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Disaggregated Optical Networks: A Survey

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Abstract
Disaggregated networks allowoperators to select components fromdifferentvendors, promotingvendorneutrality. This flexibility enables the selection of best-of-breed solutions for specific network elements. By decoupling hardware and software, disaggregated networks can potentiallyreducecosts. Operators can choosecost-effective devices and upgrade or replace themindependently. Disaggregationalsofacilitates the adoption of new technologies and innovations and oftenadheres to open standards promotinginteroperabilitybetweendifferentequipmentvendors. The YetAnother Next Generation (YANG) data modeling has been identified as the preferredlanguage to interface the management and control system. The Network Configuration Protocol (NETCONF) isgaining prominence as a Software-Defined Networking (SDN) protocolstandardized by the Internet Task Force (IETF). This paperprovides an overviewbased on a survey of the best practices employed in designing, planning, and operating a disaggregatedoptical network. It presents the general system architecture including the open software tools SDN controller (based on the Open Operating Network System (ONOS)), optical line system controller (OLC), Quality of Transmission (QoT) estimatorbased on the Gaussian Noise Simulation in Python (GNPy), and the orchestrator module.

Index Terms*:Openness,Disaggregated Optical Networks,Quality of Transmission*

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I. Introduction

Data traffic is experiencing a huge growth due to cloud computing high-definition video, 5G, IoT, machine learning, and augmented reality. This scenario has put a lot of pressure on operators that are forced to scale up transmitted bits resulting in investment costs. Historically [1], optical networks have been deployed and their parts manufactured as closed and proprietary systems. One of the reasons of closeness is that optical signals in communication systems have analog characteristics. Also, the tight coupling of control and management software with hardware components such as optical transponders, amplifiers, switches, and multiplexers/demultiplexers is a characteristic of optical systems. This integration ensured seamless integration, coordination, and operation of the optical communication systems for years. Despite efforts to open up optical transport networks and shift away from closed proprietary systems, progress toward fully open optical systems has been limited. This is primarily due to the continued necessity for co-designing and optimizing optical subsystems to achieve optimal system performance. Recent initiatives have fostered the openness in optical networks [2]. Openness refers to the concept of employing open standards interfaces, and architectures to enhance interoperability and flexibility in optical networks. It isa change from traditional, closed, vendor-locked systems towards a more flexible and interoperable architecture and an approach that fosters innovation. Various entities, including academia, standard bodies, consortia, and network operators have actively undertaken initiatives and activities to promote and advance this approach. Disaggregation [3] aims to provide network operators with greater flexibility and choice in selecting and composing individual network elements from different vendors. This includes functions such as transponders, reconfigurable optical add-drop multiplexers (ROADMs), line systems, control, monitoring, and more. The concept of disaggregation at the optical layer can be categorized into two levels: partially disaggregated and fully disaggregated. A partially disaggregated optical system sits between the traditional closed and fully disaggregated models of optical networks. It represents a step towards greater flexibility and efficiency while maintaining some level of vendor-specific control. In partial disaggregation, optical infrastructure is provided by a single vendor. Transponder cards are provided by multiple different vendors. Because transponders are used in pairs, optical connectivity is handled by the transponder manufacturer, while the optical line system is handled by the photonic manufacturer. The fully disaggregated optical systems refer to an optical network architecture where every individual optical component operates independently and exposes its programmability through a control interface. While it offers a higher degree of flexibility, it does come with increased complexity at the SDN controller level. In this case, an open ROADM system necessitates vendor interoperability for both ROADM nodes and transponders. An OpenROADM system must, in all cases, adhere to the requirements set forth by the OpenROADM Multi-Source Agreement (MSA) [4]. The Network Configuration Protocol (NETCONF), an SDN protocol that provides administration and control functionality (such as data plane device setup) and access to monitoring data, has been standardized by the IETF [5]. The NETCONF protocol offers methods for adding, deleting, and changing network device management state and data. Additionally, by using certain notifications, NETCONF may be especially indicated for monitoring reasons. Specifically, a controller has the option to receive notifications when a particular monitored parameter exceeds a predetermined threshold (for example, a pre-FEC BER greater than 10E-4) [5]. In this instance, the controller that has subscribed to the NETCONF notification is given an alarm by means of the monitoring system. YANG [5] is a modeling language that may be represented in XML, and it is the foundation of NETCONF. YANG allows for the standard description of the state information and adjustable parameters of many network devices. As a result, YANG and NETCONF offer a common method for managing and controlling networkcomponents apart from the vendor [5]. Two different types of agents were developed by the authors of [6]: an OpenROADM-based line system agent and a transponder agent based on OpenConfig. An independent SDN controller, such as one offered by the OLS Vendor or another company, is in responsibility of configuring each transponder in a manner that is independent of the vendor for the entire disaggregated network. The OpenConfig YANG schema was created for this reason in order to offer a uniform method of configuring the common transponder settings using NETCONF [7]. Vendors and network operators collaborate in the OpenROADM working group to define interoperability requirements for ROADMs. The YANG data models are utilized to encode the specified interoperability criteria [7].

II. Network Architecture

The common approach from the various scenarios presented in the literature consists of the separation of the amplifiers control plane of each optical line system (OLS) from the data plane. Transceiver, ROADM whiteboxes, and amplifier nodes make up the network system under consideration. One vendor [6] provides the optical network, which includes ROADMs and the OLS. On the other hand, transponders are provided in pairs (source and destination) and are offered by multiple vendors. Both the transponders and the OLS, which rely on separate YANG models (for instance, the transponders on Open-Config and the OLS on OpenROADM), are equipped with SDN agents that allow control communication with the central SDN Controller via the NETCONF-based SouthBound Interface (SBI). Furthermore, the transponders under consideration are enhanced with telemetry services, which allow specialized co-located streaming servers to transmit continuous monitoring data obtained from the hardware stages of digital signal processing (e.g., input/output optical power, pre-FEC BER, OSNR, or optical signal to noise ratio, chromatic dispersion, polarization mode dispersion). Each transponder vendor offers a set of specific transmission configurations, known as OP modes. To protect proprietary information, vendors often represent these OP modes as opaque attributes within the YANG data model. This means that the SDN controller can interact with these modes without needing to know their exact underlying parameters. However, this lack of transparency can hinder the controller's ability to optimally select and configure OP modes for the best network performance. The optical equipment is generally managed by the cooperation of four different software modules:

- The optical network controller (ONC).
- The optical line controller for each OLS (OLC).
- The QoT estimator (physical layer aware simulation environment).
- The open optical network controller (OONC) or orchestrator.

For interoperability and flexibility, using open standards such as NETCONF and REST is a great approach. It makes it possible for devices from different vendors to interact and operate together as a single unit [8]. A single optical network controller (ONC) is essential for managing and orchestrating open and disaggregated networks [7]. The ONC communicates with various devices in the network using open protocols, ensuring interoperability and vendor neutrality. The ONC is responsible for the routing strategy, so it determines the optimal paths for data traffic through the network, to ensure efficient resource utilization and performance. It provides orchestration by coordinating and controlling the operation of transceivers and ROADMs. Each OLS operates independently, controlled by a dedicated optical line controller (OLC). OLCs can autonomously choose the optimal transmission strategy for each line. This may involve dynamically adjusting amplifier settings based on fiber characterization data. The feedback loop closure between the ONC and OLCs is facilitated by a software computational block that estimates the quality of transmission (QoT) for each demand (source-destination pair) using physical layer descriptions and amplifier configurations, guiding the data plane for routing decisions. As an orchestrator that combines data from many software modules and synchronizes the deployment process, the OONC distributes traffic requests from the upper layers within the optical network. Fig. 1 provides the general view of the optical control framework based on information available in the literature [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

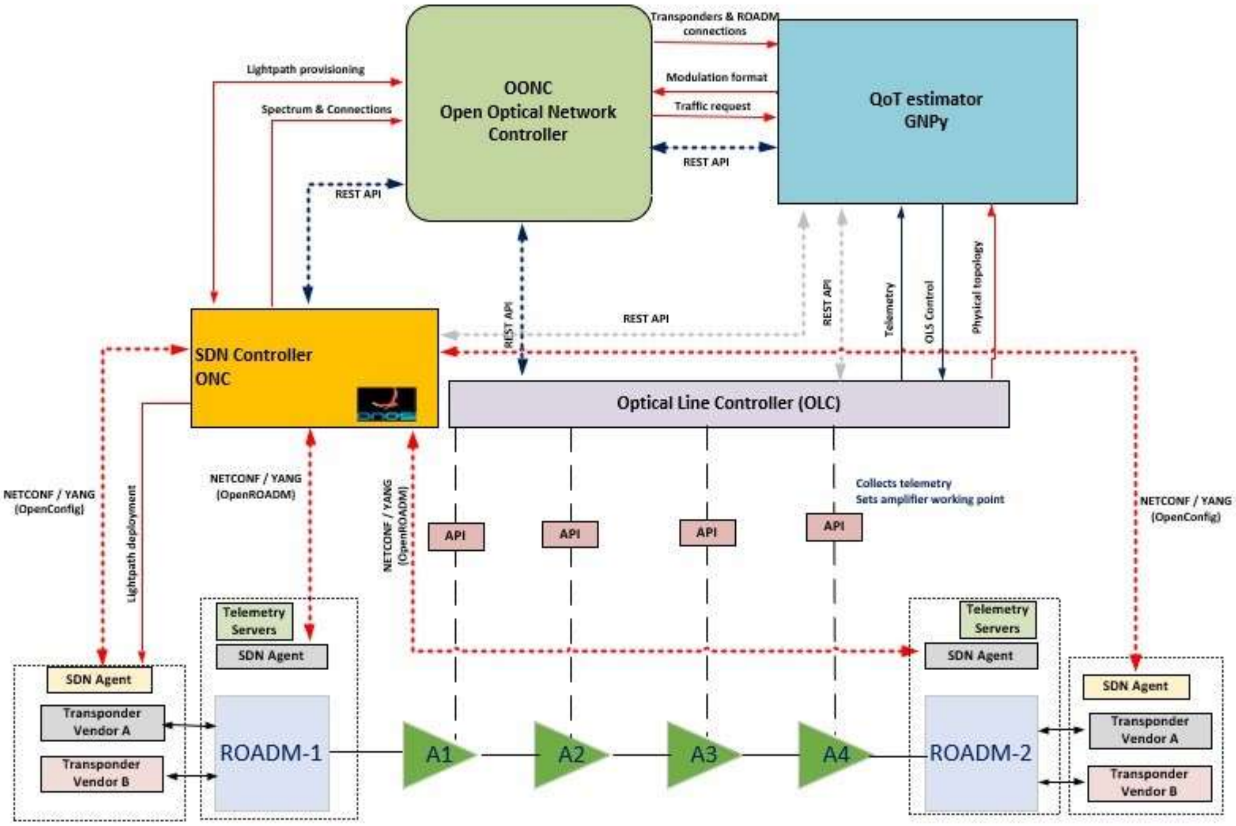

Figure 1: Optical Control Framework

A. Gaussian Noise Simulation in Python (GNPy)

GNPy is an open-source design tool developed by the Telecom Infra Project (TIP) for optical network planning and optimization. When estimating QoT, [13] it considers the current state of the network, including fiber characteristics, amplifier settings, and network topology. It calculates the generalized signal-to-noise ratio (GSNR) along the specified route. GSNR is a measure of signal quality relative to noise and impairments. So, it facilitates route planning and resource allocation. Additionally, GNPy may optimize the network by making sure that the amplifier operating points and signal launch power are adjusted to their optimal levels [16]. As it is a vendor-neutral approach, it does not require proprietary information from vendors. It uses a simplified model to estimate fiber optic signal degradation. GNPy requires the input parameters for each network element along the path to be provided in either JavaScript Object Notation (JSON) format or as Microsoft Excel files, which are internally mapped into an equivalent JSON structure. These parameters play a crucial role in calculating amplified spontaneous emission (ASE) noise and nonlinear interference (NLI) disturbance caused by fiber Kerr effects [17]. GNPytakes into account amplifier parameters such as gain and noise figure. As the ASE noise has a great contribution in the GSNR calculation, an accurate model of the amplifier is necessary. GNPy has been utilized with ONOS SDN controller as a path computation engine [18] and also as a tool for operators optimize their procurement processes as GNPy serves to compare performance from different vendors. GNPy has also been featured as a path computation engine (PCE) in a collaborative effort within TIP converged architecture for Network Disaggregation and Integration [19]. GNPy [20] uses a software representation of the physical network, including fiber spans, amplifiers, ROADMs, and other elements. This digital twin allows for virtual testing and optimization of network performance without needing to physically modify the real network. The digital twin approach offers a powerful tool for planning, designing, and optimizing optical networks. As previously described, GNPy calculates GSNR. It is a valuable metric for assessing the quality of coherent, polarization-multiplexed optical signals. Once GNSR is calculated for the source-destination demand, GNPy evaluates the maximum achievable reach for the selected transponders. GNPy assumes all links operate at full channel capacity, ensuring the worst-case scenario. It considers the cumulative impact of various impairments (noise, dispersion, nonlinearities) on GSNR as the signal traverses the link. In detail, [21] ASE noise represents the linear noise while cross-phase modulation (XPM) and self-phase modulation (SPM) represent the nonlinear noise (NLI). As SPM accumulates coherently, its effects cannot be isolated and evaluated independently, making it difficult to disaggregatethe contribution to overall GSNR degradation. The impact of SPM becomes more significant as the signal rate increases. Shorter pulse widths become are more susceptible to SPM phase distortions. To compensate for the SPM coherent accumulation, a novel span-by-span independent coefficient computation is proposed in [21] which serves as a reliable and conservative threshold for compensating for coherent accumulation of SPM in a fully disaggregated approach. Fig. 2 depicts the basic architecture of the GNPy module. The architecture [13] is centered on a core engine which is designed to deal with propagation effects and QoT estimation. The path computation engine is responsible to handle multiple requests, required bandwidth and spectrum assignment. The Network Module works with the option of using the auto-design feature when an accurate description of the network is not available.

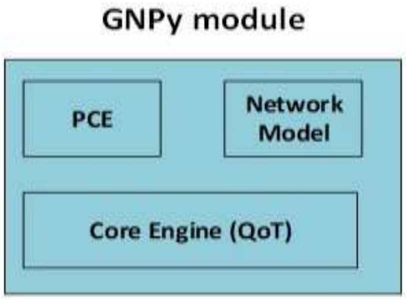

Figure 2: GNPy module basic structure)

B. Open Network Operating System (ONOS) SDN Controller

The emergence of open-source initiatives in the SDN (Software Defined Networking) space, particularly OpenDaylight and ONOS, has significantly impacted the landscape of network control and management. In this document, the focus will be given to the ONOS controller. ONOS was developed by the Open Networking Foundation (ONF) with the support of the major telecommunications parties. ONOS is designed for reliability by adopting a logically centralized but physically distributed model. Controller functionalities are distributed across synchronized instances on different machines, enhancing system scalability through balanced masterships of devices among multiple instances [22]. The advanced multi-thread software architecture further contributes to its robust design [22]. This means that smaller units of a process are run independently in parallel enhancing the performance. The Open Disaggregated Transport Network (ODTN) group was established with the goal of empowering ONOS to manage, configure, and monitor disaggregated optical networks using NETCONF/YANG protocols [23]. NETCONF and YANG provide standardized protocols and data models for configuring and monitoring networking devices. ODTN work was developed in phases to include:

- **NBI extension**: application on northbound interface (NBI) to accept optical connection requests, providing a user interface for services provisioning.
- **SBI extension**: drivers on the southbound interface (SBI) to communicate with transponders to configure and control them.

- OLS incorporation: the OLS, the system responsible for signal transmission over fiber optics.
- **OLS driver implementation**: driver development to enable control over transmitted signals and optical power levels.
- **ROADM control**: support for ROADMs allowing for flexible routing of optical signals within mesh networks.
- **Mesh Topology Management**: allowing the handling of complex mesh topologies
- **ROADM disaggregation**: ROADMs are broken down into more granular components like node degrees, filters, and optical amplifiers.
- **ROADM individual control**: allowing for fine-grained control over individual components within ROADMs, potentially optimizing resource utilization and network performance.

ONOS key tasks and responsibilities within an optical network include network state awareness (spectral usage, frequency availability, transponders and ROADMs status, network topology abstraction), communication and configuration (channel provisioning, spectral usage report toorchestrator, operation status report) and failure management (interrupt handling received from OLS relayed by OLC, node and link failure detection, trigger of restoration process, coordination with the orchestrator to update network topology). In essence, the ONOS acts as the intelligent heart of the optical network, enabling dynamic resource optimization, proactive failure management, and seamless service delivery. In order for ONOS to support a wide variety of devices [24], it is built with strong abstractions to avoid vendor lock-in. To support various use cases and modes of use, it is developed as a modular and extensible application platform, so that operators can customize it for various use cases and modes of operation. So, at the base of the architecture is the Distributed Applications Platform which provides high availability and scalability and is built on top Apache 2.0. On top of the Applications platform is the ONOS Networking Core which provides network control and network configuration abstraction. You can think of the ONOS Networking Core and Distributed Applications Platform as basically as a kernel. The ONOS Applications module acts basically as kernel extensions that can take several different shapes and forms. They can be YANG models, they can be drivers, they can be protocols, libraries. In order for the Kernel to be able to interface with the external world, there are the external adapters such as Graphical User Interface (GUI) to interface with humans, REST APIs to facilitate integration with various orchestration systems and other possible controllers such as GNPy module, gRPC for telemetry services (connecting services between different entities) and NETCONF to access configuration and state data of network devices defined in YANG models. Fig. 3 depicts the basic architecture of the ONOS SDN controller.

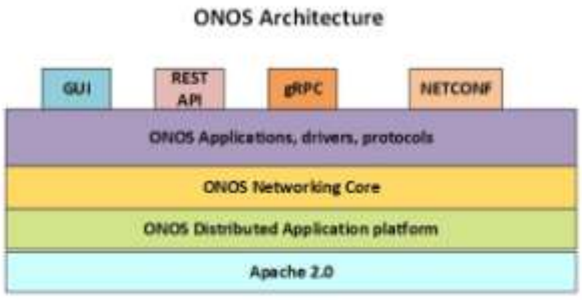

Figure 3: ONOS SDN Controller Architecture)

C. Optical Line System Controller (OLC)

The optical line system (OLS) serves as the foundation layer in modern communication networks, functioning as a physical network that transmits high-frequency analog optical signals across great distances. Traditionally, the OLS was provided as turn-key solution by a single vendor. This system consists of optical amplifiers, fibers, and ROADMs. ROADMs act as an active device that handles the routing of optical signals between input/output ports. ROADMs are considered the most complex physical component within an OLS [25]. The OLC manages the OLS from a specific vendor, communicates through APIs withThe optical line system (OLS) serves as the foundation layer in modern communication networks, functioning as a physical network that transmits high-frequency analog optical signals across great distances. Traditionally, the OLS was provided as turn-key solution by a single vendor. This system consists of optical amplifiers, fibers, and ROADMs. ROADMs act as an active device that handles the routing of optical signals between input/output ports. ROADMs are considered the most complex physical component within an OLS [25]. The OLC manages the OLS from a specific vendor, communicates through APIs withOLS and also evaluation of the lightpaths viability (computation engine) in terms of performance [12]. The OLC works in conjunction with the ONC to provide a comprehensive view of the network's physical layer and contributes to the overall network optimization and failure management (facilitates proactive fault detection). Fig. 4 provides in simplified way the OLC interactions with other entities.

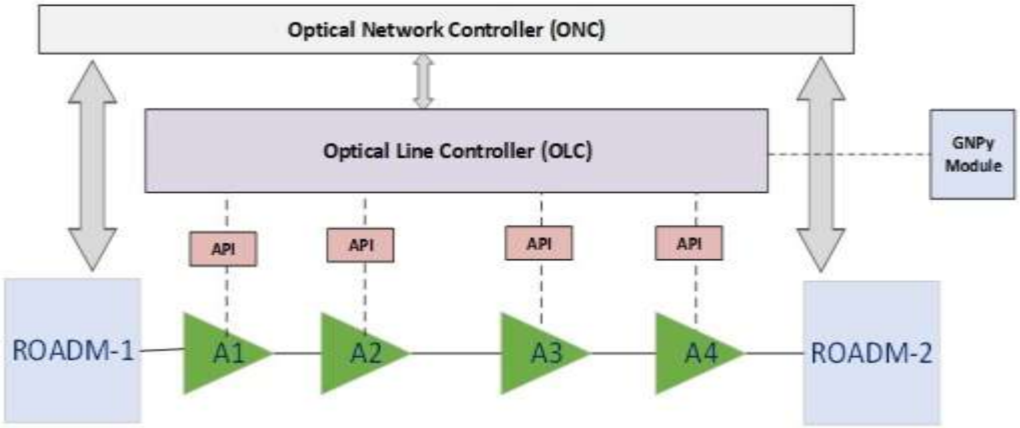

Figure 4: Optical Line Controller (OLC)

D. Orchestrator - Open Optical Network Controller (OONC)

The Open Optical Network Controller (OONC) plays a crucial role in the optical network ecosystem. It serves as a key orchestrator, implementing the northbound interface, harmonizing deployment procedures, and transparently managing lightpath allocation and restoration [26]. By leveraging information from software modules like ONC and GNPy, OONC efficiently builds the spectrum grid and routing space, making it possible to perform the routing and spectral allocation (RSA) for traffic requests from upper layers. Additionally, it handles QoT estimation, reacts to ONC failure detection by updating network topology, and communicates outcomes of connection requests to upper layers [7]. The OLS undergoes a tuning procedure to set the amplifier working points before transmission operations. A REST API facilitates data transfer between the OLC and the GNPy module which provides amplifier configuration settings [6], [12]. The optical data plane, which is entrusted to the OONC, is in charge of managing the allocation of optical connections, or lightpaths, between couples of source-destination nodes based on the traffic requests coming from the application/IP layer. The GNPy module provides support in terms of QoT estimation calculations. In the network provisioning process, the ONC retrieves photonic connections from all relevant network elements. This is communicated to thethe complete picture of the physical topology [6], [7]. In case of a connection request, the GNPy module calculates the available modulation format based on the topology and transponder characterizations. The OONC receives the evaluated modulation formats of all the available paths and performs the RSA defining the characteristics and determines the required number of the lightpaths to deploy to satisfy the traffic request [7], [15]. After configuring the transponder's operational mode and adjusting ROADMs through the ONC with the appropriate interfaces, the lightpath is activated. Subsequently, the ONC reports the outcome (success or failure) of this operation to the OONC. In [6] is proposed a workflow for dealing with network failures that requires the modification of the transponder OP mode by the ONC. It uses a REST API interface to interact with a statistics analysis module that evaluates the best operational mode to be employed. When a ROADM detects a loss-of-light event, it sends NETCONF notifications to the ONC that is in charge to perform the required actions regarding the photonic connections and interactions with other modules such as GNPy for the restored lightpath validation. For modification of the OP mode, an application is employed to use NETCONF edit-config message to edit the OP mode of the transponders. Regarding failure management, an innovative approach is the integration of the OONC with large language models (LLMs) such as ChatGPT or Google Bard. The LLM would provide the natural language interface, so network operators would interact with the orchestrator for queries regarding network troubleshooting. LLMs could provide network performance analytics, analysis of failure events, predictive analysis, and recommendations for proactive measures. Integrating the LLM with a knowledge base, failure management and provisioning problems will provide operators to define best practices for solution of network issues.

III. Results

The GNPy module employs an optimization strategy to characterize each fiber span aiming to replicate experimental measurements through the physical optical propagation model. Key parameters estimated for a single fiber span include the Raman efficiency factor, loss coefficient, connector losses, and potential losses detected by the optical domain time reflectometer (OTDR). The evaluation of network transmission performance involves setting amplifier working point, estimating GSNR based on measured BER [27], and comparing it to GNPy module's calculated GSNR. The resulting margin is calculated without considering other contributions, assuming the system operates at zero margin [7]. In [13] is demonstrated that the performance of a disaggregated optical network can be improved by using the optimal transponder OP mode based on the scenario under test. Results show that the control plane activities can be performed in few seconds pretty before the convergence of the optical layer. In [9] is proposed and validated a disaggregated optical network based on open transponders with pluggables transceivers and ROADM-based whiteboxes. The network is managed by a ONOS controller that relies on GNPy for QoT estimation and employs OpenConfig/YANG for pluggables and ROADM control from different vendors. Modulations format employed are DP-QPSK and DP-16-QAM. GNPy predictions were conservatives in all tested scenarios and the deviation for the GSNR metric for DP-QPSK modulation is within 1.1 dB.

In [5] is demonstrated the viability the use of the NETCONF protocol and the YANG data model for describing a transponder that provides monitoring capabilities. The YANG model is provided with details with examples configuration and monitoring. In [16] is proposed an algorithm for multi-vendor networks interoperability. The results showed that using optimized power levels for each fiber span provides higher performance in terms of GSNR when compared to the scenario that uses the same launched power. The article provides a detailed analysis of ASE and NLI noise models within a disaggregated optical network scenario. In [8] is showed a demonstration of the ONOS SDN controller deployed in three instances scenario. The controller is used to provision photonic connections over a disaggregated optical network consisting of two transponders and two ROADMs connected together via redundant links in order to support data plane failover. Topology information as well as links are discovered through OpenConfig interfaces and NETCONF protocol. In case of a fiber cut, ONOS recognizes the event and marks the link as failed one. In sequence, re-computation is triggered automatically. In [15] is proposed an integrated framework to execute a QoT-driven RSA in a disaggregated optical network. The framework integrates ONOS controller and the proposed QoT tool via an ONOS specific application called metroApp. QoT estimation required time is about 1s without impacting the connection provisioning setup for a lightpath demand. QoT output parameters are the required bandwidth, associated baud rate and bit rate, and the modulation format.

IV. Conclusion

In this overview it was shown the most common architecture approaches for disaggregated optical networks. It started with the description of the most common protocols for interoperability between software tools and optical device such as NETCONF, YANG, and the agents OpenROADM and OpenConfig and the movement of standard bodies, consortia and projects with the aim of defining standards for disaggregated optical networks. In addition, due to SDN's successful implementation in real networks over the last ten years, network operators now have confidence in and experience with open network technologies. The basic operations and workflow of a connectivity provisioning is described as well as the steps involved in case of a restoration of this connection. It is expected that the integration of the disaggregated optical network architecture with machine learning algorithms will provide ways of improving the performance in terms of channel quality, better RSA algorithms and time response to network events. Regarding failure management, I true believe in the integration of troubleshooting tasks with large language models (LLMs) which are machine learning models based on neural networks with the goal of processing natural language. With the introduction of retrieved augmented generation (RAG), which aims in retrieving pertinent information from a database or an external knowledge base, LLM systems can overcome its static knowledge when working in conjunction with RAG systems and provide an efficient method for troubleshooting disaggregated optical networks.

References

[1]. C. Xie et al., "Open and disaggregated optical transport networks for data center interconnects [Invited]," in Journal of Optical Communications and Networking, vol. 12, no. 6, pp. C12-C22, June 2020, doi: 10.1364/JOCN.380721.

[2]. M. Filer, M. Cantono, A. Ferrari, G. Grammel, G. Galimberti and V. Curri, "Multi-Vendor Experimental Validation of an Open Source QoT Estimator for Optical Networks," in Journal of Lightwave Technology, vol. 36, no. 15, pp. 3073-3082, 1 Aug.1, 2018, doi: 10.1109/JLT.2018.2818406.

[3]. L. Velasco et al., "Building Autonomic Optical Whitebox Based Networks," in Journal of Lightwave Technology, vol. 36, no. 15, pp. 3097-3104, 1 Aug.1, 2018, doi:10.1109/JLT.2018.2829700.

[4]. http://www.openroadm.org/

[5]. M. Dallaglio, N. Sambo, F. Cugini and P. Castoldi, "Control and management of transponders with NETCONF and YANG," in Journal of Optical Communications and Networking, vol. 9, no. 3, pp. B43-B52, March 2017, doi: 10.1364/JOCN.9.000B43.

[6]. A. Sgambelluri, A. Giorgetti, D. Scano, F. Cugini and F. Paolucci, "OpenConfig and OpenROADM Automation of Operational Modes in Disaggregated Optical Networks," in IEEE Access, vol. 8, pp. 190094-190107, 2020, doi: 10.1109/ACCESS.2020.3031988.

[7]. G. Borraccini et al., "Experimental Demonstration of Partially Disaggregated Optical Network Control Using the Physical Layer Digital Twin," in IEEE Transactions on Network and Service Management, vol. 20, no. 3, pp. 2343-2355, Sept. 2023, doi: 10.1109/TNSM.2023.3288823.

[8]. A. Campanella et al., "Reliable Optical Networks With ODTN: Resiliency and Fail-Over in Data and Control Planes," in Journal of Lightwave Technology, vol. 38, no. 10, pp. 27552764, 15 May15, 2020, doi: 10.1109/JLT.2020.2983587.

[9]. G. Borraccini et al., "QoT-Driven Optical Control and DataPlane in Multi-Vendor Disaggregated Networks," 2022 OpticalFiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2022, pp. 1-3.

[10]. F. Cugini, F. Paolucci, A. Sgambelluri, A. Giorgetti, D. Scano and P. Castoldi, "Designing Disaggregated Optical Networks," 2020 International Conference on Optical Network Design and Modeling (ONDM), Barcelona, Spain, 2020, pp. 1-3, doi: 10.23919/ONDM48393.2020.9133039.

[11]. P. Castoldi, S. Fichera, M. Gharbaoui, A. Giorgetti, B. Martini and F. Paolucci, "Disaggregated optical network control and orchestration of heterogeneous domains," 2019 24th OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC), Fukuoka, Japan, 2019, pp. 1-3, doi:10.23919/PS.2019.8817856.

[12]. R. Ambrosone et al., "Open Line Controller Architecture in Partially Disaggregated Optical Networks," 2023 International Conference on Photonics in Switching and Computing (PSC), Mantova, Italy, 2023, pp. 1-3, doi: 10.1109/PSC57974.2023.10297237.

[13]. Alessio Ferrari, Mark Filer, Karthikeyan Balasubramanian, Yawei Yin, Esther Le Rouzic, Jan Kundrát, Gert Grammel, Gabriele Galimberti, and Vittorio Curri, "GNPy: an open source application for physical layer aware open optical networks," J. Opt. Commun. Netw. 12, C31-C40 (2020).

[14]. Vittorio Curri, "GNPy model of the physical layer for open and disaggregated optical networking [Invited]," J. Opt. Commun. Netw. 14, C92-C104 (2022).

[15]. A. Giorgetti, M. Secondini, F. Cugini, A. Sgambelluri and P. Castoldi, "ONOS MetroApp for Filtering Effect Assessment in Metro Optical Networks," 2018 European Conference on Optical Communication (ECOC), Rome, Italy, 2018, pp. 1-3, doi: 10.1109/ECOC.2018.8535360.

[16]. J. Auge, V. Curri, and E. Le Rouzic, "Open design for multi-vendor optical networks," in Optical Fiber Communication Conference (OFC) 2019, OSA Technical Digest (Optica Publishing Group, 2019), paper Th1I.2.

[17]. S. Cruzes, "Optical Networks Automation: A Survey," J Sen Net Data Comm, 3(1), 144-162.

[18]. J. Kundrát et al., "Physical-Layer Awareness: GNPy andONOS for End-to-End Circuits in Disaggregated Networks,"2020 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2020, pp. 1-3.

[19]. E. Le Rouzic et al., "Operationalizing partially disaggregated optical networks: An open standards-driven multi-vendor demonstration," 2021 Optical Fiber Communications Conference and Exhibition (OFC), San Francisco, CA, USA, 2021, pp.1-3.

[20]. [20] J. Kundrát et al., "GNPy: Lessons Learned and Future Plans [Invited]," 2022 European Conference on Optical Communication (ECOC), Basel, Switzerland, 2022, pp. 1-4.

[21]. A. D'Amico, E. London, E. Virgillito, A. Napoli and V. Curri, "Quality of Transmission Estimation for Planning of Disaggregated Optical Networks," 2020 International Conference on Optical Network Design and Modeling (ONDM), Barcelona, Spain, 2020, pp. 1-3, doi: 10.23919/ONDM48393.2020.9133012.

[22]. A. Giorgetti, R. Casellas, R. Morro, A. Campanella and P. Castoldi, "ONOS-Controlled Disaggregated Optical Networks,"2019 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2019, pp. 1-3.

[23]. M. De Leenheer, Y. Higuchi and G. Parulkar, "An open controller for the disaggregated optical network," 2018 International Conference on Optical Network Design and Modeling (ONDM), Dublin, Ireland, 2018, pp. 230-233, doi:10.23919/ONDM.2018.8396136.

[24]. [24] https://opennetworking.org/onos/

[25]. J. Kundrát, O. Havliš, J. Jedlinský and J. Vojtech, "Openingˇ up ROADMs: Let Us Build a Disaggregated Open Optical Line System," in Journal of Lightwave Technology, vol. 37, no. 16, pp. 4041-4051, 15 Aug.15, 2019, doi: 10.1109/JLT.2019.2906620.

[26]. R. Casellas, R. Martínez, R. Vilalta and R. Muñoz, "Control, Management, and Orchestration of Optical Networks: Evolution, Trends, and Challenges," in Journal of Lightwave Technology, vol. 36, no. 7, pp. 1390-1402, 1 April1, 2018, doi: 10.1109/JLT.2018.2793464.

[27]. E. Rivera Hartling et al., "Design, Acceptance and Capacity of Subsea Open Cables," in Journal of Lightwave Technology, vol. 39, no. 3, pp. 742-756, 1 Feb.1, 2021, doi:10.1109/JLT.2020.3045389.