Opening up ROADMs: Let Us Build a Disaggregated Open Optical Line System

Jan Kundrát, Ondřej Havliš, Jaroslav Jedlinský, and Josef Vojtěch, *Senior Member, IEEE*

***Abstract*—At the lowest layer of today's communication networks is an optical line system (OLS), a physical network of equipment, which carries high-frequency analog light signals over thousands of kilometers. Traditionally, an OLS was delivered as a turn-key solution by a single vendor. Within an OLS, reconfigurable optical add/drop multiplexers (ROADMs) are active devices responsible for routing spectral chunks between input and output ports. ROADMs are arguably the most complex physical component of an OLS. In this paper, we describe an open design of a Czech Light ROADM, including the optical hardware, electronics, software, and the northbound communication interface. The performance of the ROADMs is evaluated in two test scenarios.**

***Index Terms*—Disaggregation, optical DWDM network, reconfigurable add-drop multiplexer, reconfigurable architectures, resource allocation, resource sharing, ROADM, spectrum sharing, transmission systems, white box, YANG.**

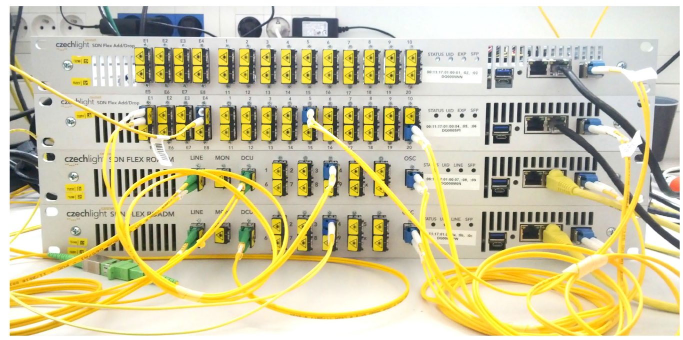


Fig. 1. A round of four ROADM prototypes undergoing initial bring-up at CESNET laboratories in Prague (September 2018). Top to bottom: two Route-and-Select Add/Drop units (Section III-B), two Line Degree units (Section III-A).

I. Introduction

OPTICAL Line Systems (OLS) provide infrastructure which carries optical signals over long distances and build the core of today's Internet. Reconfigurable Optical Add-Drop Multiplexers (ROADM) are a key building block [1]. These devices are located within the network nodes, and they route chunks of optical spectrum among fiber directions, filtering, attenuating and amplifying the optical signals as they travel through. ROADMs are ubiquitous and readily available on the market these days. This paper presents a comprehensive description of how one possible ROADM design can be built in an open manner using components which are available for procurement in small-quantities. The design and assembly of the system is within resources of a laboratory of a National Research and Education Network (NREN).

CESNET, a Czech research and education network, has been working on individual components of an OLS system under the Czech Light name since 2004 [2]. Originally starting with amplifiers, optical switches and specialty equipment, a fixed-grid ROADM [3] with NETCONF [4] northbound control interface was introduced in 2016.

This paper describes a next step in our development, a set of 1U "pizza box" modules for building Flexgrid, Colorless, Directionless and Contentionless ROADM nodes in an open manner.

We are certainly not the only non-vendor entity building disaggregated network elements in their laboratories. Researchers from the Metro-Haul project utilized "two low cost ROADM prototypes developed by TIM" [5] for their hierarchical SDN controller. ADVA announced a successful trial of their transponder platform over Tencent's in-house OLS, the OPC-4 [6]. To the best of our knowledge, however, we are the first non-vendor to:

- Document the design in a publicly accessible manner, enabling others to reproduce our work and build upon it.
- Create a prototype suitable for production deployments and designed with resilience, redundancy and use outside of a controlled lab environment.

The rest of this paper is structured as follows. Section II summarises operation of generic ROADMs and their expected feature set and refers to existing literature for analysing trade-offs in possible ROADM optical designs. Section III describes the optical design we chose including the optical schematics of two ROADM prototype models. In Section IV, we describe the custom made hardware, the commercially available components which were used, and certain challenges which were overcome during development. Section V provides a reference of the software architecture, including both existing open-source software

Manuscript received December 13, 2018; revised March 4, 2019 and March 18, 2019; accepted March 18, 2019. Date of publication March 27, 2019; date of current version July 31, 2019. This work was supported in part by the Ministry of Education, Youth and Sport of the Czech Republic as part of the CESNET E-infrastructure Project LM2015042 and in part by the project "E-infrastructure CESNET—modernization," CZ.02.1.01/0.0/0.0/16_013/0001797. *(Corresponding author: Jan Kundrát.)*

J. Kundrát is with the Department of Photonic Networks, CESNET a.l.e., 160 00 Prague, Czech Republic, and also with the Faculty of Mathematics and Physics, Charles University, 110 00 Prague, Czech Republic (e-mail: jan.kundrat@cesnet.cz).

O. Havliš, J. Jedlinský, and J. Vojtěch are with the Department of Photonic Networks, CESNET a.l.e., 160 00 Prague, Czech Republic (e-mail: ondrej.havlis@cesnet.cz; jaroslav.jedlinsky@cesnet.cz; josef.vojtech@cesnet.cz).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2019.2906620

This work is licensed under a Creative Commons Attribution 3.0 License. For more information, see http://creativecommons.org/licenses/by/3.0/

as well as software developed for the ROADMs. The real-value utility of the ROADM prototypes is evaluated in Section VI. Finally, Section VII concludes the paper, providing a summary and an outline of our future plans.

II. Requirements

The end purpose of a ROADM is to facilitate Media Channel (MC) routing over a fibre network. A given spectral band (such as the C-band) is divided into slices which are then routed between various input and output ports of the ROADM. This forwarding capability is defined in terms of frequency boundaries (i.e., what media channel to route), the termination points of the MC, and adjustments to the signal power.

In addition to forwarding of light, the signal should be monitored in some manner. As the ROADM operates exclusively in the photonic domain, the set of measurements does not involve deep insight into the signals which are carried. The measurements concentrate strictly on properties of the spectrum.

Any other functionality only serves a supporting function for this primary goal of spectrum management.

A. Spectrum Provisioning

Modern ROADMs operate on flexgrid basis, i.e., with spectrum slices of variable width and located at various channel center frequencies [7]. The actual granularities of ROADM operation (required alignments of the slices, or the granularity of their widths) vary between device models.

The filtering and media channel routing is often realized by Wavelength Selective Switches (WSS). A WSS consists of N input ports and M output ports, and can be configured to route sections of spectrum between a given input port to an output port. This forwarding comes with a built-in attenuation due to the device's Insertion Loss (IL).

In terms of media channel routing, two basic types of connections are present within a ROADM node. The *express* connections route MCs between ROADM lines (nodal degrees). The *local* or *Add/Drop* connections offer a way of inserting and extracting client signals at the local node, using a single-wave interface towards the transponder modules. There is a simple taxonomy of ROADM according to the capabilities of the Add/Drop ports:

- A *Colorless* port is a client-facing port which can be reconfigured to carry any "color" (wavelength) of light.
- *Directionless* capability means that the signal passing through a given client port can be routed towards any line degree.
- Finally, a *Contentionless* Add/Drop configuration enables carrying more then one instance of the same wavelength (via a different express connection) through a single Add/Drop unit.

Modern ROADMs tend to be colorless and directionless. Contentionless designs are understood and possible, but in absence of readily-available M $\times$ N WSSes they require massive amplifier arrays and/or multicast optical switching.

B. Spectrum Monitoring

A basic measuring device is a photodiode (PD). As a light-sensitive instrument, the PDs measure the intensity of light which is hitting the PD's active area. The PDs can be characterized by their spectral sensitivity, i.e., their response to a unit power of light in different frequencies. Each physical measurement should be characterized by its associated spectrum.

A more advanced measuring device is an Optical Channel Monitor (OCM). An OCM can be modeled as a serial combination of a filter, possibly tunable, followed by a photodiode. In a flexgrid ROADM, the OCM is typically also capable of flexgrid operation. An OCM can therefore measure the optical power being transmitted in a given media channel.

If the flexgrid OCM offers a better resolution than one bin per media channel, the device can be also used for more advanced measurements. An example of these is a Power Spectral Density (PSD) measurement which offers a rough characterization of the channel's spectral characteristics.

C. Amplification

As the signal travels through the optical fibre, its energy is being dissipated along the path. A typical figure is at least 10 dB per 50 km of fiber. The modules described above (WSS and OCM) also incur certain losses. In case of a WSS, the IL is typically between 4 dB to 8 dB. An OCM or PD by definitions consumes all incoming light, and is therefore typically placed on an optical tap which redirects a fraction of the optical power towards the measuring sensor while passing through the remaining part of the signal. The typical IL for the signal path of a 1% tap is 0.2 dB, with the PD/OCM measuring a value of power which is 21 dB below the original signal source. For a 1:8 coupler, the IL is typically at about 11 dB. Optical connectors also have IL, in our case up to 0.5 dB per each connection [8].

The most common device used for amplification is an Erbium-Doped Fiber Amplifier (EDFA) [9]. There are other options, such as Raman amplification, but they are not suitable for compensating losses within the ROADM box itself.

D. Laser Safety Considerations

Legal requirements control the safe operation envelopes of DWDM fibre equipment. The most important documents and recommendations related to laser safety of communication fibre systems are EN 60825-1, EN 60825-2, IEC/TR 61292-4, ITU-T G.664, ANSI Z136.2, etc. The following are the basic limitations for a user-accessible connector and the C-band:

- The aggregate power in a single mode fiber must not exceed **+21.3 dBm** in order to qualify for the 1 M hazard level.
- Devices operating within *unrestricted environment* must reduce the power to at most **+10 dBm**, i.e., Class 1 power, within a few seconds upon a link break.

E. Minimal Signal Strength

As the signal gets weaker, it is more difficult to amplify it to a fixed target value because the noise floor imposed by, e.g., Amplifier Spontaneous Emission (ASE) starts contributing more to the total Optical Signal-to-Noise Ratio (OSNR) [10]. The signal must not get "too weak" before reamplification at any given place in the network, otherwise the OSNR is irreparably affected.

Based on [11, p. 5–6], for a target OSNR of 17.0 dB, signal launch power at 0.0 dBm, ten EDFA amplifiers with $NF = 6$, the span loss (and therefore amplifier gain after each span) is equal to 25.0 dB. This corresponds to ad-hoc empirical evidence gathered at CESNET's optical network. As a rule of thumb, we therefore designed the ROADM system in such a way that the signal never reaches substantially weaker power levels than -25 dBm.[1]

F. Miscellaneous Requirements and Add-On Features

Apart from the primary functions of a ROADM (spectrum routing, monitoring and amplification), the DWDM equipment often integrates add-on features. Some of these are considered a must in contemporary networks while others serve as a convenience feature for making the operators' life easier.

1) Optical Supervisory Channel: An OSC implements an in-band channel for device-to-device communication. OSC might be located just outside of the C-band, in a frequency no longer suitable for efficient EDFA amplification, often at 1511 nm. Lack of amplification is not an issue because the OSC is terminated after each Optical Transmission Section (OTS). OSC is often utilized as a tool for implementing the Automated Power Reduction (APR) and Automated Laser Shutdown (APR) safety mechanism (cf. Section II-D). There are several options on how to combine the OSC signal with the signal-detect feature of the integrated pre-amplifier at the line input [12]. The OpenROADM specification [13] also mandates a safety-critical control loop utilizing the OSC to perform an Automated Line Shutoff (ALSO).

2) Optical Time Domain Reflectometry: A line-facing ROADM node might feature an integrated OTDR. OTDR sends a series of pulses into the fiber, measuring the reflections from fiber breaks, connectors, etc., and the time it takes for a particular pulse shape to arrive back to the transmitter. After analysing the reflections, the OTDR device can possibly point out the location of, e.g., a fibre break with reasonable accuracy.

Some OSC modules available on the market [14] integrate OTDR measurements into the SFP pluggables. This implementation uses vendor-specific offsets in the SFP module's register space to control the OTDR functionality, request measurements and report back processed results. In this case, the OTDR signal reuses the same Tx laser, and therefore the same optical bandwidth as the OSC channel.

3) Connection Identification: A built-in, low-power light source can be routed into a set of output ports for identifying cable connections. The spectrum of this light source is usually just outside of the C-band so that a suitable modified WSS can still route it. A light detector can detect to which of the input ports this light signal is brought from another unit in the same ROADM node. A typical implementation requires a WSS with a wider-than-normal transmission band, or a sacrifice of at least one data channel, or a WSS which operates in a 2:N mode instead of the more common 1:N configuration. Given sufficient intelligence in the network management layer and just one extra transceiver in the network, a similar functionality can be implemented on-demand, in-band, as long as the network is not fully occupied.

G. Possible ROADM Designs

ROADM nodes can be designed in a variety of ways [15]. We rejected some of the more exotic ideas [16] and focused instead on WSS-based ROADM designs. The benefits and limitations of various designs have been widely understood in literature [1], [17], [18].

It seems [19], [20] well established that the most critical properties (in terms of wavelength use blocking over the network and therefore the network versatility) are the *Colorless* and *Directionless* properties. *Contentionless* designs can be avoided at the cost of only slightly more complex wavelength allocation plan, but with significant monetary savings.

The industry also appears to favor the *Route-and-Select* design of line degrees [21] as they allow for cost-effective design of Add/Drop units (cf. Sections III-C and III-D) despite requiring twice the number of WSSes [22].

Due to the inherent losses in all components, an integrated amplification element [23] is a reasonable design approach which is these days common in the industry.

If the ROADM node integrates with a high-resolution OCM, the fine-detailed spectral measurements can be used to evaluate signal impairment [24].

III. Optical Architecture

We selected the Route-and-Select design with colorless, directionless Add/Drop units. The ROADMs integrate EDFAs to compensate for internal losses as well as to accommodate a wider range of input signal power levels.[2] A multi-input OCM monitors performance of carried media channels.

Each ROADM site consists of N Line Degree units handling long-reach connections to other ROADM sites and M Add/Drop units for local termination of channels (Fig. 3). Our design scales up to $N <= 8$ and $N + M <= 10$, e.g., it is possible to build an eight-degree ROADM site with two redundant Add/Drop units.

A. Line Degree ROADM Node

Optical scheme of the *Line Degree* ROADM box is shown in Fig. 4(a). Degrees are equipped with built-in OSC filters and support bidirectional OTDR-via-OSC. Line-facing ports feature a monitoring tap (1% power ratio). An optional Dispersion Compensating Unit (DCU) can be connected to the EDFA's output when carrying signals prone to chromatic dispersion. A four-channel OCM is used to measure power distribution among carried media channels before and after each amplifier.

[1] This estimate is in our opinion the least well-defined criterion of this paper.

[2] Our design is ready for the 100 Gbps PAM4 dual-carrier modules [25] whose signal level demands require amplification even for a back-to-back operation, for example.

The OpenROADM specification does not suggest running a local control loop for channel power due to the risk of inducing oscillations to the network. As such, our current hardware defers channel equalization to a central controller. All required properties are made available over the northbound NETCONF interface.

1) Power Constraints: As explained in Sections II-D and II-E, signal power must be kept within a set of boundaries at all times. In our case, the aggregate power across all channels must not exceed 21 dBm at an accessible external port, while any given signal must not weaken below −25 dBm at any place in the ROADM.

The EDFA modules which we procure impose an upper limit of +21.5 dBm at their output ports. In a traditional DWDM with 50 GHz grid, up to 96 channels can be transmitted over the multi-wavelength interfaces (*Line IN*, *Line OUT*, and the *Express* ports). This results in a dynamic range of almost **20 dB**, possibly more with flexgrid.

We wanted to be able to achieve launch power +0 dBm per channel at the *Line OUT* in order to operate over 25 dB fiber spans without additional amplification. With the worst-case WSS IL of 8 dB (as per datasheet), this led to an EDFA gain of 22 dB in the *Express IN* → *Line OUT* direction and the expected power target of −12 dBm at the *Express* ports.

An incoming channel at −25 dBm at *Line IN*, along with filter penalties (cf. Section II-C), DCU, and worst-case WSS IL requires gain of 27 dB in the *Line IN* → *Express OUT* if the *Express OUT* shall reach −12 dBm per channel. However, due to the huge dynamic range of the DWDM system, when using 96 channels, this corresponds to +20.6 dBm at the EDFA output already. Even a small increase to −24 dBm per channel at *Line IN* leads to EDFA saturation as its output power exceeds +21.5 dBm.[3] This highlights the importance of careful channel power equalization within a DWDM network, especially when utilizing all channels available in the C-band.

B. Route-and-Select Add/Drop ROADM Node

A Route-and-Select Add/Drop node is shown in Fig. 4(b). While conceptually similar to the Line Degree node, this design includes a built-in 8:1 splitter/coupler towards the Express direction. We used 1:N WSS devices, and as such these splitters effectively implement the *Directionless* functionality. This design does not fulfil the *Contentionless* criterion on its own. Multiple redundant Add/Drop units are required if one wavelength received from multiple directions is to be locally terminated. An assembled prototype is shown in Fig. 2. This Add/Drop unit offers rich filtering and monitoring capabilities which make it suitable for deploying Alien Wavelengths [26].

C. Passive Add/Drop for Two-Degree ROADMs

The Route-and-Select approach we chose for the line degrees pays off especially in case of a two-degree ROADM node. Only

[3]This appears to be a common limitation of commercially available amplifiers based on our market research.

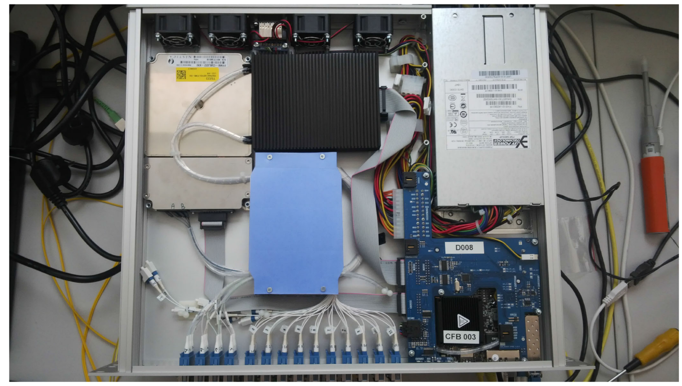


Fig. 2. Internals of the Route-and-Select Add/Drop ROADM unit (Section III-B) with twenty local ports.

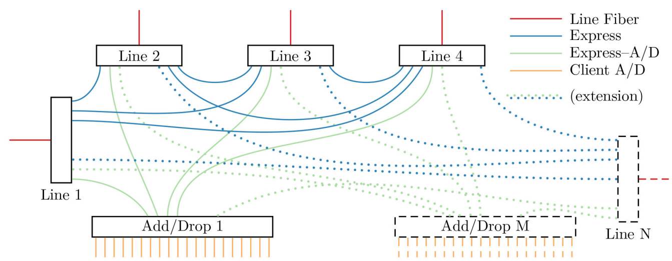


Fig. 3. Extensible ROADM design.

one WSS port is consumed by the express connection, leaving eight ports (cf. Section IV-A) available for local add/drop. Because the whole node is only two-degree, the add/drop connections can be easily connected either via Y-cables or through a set of passive splitters.

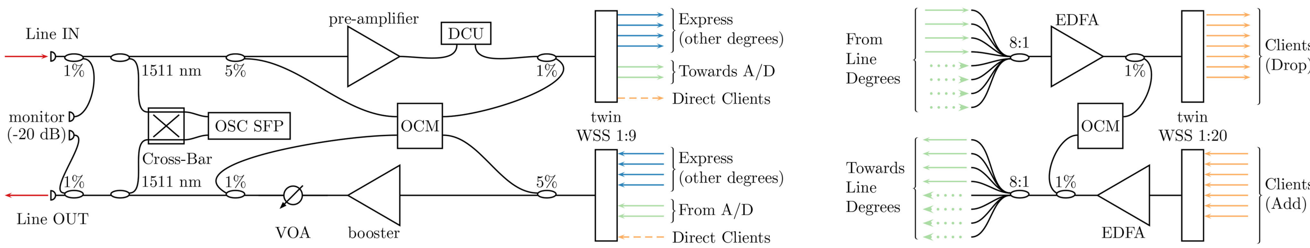
An Add/Drop node supporting Colorless, Directionless and Contentionless termination of up to eight client ports requires only the following components:

- 16 pcs of 1:2 splitters with LC/UPC connectors,
- 24 pcs of duplex LC/UPC connector couplers,
- a simple optical enclosure.

One could use a similar design for nodal degrees higher than two, but – for the general case – the limiting factor is the number of ports in the WSS of the line units. In a node degree of four, only six channels (in total, per the whole ROADM location) are available for local access in this approach.

D. Coherent Add/Drop

Modern coherent systems [27] have an ability to "tune-in" their receivers into a single frequency. Their design, in other words, implicitly filters out other signals which might be present at the receiver's optical input. For those transceivers it is not necessary to use WSS filtering in the DROP path of the signals. The transceivers still impose certain limits on the signal and the number of non-filtered channels, including the input power damage thresholds (which must account for presence of multiple simultaneous signals), the broadband noise and cross-talk.



(a) Line Degree unit (b) Route-and-Select Add/Drop unit

Fig. 4. Internal optical schemas of ROADM units.

A similar approach to Section III-C can be applied here, using passive couplers and splitters. As the number of nodes or client ports get higher, the losses exceed the optical performance offered by the line degrees (cf. Section III-A), and the signals presence exceeds capabilities of coherent receivers. A cost-effective Add/Drop node for up to eight client ports can be constructed with four 1:8 splitters, a dual-stage EDFA and a PD tap array.

Unlike the other ROADM types references in this paper, we have not built this network element yet (cf. Section VII-A). A new component not used in other active nodes described so far is the tap array with an integrated photodiode and digital readout via I2C bus. We chose to use the ITMA series from Oplink [28] due to their commercial availability in single-digit quantities.

IV. Selected Hardware

Our selection criteria were driven by our design needs, market availability, price, and our pre-existing business relations with the suppliers. In-house software (cf. Section V-D) is used to handle all low-level optical-specific communication.

A. Wavelength-Selective Switches

We selected two models of Nistica "Full Fledge" twin-module series mainly due to our prior experience with previous models and our understanding of their performance. The channel width granularity of 3.125 GHz in particular enabled us to control channel pass-band in a detailed manner. In the line units we use the nine-port NSP00702 while in the Route-and-Select Add/Drop units we deployed a twenty-port NSP00700. Both modules are available in twin 1:N configuration.

The modules are controlled over a set of auxiliary General Purpose Input/Output (GPIO) and either an I2C interface, or a serial Universal Asynchronous Receiver/Transmitter (UART). The Linux kernel implementation of I2C imposes certain limitations on variable-length transfers, which is why we chose the serial interface. In our design, a twin module is mounted into the ROADM chassis and connected over a flat ribbon cable carrying communication channels, GPIOs, and power.

B. Amplifiers

We selected an OEM amplifier with two independently operated stages. The physical connection is similar to the WSS module above. A ribbon cable carries multiple GPIO signals for out-of-band safety-critical control (APR, ALS, etc), a serial UART for management and control, and the power feed.

The amplifier module is able to operate in Automated Gain Control (AGC) mode with transient suppression. Several taps with PDs are integrated for its built-in control loop and outside access. Dedicated input signals control safety features (cf. Section II-D).

C. Optical Channel Monitors

We selected the Lumentum 21159239 OCM which is available in several variants. Our line degree models utilize a four-input model in order to be able to better react to amplifier gain variation (cf. Section III-A for details). In the Add/Drop unit we went with a two-port module as the gain flatness can be compensated in the next ROADM stage in the line degree.

Certain operations of the OCM result in a substantial amount of data to be transmitted. If we communicated over UART, scan results would take several seconds, reducing the effective end-to-end scanning performance by at least an order of magnitude. We are therefore communicating over the complimentary SPI interface which can be clocked up to 16 MHz. This had an implication on module location within the chassis as we worked to reduce the trace lengths of the SPI bus (cf. Section IV-D1 for other SPI bus usage at up to 26 MHz). The OCM module is therefore placed between the embedded computer board and the power supplies, next to the CPU heat sink. This is not optimal from the thermal point of view, but the OCM module's temperature stayed well within the manufacturer's specification during our testing.

D. Embedded Computer

The set of requirements for choosing an appropriate embedded computer was as follows:

- Linux support. We preferred a board which was able to run a mainline Linux kernel with no substantial modifications because we wanted to create a ROADM, not to port Linux to a new board.
- At least one SFP port on-board. We required direct access to the pluggable's I2C bus in order to utilize the integrated OTDR capabilities (cf. Section II-F2).
- Long-term availability. Based on our previous experience, we wanted to ensure that the same board will be available on the market for at least five years.

- Peripheral connectivity. The optical components require certain communication interfaces. The embedded computer must be able to simultaneously drive all components.
- Price. The board is one of the cheaper components on the final bill of materials, but we preferred to invest into components which affect the optical performance.

In practice, the most limiting factor was the requirement of an integrated SFP port with I2C access to the pluggable. The Clearfog Base [29] by Solid Run matched all our requirements. It is built around a System-on-Module (SoM) sub-board with the CPU (Central Processing Unit), DDR RAM (Double-Data-Rate Random Access Memory) and embedded flash storage (eMMC). The SoM is plugged to a carrier board which implements power management, breaks out the PCIe bus to standard interfaces and provides network connectivity.

However, the selected board only provides external connectivity to one UART, one SPI bus, one I2C bus and a limited number of physical GPIOs. The number of GPIO pins was severely limited, but as we did not require time-critical operation over GPIOs, an SPI or an I2C GPIO expander were acceptable. In a similar manner, the UART communication can be intensive at times, but our modules did not support communication at baud rates over 115'200 Baud.

1) Input/Output Requirements: Our design required several UARTs: one for each (twin) WSS module, one for each (possibly two-stage) EDFA module, and one for the initial OCM bring-up. Each EDFA module requires eleven GPIOs, the WSS module uses five GPIOs, and the OCM uses three signals. The power supply module uses PMBus for communication (which is I2C compatible) and one digital input for out-of-band signalling. In total, at least twenty GPIOs are required.

There is no I2C multiplexer between the SoM's I2C master block and the SFP cage, and the same I2C bus is also routed to the external pin header. That constituted a problem because the SFP MSA standard prescribes I2C slave address `0x50` and `0x51` for module's EEPROM interface. The same address is also used for PMBus power supplies. We opted to solve this conflict of I2C device addresses via the LTC4316 [30] address translator. Due to a non-compliance in the firmware of the power supply microcontrollers, though, we had to resort to bit-banging the I2C bus and accessing the PMBus through software.

To accommodate the four required UARTs, we selected the MAX14830 [31], a quad UART attached over the SPI interface. We substantially improved the performance of the Linux kernel driver (`max310x.c`) so that it better utilizes the chip's hardware capabilities [32]. Previously, the bandwidth of a 26 MHz SPI bus was not sufficient to drive four full-duplex UARTs at 115'200 Baud. Our patches reduced the total overhead and enabled full-speed operation without buffer overruns. These modifications were accepted upstream and released starting in Linux kernel 4.16.

We contributed a number of additional patches, including to the GPIO expander, the LED driver, and the SPI master driver. In total, over twenty patches were merged to the Linux kernel as of `4.20-rc1`.

The main printed circuit board which interfaces the optical peripherals with the embedded computer is shown in Fig. 5. The complex outline is a result of mechanical requirements due to the depth and location of the power supplies, the computer's SFP cage, CPU heat sink and the board's boot vector jumpers. The highest-speed signals routed at the board involve the SPI bus clocked at 26 MHz.

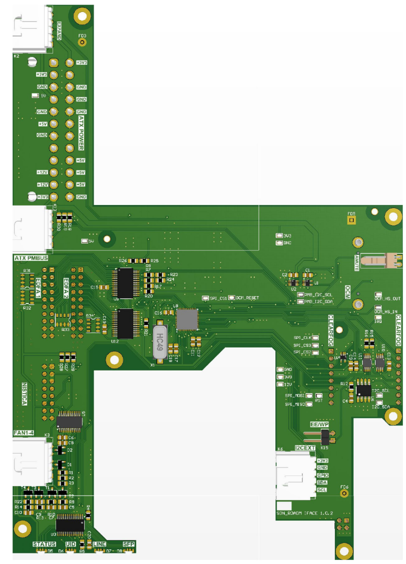


Fig. 5. Rendering of main electronic interface board.

E. Power Supplies, Cooling and Enclosure

We were able to fit all required electronics, including the fusion splices and reserve fiber length, into a commercially available 1U chassis. The front and rear panels were water-jet cut by an external contractor to create air intakes for ventilation as well as fiber and cable connections.

We wanted to ensure that the ROADMs are usable in real-world scenarios which require a high level of resiliency. As such, we required redundant, hot-plug power supplies and fan modules.

We chose to use power supplies conforming to the PMBus [33] industry standard. The particular model which we selected supports digital readout of temperature, fan speed, all voltages as well as the power consumption and per-output current measurement. As an additional feature, the fan speed can be increased via a software command.

The situation with fans was more complicated. We were not able to source hot-pluggable fan modules for 1U rack cases on the market in small-quantity batches. We therefore decided to use the case's rear access panel as a single hot-plug unit. During our testing, the device exhibited sufficient thermal inertia to be able to sustain short operation (at least five minutes) with no fan tray installed, and just on one-PSU cooling.

The fans which we choose are DC brushless models powered by 12 V using just two electric wires. An AC-coupled ADT 7463 [34] handles fan speed readout, stuck fan detection and PWM fan speed control for acoustic noise management. This chip also provides additional voltage monitoring in addition to one available in the PMBus power supply modules.

F. Manual Prototype Assembly

An initial round of prototypes were assembled by hand in our laboratory in Brno. The average time required for any given box was roughly three working days, including the fiber splicing, mechanical work and required additional logistics.

V. Software Architecture

As established earlier, the main northbound interface of the ROADM is the NETCONF protocol. We put a strong emphasis on using open-source software throughout our product, and that led us to choose the Sysrepo and Netopeer2 projects [35]. This determined the overall architecture of the application level. All services which offer NETCONF configuration connect to the `sysrepod` daemon and register callbacks for configuration changes and for operational data retrieval. The remaining software on the box only ensures that these services remain available. The overall software architecture is reused from our earlier project [3].

A. Linux System

On the system level, we chose the Buildroot [36] framework for generating the operating system images. The embedded CPU and RAM resources allowed us to use a modern, fully-fledged userspace architecture with the GNU C Library and the `systemd` [37] as an `/sbin/init` system. The `systemd` is built around *units* which describe not just traditional services and daemons, but also device nodes, file systems, etc. It manages a stateful dependency tree among units and hence all aspects of a system boot [37, Part 3]. Its feature set, integration with the hardware watchdog, etc., proved valuable – even though it required more tuning than we expected.

B. NETCONF Protocol Stack

The Sysrepo provides a service which tracks contents of several data stores [38], such as `startup` [4, Sec. 8.7] and `running` [4, Sec. 8.2], each holding data for a set of YANG modules. When an external agent attempts to modify the data contained within these data stores, Sysrepo invokes callbacks registered by application code. In a similar manner, when operational data are requested, Sysrepo asks an appropriate application to obtain the data in a domain specific manner – perhaps by consulting some hardware sensor, or reading a software counter. Once the requested data are available, the application returns data to Sysrepo which passes them to the original client, typically over the NETCONF protocol.

C. YANG Models for Northbound Access

In a similar manner to our earlier work [3], we did not want to design yet another incompatible YANG model. Since that time, the YANG-centric view of the OLS landscape [39] changed.

The OpenROADM[4] project continued in their release cadence, and a flexgrid-capable model become available. However, the *Device* portion of OpenROADM YANG models focuses on ROADMs with a local controller, something which is hard to support in a disaggregated design of the ROADM node itself which consists of separate ROADM units, each with its own instance of a local operating system.

[4]CESNET joined the OpenROADM MSA in summer 2018.

While the OpenConfig protocol is popular on higher network layers and is also used for targeting transponders by some open source projects including the Open Disaggregated Transport Network (ODTN) [40] of the Open Networking Foundation, we are not aware of any effort at using it for flexgrid, modular ROADMs.

Since 2017, one newcomer has emerged. Shepherded by Infinera and donated to the TIP community, the OpenDevice [41] YANG models take a very different and radical approach compared to OpenROADM and our own proposals. The OpenDevice model attempts to provide direct, low-level access to individual optical building blocks within a ROADM unit, such as to each WSS, EDFA, OCM and PD. We consider this approach very interesting, but the model was still in development and not ready as of December 2018.

We nonetheless took some data types from the OpenDevice proposal. The structure of the YANG model we used for ROADM prototyping and demonstrations (cf. Section VI) consists of three blocks as shown in Listing 1:

- At first, a list of all possible MCs which might be passing over the ROADM is defined. There are no restrictions on channel overlap at this point.
- A subset of the MCs defined above is provisioned for the optical cross-connect, i.e., the media channels are realized over the WSS. A desired attenuation is also set at this level. These media channels might not be the same in both directions (e.g., line → express vs. express → line), but channels routed in one direction must not overlap.
- Finally, a possibly different set of media channels is selected for monitoring via an OCM. This allows for insight into multi-carrier superchannels.

There are also efforts into bringing streaming telemetry, i.e. devices continuously sending a stream of performance metrics, to ROADMs [42], for example via the gRPC/gNMI protocols.

D. Low-Level Application Software

We developed a key-value oriented abstraction API to serve for property retrieval and modifications via NETCONF utilizing Sysrepo. The glue code connects Sysrepo callbacks (implemented in the C programming language) with an abstracted C++ interface. The API is reasonably straightforward as indicated in Listing 2.

Each low-level optical module is accompanied by an instance of a `Driver`, a class which provides actual access to individual module's functionality. Operation of a driver for a hypothetical thermal-control device is shown in Listing 3.

They key-value schema uses the `/` (slash) character as a hierarchy level separator. This corresponds to the XPath notation as used in the YANG schema trees [43, Section 6.4] and allows mapping per-device properties into YANG leafs which are available over NETCONF.

Listing 1: Tree View of the ROADM YANG Model.

```
module: czechlight-roadm-device
  +-rw channel-plan
  | +-rw channel* [name]
  | +-rw name string
  | +-rw lower-frequency
  | opendevice-types:dwdm-frequency-mhz
  | +-rw upper-frequency
  | opendevice-types:dwdm-frequency-mhz
  +-rw connections* [channel]
  | +-rw channel -> /channel-plan/channel/name
  | +-rw description? string
  | +-rw add!
  | | +-rw port device-dependent-port-type
  | | +-rw (mode)
  | | +-:(attenuation)
  | | +-rw attenuation decimal64
  | +-rw drop!
  | +-rw port device-dependent-port-type
  | +-rw (mode)
  | +-:(attenuation)
  | +-rw attenuation decimal64
  +-ro channel-power* [channel]
  | +-ro channel -> /channel-plan/channel/name
  | +-ro power* [location]
  | +-ro location string
  | +-ro optical-power
  | opendevice-types:optical-power-dBm
  +-ro aggregate-power* [location]
   +-ro location string
   +-ro optical-power
         opendevice-types:optical-power-dBm
```

Listing 2: Driver Abstraction API.

```
using Value = variant<
string, bool, uint8_t, int8_t, /* ... */
 int64_t>;
using Tree = map<string, Value>;

struct Driver {
// Single-value operations
virtual Value read(const string& name)=0;
virtual void write(const string& name, const
 Value& v)=0;

// Batched operations
virtual Tree read(const vector<string>& names);
virtual void write(const Tree& props);
}
```

Listing 3: Operation of an Example "Thermal Device" Driver.

```
ThermalDriver dev;

// Check device temperature
assert(get<double>(dev
.read("zone/1/temperature"))
< 150.0);

// Control fan speeds
dev.write({
{"fan/1/speed", int16_t{8'000}},
{"fan/2/speed", int16_t{6'500}},
});
```

In case of a ROADM, basic functionality required developing low-level module drivers for the WSS modules, the EDFA amplifier, and the OCM channel monitor. Because the key-value API assumes a direct mapping of property names into the XPath-indexed tree of YANG leafs, we inserted an additional translation layer for rewriting property names. This proxy driver decouples low-level, module-specific functionality (such as "set EDFA stage 1 mode to AGC with 27 dB gain" or "check for the LOS condition at stage 2") from high-level ROADM features. Our ROADMs are therefore ready for exporting several available northbound interface implementations (e.g., OpenConfig and OpenROADM) without having to modify the low-level driver code (cf. Section V-C).

E. Software Updates

Internally, we employ agile software development practices and want to be able to push new software versions to the hardware with little effort. At the same time, the requirements included system resiliency in face of software issues. If an updated system image fails to boot (regardless on whether it is a kernel problem prior to launching `init`, or a stuck userspace), we wanted the system to revert to its previous software release with no external input. This is important for both Continuous Integration and for real-world deployments in inaccessible locations.

The system is built around a fully redundant partitioning using the A/B firmware slots with the embedded storage split into two equivalent halves. The bootloader keeps track of the number of remaining boot attempts for each slot. The count starts at three, and the bootloader will prefer a slot with non-zero remaining attempts. Upon a successful boot, which is defined as all `systemd` units (cf. Section V-A) being successfully activated, the boot count is reset to the initial value. Early in the boot process, the U-Boot arms the CPU's hardware watchdog timer and configures it with a two-minute timeout. If the system does not reach the fully up-and-running state in two minutes, the watchdog reboots the CPU. That way, we guarantee that the system will recover itself within six minutes at the latest upon a buggy software update.

We used the RAUC [44] software tooling to automate software updates.

VI. Performance Validation

As of December 2018, we built several flexgrid Add/Drop units (with twenty client ports each), several Line Degree units (with nine ports for local and express traffic), and one passive Add/Drop. After an initial bring-up in the laboratory, we verified several test cases to demonstrate that the design is sound, and that the ROADMs are fit for their purpose.

A. Voyager Interoperability

The objective of this test was to verify that our design provides sufficient OSNR headroom for long-haul transmissions using modern signal modulation. At the time of the test, the team had access to two Voyager transponders [45] manufactured by

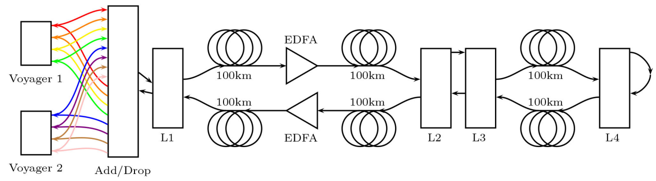
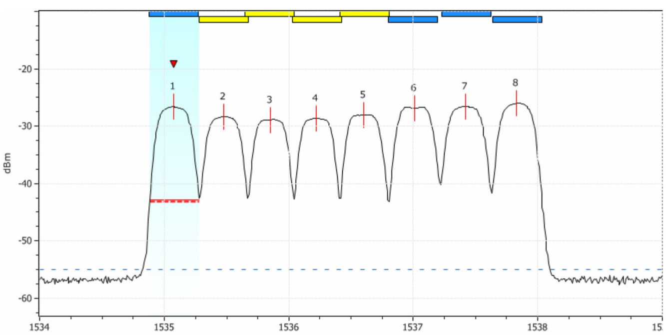
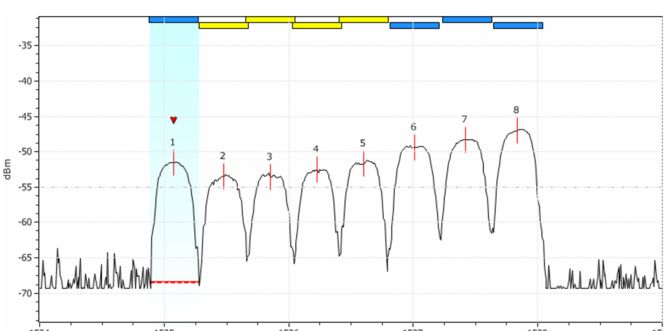


Fig. 6. Topology of the Voyager trial.



(a) Signals launched into the line after passing two ROADM nodes, an Add/Drop and a Line Degree



(b) Signals after 600 km without power equalization

Fig. 7. Spectrum traces of Voyager interoperability trial as captured on ROADM's built-in tap ports (−21 dB attenuation).

ADVA. We created a sample network in our laboratory to simulate connections over five ROADM nodes and total of 600 km G.652.D fiber. See Fig. 6 for details.

We configured the transponders on a 50 GHz frequency grid using eight adjacent channels, each at 200 Gbps using the 16QAM modulation. In order to verify operation with more amplifiers, we used a legacy Czech Light in-line EDFA. Because the legacy in-line amplifiers do not ship with a built-in OSC channel, the APR feature (cf. Section II-D) was not enabled in these tests. All spans were 100 km long, with an amplification (either an in-line EDFA, or via an EDFA module integrated in a ROADM line degree box) compensating the fibre losses.

During this testing, we were able to carry 1.6 Tbps of traffic over 600 km of fiber while staying within the acceptable FEC margins. As seen from the spectral traces at the beginning and end of the path (Fig. 7), the setup was not optimized, with no equalization of individual channel power. Since the purpose of this test was not to find an absolute margin of the OLS nor to evaluate performance of Voyager transponders (see, e.g., [46] for the expected limitations of the technology), we have not pushed the system further in terms of span count or the total gain loss.

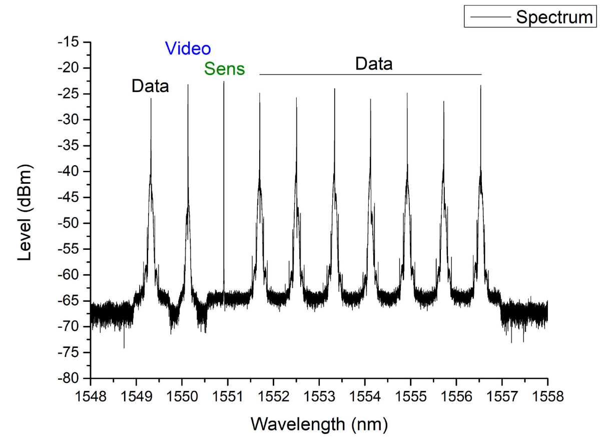


Fig. 8. Spectrum trace of the primary path at the TIP demo.

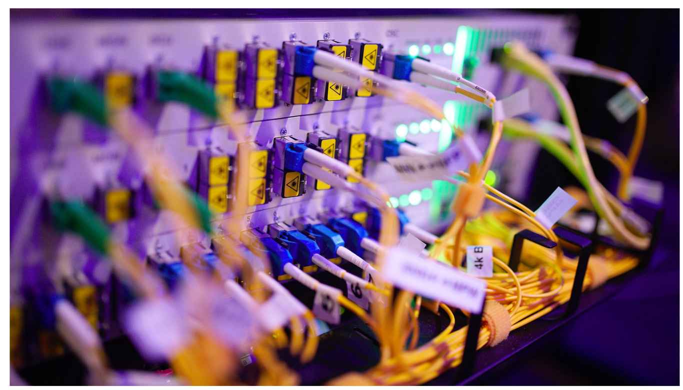


Fig. 9. Close-up of a Czech Light ROADM at the TIP Summit in London (October 2018).

B. Telecom Infrastructure Project Demonstration

For the Telecom Infrastructure Project (TIP) Summit 2018 in London, we created an interactive demonstration which showcased a combination of our ROADMs with a photonic sensing system. A continuous-wave laser source was multiplexed into a fiber path in between a set of nine 10 Gbps NRZ-OOK channels.[5] Multiplexing was done via the Route-and-Select Add/Drop ROADM node, effectively treating the sensing signal as an Alien Wavelength. The sensing signal passed through the same WSSes, EDFAs, etc., as the data signals.

The spectrum trace of the setup is shown in Fig. 8. We routed the fiber line through a flowerpot filled with gravel. Booth visitors were encouraged to induce vibrations via striking the gravel's surface by a rubber hammer. This setup simulated construction works (e.g., excavation) in the vicinity of fiber buried underground [47].

[5]We used 10 Gbps signals in order to keep the acoustic noise of the demonstration setup in manageable levels.

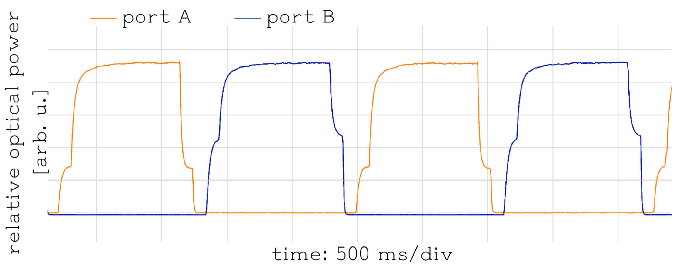


Fig. 10. Optical output power vs. time when switching ROADM channel routing.

The signal was extracted via another Add/Drop ROADM node at the far end of the span and connected via a polarization beam splitter into a balanced photodetector (Thorlabs PDB110C). The electric signal from the detector was analysed by a purpose-built circuit designed by CESNET whose digital output indicated whether the optical line was detecting vibrations along its path. An SDN controller listened for these events and proactively re-routed all important Alien Wavelengths (eight channels at 50 GHz grid) via another disjoint line over a second pair of ROADM line degrees. An uncompressed 4K video signal was transmitted within one of the 10 Gbps data signals to demonstrate effects of a switch-over to the audience. A status dashboard indicated signal routing via ROADMs and feedback from the sensing system.

C. Control and Operational Parameters

The WSS module is specified to require up to 1 second settling time when adjusting channel routing. Fig. 10 shows a typical optical response to a change of routing initiated over NETCONF. In our testing, the period of darkness, as defined by > 3 dB attenuation, is typically 200 ms. Request processing over NETCONF completes in 150–180 ms (these SW- and HW-induced latencies overlap).

OCM data can be sampled in 305 ms from all four taps (cf. Section IV-C) when measuring 96 channels at the 50 GHz grid.

Typical power consumption is 30 W per each 1U ROADM unit – without utilizing the SoM's power saving features.

VII. Conclusion

This paper describes optical design, as well as hardware and software implementation of an open, modular, flexgrid, colorless, directionless ROADM system. Two flexible hardware models were designed, one for Line Degrees supporting up to eight-degree ROADM configurations, one for Add/Drop of up to twenty local signals. Eight prototypes were built to verify feasibility of our design and to demonstrate features of such an OLS.

The ROADMs were developed at CESNET as a part of the Czech Light family of open DWDM devices. With a mostly-open-source software stack, they present a first publicly available Optical Line System. It is our hope that this paper will help bring us – the optical networking community – closer towards full disaggregation of transport networks [48].

A. Future Work

Now that sufficiently open network elements are available, the one missing piece of the puzzle is an SDN controller and a service orchestrator. Recent developments within the ONOS community and the ODTN project in particular [40] look promising. They will, however, have to be augmented by an appropriate open implementation of the OLS management system for low-level media channel provisioning. For a reliable Path Computation (PC), a dependable simulation environment is crucial. The TIP's Open Optical Packet Transport (OOPT) Photonic Simulation Environment (PSE) [49] is a very promising candidate.

In terms of hardware, an intermediate step for authors of this paper is to verify the design of a cost-effective *Coherent Add/Drop* unit (cf. Section III-D). This is planned for Q1/2019.

2019 appears to be an exciting time in terms of open optical networking. Developments in transport interfaces, such as the ONF TAPI [50] project, might well help us get closer to production deployments of SDN at L0 in a multivendor environment.

Acknowledgment

The authors would like to thank Míla Hůla, Pavel Škoda, Michal Altmann, Jan Radil, and Rudolf Vohnout for their valuable contribution towards this article.

References

[1] S. Gringeri *et al.*, "Flexible architectures for optical transport nodes and networks," *IEEE Commun. Mag.*, vol. 48, no. 7, pp. 40–50, Jul. 2010.

[2] J. Radil, J. Vojtěch, M. Karásek, and S. Šíma, "Dark fibre networks and how to light them," in *Proc. 4th Quilt Opt. Netw. Workshop*, Fort Lauderdale, FL, USA, 2006. [Online]. Available: https://photonics.cesnet.cz/_media/publications/fiber-optics/2006/radil-quilt.pdf

[3] J. Kundrát *et al.*, "YANG/NETCONF ROADM: Evolving open DWDM toward SDN applications," *J. Lightw. Technol.*, vol. 36, no. 15, pp. 3105–3114, Aug. 2018. [Online]. Available: http://jlt.osa.org/abstract.cfm?URI=jlt-36-15-3105

[4] R. Enns, M. Björklund, A. Bierman, and J. Schönwälder, "Network Configuration Protocol (NETCONF)," RFC 6241, Jun. 2011. [Online]. Available: https://rfc-editor.org/rfc/rfc6241.txt

[5] R. Morro *et al.*, "Automated end to end carrier ethernet provisioning over a disaggregated WDM metro network with a hierarchical SDN control and monitoring platform," in *Proc. Eur. Conf. Opt. Commun.*, Sep. 2018, pp. 1–3.

[6] Tencent trials ADVA FSP 3000 TeraFlex^{TM} 600G DCI technology over its open line system OPC-4. Press release, 2018. [Online]. Available: https://www.advaoptical.com/en/newsroom/press-releases/20181112-tencent-trials-adva-fsp-3000-teraflex-600g-dci-technology-over-its-open-line-system-o pc-4

[7] *Spectral Grids for WDM applications: DWDM Frequency Grid*, ITU-T Std. G.694.1, Rev. 02/2012, 2012. [Online]. Available: https://www.itu.int/rec/T-REC-G.694.1-201202-I/en

[8] K. Ly, Random mating IL vs. IL by master jumper. Whitepaper. SENKO. Mar. 2012. [Online]. Available: http://www.senko.com/fiber/pdf_brochure/IL-random-mating-master-jumper.pdf

[9] P. M. Becker, A. A. Olsson, and J. R. Simpson, *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*. Amsterdam, The Netherlands: Elsevier, 1999.

[10] A. E. Willner and S.-M. Hwan, "Transmission of many WDM channels through a cascade of EDFA's in long-distance links and ring networks," *J. Lightw. Technol.*, vol. 13, no. 5, pp. 802–816, May 1995.

[11] P. Škoda and J. Vojtěch, "White paper—Optical reach of photonic services—GÉANT," 2013. [Online]. Available: https://geant3.archive.geant.org/Media_Centre/Media_Library/Media%20Library/GN3-13-162_MJ1.2.3_White-Paper_Optical-Reach-of-Photonic-Services_v3.pdf

[12] *Optical Safety Procedures and Requirements for Optical Transmission Systems*, ITU-T Standard G.664, Rev. 10/2012, 2012. [Online]. Available: https://www.itu.int/rec/T-REC-G.664-201210-I/en

[13] "OpenROADM v2 device whitepaper (version 1.1)," 2018. [Online]. Available: https://0201.nccdn.net/1_2/000/000/134/c50/Open-ROADM-MSA-release-2-Dev ice-White-paper-v1-1.pdf

[14] N. Parkin, M. Bartur, D. Nesset, and D. Jenkins, "Gigabit SFP transceiver with integrated optical time domain reflectometer for ethernet access services," in *Proc. 39th Eur. Conf. Exhib. Opt. Commun.*, Sep. 2013, pp. 1–3.

[15] B. Collings, "New devices enabling software-defined optical networks," *IEEE Commun. Mag.*, vol. 51, no. 3, pp. 66–71, Mar. 2013.

[16] S. Sarmiento *et al.*, "Cost-effective DWDM ROADM design for flexible sustainable optical metro-access networks," *J. Opt. Commun. Netw.*, vol. 9, no. 12, pp. 1116–1124, Dec. 2017. [Online]. Available: http://jocn.osa.org/abstract.cfm?URI=jocn-9-12-1116

[17] R. Shankar *et al.*, "Multi-degree ROADM based on wavelength selective switches: Architectures and scalability," *Opt. Commun.*, vol. 279, no. 1, pp. 94–100, 2007.

[18] V. Abedifar *et al.*, "Design and simulation of a ROADM-based DWDM network," in *Proc. 21st Iranian Conf. Elect. Eng.*, May 2013, pp. 1–4.

[19] Y. Li, L. Gao, G. Shen, and L. Peng, "Impact of ROADM colorless, directionless, and contentionless (CDC) features on optical network performance [invited]," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 4, no. 11, pp. B58–B67, Nov. 2012.

[20] J. M. Simmons, "A closer look at ROADM contention," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 160–166, Feb. 2017.

[21] B. C. Collings, "Advanced ROADM technologies and architectures," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, Mar. 2015, Paper Tu3D.3.

[22] M. Filer and S. Tibuleac, "N-degree ROADM architecture comparison: Broadcast-and-select versus route-and-select in 120 Gb/s DP-QPSK transmission systems," in *Proc. Opt. Fiber Commun. Conf.*, Mar. 2014, Paper Th1I.2.

[23] S.-K. Liaw *et al.*, "Bidirectional reconfigurable optical add-drop multiplexer with power compensation built-in optical amplifiers," *J. Opt. Netw.*, vol. 7, no. 7, pp. 662–672, Jul. 2008. [Online]. Available: http://jon.osa.org/abstract.cfm?URI=jon-7-7-662

[24] L. Velasco *et al.*, "Learning from the optical spectrum: Soft-failure identification and localization [invited]," in *Proc. Opt. Fiber Commun. Conf. Expo.*, Mar. 2018, Paper W1G.1.

[25] M. Filer *et al.*, "Demonstration and performance analysis of 4 Tb/s DWDM metro-DCI system with 100 G PAM4 QSFP28 modules," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, Mar. 2017, Paper W4D.4.

[26] H. Wessing *et al.*, "Alien wavelengths in national research and education network infrastructures based on open line systems: Challenges and opportunities," *J. Opt. Commun. Netw.*, vol. 11, no. 3, pp. 118–129, Mar. 2019. [Online]. Available: http://jocn.osa.org/abstract.cfm?URI=jocn-11-3-118

[27] K. Kikuchi, "Fundamentals of coherent optical fiber communications," *J. Lightw. Technol.*, vol. 34, no. 1, pp. 157–179, Jan. 2016.

[28] "Tap PD array with I2C, single-mode—Oplink," Datasheet, 2018. [Online]. Available: http://www.oplink.com/passive/detail/110.html

[29] "SolidRun ClearFog Base," 2018. [Online]. Available: https://www.solid-run.com/marvell-armada-family/clearfog/

[30] "LTC4316—Single I2C/SMBus address translator," Datasheet, 2018. [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/431 6fa.pdf

[31] "MAX14830 quad serial UART with 128-word FIFOs," Datasheet, 2018. [Online]. Available: https://www.maximintegrated.com/en/products/interface/controllers-expan ders/MAX14830.html

[32] "Accepted contribution of CESNET to the Linux kernel," Git repository, 2019. [Online]. Available: https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/log/?qt=author&q=jan.kundrat%40cesnet.cz

[33] PMBus$^{\mathrm{TM}}$ power management defined. Project homepage, 2010. [Online]. Available: http://pmbus.org/

[34] "ADT7463: Remote thermal controller and voltage monitor," Datasheet, 2018. [Online]. Available: https://www.onsemi.com/pub/Collateral/ADT7463-D.PDF

[35] sysrepo—YANG-based configuration and operational state data store for Unix/Linux applications. Project homepage, 2019. [Online]. Available: http://www.sysrepo.org/

[36] T. Petazzoni, "Buildroot: A nice, simple and efficient embedded Linux build system," in *Proc. Embedded Linux Syst. Conf.*, 2012. [Online]. Available: http://thomas.enix.org/pub/conf/rmll2012/buildroot.pdf

[37] L. Poettering, K. Sievers, and T. Leemhuis, "Control centre: The systemd Linux init system," *The H Open*, 2012. [Online]. Available: http://www.h-online.com/open/features/Control-Centre-The-systemd-Linux-init-system-1565543.html

[38] M. Björklund *et al.*, "Network Management Datastore Architecture (NMDA)," RFC 8342, Mar. 2018. [Online]. Available: https://rfc-editor.org/rfc/rfc8342.txt

[39] T. Szyrkowiec, A. Autenrieth, and W. Kellerer, "Optical network models and their application to software-defined network management," *Int. J. Opt.*, vol. 2017, 2017, Art. no. 5150219.

[40] M. D. Leenheer, Y. Higuchi, and G. Parulkar, "An open controller for the disaggregated optical network," in *Proc. Int. Conf. Opt. Netw. Des. Model.*, May 2018, pp. 230–233.

[41] "TIP OOPT OLS YANG models—Opendevice," Git repository, 2018. [Online]. Available: https://github.com/Telecominfraproject/oopt-open-optical-models

[42] P. Castoldi *et al.*, "Optical white box: Modeling and implementation," in *Proc. 20th Int. Conf. Transp. Opt. Netw.*, Jul. 2018, pp. 1–4.

[43] M. Björklund, "The YANG 1.1 Data Modeling Language," RFC 7950, Aug. 2016. [Online]. Available: https://rfc-editor.org/rfc/rfc7950.txt

[44] RAUC: Safe and secure embedded Linux updates. Project homepage, 2018. [Online]. Available: https://rauc.io/

[45] "Facebook Voyager transponder," 2016. [Online]. Available: https://code.fb.com/connectivity/an-open-approach-for-switching-routing-and-transport/

[46] H. Zhang *et al.*, "Real-time transmission of 16 Tb/s over 1020 km using 200 Gb/s CFP2-DCO," *Opt. Express*, vol. 26, no. 6, pp. 6943–6948, Mar. 2018. [Online]. Available: http://www.opticsexpress.org/abstract.cfm?URI=oe-26-6-6943

[47] T. Horvath *et al.*, "Simultaneous transmission of accurate time, stable frequency, data, and sensor system over one fiber with ITU 100 GHz grid," *Opt. Fiber Technol.*, vol. 40, pp. 139–143, Jan. 2018.

[48] E. Riccardi *et al.*, "An operator view on the introduction of white boxes into optical networks," *J. Lightw. Technol.*, vol. 36, no. 15, pp. 3062–3072, Aug. 2018.

[49] M. Filer *et al.*, "Multi-vendor experimental validation of an open source QoT estimator for optical networks," *J. Lightw. Technol.*, vol. 36, no. 15, pp. 3073–3082, Aug. 2018.

[50] V. Lopez *et al.*, "Transport API: A solution for SDN in carriers networks," in *Proc. 42nd Eur. Conf. Opt. Commun.*, Sep. 2016, pp. 1–3.