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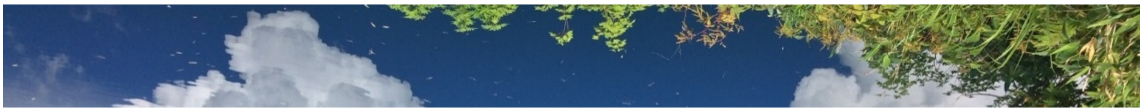
White Paper



Cyber Photonic Platform: Automatizing the Physical Layer for Total Network Automation

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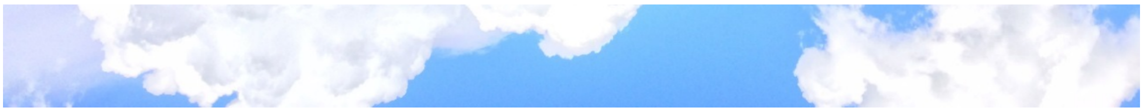

Abstract: This white paper addresses the issues involved in building a platform that simplifies the utilization of the optical physical layer for any upper layers (L2, L3, or applications) through softwarization. The softwarization of the optical physical layer requires the definition of a network-scale hardware abstraction along with modularity of the hardware. The architecture, optical component classification, operational information flow, and operation scenarios are described, and the current technological status toward such a new platform is investigated. This white paper is intended for readers who are interested in high-bandwidth, low-latency networks enabled by optical networks, such as network researchers, small and large network operators, and service providers.

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1. INTRODUCTION

Since the early 1970s, optical fiber communication systems have been deployed worldwide to form the basis of the modern global information society. Thus, the present information network is built upon an "optical layer" offering bandwidth and transmission over long distances, while the L2/L3 layers on top of it offer switching functions. Historically, there have been several attempts to add reconfigurability and/or path switching capabilities to the optical layer in order to off-load upper layers. One example is generalized multi-protocol label switching (GMPLS), for which many technical issues have been addressed and resolved, especially regarding the control software. However, these efforts have seldom been adopted for real-world usage. There are two main reasons for this. The first concerns technical aspects, such as the difficulty in maintaining optical transmission quality over various optical path settings with varied dispersion and optical signal-to-noise ratios (OSNR), as well as immature interoperability of optical transceivers. The second reason, which is complex and time-varying in nature, concerns the business model: simply speaking, the demand for this enhancement to the optical layer was not strong enough while many upper-layer alternatives were available.

Looking to the future, however, the typical data size of network traffic will be further increased by the dissemination of 4K/8K video content and AI big data services through the 5G mobile infrastructure. Additionally, many emerging applications will require more stringent low-latency for the transmission of ever greater quantities of data. The optical layer has inherent features of ultra-high bandwidth, ultra-low latency, ultra-low energy, and high security. Unlike packet-based L2/L3 layers, the optical layer can obtain these features simultaneously. This is because the L2/L3 layers are heavily reliant on CMOS scaling, which is subject to a fundamental slowdown as Moore's law begins to fail. Thus, the conventional architectural division of labor between optical and upper layers will have to be redressed, and the optical layer should be made more reconfigurable, and as agile and usable as possible, through the introduction of intelligent control software or a resource management scheme. In other words, the optical layer should allow optical path switching functionalities by fiber matrix switches, wavelength selective switches, and so on.

For the optical layer to be truly useful in the network systems that are orchestrated across multiple layers through holistic resource management, it must not only be fully "softwarized," but also "automated," allowing the orchestrator to utilize the optical layer as easily as the upper layers at the software level. The conventional physical deployment and maintenance of the optical layer, which requires a significant body of highly skilled labor, is not appropriate for a new architecture that orchestrates the optical layer. However, the recent development of digital coherent technology has indeed automated the settings of optical transmission, and significantly enhanced interoperability. Considering these advances, both technological and economical aspects are suitably mature for the softwarization and automation of the optical layer.

This white paper addresses the concept of the platform upon which the optical layer is fully softwarized and automated. The platform shall be open and standardize the disaggregation and abstraction of the optical layer in both the physical and logical senses, ensuring universal use for any upper-layer architecture. An open disaggregated platform enables global trade and commerce of technologies, permitting extremely efficient operation of systems comprising multi-vendor and multi-generation components. “Plug-and-play” operation of optical components is also addressed to better facilitate the automation of the platform.

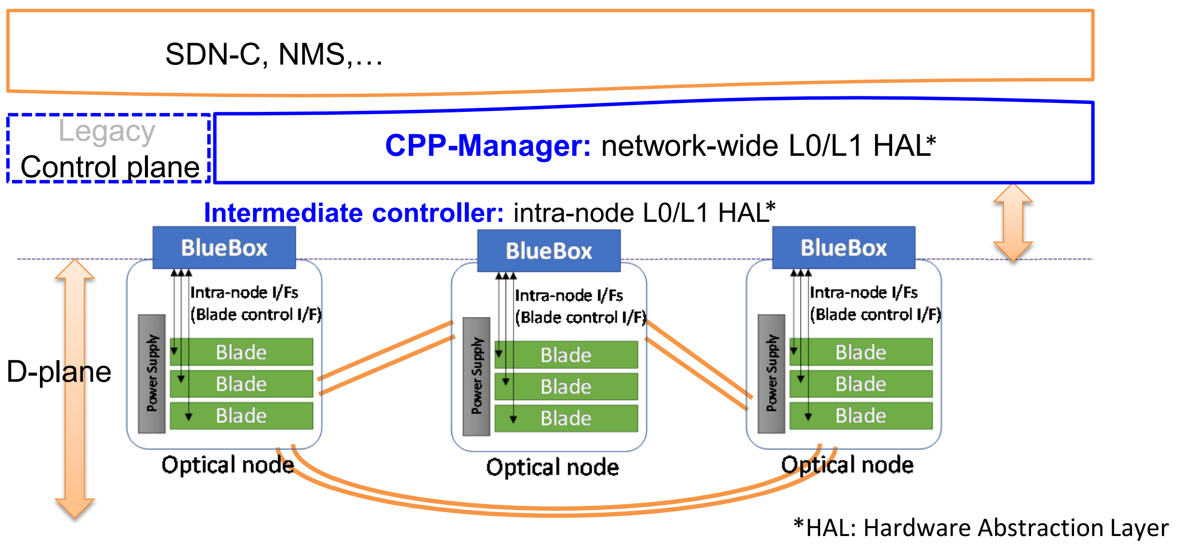
In allowing full automation, the platform makes the optical layer as usable as the upper layers, as well as being dynamically and directly cooperative with various applications. For example, by cooperating with the 5G radio access network, the optical layer offers an efficient network environment for wide-area, high-bandwidth, real-time, and mission-critical cloud applications. To substantiate such emerging applications, enhanced usability and automated operations in the optical layer are indispensable for building a truly secure, robust, disaster-proof, and sustainable cloud infrastructure for Society 5.0.

The proposed platform is named “cyber photonic platform” (CPP), emphasizing that the optical layer is an essential part of cyber physical systems. CPP transforms the optical layer, which has often been decried as costly, burdensome, and formidable, into something that is inexpensive, fast, and easy.

2. ARCHITECTURE OVERVIEW

CPP manages the optical physical layer (including the performance, construction, and configuration) and quickly provides available transmission capacity to the upper-layer networks (i.e., L2 or L3).To realize such a platform, a centralized network manager that comprehends the optical physical layer details is needed, as well as distributed controllers to reduce the workload of the centralized manager and conduct some localized operations. Figure 1 provides an overview of the CPP architecture. The **CPP-Manager**, which is in charge of the optical physical layer management, is placed between a software-defined network (SDN) controller or network management system (NMS) and the D-plane. The D-plane is the data plane of CPP, and is constructed with the **blades**, as shown in Fig. 1. The blades incorporate optical transport equipment or optical devices; they can be referred to as a basic unit for building the D-plane. The **intermediate controller** provides an integrated control mechanism among the blades to the CPP-Manager. The concept of the intermediate controller has been published as an IEC Technical Report[1]. In the remainder of this white paper, the intermediate controller is referred to by its development codename in CPP, BlueBox. The conventional connection between the data plane and the SDN controller or NMS is also supported via the legacy control plane.

A feature of CPP is its encapsulation of the whole optical physical layer (not only individual optical transport equipment). Such a platform can define a boundary around the optical physical layer, and then facilitate cross-boundary cooperation/optimization. Therefore, the CPP can shift the automation levels[2] upwards on each of the optical network operation lifecycles, i.e., planning, installation, path provisioning, and maintenance.



[1] IEC TR 62343-6-10:2017(E), "Dynamic modules – Part 6-10: Design guide – Intermediate controller for multiple dynamic module systems," 2017-03-22, Ed1.0

[2] The automation levels can be described as follows: (1) no-automation, where experienced operators manually handle the optical network, (2) partial automation, where experienced operators primarily handle the network with automated system supports, (3) half-automation, where an automated system primarily handles the network with experienced operators' approval, and (4) full-automation without experienced operators. The CPP operators will include carrier network operators as well as enterprise, datacenter, campus, and private network operators.

Fig. 1: CPP architecture

2.1. CPP-MANAGER: NETWORK-WIDE L0/L1 HAL

The CPP-Manager automates the optical physical layer management, which includes optical physical topology management, bridging between the optical physical topology and the upper layers, optical path provisioning, and signal quality management. That is, the CPP-Manager wraps details of the optical physical layer and can be referred as a network-wide L0/L1 hardware abstraction layer (HAL). Figure 2 illustrates the software modules that form the CPP-Manager. These modules can be explained as follows.

- ✓ **CPP-Manager core** provides fundamental functions of the CPP-Manager. The **node handler** provides an interface between the intermediate controller and software modules in the CPP-Manager. The **policy manager** manages the CPP-Manager policies regarding data collection, logging, authorization of database access, or priority rankings of the software modules within the CPP-Manager. The **physical layer data collector** is a software module that collects optical physical layer data and stores the data in the appropriate databases. The physical layer data collector also provides an interface to an operator for manual data input.

- ✓ **Topology management base** forms a basis for logical and physical topology management. The **physical topology DB** stores inventories of the blades installed in the network, blade functionalities, and intra/inter-node cabling information. The **logical topology manager** receives traffic demands from the higher network layers and translates them to optical path demands. The logical topology manager also translates the optical path connections to logical topologies that can be referenced by an SDN controller or NMS. The **physical topology manager** calculates and assigns optical layer resources to the optical path demands and issues blade configuration information for path provisioning or deletion. The **resource reservation DB** stores information on the resource utilization over time and the resource assignment results.

- ✓ **Quality management base** manages optical physical layer performance. The **monitoring DB** stores monitoring data about the optical physical layer, as measured by monitoring functionality blades (see section 3.1). The **test agent** assesses the transmission performance of the optical paths before path provisioning. The **simulation model manager** generates transmission simulation models, updates them based on the monitoring data, and estimates the transmission performance. The **quality design DB** stores the generated simulation models and the estimated and/or monitored performance. The **quality optimizer** adjusts transmission parameters when the transmission performance is not sufficient.

- ✓ **Alarm/warning handler** triggers restoration and raises suggestions for blade repair/replacement upon receiving an alarm/warning from the intermediate controllers. The **planning helper** makes suggestions regarding blade installation or updates by referring to the resource reservation DB. The **maintenance helper** makes suggestions for blade replacement or updates by referring to the quality design DB. The **black box plug-ins** manage distinctive operations dedicated to a specific blade; this software module will be provided by a vendor developing the corresponding blade to maximize the blade performance.

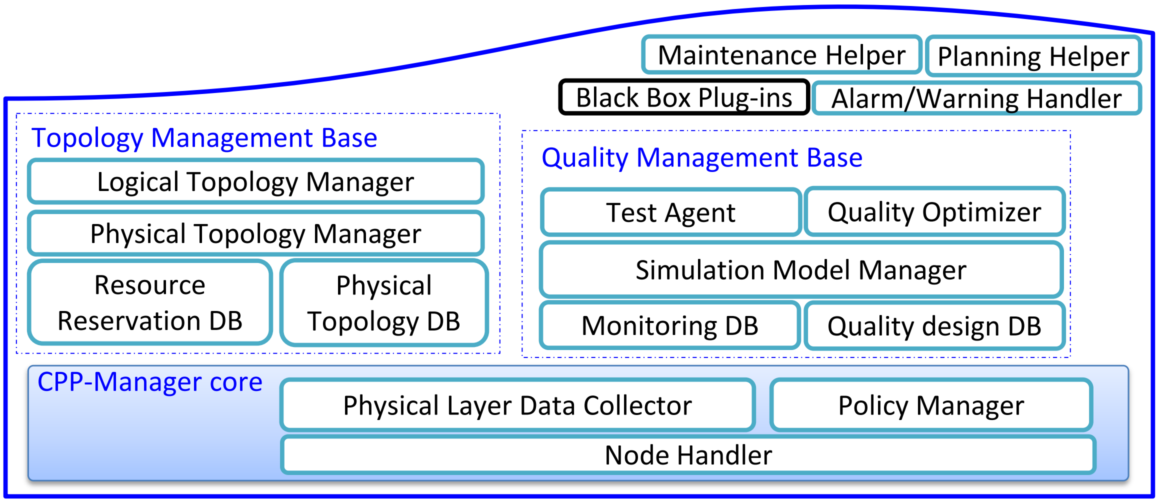


Fig. 2: Software architecture of CPP-Manager

2.2. BlueBox: Intermediate Controller

The intermediate controller encapsulates the interfaces of multiple blades and makes the various blades behave as a single optical node. Thus, BlueBox can be referred as an intra-node HAL. Figure 3 illustrates the software modules that constitute the intermediate controller.

- ✓ **Interface (IF) to CPP-Manager** provides an interface to the CPP-Manager.
- ✓ **IF to blades** provides an interface to the blades within the optical node.
- ✓ **Intra-node policy manager** manages intra-node operations, such as the distributed operations that the CPP-Manager delegates to the BlueBox (e.g., the fast protection switching described in section 6.3.3). The intra-node policy manager also manages intra-node data handling policies such as alarm notifications or filtering, which are sent to the CPP-Manager.
- ✓ **Blade installation handler** works at the blade installation process (see section 5.1).
- ✓ **Blade handler** is a software module for controlling the corresponding blade.
- ✓ **Intra-node data logger** collects data within the optical node according to the intra-node policy manager.
- ✓ **Intra-node alarm handler** receives and responds to alarms/warnings from blades within the optical node according to the intra-node policy manager.

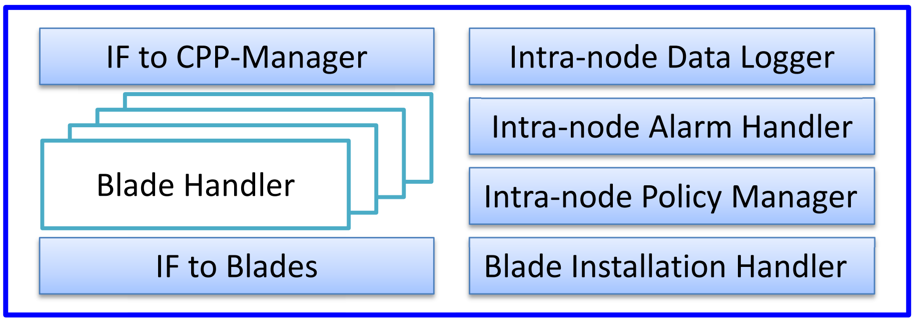


Fig. 3: System architecture of BlueBox

3. Blade Specifications

3.1. Functionality Classifications

The minimal set of blade functionalities consists of the five features described below. Each blade can have one or more functionalities.

- ✓ **Transponder functionality** is provided by transponders or transceivers that can change the transmission medium (e.g., optical to electrical/electrical to optical), modulation format (e.g., QPSK to 16 QAM), or data format (e.g. Ether to HDMI).
- ✓ **Switching functionality** is typically provided by optical switches, optical filters, or ODU cross-connects that can select or change the route taken by a signal.
- ✓ **Leveling functionality** is typically provided by optical amplifiers or variable optical attenuators that can change the power of the optical signals. (Note that the insertion loss of a blade is not defined as a leveling functionality.)
- ✓ **Monitoring functionality** measures physical layer data related to signal quality, such as OSNR, bit error rate (BER), or optical power. Based on the monitoring data, some blades send alarms to BlueBox.
- ✓ **Quality functionality** changes or adjusts values related to optical signal quality (except optical signal power), such as dispersion.

A switching functionality model that can describe different switching functionalities universally is mathematically formulated in section 6.3.4. The other functionality models will be investigated in the future.

3.2. Minimal API

Each of the five functionalities has to support *configuration* and *observation* as a minimal API for dynamic path provisioning and/or deletion. Some information-exchanging API is also needed at the installation step, as explained in section 4. Table 1 lists the parameters of the minimal API for the five functionalities, where O indicates that the parameter is optional.

Table 1: Minimal API for the Five Blade Functionalities

	Configuration	Observation	Info. ex.
Transponder functionality	port number (O), data format (O), modulation format (O), channel (O)	port number (O)	
Switching functionality	input port, input channel, output port, output channel	input port (O), output port (O)	
Leveling functionality	port number, gain value, channel (O)	port number (O) channel (O)	
Monitoring functionality	port number (O), channel number (O), monitoring item (O), threshold (O)	port number (O), channel (O), monitoring item (O)	
Quality functionality	port number (O), adjusting item (O), value	port number (O), adjusting item (O)	

3.3. Electromechanical Specifications

Guidelines for the physical implementations of the blades have been developed[3], where a 19-inch rack-mount 1RU-height blade is defined as the typical mechanical dimensions of a blade. Minimum requirements including design guidelines for the front panel and housing, options for the electrical power supply, and some degree of freedom for the control interface are described. Blade prototype implementations are shown in Fig. 4.

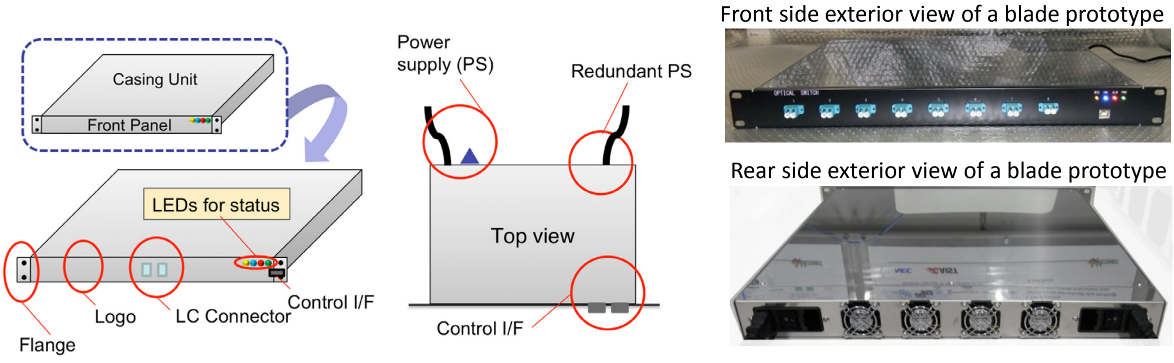


Fig. 4: Blade configuration diagram and prototype pictures

[3] CPPC guidelines, "Specification guidelines for the rack and blade of disaggregate optical transport/node systems," available at http://xxx.cppc-xxx.xxx

4. Exchanged Information

This section describes the minimal set of information that the CPP-Manager, BlueBox, and blades must exchange to handle the optical physical layer. Figure 5 provides an overview of the information flow.

- ✓ **Alarm information** is sent by the CPP-Manager to notify the operators of alarms in the optical physical layer.
- ✓ **Operation information** is input by the operators to handle alarms, suggestions, or exceptions raised by the CPP-Manager.
- ✓ **Blade placement** and **intra/inter-node cabling information** includes location information about individual blades and the D-plane connectivity information indicating which optical port of a blade is physically connected to which optical port of another (or the same) blade via intra/inter-node cabling. This information is collected and assessed in an installation step, as explained in section 5.1, and stored in the physical topology DB in the CPP-Manager. The information can be input by an operator or collected via some mechanism for optical network topology discovery.
- ✓ **Blade functionality information** includes the performance/specifications of the blades, which functionalities (defined in section 3.1) the blade is equipped with, and the functionality models. This information is exchanged in an installation step, as explained in section 5.1, and stored in the physical topology DB in the CPP-Manager.
- ✓ **Blade status information** indicates the blade status as being active, inactive, or failed. This information is stored in the physical topology DB and mainly exchanged during an installation step, although it can be shared at any time if necessary.
- ✓ **Blade control command information** includes command formats for controlling the individual blades.
- ✓ **Demand information** specifies the traffic demands to be accommodated in optical paths, including the source, destination, required bandwidth, and required latency. The information is sent from an SDN controller, NMS, or an application. It is then stored in the resource reservation DB before being mapped to the optical path demands by the logical topology manager.
- ✓ **Blade configuration information** is stored in the resource reservation DB as a result of path computations. The CPP-Manager sends this information to BlueBoxes for path provisioning or deletion. Each BlueBox translates the blade configuration information to the corresponding control commands based on the blade control command information, and then sends the commands to the individual blades.
- ✓ **Monitoring data information** includes the data measured by the monitoring functionality blades. This information is collected via BlueBox and stored in the monitoring DB. The information is constantly collected by the physical data collector as a background process, and can also be triggered by a test agent for a specific test process. The monitoring data is processed to assess the path quality, and the processed data are stored in the quality design DB.

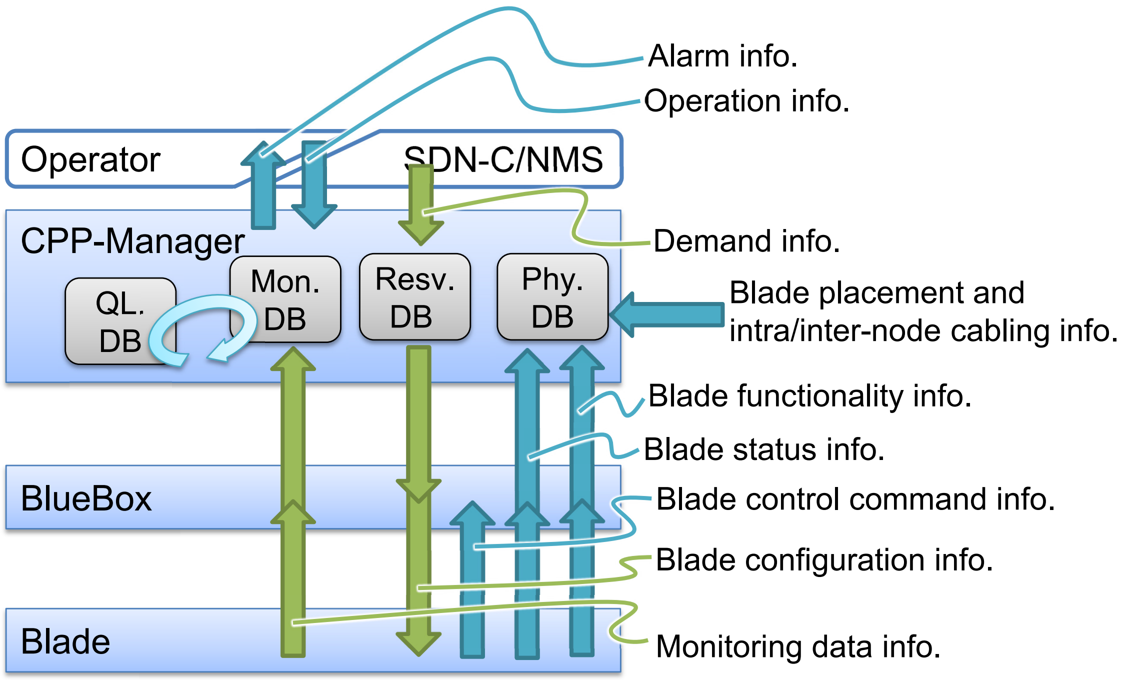


Fig. 5: Overview of the flow of the exchanged information; the green arrows denote dynamic path provisioning/deletion and the blue arrows denote installation or maintenance cycles.

5. Common Procedures

5.1. Planning, Installation, and removal

This section describes the automatic recognition of newly installed or removed blades, and the structure of the blade control system. The functions required for this procedure are the automatic recognition of blade insertion and removal, recognition of blade type, recognition of blade performance, storage of blade control commands, and update of the physical topology database. Examples of these procedures are shown below.

INSTALLATION

I. The [planning helper][M] detects areas that may face a shortage of optical physical resources and makes appropriate suggestions or receives requests from the upper layer for optical infrastructure expansion.

II. A site worker installs a blade and optical fibers in the target area.

III. BlueBox recognizes the insertion of the blade through the [blade activation status information][I].

IV. Activates the [blade installation handler][B].

V. BlueBox recognizes the type and performance of the blade through the [blade functionality information][I].

VI. Stores control commands to the [blade handler][B] as [blade control command information][I].

VII. Updates the [physical topology DB][M] through the [blade functionality information][I] (the connection status is an estimation at this point).

REMOVAL

I. BlueBox detects the removal of the blade through the [blade activation status information][I].

II. Through the [alarm information][I], the [alarm handler][M] sends an error message to the operator if an active path exists in the relevant area, and an alarm message if an active path does not exist.

III. The operator confirms that the removal is appropriate and enters the [operation information][I].

IV. The [physical topology manager][M] requests BlueBox to delete the corresponding [blade handler][B].

V. The BlueBox deletes the corresponding [blade handler][B].

VI. The [physical topology manager][M] updates the [physical topology DB][M].

VII. If an error occurs, the procedure described in section 5.6 is activated.

[M] indicates system modules in the CPP-Manager. See Fig. 2.
[B] indicates system modules in BlueBox. See Fig. 3.
[I] indicates exchanged information. See Fig. 5.

5.2. Misconfiguration Detection

This section describes how to check the fiber connection status among the blades installed or removed via the procedure in section 5.1. The functions required for this procedure are the generation of a test signal for checking the fiber connection, receipt of a test signal, checking the received test signal, and updating the physical topology database. An example of this procedure is shown below. In this example, only the connection between a newly installed transponder functionality blade and an already-deployed optical node is checked. The intra-node cabling in the already-deployed optical node is assumed to have passed the checking stage.

I. Activate the [test agent][M].

II. Generate and send a test signal via the applicable transponder through the [blade configuration information][I].

III. The [test agent][M] identifies the signal in reference to the [monitoring DB][M] generated through the [monitoring data information][I].

IV. The signal is checked against the [physical topology DB][M].

V. An error message is sent to the operator through the [alarm information][I] if the connection is not in the expected status.

5.3. Quality Estimation

This section describes how to check the link performance and transponder performance in the new optical physical layer updated via the procedures in sections 5.1 and 5.2. The functions required for this procedure are the generation of simulation models of transmission paths (links), calculation of the performance based on the simulation model, storage of the estimated transmission performance combining the transponder and link performance, correction of the estimated transmission performance based on monitoring information, and data entry into the quality management database. In this procedure, the parameters (optical output, wavelength, etc.) of the transponder are determined in advance. An example of this procedure is shown below.

I. The [simulation model manager][M] generates and retains a simulation model for each link.

II. Activate the [test agent][M].

III. Select target transponder and target link in reference to the [resource reservation DB][M] and [physical topology DB][M].

IV. Calculate performance of the target transponder based on simulation model (generalize all targets using Q-value, etc.).

V. Store the transmission performance estimated as a combination of the transponder and link in the [quality design DB][M]. The [test agent][M] refers to the [monitoring DB][M] and corrects the [quality design DB][M] as needed.

5.4. Quality Assessment

This section describes the optical path quality assessment based on the estimated transmission performance generated in section 5.3. The functions required for this procedure are the identification of link-wise transmission performance, calculation of transmission performance on the target path, and confirmation of the required performance. An example of this procedure is shown below.

I. The [logical topology manager]^{M} selects the target path from the upper-layer policy.

II. The [physical topology manager]^{M} selects the transponder and link corresponding to the target path from the optical physical layer information converted by the [logical topology manager]^{M}.

III. Retrieve link-wise transmission performance of all links included in the target path from the [quality design DB]^{M}, and calculate the total transmission performance along the target path (path performance is calculated by summing the link performance).

IV. Check whether the required performance is achieved.

V. If the required performance is not achieved, calculate the performance of subsequent candidate paths (e.g., different routes or different wavelengths).

VI. Update the [resource reservation DB]^{M} with the tentative reservation of selected paths.

5.5. Check Link-up Status and Handle Link-up Failures

This section describes how to check the path link-up status of the path selected in section 5.4. The functions required for this procedure are the generation of a test signal for checking the path link-up status, receipt of the test signal, checking of the quality of the received test signal, adjustment of transponder parameters, update of the quality management database, and update of the resource reservation database. An example of this procedure is shown below.

I. Activate the [test agent]^{M} and [quality optimizer]^{M}.

II. Generate and send a test signal via the corresponding transponder through the [blade configuration information]^{I}.

III. The [test agent]^{M} checks the signal quality in reference to the [monitoring DB]^{M} generated through the [monitoring data information]^{I}.

IV. If the signal quality does not meet the required performance, the [quality optimizer]^{M} adjusts the parameters (power, wavelength, etc.) of the transponder through the [blade configuration information]^{I}.

V. The [test agent]^{M} checks the signal quality again through the [monitoring data information]^{I}.

VI. If the signal quality meets the required performance, the [resource reservation DB]^{M} is updated by turning one of the corresponding tentative reservations into an official reservation, and unlocking other tentative reservations.

VII. As the number of wavelengths has changed, the transponder performance of the affected link is recalculated.

VIII. Update the [quality design DB]^{M}.

IX. If the signal quality does not meet the required performance, go back to step II to check the subsequent tentative reservation path.

X. If none of the tentative reservation paths meet the required performance, update the [quality design DB]^M, reject the reservation, and update the [resource reservation DB]^M.

5.6. Path Failure Detection & Recovery

This section describes the detection of errors in operational paths and the recovery behavior. The functions required for this procedure are the detection of optical signal loss, identification of the failure part, update of the quality management database, and notification to the operator. An example of this procedure is shown below.

I. Detect optical signal loss in reference to the [monitoring DB]^M generated through the [monitoring data information]^I.

II. If the [physical topology manager]^M specifies any protection, BlueBox switches paths.

III. If no protection is specified, perform the procedure in section 5.4 for rerouting the failed paths.

IV. Specify the failure part, and record in the [physical topology DB]^M that is should not be used for path calculations.

V. The [alarm handler]^M notifies the operator of the failure part through the [alarm information]^I. The operator replaces it, and performs the procedure in section 5.1.

5.7. Blade Degradation Monitoring & Maintenance

This section describes the detection of blade deterioration and maintenance. The functions required for this procedure are the monitoring of the signal required to determine deterioration, deterioration judgment, and notification to the operator. An example of this procedure is shown below.

I. Detect deterioration using monitoring information. If the level of deterioration is above some threshold level, it is treated as a fault (i.e., same procedure as installing and removing).

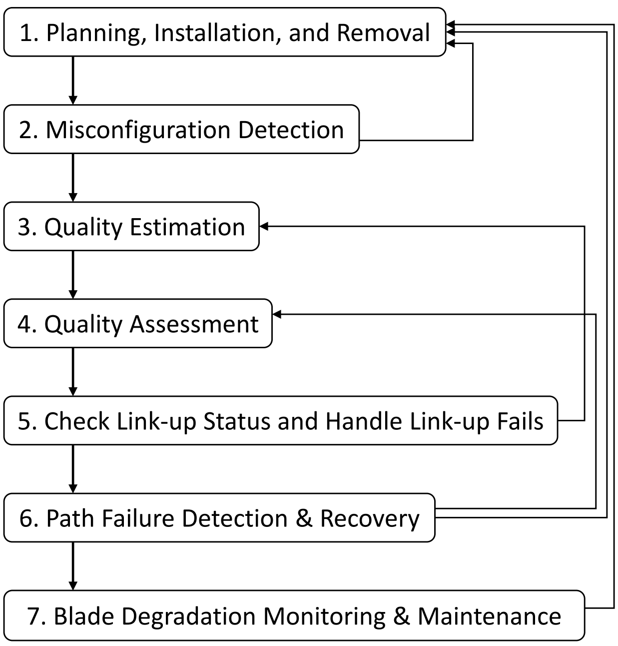


Fig. 6: State change diagram of the common procedures

6. Technical Implications

This section discusses technological trends and readiness toward an optical layer automation platform (i.e., CPP), use cases that can be achieved or extended by CPP, and emerging technologies that enable or enhance CPP.

6.1. Feasibility

6.1.1. Software: Legacy of GMPLS

GMPLS was an early effort to enable dynamic provisioning and restoration in optical transport networks[4,5]. Extensive worldwide R&D and standardization efforts have enhanced the maturity of GMPLS technologies. One of the most significant technological achievements of GMPLS is the introduction of a control plane, which enables signaling protocol, topology discovery, and path computation in optical transport networks. Separation of the control plane from path computation elements[6] has stimulated extensive R&D efforts regarding the programmability of the control plane to facilitate OpenFlow[7], an SDN technology. The controller interacts with the data plane via a southbound interface and with applications via a northbound interface. Research efforts to define such APIs and open-source software development efforts have lifted the technological maturity of programmability in packet switching and routing networks. Network Function Virtualization further improved programmability in the data plane by decoupling network function data plane software from middle-box appliances[8]. Furthermore, P4[9] aims to introduce programmability into packet switch data plane hardware. This packet-processing language allows programmers to specify the data plane behavior. The logically centralized control paradigm is applicable to large-scale networks, with consensus algorithms employed for distributed databases scattered across multiple physical controller devices. Given the technological maturity of GMPLS and related technologies, the programming of disaggregated optical transport networks is readily feasible.

6.1.2. Hardware: Evolution by digital coherent technology

In the late 2000s, a drastic change occurred in optical transport as digital coherent technology emerged and became popular. This had a significant impact on the feasibility of CPP in terms of hardware.

In legacy optical transport systems before digital coherent technology, the waveform, bandwidth, and bitrate of optical signals were fixed and optimized according to a vendor-specific design. There were no means to adaptively cope with waveform distortion and quality degradation of optical signals caused by optical filtering effects through reconfigurable optical add-drop multiplexers

[4] A. Banerjee, J. Drake, J.P. Lang, B. Turner, K. Kompella, and Y. Rekhter, "Generalized multiprotocol label switching: an overview of routing and management enhancements," IEEE Commun. Mag., vol. 39, no. 1, pp. 144-150, Jan. 2001.

[5] Y. Ye, C. Assi, S. Dixit, and M.A. Ali, "A simple dynamic integrated provisioning/protection scheme in IP over WDM networks," IEEE Commun. Mag., vol. 39, no. 11, pp. 174-182, Nov. 2001.

[6] A. Farrel, J. Vasseur, and J. Ash. "A Path Computation Element (PCE)-Based Architecture," Internet Engineering Task Force, RFC 4655, Aug. 2006.

[7] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "OpenFlow: Enabling innovation in campus networks," ACM SIGCOMM Comput. Commun. Rev., vol. 38, no. 2, pp. 69-74, Apr. 2008.

[8] B. Han, V. Gopalakrishnan, L. Ji, and S. Lee, "Network function virtualization: Challenges and opportunities for innovations," IEEE Commun. Mag., vol. 53, no. 2, pp. 90-97, Feb. 2015.

[9] P. Bosshart, D. Daly, G. Gibb, M. Izzard, N. McKeown, J. Rexford, C. Schlesinger, D. Talayco, A. Vahdat, G. Varghese, and D.Walker, "P4: Programming protocol-independent packet processors," SIGCOMM Comput. Commun. Rev., vol. 44, no. 3, pp. 87-95, Jul. 2014.

(ROADMs) or transmission impairments due to chromatic dispersion, polarization-mode dispersion, and nonlinear effects of fibers. Note that these transmission impairments depend on the route taken through the optical fiber network, and some vary in time even for a fixed route. As a result, the design and arrangement of whole transport systems, including optical transceivers, transmission lines, and repeaters, had to be optimally managed by a single vendor with sufficient margins of signal quality to operate over optical networks. This was an obstacle to a flexible, automatically tuned, and disaggregated optical transport layer, all of which are desired in CPP.

Fortunately, digital coherent technology[10,11] emerged as a game-changer in optical transport, providing several excellent features: 1) high sensitivity, which is intrinsic to coherent detection and achieved by soft-decision forward error correction[12], 2) generation and detection of high-capacity signals with spectrally efficient modulation formats and waveform shaping, including polarization multiplexing, and arbitrary vector modulation of the quadrature amplitudes of a complex optical field, 3) adaptive compensation of various waveform distortions, and 4) software control of signal properties such as the bandwidth, modulation format, and bitrate. These features significantly relax the limitations imposed on legacy systems and facilitate multi-vendor interoperability of optical transport with a variety of routing selections. To conclude, digital coherent technology is the key to flexible and scalable, disaggregated, and automatically (re)configured optical networks.

In addition to evolution by digital coherent technology as a key enabler of CPP in terms of hardware, other hardware components such as optical switches and optical amplifiers are also being readied to accommodate flexible operations corresponding to automatically (re)configured physical conditions. The software-defined operations of both digital coherent transmission systems and elements in nodes should facilitate the deployment of CPP.

6.2. Important Use Cases

6.2.1 Automatic network orchestration

SDN is defined as a control framework that supports the programmability of network functions and protocols by decoupling the data plane and the control plane. The separation of the data plane from the control plane makes SDN a suitable technology for end-to-end automatic network orchestration across multiple network domains with heterogeneous and incompatible control plane and data plane technologies[13]. The introduction of SDN in the optical layer has the potential to facilitate application-specific network slicing in the optical layer, as well as the coordination and orchestration of higher network layers, as shown in Fig. 7.

However, physical layer control systems are complicated by transmission engineering requirements, including the quality of transmission (QoT), optical power stability, and multidomain service guarantees[14]. Therefore, it is necessary to manually recognize and abstract the network component parameters of the optical nodes, optical links, and operation parameters for network control. This process would normally take days to weeks to implement service deployment or network reconfiguration. Considering this situation, if CPP were applied to control mechanism of optical

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[10] K. Kikuchi, "Fundamentals of Coherent Optical Fiber Communications," J. Lightw. Technol., vol. 34, no. 1, pp. 157-179, 2016.

[11] S.J. Savory, "Digital Coherent Optical Receivers: Algorithms and Subsystems," J. Sel. Top. Quantum Electron., vol. 16, no. 5, pp. 1164-1179, 2010.

[12] K. Onohara et al., "Soft-Decision-Based Forward Error Correction for 100 Gb/s Transport Systems," J. Sel. Top. Quantum Electron., vol. 16, no. 5, pp. 1258-1267, 2010.

[13] R. Vilalta et al., "The Need for a Control Orchestration Protocol in Research Projects on Optical Networking," published in The European Conference on Networks and Communications 2015 (EUCNC2015).

[14] Y. Li et al., "Optical Physical Layer SDN," J. Opt. Commun. Netw., vol. 10, no. 1, pp. A110-A121, 2018.

networks, the operation could be simplified by eliminating the need for manual parameter settings and operation labor, thus reducing configuration mistakes. As a result, the network control process could be completed in minutes or less. Furthermore, CPP has the potential to improve the flexibility (e.g., zero touch provisioning) and fault tolerance of optical networks.

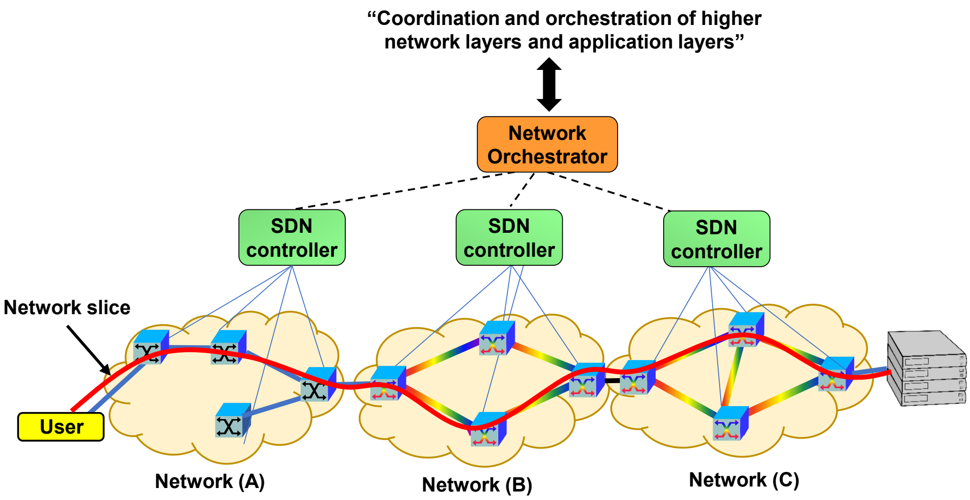


Fig. 7: Concept of network orchestration in the optical layer

6.2.2. Disaster recovery

The resilience of an optical network should be ensured to guarantee 99.999% service availability in daily service and to recover quickly in case of disasters. From the perspective of disaster recovery, and in light of R&D in CPP regarding disaggregation, openness, multi-vendor interoperability, abstraction, programmability, and automation, CPP can meet any reasonable requirements.

In the D-plane, to achieve quick recovery of damaged node systems (e.g., ROADMs), the open and multi-vendor interoperable disaggregated subsystems (e.g., transponder, ADD/DROP, optical amplifier) can be employed as recovery resources to quickly replace the damaged subsystems in the CPP-based node systems, disregarding the vendor boundary. Moreover, the disaggregated subsystems can even be integrated into legacy node systems to recreate the lost functionalities[15]. As shown in Fig. 8, these goals are achievable with CPP because of the openness and interoperability among multi-vendor products at the subsystem level. With standardized APIs for control/management/orchestration, and the abstraction mechanisms of CPP that can flexibly cope with diversified subsystems (e.g., have different intra-node structures and corresponding constraints)[16,17], rapid integration and automatic control of multi-vendor-based CPP networks can be achieved after a disaster.

In addition to D-plane recovery, the quick recovery of the damaged control and management plane network is highly desirable. With the quickly recovered control and management plane, as

[15] M. Shiraiwa, N. Yoshikane, S. Xu, T. Tsuritani, N. Miyata, T. Mori, M. Miyabe, T. Katagiri, S. Yoshida, M. Tanaka, T. Hayashi, H. Sugiyama, I. Satou, M. Mikuni, S. Okamoto, N. Yamanaka, B. Jeong, Y. Awaji, and N. Wada, "Experimental demonstration of disaggregated emergency optical system for quick disaster recovery," IEEE J. Lightwave Technol., vol. 36, no. 15, pp. 3083-3096, Apr. 2018.
[16] K. Ishii, A. Takefusa, S. Namiki, and T. Kudoh, "Topology description generation and path computation framework for dynamic optical path network with heterogeneous switches," in Proc. OFC 2018, Tu3D.7, Mar. 2018.
[17] S. Xu, N. Yoshikane, M. Shiraiwa, T. Tsuritani, H. Harai, Y. Awaji, and N. Wada, "Node internal modeling for network recovery with emergency optical systems," in Proc. OFC 2018, M4A.2, Mar. 2018.

shown in Fig. 8, operators can quickly collect network damage information, which enables early and optimal planning for cost-effective and rapid recovery, and control the surviving optical network resources to offer emergency optical communication services after the disaster. Control and management plane network self-healing schemes and optical supervisory channel recovery schemes[17] have been proposed. Incorporating such control and management plane recovery schemes into CPP significantly enhances the resilience of optical networks.

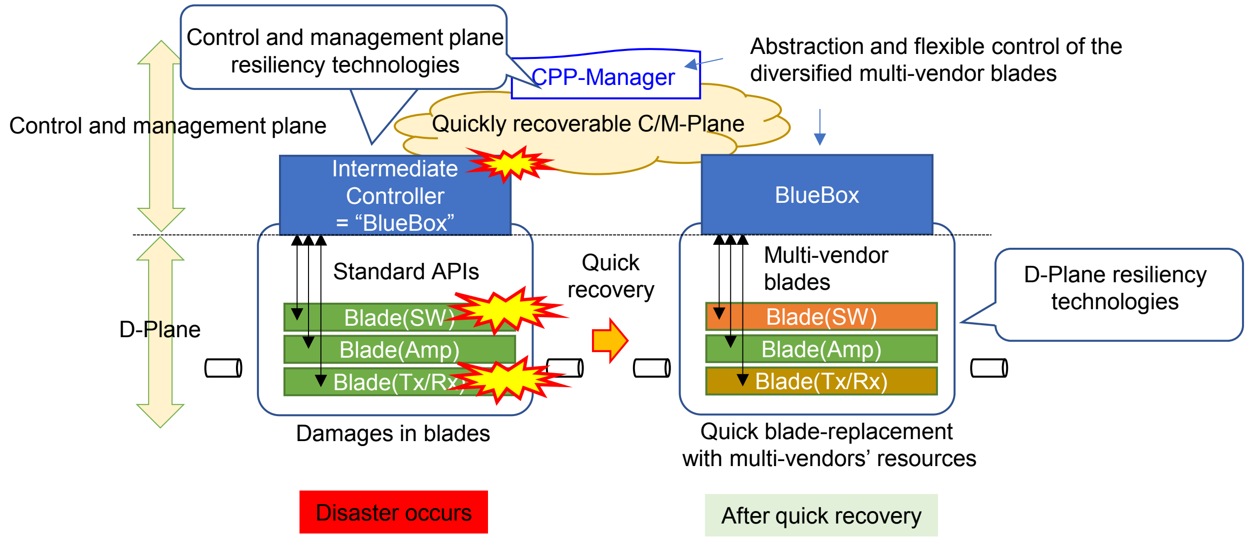


Fig. 8: Enhanced resilience with CPP technologies (in disaster recovery)

6.2.3. Post-Moore's law computing

Moore's law is soon expected to fail because of technological and economical limitations. Indeed, the performance improvement of general-purpose processors and memory density has been slowing down. This is leading to post-Moore-era computing. Various specialized processing accelerators have been proposed for specific purposes, including deep learning ASICs, neuromorphic, analog, and quantum computers. The use of such heterogeneous accelerators is the key to achieving sustainable performance improvement in the post-Moore era. Based on this background, disaggregated data center architectures such as flow-centric computing [18] have been proposed. Resource disaggregation is a promising solution to the limitations of current data centers, such as the lack of operational flexibility, low resource utilization, and low maintainability. Resources such as the CPU, accelerator, memory, and storage are pooled and interconnected via a high-speed network, as shown in Fig. 9 (left). According to user requirements, the data center operating system (OS) constructs a slice, i.e., a data processing environment, from the pool and provides it to the user, as shown in Fig. 9 (right). Data movement among components is unavoidable on such a heterogeneous system, and this is the performance bottleneck. Therefore, a high-speed data center network technology is required that enables the faster movement of data in a highly energy efficient manner, with an approximate energy per bit of less than that required for DRAM access (1 pJ/bit) and bandwidth per fiber equivalent to memory bandwidth (tens of Tbps). This presents an opportunity for open optical transport/node systems. In terms of the system architecture, holistic resource management is essential (here, holistic means that a data center OS can dynamically control and optimize optical paths in cooperation with slice construction/destruction). An API-friendly optical transport/node system is required for such controllability and manageability.

[18] R. Takano and T. Kudoh, "Flow-centric Computing Leveraged by Photonic Circuit Switching for the Post-Moore Era," IEEE/ACM International Symposium on Networks-on-Chip (NOCS) 2016, Sep. 2016.

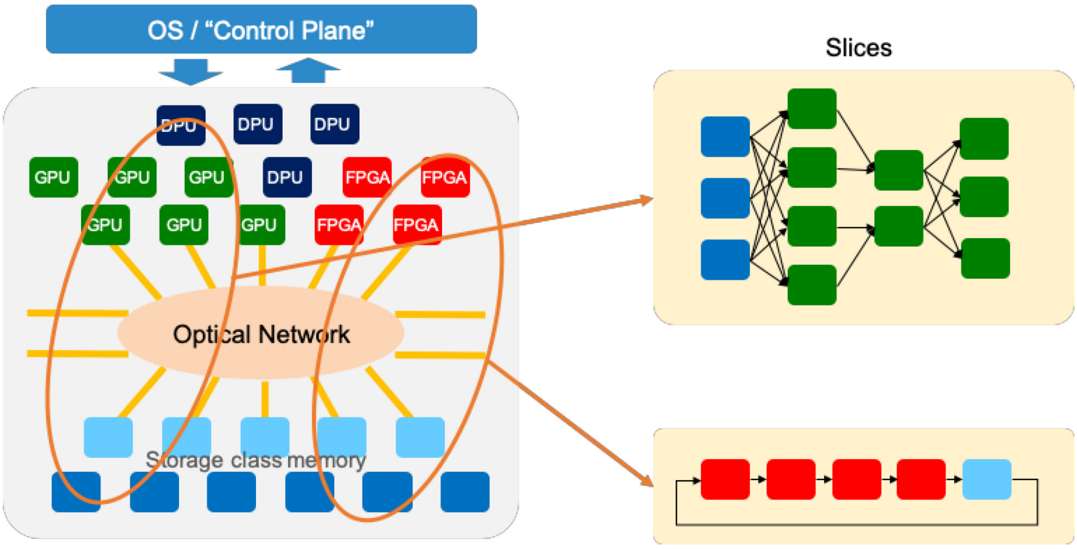


Fig. 9: Flow-centric computing

6.3. Enabling Technologies for CPP

6.3.1. Monitoring physical properties

The monitoring technology utilized to assess the optical signal transmission quality is very important as the basis of efficient optical network operation, as determined by the quality management module of the CPP-Manager. To date, simple monitors such as optical power monitors or BER monitors have been used in optical networks. An example application using the BER monitor is the QoT estimator with a learning process[19]. The learning process enables the optimum assignment of modulation format, resulting in a 15% improvement in the total network throughput.

Future optical transport equipment will offer a variety of programmability, and so more sophisticated monitoring technologies are required to derive better performance from the optical network. Recently, advanced monitoring of the optical physical layer using machine learning has been studied, and a deep neural network that estimates OSNR from received optical I/Q signals has been proposed[20].

Optical physical layer monitoring technology leveraged by a deep neural network is expected to realize not only the monitoring of physical quantities, but also the detection and/or prediction of failures and/or degradations. Furthermore, deep neural networks may be able to extract sophisticated parameters whose physical meaning cannot be comprehended by humans, and realize advanced optimal control of the optical network.

6.3.2. Autonomous management of optimal operations

As the performance and functionality of the optical network becomes greater, the number of transmission parameters increases tremendously. This may prevent the centralized network controller from handling all control workloads of the network. A possible solution for this issue is for optical

[19] S. Oda, M. Bouda, O. Vassilieva, Y. Hirose, T. Hoshida, and T. Ikeuchi, "Network Capacity Improvement by Quality of Transmission Estimator with Learning Process," in Proc. of ECOC2017, paper Th.2.C.4, 2017.
[20] T. Tanimura, T. Hoshida, T. Kato, S. Watanabe, J.C. Rasmussen, M. Suzuki, and H. Morikawa, "Deep Learning Based OSNR Monitoring Independent of Modulation Format, Symbol Rate and Chromatic Dispersion," in Proc. of ECOC2016, paper Tu.2.C.2, 2016.

nodes to communicate all control signals and optimize the operation autonomously under the supervision of the centralized network controller (see Fig. 10). Autonomous local control may also help in the recovery of optical paths following a disaster in which the control and management plane connections between some optical node and the centralized network controller are lost and/or the centralized network controller itself is down.

An autonomous local control technology using frequency shift keying in-band supervisory signals between paired transceivers has been reported [21]. This technology can detect the configuration mismatch between paired transceivers, as well as the frequency drift of adjacent channel(s) due to some failure, and can fine-tune the central frequency of the transmitting channel to minimize the interference from the drifted adjacent channel(s).

It is important to combine centralized and distributed local control mechanisms adequately considering the network elasticity and resiliency as well as the optical transmission performance and scalability. In CPP, such coordinated control is managed by the CPP-Manager, which delegates some quality management base functionalities to the BlueBoxes and/or blades.

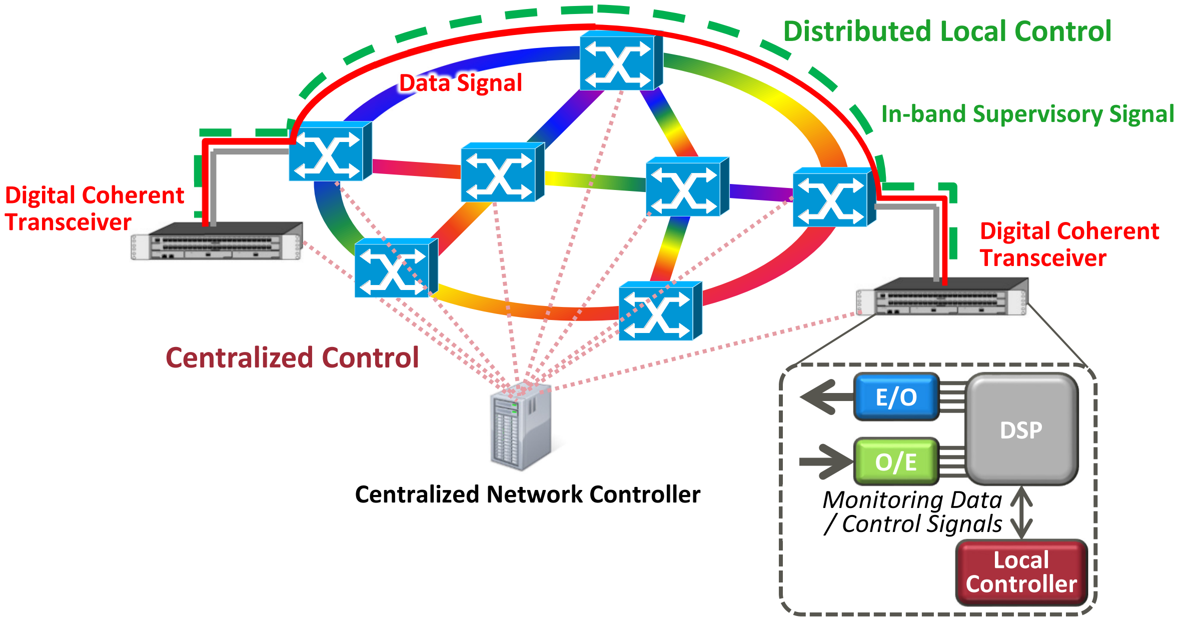


Fig. 10: Autonomous local control for optimal operations under the supervision of the centralized network controller

6.3.3. Inter-blade cooperation for path protection

Disaggregated optical nodes are also required to detect alarms and react in real time, as in conventional aggregated node systems for reliable optical networks. An intra-node controller that handles the operation of optical component units within a disaggregated node to guarantee fast node controls is proposed. This intra-node controller realizes inter-blade cooperation. Fast protection experiments were carried out using a pair of disaggregated node systems that included a Si multicast switch (MCS), transponder, and intra-node controller. Figure 11 shows the experimental setup. Using this setup, 1:1 optical switching as fast as 3 ms was demonstrated.

[21] Y. Ge, S. Oda, Y. Zhao, G. Huang, S. Yoshida, H. Nakashima, Y. Akiyama, Y. Hirose, Z. Tao, and T. Hoshida, "Autonomous and Real-time Controlled Transceiver Prototype with FSK Supervisory Signal and Performance Monitoring," in Proc. of ECOC2017, paper M.2.F.5, 2017.

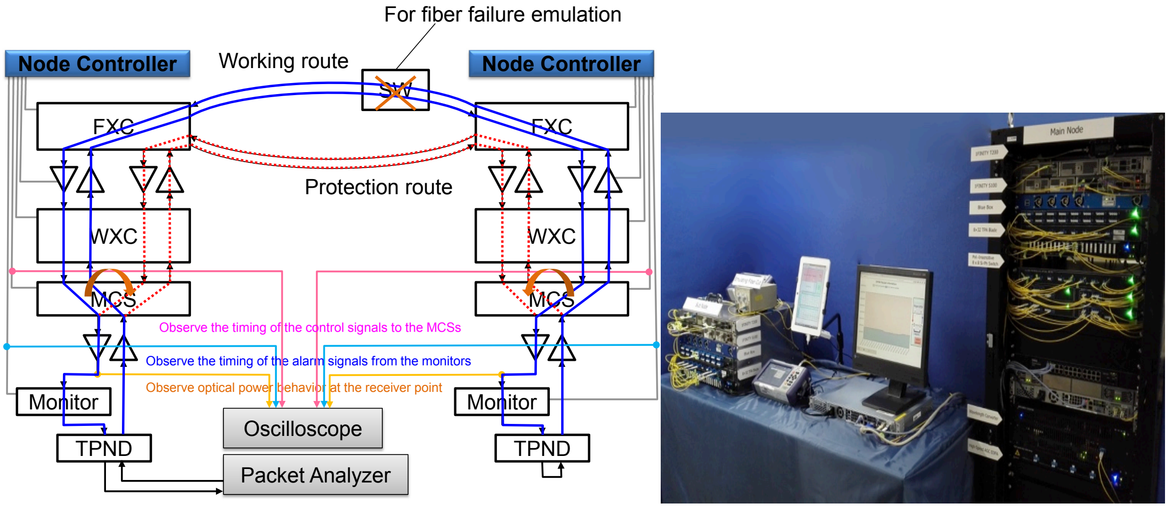


Fig. 11: Inter-blade cooperation for fast protection

6.3.4. Optical physical topology description scheme and path calculation

The heterogeneous optical nodes consisting of arbitrary blade combinations should be consistently handled in CPP. Thus, detailed information about the optical physical topology, including inter-blade physical connections (i.e., intra-node cabling) and the functionalities of individual blades, should be described in a machine-readable and automation-friendly manner.

An optical physical topology description scheme has been proposed and evaluated through path computation[16,22,23]. In the description scheme, the switching functionalities of individual blades are defined using Integer Linear Programming. Different switching functionalities such as a wavelength-selective switch (WSS) and fiber cross-connect (FXC) can be defined in a common format and processed by a common software program for path computations. The switching functionality of whole optical nodes or optical networks is generated by building the individual functionalities of the interconnected blades (see Fig. 12). Such a formulation facilitates the systematic and automated generation of path search spaces within optical networks comprising various switching functionality blades, which can lead to rapid hardware updates. In contrast, conventional models of blade functionalities typically employ human-friendly labels such as WSS or FXC to describe the functionalities. Furthermore, the conventional topology description typically treats a whole optical node as a vertex in a search graph, and does not consider configurations inside the node. Such a conventional scheme includes ambiguities in the functionality definitions and, as a result, the automation level can be limited within the pre-determined network configurations.

[22] K. Ishii, A. Takefusa, S. Namiki, and T. Kudoh, "Multi-granular optical path computations based on physical network topology descriptions," in Proc. OECC2018, paper 6A1-2, 2018.
[23] K. Ishii, A. Takefusa, S. Namiki, and T. Kudoh, "Efficient path calculation scheme for advance reservation of hierarchical optical path network using continuous variables to represent switch states," in Proc. PSC2018, paper Fr3A.2, 2018.

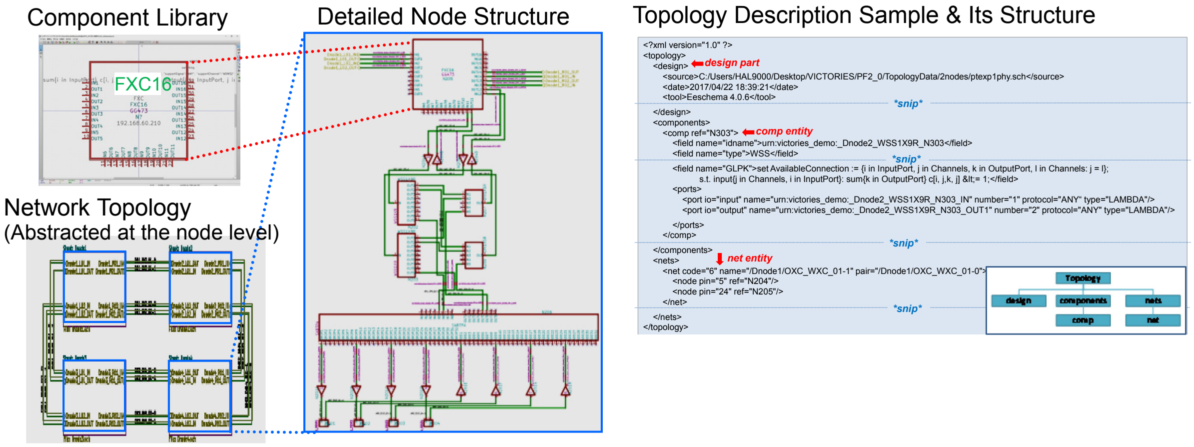
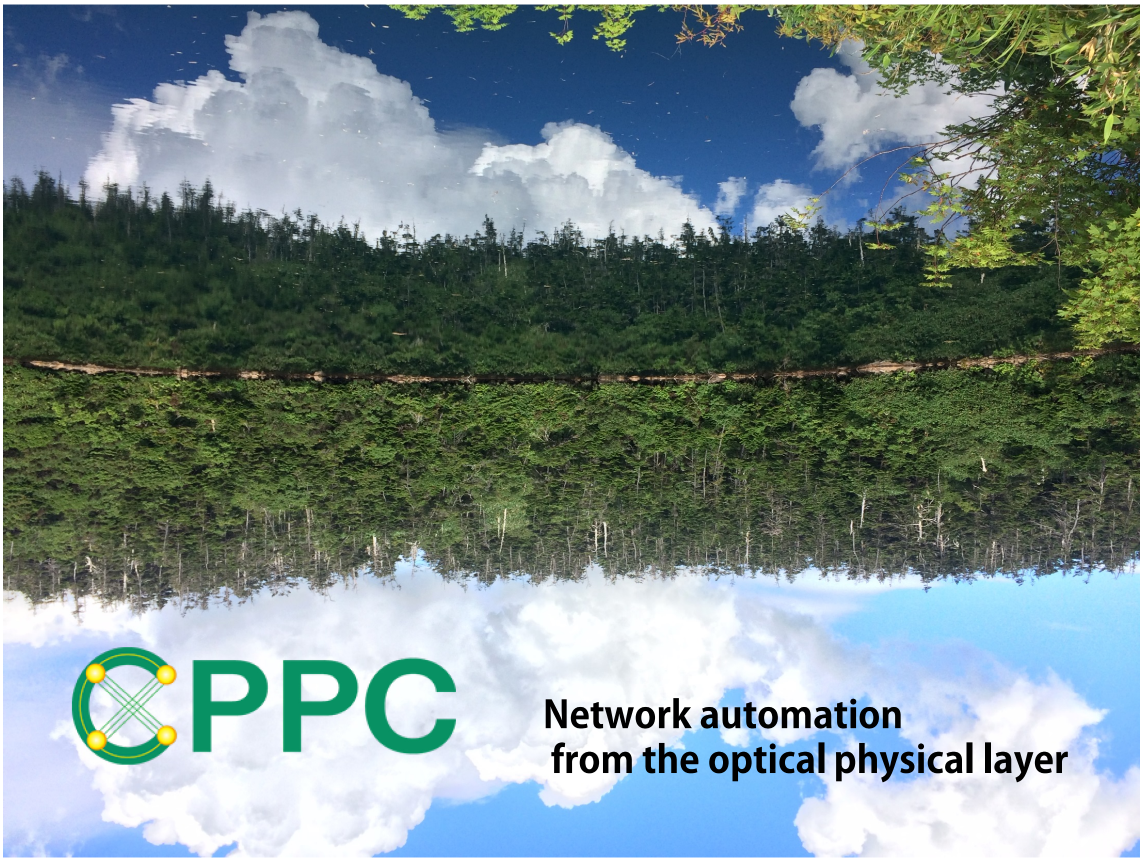


Fig. 12: Concept and sample of the proposed topology description scheme

7. Glossary

- **4K/8K:** display resolutions. 4K corresponds to approximately 4000 (horizontal) × 2000 (vertical) pixels and 8K corresponds to approximately 8000 × 4000 pixels. Several different standards are defined according to the detailed pixel numbers, frame rate, or color depth. 4K/8K offers higher-definition digital images and more realistic sensations than conventional HD, so it is promising for future video applications such as remote coexistence.
- **Blade:** building block of the optical physical layer in CPP. A blade is implemented in a certain size box (blade) that includes optical devices, control circuits (if necessary), and an interface for BlueBox.
- **BlueBox:** development codename of intermediate controllers in CPP. The name is derived from an initial developer drawing a square with a blue marker on a whiteboard to explain the concept and architecture. The abbreviation "BB" is used among developers.
- **Digital coherent technology:** combines coherent optical communication technology and digital signal processing technology to realize large-capacity optical signal transmission. In coherent optical communication technology, frequency modulation and phase modulation become applicable by demodulating the optical signal according to the interference between the signal and a local oscillator in the receiver. The digital signal processing technology processes the digital data sampled at the receiver, which enables adaptive compensation of signal distortions peculiar to optical fiber transmission such as chromatic dispersion and polarization dispersion. Powerful error correction processing such as forward error correction becomes applicable thanks to digital signal processing.
- **Disaggregation:** system construction mechanism, particularly in optical networks, that is not based on conventional all-in-one optical transport equipment, but introduces modular optical transport equipment disaggregated for each function and enables construction of a whole optical network with arbitrary modules. Benefits such as CAPEX reduction, agile installation, flexible planning, and application expansion of optical networks are expected. Multi-vendor operation is implicitly assumed in such disaggregation systems. For long-haul transmission, in particular, the guarantee of transmission performance is one of the most important technical issues. From an operational point of view, designing responsibility divisions is a strong concern.
- **D-plane:** optical physical layer configuring the data plane of CPP.
- **Hardware abstraction:** conceals the detailed setting parameters of the optical communication devices constructing the optical physical layer from the upper control/management planes consisting of an SDN controller or NMS. With such hardware abstraction, agile optical physical layer configuration can be achieved without placing an additional workload on the upper-layer control/management planes.
- **Intra/inter-node cabling:** optical fiber connection among the optical ports of the blades in CPP. Attributes such as distance are managed in the topology information. If multi-core fibers are installed, the optical fiber connection corresponds to an optical fiber core connection and the core groups belonging to the same multi-core fiber are described in the topology information as an attribute. Inter-node cabling over a certain distance (e.g., 10 km) is sometimes called a *fiber link*.

- **Optical node:** optical communication node in CPP, which consists of a set of blades controlled by the same BlueBox.
- **Optical physical layer:** transponders, optical switches, optical amplifiers, and so on, interconnected via optical fibers, which form the optical data plane. The optical physical layer managed by a CPP-Manager is referred to as the D-plane.
- **Society 5.0:** a concept of future society proposed by the Japanese government. Economic development and the resolution of social problems are simultaneously envisioned by combining cyberspaces where IoT, Big Data, AI, etc. exist, and physical spaces where people live. See https://www8.cao.go.jp/cstp/society5_0/index.html.



ABOUT CPPC

The Cyber Photonic Platform Consortium (CPPC) was established on April 1, 2018, as one of the AIST consortia. The purpose of CPPC is to drive the automation of an optical network layer leading to new market creation, and to pursue the sustainable development of the future information communication industry.

For more information about CPPC, please go to https://unit.aist.go.jp/esprit/cppc/.

This white paper was written by the technical committee of CPPC. In addition to AIST, the technical committee members are NEC, Fujitsu, NICT, KDDI Research, the University of Tokyo, NII, and Tokyo City University.