetry data and give each application the freedom to define its unique way of flagging exceptions and the network reconfigurations upon hard/soft failures [18]. Specifically, in the framework, the network services (*i.e.*, applications) utilize the ML-INT scheme to realize distributed but fine-grained monitoring and only flag alarms to the centralized controller when they find the exceptions according to their specific QoS requirements, while the controller leverages an AI module to analyze the alarms together with its own coarse lightpath-level monitoring results for reaching timely and wise NC&M decisions.

Fig. 2 illustrates the detailed architecture of the AI-assisted NC&M framework [18]. Here, the performance monitoring and troubleshooting are performed with hybrid centralized/distributed processing. As an SD-IPoEON can carry numerous applications and each application has its own concerned end-to-end performance metric(s) and QoS demand(s) [27, 28], we allocate an application-level monitor to each application and enable it to utilize the ML-INT scheme to collect and analyze its concerned metrics for performance monitoring and troubleshooting. Each application-level monitor can specify the exceptions based on the QoS requirements of the application, flag alarms to the controller in an distributed way, and even provide suggestions on how to resolve the found hard/soft failures based on its preliminary analysis. In the mean time, the controller also perform coarse lightpath-level monitoring to collect the performance metrics such as packet loss rate, OSNR, *etc*, regarding each lightpath. Next, it combines the results of lightpath-level monitoring with the alarms and suggestions from the application-level monitors, and inputs them to the AI-assisted network control module in it. We have trained the AI module to learn the correlation among the applications' service provisioning schemes, the application/lightpath-level monitoring results, and hard/soft failure scenarios [29, 30], and thus it can determine the suitable network reconfiguration schemes to address the exceptions quickly. The traffic engineering database (TED) in the controller stores the service provisioning schemes of the applications' flows. Then, the controller implements the reconfigurations to restore the services of the affected applications.

IV. Conclusion

We explained our design of the network nervous system (NNS) that leverages hybrid centralized/distributed processing to achieve automatic and effective NC&M for realizing AI-assisted service provisioning in IPoEONs. The NNS was mainly based on two innovations: 1) a flexible ML-INT scheme to monitor an IPoEON in realtime, and 2) an AI-assisted NC&M framework that utilizes hybrid centralized/distributed processing to analyze the telemetry data for achieving application-aware service provisioning.

Acknowledgments

This work was supported by the NSFC projects 61871357 and 61701472, and CAS key project (QYZDY-SSW-JSC003).

References

[1] P. Lu *et al.*, "Highly-efficient data migration and backup for Big Data applications in elastic optical inter-datacenter networks," *IEEE Netw.*, vol. 29, pp. 36–42, Sept./Oct. 2015.

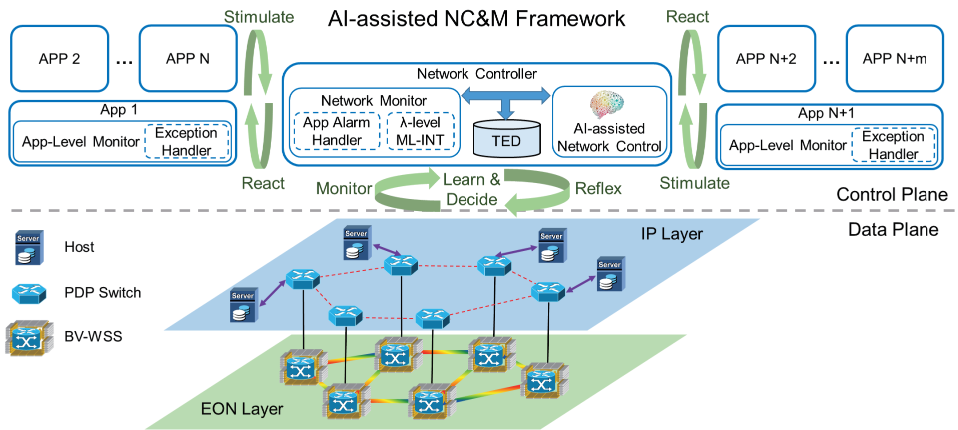

Fig. 2. Our AI-assisted NC&M framework, APP: application, TED: traffic engineering database (adapted from [18]).

[2] L. Gong and Z. Zhu, "Virtual optical network embedding (VONE) over elastic optical networks," *J. Lightw. Technol.*, vol. 32, pp. 450–460, Feb. 2014.

[3] J. Yao, P. Lu, L. Gong, and Z. Zhu, "On fast and coordinated data backup in geo-distributed optical inter-datacenter networks," *J. Lightw. Technol.*, vol. 33, pp. 3005–3015, Jul. 2015.

[4] L. Gong, Y. Wen, Z. Zhu, and T. Lee, "Toward profit-seeking virtual network embedding algorithm via global resource capacity," in *Proc. of INFOCOM 2014*, pp. 1–9, Apr. 2014.

[5] M. Zeng, W. Fang, and Z. Zhu, "Orchestrating tree-type VNF forwarding graphs in inter-DC elastic optical networks," *J. Lightw. Technol.*, vol. 34, pp. 3330–3341, Jul. 2016.

[6] Z. Zhu *et al.*, "Build to tenants' requirements: On-demand application-driven vSD-EON slicing," *J. Opt. Commun. Netw.*, vol. 10, pp. A206–A215, Feb. 2018.

[7] Cisco Visual Networking Index: Forecast and Methodology, 2017-2022. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html

[8] O. Gerstel, M. Jinno, A. Lord, and S. Yoo, "Elastic optical networking: A new dawn for the optical layer?" *IEEE Commu. Mag.*, vol. 50, pp. s12–s20, Feb. 2012.

[9] L. Gong, X. Zhou, W. Lu, and Z. Zhu, "A two-population based evolutionary approach for optimizing routing, modulation and spectrum assignments (RMSA) in O-OFDM networks," *IEEE Commun. Lett.*, vol. 16, pp. 1520–1523, Sept. 2012.

[10] Z. Zhu, W. Lu, L. Zhang, and N. Ansari, "Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing," *J. Lightw. Technol.*, vol. 31, pp. 15–22, Jan. 2013.

[11] L. Gong *et al.*, "Efficient resource allocation for all-optical multicasting over spectrum-sliced elastic optical networks," *J. Opt. Commun. Netw.*, vol. 5, pp. 836–847, Aug. 2013.

[12] Y. Yin *et al.*, "Spectral and spatial 2D fragmentation-aware routing and spectrum assignment algorithms in elastic optical networks," *J. Opt. Commun. Netw.*, vol. 5, pp. A100–A106, Oct. 2013.

[13] M. Zhang, C. You, H. Jiang, and Z. Zhu, "Dynamic and adaptive bandwidth defragmentation in spectrum-sliced elastic optical networks with time-varying traffic," *J. Lightw. Technol.*, vol. 32, pp. 1014–1023, Mar. 2014.

[14] P. Lu and Z. Zhu, "Data-oriented task scheduling in fixed- and flexible-grid multilayer inter-DC optical networks: A comparison study," *J. Lightw. Technol.*, vol. 35, pp. 5335–5346, Dec. 2017.

[15] S. Liu, W. Lu, and Z. Zhu, "On the cross-layer orchestration to address IP router outages with cost-efficient multilayer restoration in IP-over-EONs," *J. Opt. Commun. Netw.*, vol. 10, pp. A122–A132, Jan. 2018.

[16] W. Lu, X. Yin, X. Cheng, and Z. Zhu, "On cost-efficient integrated multilayer protection planning in IP-over-EONs," *J. Lightw. Technol.*, vol. 35, pp. 5335–5346, Dec. 2017.

[17] B. Kong *et al.*, "Demonstration of application-driven network slicing and orchestration in optical/packet domains: On-demand vDC expansion for Hadoop MapReduce optimization," *Opt. Express*, vol. 26, pp. 14 066–14 085, 2018.

[18] H. Fang *et al.*, "Building network nervous system with multilayer telemetry to realize AI-assisted reflexes in software-defined IP-over-EONs for application-aware service provisioning," in *Proc. of OFC 2019*, pp. 1–3, Mar. 2019.

[19] N. McKeown *et al.*, "OpenFlow: Enabling innovation in campus networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 38, pp. 69–74, Mar. 2008.

[20] S. Li *et al.*, "Protocol oblivious forwarding (POF): Software-defined networking with enhanced programmability," *IEEE Netw.*, vol. 31, pp. 12–20, Mar./Apr. 2017.

[21] I. Maor *et al.*, "First demonstration of SDN-controlled multi-layer restoration and its advantage over optical restoration," in *Proc. of ECOC 2016*, pp. 1–3, Sept. 2016.

[22] B. Niu *et al.*, "Visualize your IP-over-Optical network in realtime: a P4-based flexible multilayer in-band network telemetry (ML-INT) system," *IEEE Access, submitted*, pp. 1–9, Apr. 2019.

[23] C. Kim *et al.* In-band network telemetry (INT). [Online]. Available: https://p4.org/assets/INT-current-spec.pdf

[24] P. Bosshart *et al.*, "P4: Programming protocol-independent packet processors," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 44, pp. 87–95, Jul. 2014.

[25] X. Chen *et al.*, "Flexible availability-aware differentiated protection in software-defined elastic optical networks," *J. Lightw. Technol.*, vol. 33, pp. 3872–3882, Sept. 2015.

[26] J. Yin *et al.*, "Experimental demonstration of building and operating QoS-aware survivable vSD-EONs with transparent resiliency," *Opt. Express*, vol. 25, pp. 15 468–15 480, 2017.

[27] Z. Zhu, S. Li, and X. Chen, "Design QoS-aware multi-path provisioning strategies for efficient cloud-assisted SVC video streaming to heterogeneous clients," *IEEE Trans. Multimedia*, vol. 15, pp. 758–768, Jun. 2013.

[28] K. Han *et al.*, "Application-driven end-to-end slicing: When wireless network virtualization orchestrates with NFV-based mobile edge computing," *IEEE Access*, vol. 6, pp. 26 567–26 577, 2018.

[29] R. Proietti *et al.*, "Experimental demonstration of machine learning-aided QoT estimation in multi-domain elastic optical networks with alien wavelengths," *J. Opt. Commun. Netw.*, vol. 11, pp. A1–A10, Jan. 2019.

[30] G. Liu *et al.*, "Hierarchical learning for cognitive end-to-end service provisioning in multi-domain autonomous optical networks," *J. Lightw. Technol.*, vol. 37, pp. 218–225, Jan. 2019.