POLITECNICO DI TORINO

Master Of Science

in COMMUNICATION COMPUTER NETWORK ENGINEERING

2022/2023

April 2023

Master's Degree Thesis

Towards the Opening of Optical Networks: Horizons and Ongoing Standardization

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Abstract

The Internet architecture and protocols have been extremely successful in recent decades due to their simplicity and scalability with best effort services. The applications were Web-based and contained limited multimedia content. The support for digital media is one of the fastest growing requirements of the Internet as demand transitions from services designed for text and images to those intended to support high quality streaming multimedia. The optical networks are the principal actor to satisfy this requirement. Looking at the near future, emerging network applications are sensitive to latency, jitter, loss rate, and/or flow completion time. Unlike today's web applications, the new ones are expected to be more complex and to serve a larger number of consumers, pursuing an automatic management and optimization of the service degradation. For example, vehicle-to-everything (V2X) networks require guaranteed network services with low latency and a low loss rate. Even with human consumers, emerging multimedia applications, such as holographic communication, immersive virtual reality (VR), augmented reality (AR), and extended reality (XR), telemedicine, remote surgery, and cloud gaming, require much more stringent network quality of service (QoS), including bounded latency and ultra-high throughput. There has been a distinct synergy between the requirements of new applications and the next-generation of optical networks, which must support the rising demand by businesses and consumers for Internet-based communications and services. Fiber optic cables and devices are used across multiple sectors, not just the well-known ones like telecom, but are also critical in data centers, in the military and aerospace, energy utilities, municipal, campus, and other sectors. Fiber optic networks serve as the primary technology approach for high-speed communications around the globe, and telecom service providers and operators are rapidly growing, upgrading fiber optical network infrastructures both in hardware and software.

The network elements that form an optical network are optical line systems, transponders, ROADM (reconfigurable optical add & drop multiplexer) nodes, transceivers, and optical fiber cables. Initially, the optical networks were used only to increase the data capacity, built with proprietary hardware and software systems. The configuration of optical networks was static, independent from any applications. In the propagation between the source/destination nodes, the application data crossed few or

many static optical networks, each having an independent configuration. With new application requirements, each network element must be compatible with a common application software regardless of the adopted hardware. Also each network element of different vendors must be synchronized with respect to a centralized controller, and must react to guarantee that the data traveling along the network is aligned to the application requirements. Since the foundation of the Mandatory Use Case Requirements for SDN for Transport (MUST) Subgroup within the Open Optical & Packet Transport (OOPT) Project Group, powered by the Telecom Infra Project (TIP), some of the world's most important service providers have collaborated to define the requirements for an SDN-based open and disaggregated transport network architecture. The optical workstream in MUST focused on optical transport has produced a common and unified set of guidelines that describe a future-proof strategy towards the realization of a disaggregated open optical network.

After a general overview of the main aspects concerning optical networks, the aim of this research is to treat as the new application requirements, the interaction between Internet users and their continuous growth have modified and will continue to modify the architecture, the management of optical networks and the business model of Telco service providers. The possible standard to implement automation in future disaggregated optical networks can be a common data model to describe each hardware component of each network optical element as YANG, each network optical element communicates with NETCONF protocol and all is orchestrated by SDN controller ONOS.

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1. Introduction to Optical Networks

Telecommunication has made it possible to send vast amounts of data over long distances. Optical network uses a light to send data between source and destination over fiber cables at light speed, making it offer a wide range of benefits to the telecommunication sector world wide with its provision of higher bandwidth which leads to faster data speed, longer transmission distance, and improved latency. Optical networks serve as the backbone of the broadband internet worldwide, utilizing the use of optical fiber and in the last decade the optical fiber is used also in the home as point of access to Internet. Our society is changing into a more cyber-physical oriented one in which virtual and augmented realities will provide a wealth of experiences to the real world through digital transformation. The most important infrastructure of such a new society is, of course, next-generation communication networks and computing platforms with which very low latency and ultra-high bandwidth are indispensable and should be power efficient to achieve a sustainable society. Photonics is the key technology to enable both superhighway networks and high-performance computing with lower power consumption. The proliferation and popularization of bandwidth intensive services enabled by Internet medium such as 4K and 8K ultra-high-definition video streaming, immersion into virtual reality (VR) and/or augmented reality (AR), and autonomous vehicles will certainly drive explosive growths of Internet traffic [31].

The increase in bandwidth, data-hungry applications, constraints of video and audio applications requirements (minimum delay, minimum jitter, minimum bandwidth), the exponential growth of internet traffic and its diversified services require optical networks capacity to expand accordingly.

Optical networks widely deployed today (see Fig. 1.1) are architectured in a hierarchy of access, metro, core, and long-haul networks where long-haul can be divided into terrestrial and submarine networks. Large data centers are located on main long haul lines, and in metro networks are often configured in dual-homed arranged for redundancy and protection of data. The back-bone networks are used to transfer information for long paths around the globe and they are implemented by means of high-capacity optical links. Access networks are the infrastructure that permits the communication between end-user and back-bone networks : the implementation involves the use of a mixture of wired and wireless solutions [10].

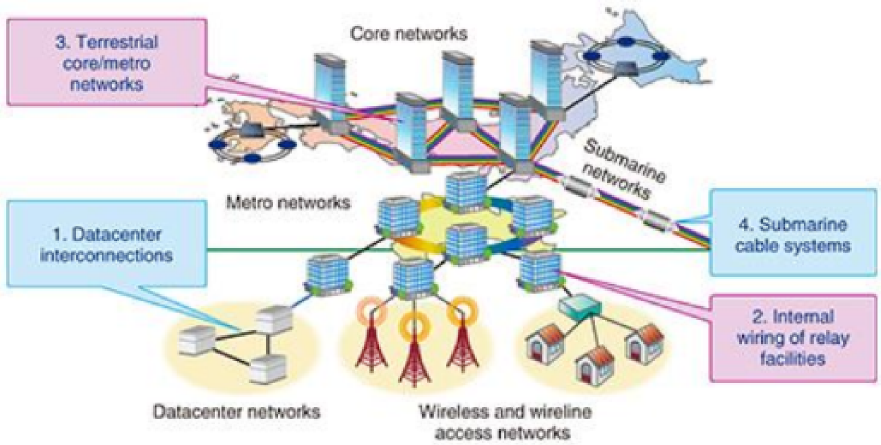


Figure 1.1: Logical subdivision of an optical network [10].

In this thesis, we consider the present and possible scenarios for the future of optical networks.

- **Chapter 2**: **Background of optical networks** presents an overview of the state of the art of each single network element and their interactions inside optical networks.
- **Chapter 3**: **Challenge in architecture development** presents the study of the reason is necessary an evolution of the Internet architecture versus an optical disaggregated optical network considering also the advantage of economic aspects. As reason for the new evolution of Internet infrastructure we highlighting the evolution of digital society as the need that each user needs to have more bandwidth to access the Internet network, the applications require to set thresholds for low latency, packet loss and how in the 5G network the application requirements are supported enabling the network slicing and the data traffic is transported inside optical networks.
- **Chapter 4: Physical layer abstraction** presents an open software GNPy [24] used to calculate and eventually allocate the best optical path in order to have the best quality of transmission between source and destination.
- **Chapter 5: NETCONF protocol [7]** as possible standard protocol used to communicate between SDN and each single optical device in order to retrieve/set the parameters according with the data traffic requests

- **Chapter 6: YANG data model language [8],** used to describe each optical device built from different vendors. We presents an overview of the architecture and an example of its use inside disaggregated optical network
- **Chapter 7: SDN,** centralized software approach used to manage an entire optical network. We present the ONOS [2] as a possible SDN orchestrator used to manage optical networks, analyzing both the architecture and some typical operations.
- **Chapter 8: Future and possible scenarios** summarize the optical networks change in order to support the growth of bandwidth requirements and the application constraint parameters.

2. Background of Optical Networks

A commonly used figure of merit for communication systems is the bit rate/distance product, BL, where B is the bit rate and L is the distance after which an optical signal must be regenerated to maintain its fidelity.

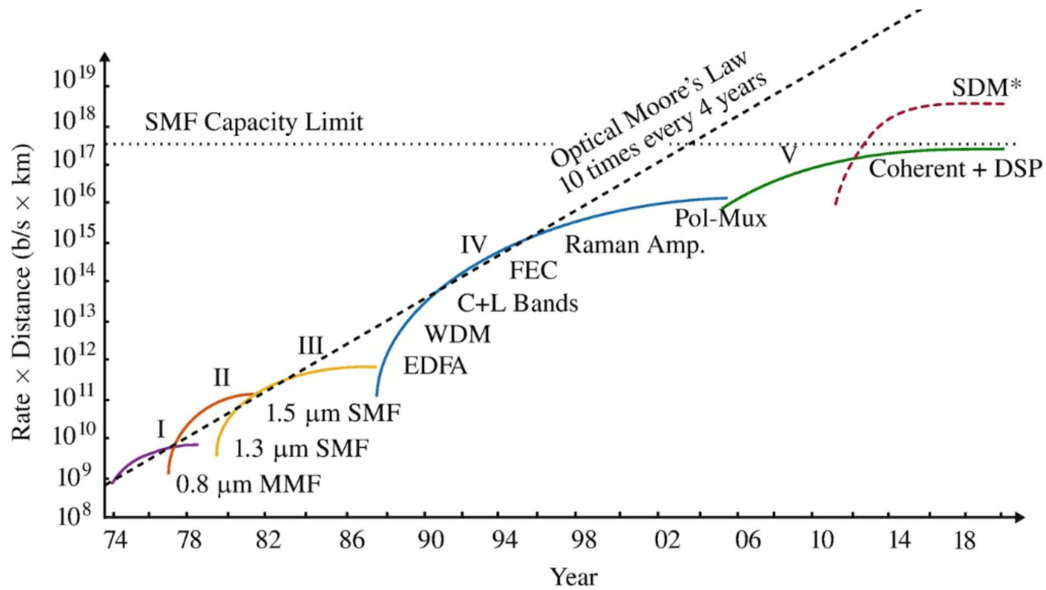


Figure 2.1 Evolution of the BL product [5].

Fig. 2.1 shows the evolution of the BL products over time. Optical communication systems are known to have a large bandwidth, and this bandwidth can be used to transmit a large volume of data over large distances. Thus, the BL product is the most suitable metric to quantify the quality of a fiber optical link and the capabilities of different technological generations. The interesting feature in Fig. 2.1 is the shape of the curves corresponding to different generations. Each curve begins with a large derivative that then decreases over time. This great derivative corresponds to the introduction of disruptive technologies, with the potential to revolutionize the state-of-the-art in a short time. These disruptive technologies are then followed by incremental contributions that are equally important to the evolution of technology [5].

The first generation of optical communication systems used light-emitting diodes (LEDs) and lasers at 0.8 μm operating in graded-index multimode fibers. Limited by modal dispersion, these systems reached several hundreds of Mb/s · km. The development of Single Mode Fibers (SMFs) in the early eighties overcame the problem of modal dispersion, inaugurating a second generation of optical fiber communication systems also with the development of new light-emitted source in the window near 1.3 μm, where the fiber attenuation is lower. The third generation of the mid-eighties moved the operating wavelength window from 1.3 μm to 1.5 μm, further reducing the attenuation of the optical fiber channel. The fourth generation of the late eighties promoted a quantum leap in optical communications and enabled a new era of low-cost data transmission. With the development of single-mode systems operating at 1.5 μm, the main limitation of optical transmission systems moved from the optical fiber to the electronics, a situation known as electronic bottleneck.

Specifically, although the fiber had enough unexploited bandwidth, it remained unused because the electronics could not modulate and detect signals at those rates. The natural solution to this problem is to use frequency division multiplexing, in which different signals share the same fiber, using different portions of the spectrum. The trend toward frequency division multiplexing or, in optical communications, WDM is explained in Fig. 2.2(a) and (b).

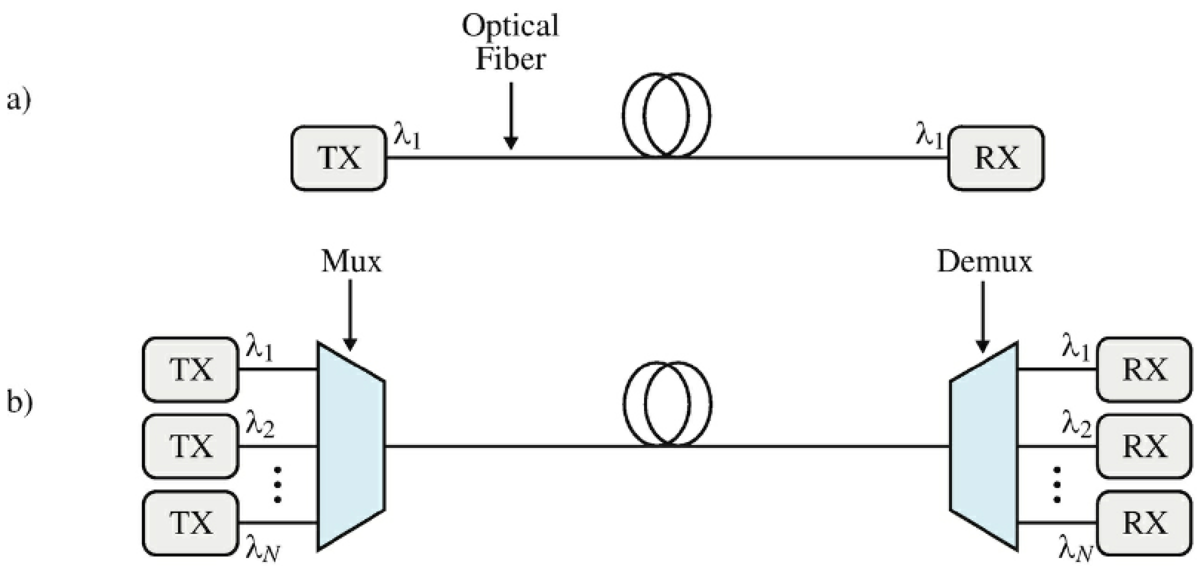


Figure 2.2 (a) Single-wavelength unamplified optical transmission [5]
(b) WDM unamplified short-reach system [5]

Fig. 2.2(a) shows the configuration of third-generation systems, in which the transmitter and receiver were interconnected by a single optical signal transmitted over a single fiber. In this configuration, increasing the link data rate would require the activation of additional fibers. Using WDM, the outputs of several transceivers operating in different wavelengths are optically multiplexed into a single fiber using a multiplexer (see Fig. 2.2(b)). At reception, the wavelength-multiplexed signals are separated using a demultiplexer. In principle, this solution solves the electronic bottleneck, but it is still not scalable in terms of cost. As the fiber attenuates the signal, it needs to be regenerated periodically in the electronic domain to be able to recover the transmitted bits. The problem of this approach is that opto-electro-optical converters are expensive, and each operating wavelength requires its own regenerator (see Fig. 2.2(c)) [5].

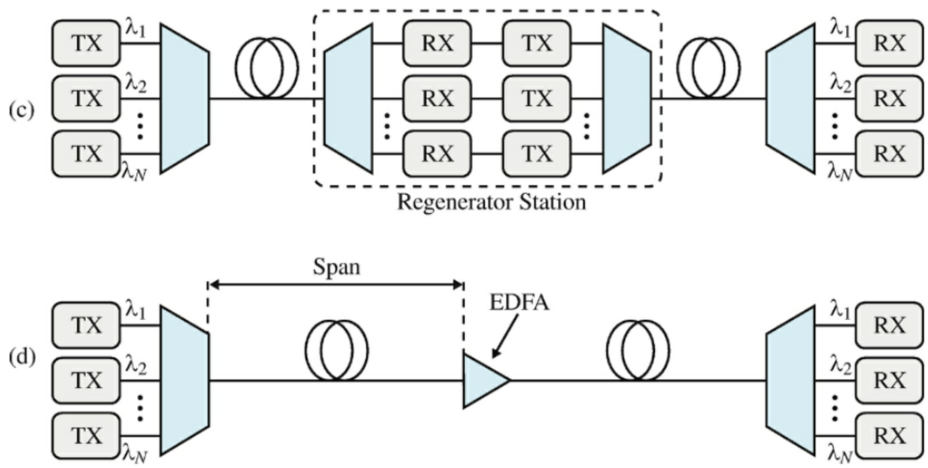


Figure 2.2 (c) WDM unamplified long-reach system [5].
(d) WDM long-reach system with EDFA amplification [5].

As a consequence, the cost of a regenerator station becomes proportional to the number of active wavelengths. As the distance between two regeneration stations typically does not exceed 100 km, the cost of long-haul optical links with thousands of kilometers and tens of regeneration stations was prohibitive. The solution to this problem came with the invention of an ingenious and relatively inexpensive device, capable of amplifying all wavelengths in the optical domain, without any opto-electro-optical conversion. The erbium-doped fiber amplifier (EDFA) revolutionized not only optical communications, but also made possible the information society in which we live today. The importance of the invention of the EDFA can be understood by comparing Fig. 2.2 (c) and (d). Prior to the invention of EDFA, even with WDM, the optical signal for each channel (or wavelength) needed to be periodically regenerated in the electronic domain to compensate for link losses. This regeneration needed to be performed at distances of less than 100 km. Therefore, a WDM link of 20 wavelengths and 1000 km required 9 × 20 = 180 opto-electro-optical regenerators. With the advent of EDFA, these 180 regenerators could be replaced by only 9 EDFAs, with each EDFA having a lower cost than a single regenerator. The fourth generation of optical systems lasted until the mid-2000s, when the technological revolution enabled by the Internet, the expansion of mobile equipment, and the popularization of cloud services required the development of a new disruptive technology. It is in this context that the digital coherent systems appeared, inaugurating the fifth generation of optical transmission systems. The sixth generation of optical systems but the current state of the art points to the development of technologies that exploit space-division multiplexing (SDM) [5].

The metro network environment is one of the network segments with considerable variety in terms of the presence of data traffic granularities, varying from below 1 Gb/s up to 800 Gb/s, with different modes of communication and traffic profiles, different patterns of traffic distribution, both in time and space, coexisting in the same network segment. Also, design decisions, such as the chosen network topology and architecture or the transmission system, result in a significant impact on the traffic generated in other network segments such as core networks and access networks [10].

2.1 Architecture

Metropolitan optical transport networks are composed of nodes in the optical path layer. The nodes perform various functions from a structural perspective, in the role of traffic aggregation hub (which does not generate traffic) or edge nodes (on the border between two different networks). From a physical perspective, each node has a set of equipment necessary to establish the end-to-end optical paths. From a *structural perspective*, network nodes can also be defined with different terminologies according to the role represented in each network segment as well as the functionality of the specific segment [10].

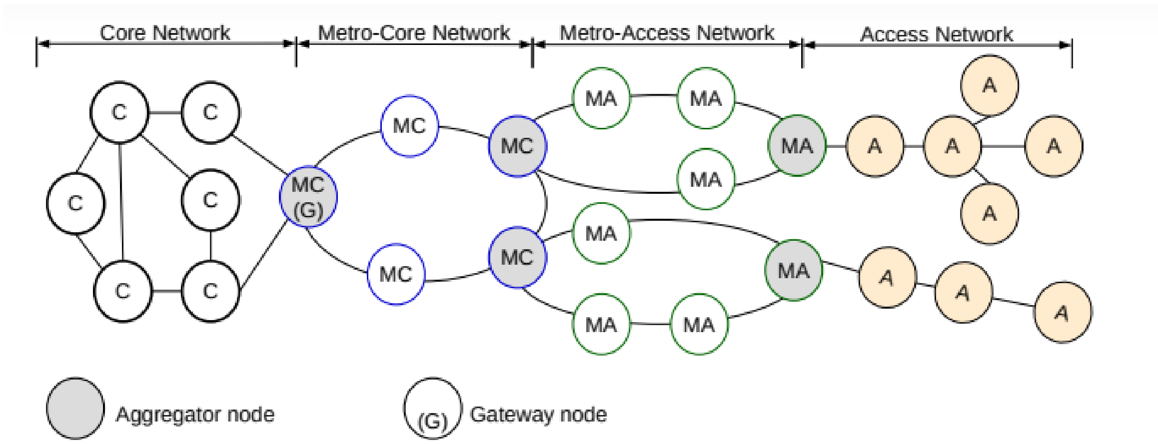


Figure 2.1.1: Structure of an optical transport network [10].

In Fig. 2.1.1, core network nodes with letter C are represented as black circles, the metropolitan segment is divided into two levels, being metropolitan-core network nodes with letters MC represented as blue circles, and metropolitan-access network nodes with letters MA represented by green circles. Further, the segment of nodes in the access network, with the letter A, is represented by circles filled in beige. The letter G in parenthesis identifies the node that is the gateway to the core network. The fully colored gray nodes play the role of traffic aggregator for a given network level immediately below.

The switching nodes in the metropolitan networks are also called Metro-Core (MC) and are located in Points-of-Presence (POPs). The nodes in the Metro-Access network are also called Metro-Aggregation (MA) and are usually where the Central Offices (CO) are located. Another segment (not shown in the figure), which is positioned to the right of the access network, can be mentioned as the device layer used to aggregate end customers and/or applications [10].

Dually, from a *physical perspective*, the optical network architecture is the set of equipment developed independently as switches, multiplexer/demultiplexers, transmitters/receivers, amplifiers, passive elements and transmission media (optical fiber) [10]. Fig. 2.1.2 shows a list of elements that will be highlighted below.

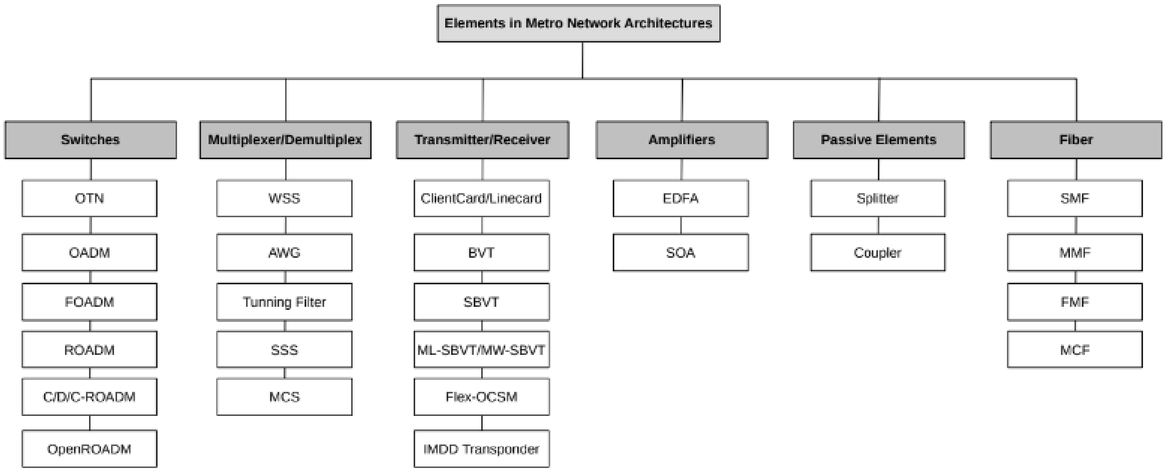


Figure 2.1.2: Main equipment involved in optical network infrastructures [10]

The optical spectrum in optical fibers is divided into several windows or bands for better use of the region with lower attenuation. Fig. 2.1.3 shows the optical transmission power loss measured in *decibels per kilometer (dB/Km)*.

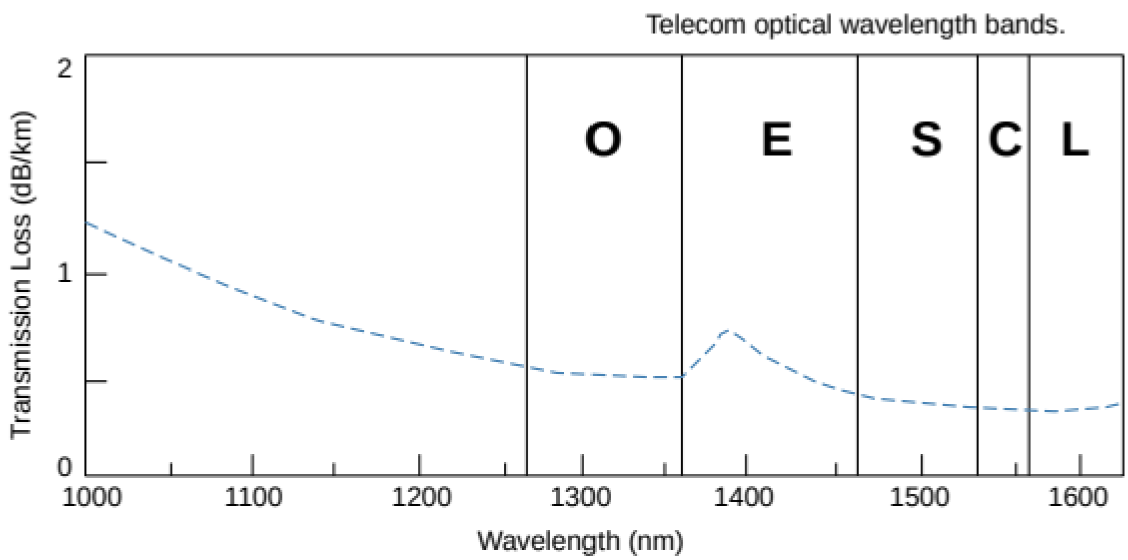


Figure 2.1.3: Behavior of the fiber transmission loss as the wavelength varies [10].

The power loss varies according to the wavelength of the chosen light and the composition of the transparent medium. The lowest loss occurs at a wavelength of 1550 nm inside the C band, which is commonly used for long distance transmissions, followed by the L band. Each transmission band has particular restrictions and requires specific equipment for its adoption. In Fig. 2.1.4, there is a sketch of an optical network with the main components: this design can be used to describe the Internet connections or any optical connection between two end-nodes (Network Users can be data centers, cloud networks,).

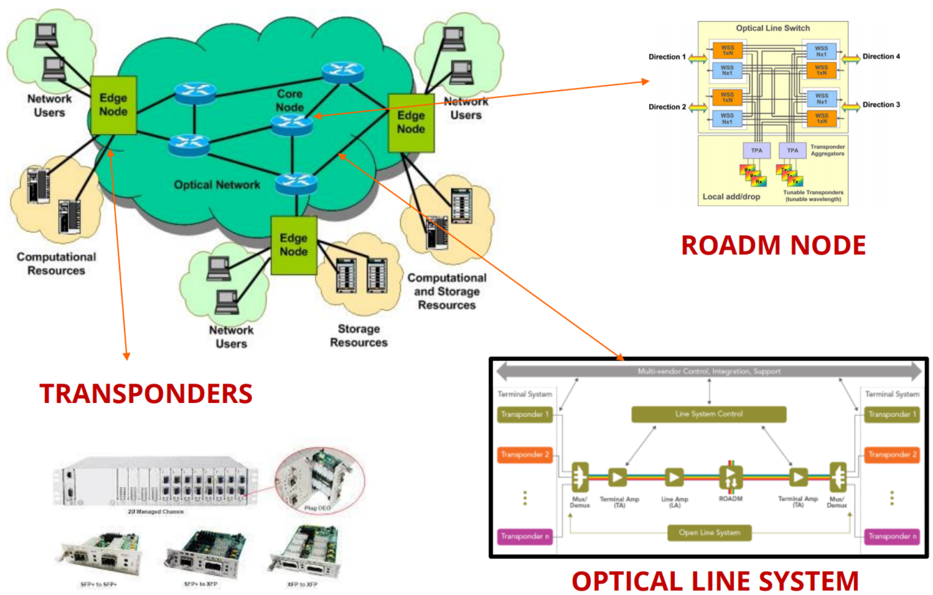


Figure 2.1.4 Sketch of an optical network and its main components

2.2 Optical Components

An optical network is a communication system that uses light signals instead of electronic ones to send information between two or more end-nodes. Optical networks comprises ROADMs, transponders, optical amplifiers and optical line systems.

2.2.1 ROADMs

Lightpath forwarding between nodes is carried out by **ROADM**. The main building block in ROADMs is a Wavelength Selective Switch (WSS), whose logical operation is exemplified in Fig. 2.2.1.1.

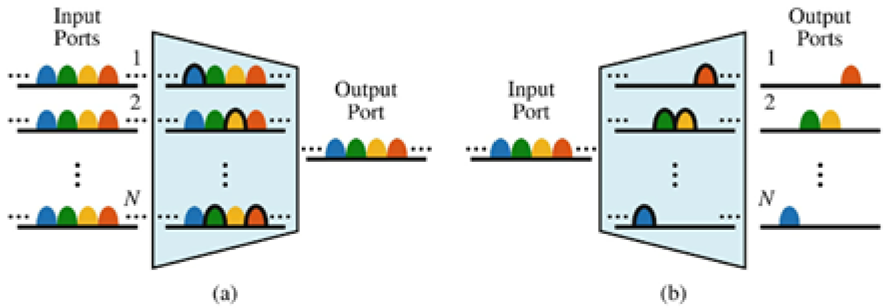


Figure 2.2.1.1 (a) WSS Multiplexer (b) WSS Demultiplexer [5]

Working as a multiplexer, the WSS is able to select any set of wavelengths from any of its input ports and steer it to a unique output port (Fig. 2.2.1.1(a)). Working as a demultiplexer, the WSS is able to select any set of wavelengths from a unique input port and steer it to the output ports (Fig. 2.2.1.1(b)).

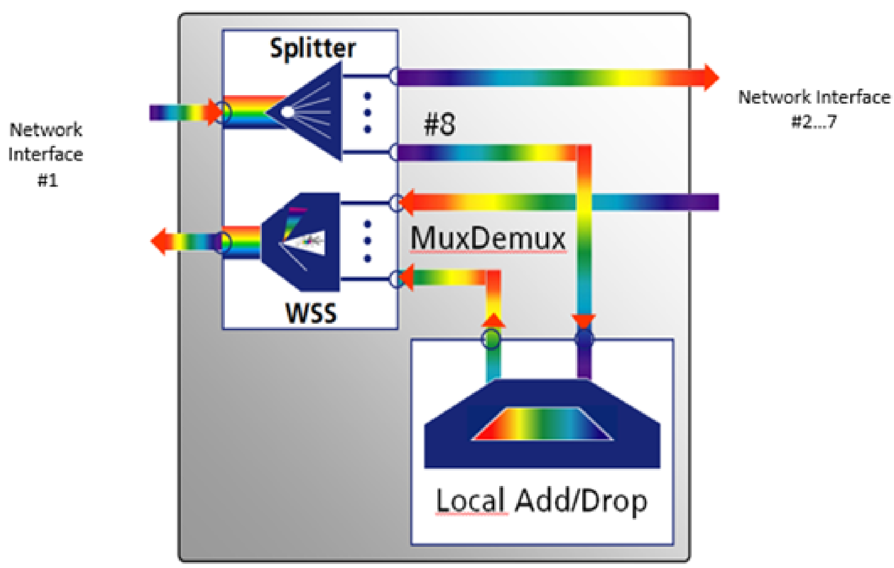


Figure 2.2.1.2 ROADM sketch [5]

In the Fig. 2.2.1.2, the ROADM generally consists of two major functional elements: a wavelength splitter and a WSS. In every junction node there are many ROADM modules as many degrees there are in the node. (Node with 5 degree = 5 ROADM module in the node). Among several desired properties, ROADMs are classified according to specific features: **colorless, directionless, contentionless**.

Colorless	Simple ROADMs comprise one WSS for each direction, also referred to as "one degree". The wavelengths are still assigned and fixed add/drop transceivers used. Colorless ROADMs do away with this limitation: With such ROADMs, any wavelength or color can be assigned to any port. No truck rolls are required as the complete setup is software-controlled. Filter modules must be implemented for the colorless feature.
Directionless	This often appears in conjunction with the term "colorless". A directionless design removes a further ROADM limitation. The need to physically reconnect the transmission fibers is eliminated using directionless ROADMs as there are no restrictions with regard to direction, for example, southbound or northbound. Directionless ROADMs are the most widely spread ROADM design as they allow the add/drop of a wavelength from the supported ITU grid on any line interface. In case of a directionless-only variant, the add/drop ports are specific to a defined wavelength. Using the colorless option, the ports can also be non-wavelength-specific. The directionless technology is mostly deployed for re-routing wavelengths to other ports as required for restoration purposes. Other applications are also possible, for example, in bandwidth-on-demand situations. ROADMs not supporting the directionless feature are subject to some limitations with regard to flexibility.
Contentionless	Though colorless and directionless, ROADMs already offer great flexibility, two wavelengths using the same frequency could still collide in a ROADM. Contentionless ROADMs provide a dedicated internal structure to avoid such blocking.

The first generation of architecture was in optical-electrical-optical (O-E-O) mode, where a lightpath is terminated and regenerated at every intermediate node. A network configured in this mode performs O-E-O conversion of the signals at every endpoint of each transmission system. The adoption of optical bypass is a mechanism where a

lightpath remains fully in the optical domain. Optical bypass operation has then become a dominant technology adopted by the majority of carriers in both metro and core/backbone networks in the last two decades [31].
Reconfigurable optical add/drop multiplexers (ROADMs) are the key elements in building the next-generation, dynamically reconfigurable optical networks. ROADMs enable dynamic add/drop or express pass-through of individual wavelength division multiplexed (WDM) channels or groups of channels at network nodes without the need for costly optical–electrical–optical (O–E–O) conversions. Common issues to consider are control and management plans to properly configure the node and perform essential signaling and switching functions, as well as mitigation of transient effects induced by optical amplifiers. In WDM networks, the transient may be caused by the dynamic adding or dropping of optical channels or by performing protection, provisioning or reconfiguration in the optical layer. When even a small transient is generated at the beginning of a chain of optical amplifiers, it accumulates in the chain and increases in amplitude [12].
The open DWDM optical line system provides reconfigurable optical add/drop multiplexing and pass-through of channels in multi-degree nodes. The pass-through enables channels to be switched from one degree to another within the same ROADM node. Channels configured to take a pass-through path entering on one degree are demultiplexed and routed to the designated pass-through port on the other ROADM degree, which multiplexes the channels and sends them out the line port of the ROADM degree to the next node in the path.

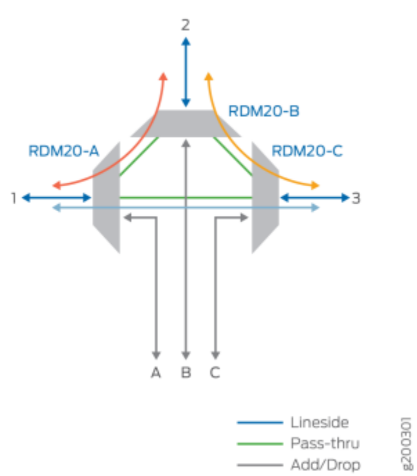


Figure 2.2.1.3 Allowable channel connectivity using pass-through [15].

In the configuration shown in Fig. 2.2.1.3, channels are add/dropped to any of the three directions served by the node based on which ROADM element they are physically connected to, or channels can be passed from one degree to another over the pass-through path between each degree in the node. The multi-degree ROADM node in Fig. 2.2.1.3 consists of the following ROADM elements and degrees:

- 3 ROADM degrees:
  - Degree 1 is specific to direction 1:RDM20-A
  - Degree 2 is specific to direction 2:RDM20-B
  - Degree 3 is specific to direction 3:RDM20-C
- 3 ROADM elements:
  - ROADM element RDM20-A serves ROADM degree 1
  - ROADM element RDM20-B serves ROADM degree 2
  - ROADM element RDM20-C serves ROADM degree 3

Using pass-through connections, you can create a flexible connectivity map for the ROADM node. By interconnecting all ROADM degrees to all other ROADM degrees within the same node using pass-through, you can establish a fully non-blocking switching matrix [13].

With the Internet, mesh networks became the standard. Nodes in mesh topology can be characterized by their degree, which is the number of neighboring nodes. The higher is node degree the more complex the node switching architecture:

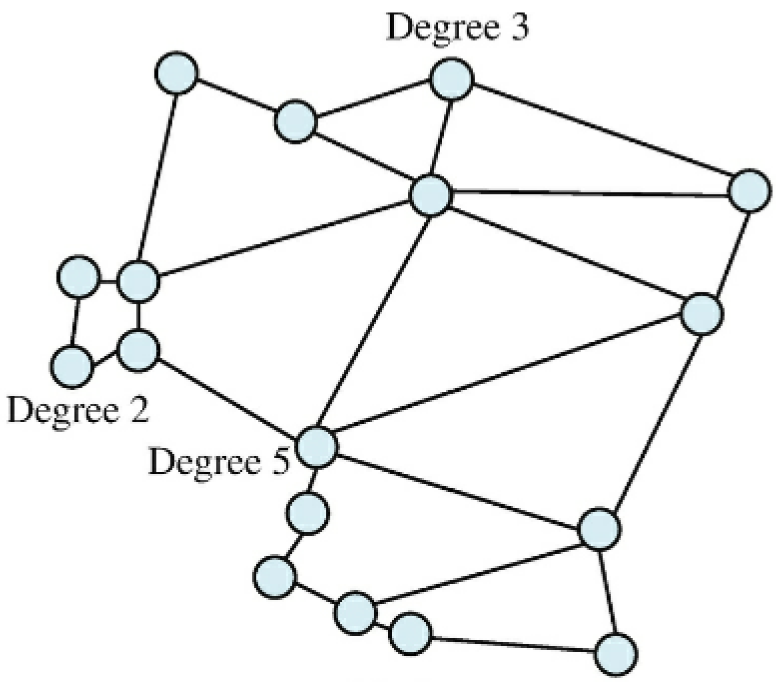


Figure 2.2.1.4 Mesh Optical Network[5]

A mesh topology is defined as such by the existence of several interconnected nodes with a degree greater than 2. Lightpath forwarding is carried out by ROADMs. Current optical systems offer flexibility in several dimensions, and this is only possible thanks to symbiotic advances in transmission (with coherent detection) and networking (with a flexible grid, WSSs and ROADMs) [5].

2.2.2 Transponder

Transponders are signal converters from the optical to the electronic domain, or vice-versa. At each entrance door, there is a traffic receiving device (Rx) and there is a traffic transmitting device (Tx) at each exit port. At each end of the path between nodes a transmitter (to send a signal over the wavelength) and a receiver (to receive signal over the wavelength) will be required. A combination of transmitter and receiver is defined as a transceiver. The building blocks of these elements are synthesized and are shown in Fig. 2.2.2.1.

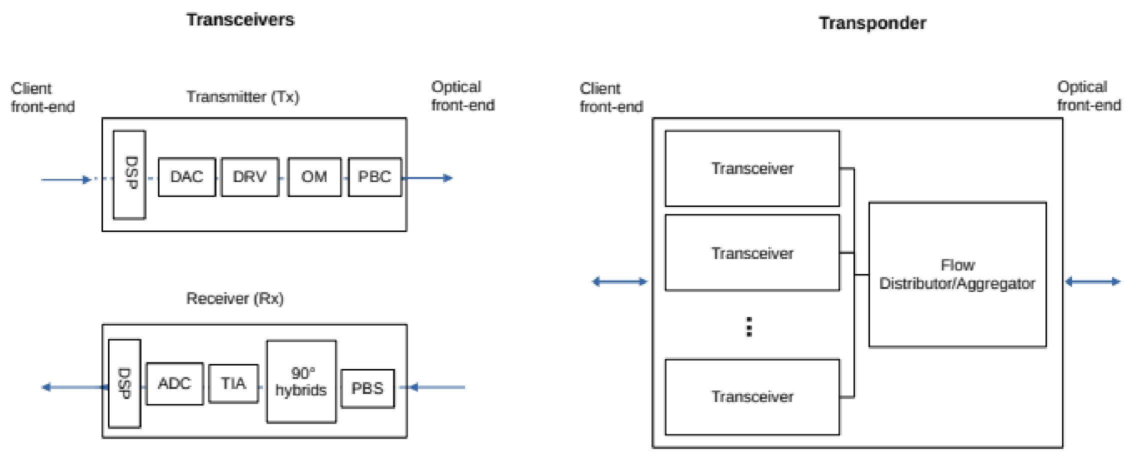


Figure 2.2.2.1 Transceiver and Transponder [10].

At the transmitter, the signal is processed in Digital Signal Processing (DSP), in a process capable of improve its efficiency : this signal is converted to an analog signal using Digital Analog Converter (DAC) and modulated on Modulator Driver (DRV) to avoid a degradation in quality. Then the signal is modulated by Optical Modulator (OM), in-phase and in-quadrature components, and their components are combined by a Polarization Beam Converter (PBC) to be transmitted in the optical domain [10].
At the receiver, the Polarization Beam Splitter (PBS) splits the signal into components that are sent to power dividing. Then the signal is amplified with Transimpedance Amplifiers (TIA) to guarantee stability while making the signal able to be converted and digitized, then passes through the Analog Digital Converter (ADC). In the sequence the signal is sent to the DSP to adapt the expected data rate. The role to treat the signal in the receiver is to create a signal equal to the signal transmitted so it is possible to determine the difference between signal transmitted and received and correct data rate, modulation format [10].

2.2.3 Optical Amplifier

The simplest solution to attenuation would be to increase the power with which optical signals are launched into the fiber. However, the indiscriminate increase in power strengthens nonlinear fiber effects that degrade the system performance. The alternative solution adopted in long-distance optical systems is the periodic insertion of optical amplifiers along the link. Among existing solutions, the erbium-doped fiber amplifier

(EDFA) is the most widely used. EDFAs operate typically in the C-band (1530–1565 nm), but L-band (1565–1625 nm) designs are also available commercially. Optical amplification in EDFAs is based on the process of stimulated emission (just as with lasers). The choice of the erbium ion (Er^{3+}) as dopant is due to the fact that the difference between two of its energy levels corresponds to wavelengths close to 1550 nm, which is exactly the lowest attenuation band in the fiber. The typical architecture of an EDFA is depicted in Fig. 2.2.3.1 (b). A pump laser operating at wavelengths of 980 or 1480 nm is coupled to the doped fiber using a WDM multiplexer. Both the signal and the pump propagate through the EDF, leading to signal amplification. Finally, the pump is separated again from the signal by a WDM demultiplexer. An isolator is usually placed at the amplifier output to prevent backscattering of light into the amplifier because of the high output power levels. The purpose of optical amplifiers is to impart optical gain to input signals. Naturally, this gain is limited, constrained by the pump signal and the properties of the gain medium [5].

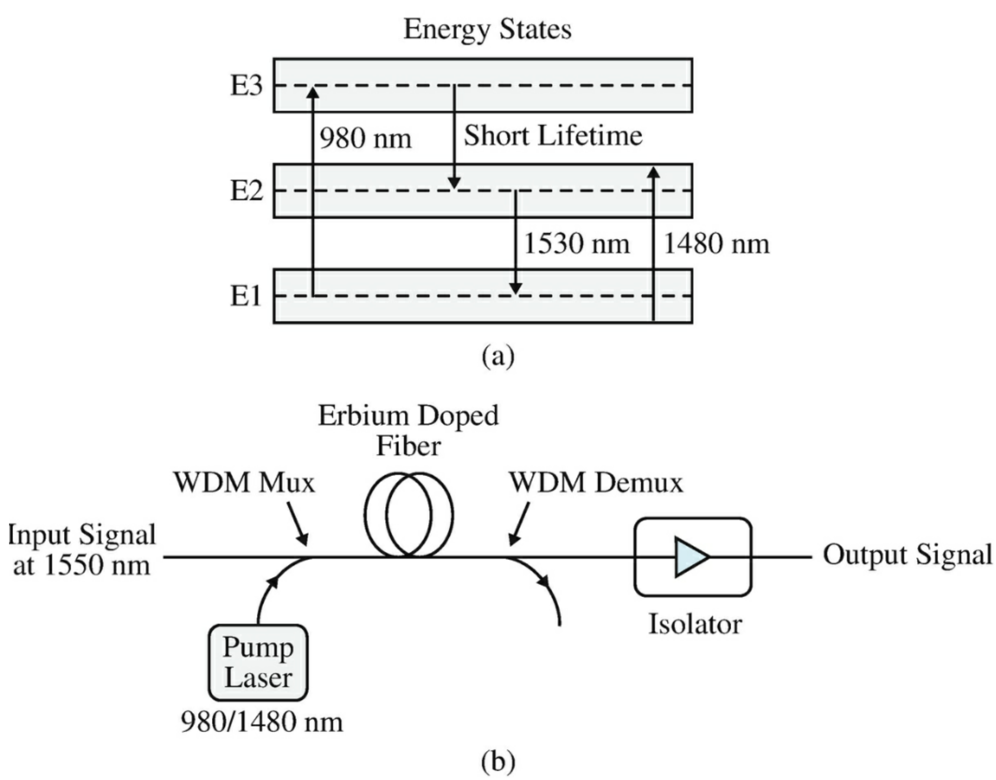


Figure 2.2.3.1 EDFA Amplification: (a) energy level, (b) architecture [5]

Fig. 2.2.3.1 (a) shows the energy levels of Er^{3+} ions on silica involved in the EDFA amplification process. It is desired to obtain a large population in E2 to favor the stimulated emission process in the transition from E2 to E1. Such population inversion can be achieved in two ways. The first way is to pump ions from E1 to E3 at 980 nm. As the lifetime of ions in E3 is short (τ 32 = 10 μs) [16], ions quickly transition to E2 through the process of spontaneous emission. The second way is to pump ions directly to E2 at 1480 nm, where the ion lifetime is longer (τ 21 = 10 ms). In general, pumping at 980 nm is more efficient, attaining larger gains and adding less noise. In addition, 980-pumping also facilitates pump multiplexing, as it is further away from the 1550-nm signal channels. On the other hand, as the fiber has a lower attenuation at 1480 nm than at 980 nm, 1480-nm pumping is recommended in specific applications involving remote pumping as in hostile areas, where optical pumps propagate along the signal over the transmission fiber [5].

2.2.4 Optical Line System

The optical transport for core and metro networks are subdivided in two main categories: fixed grid and flexible grid. The ITU has proposed a set of standards to define the use of optical spectrum. In a fixed grid the 4 THz C-base spectrum is divided into 80 channels spaced each other by 50 GHz or the 4 THz C-base spectrum is divided into 40 channels spaced each other by 100 GHz. Each channel is assigned a defined central frequency f and 50 GHz of spectrum (f-25 GHz to f +25 GHz) around the central frequency. Currently deployed 10, 40, and 100 Gb/s transponders [11].

For optimum utilization of spectral resources and to accommodate heterogeneous bandwidth demands, the ITU-T has defined a flex grid recommendation. The flex-grid recommendation allows for a flexible division of the optical spectrum and defines the concept of a frequency slot, in addition to a nominal central frequency and a channel/carrier spacing. A frequency slot is defined by its nominal central frequency and its slot width. The first is defined as 193.1 + n x 0.00625 THz, where n is a positive or negative integer. The slot width is defined as 12.5 GHz x m, where m is a positive integer. Thus, the minimum slot width is 12.5 GHz. A channel’s nominal central frequency identifies its position in the spectrum and slot width determines the occupied spectrum. Different slot widths can be allocated to accommodate different spectral needs [11].

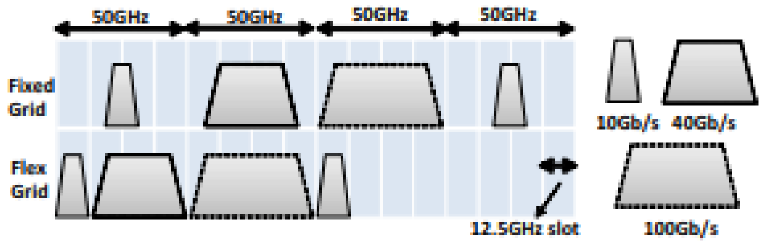


Figure 2.2.4.1 Fixed Grid and Flex Grid [11].

Nyquist wavelength-division multiplexing (NWDM) is a more flexible form of WDM that limits channel spacing to transmission rate by generating almost rectangular spectra, with negligible crosstalk and inter symbol interference [10].
Traditional Dense Wavelength Division Multiplexing (DWDM) technology is no longer enough to meet the extensive growth in the demand of bandwidth in an efficient and effective manner under the fixed grid environment. To overcome the challenges, an Elastic Optical Network (EON) paradigm comes into existence. It uses flexible grid technology that removes the limitations of fixed grid increasing the channel capacity with proper utilization of optical spectrum.
State-of-the-art optical communication systems:

- 400 Gb/Sec per channel
- 100 Channel per fiber
- Several fibers/cable
- It means 50 bi-directional fiber pair
- Overall fiber bi-directional capacity $C = 400\ 100\ 50 = 2\ 10^{6}\ Gb/sec$

A fast End User Home Internet connection operates at 1 Gb/sec (1000 10^{6} bit/sec) : to reach 10 Tbit/sec (10 10^{12} bit/sec) a single fiber (125 µm diameter) can carry $\left(\frac{10\ 10^{12}}{1000\ 10^{6}}\right) = 10000$ Internet connection at 1 GB/sec. A single cable includes at least 10 fibers so a single cable can carry up to 100000 Internet connections at 1 Gb/sec.
The trend in using Frequency Division Multiplexing (FDM) or in optical communication WDM is explained in Fig. 2.2.4.2 where at the transmitter the output of several transceivers operating in different wavelengths are optically multiplexed into a single fiber using a multiplexer. As the fiber attenuates the signal, it needs to be regenerated

periodically with Erbium-Doped Fiber Amplifiers (EDFAs) capable of amplifying all wavelengths in the optical domain without any opto-electronic-opto conversion.

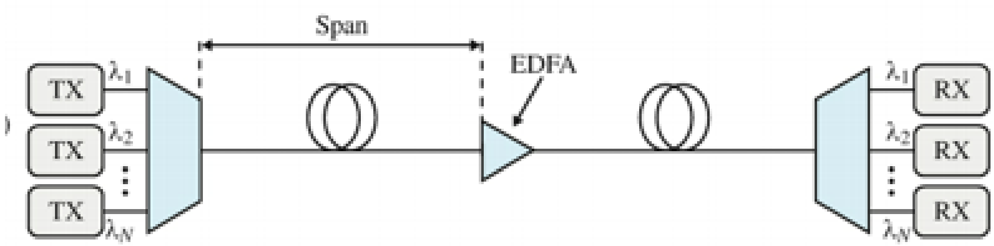


Figure 2.2.4.2 WDM optical system with EDFA [5].

Digital coherent optical systems are mainly deployed in high data rate optical networks intended to provide Internet traffic between geographical locations. The vast majority of signals transmitted in today's optical networks originate from Ethernet-based routers, which aggregate various low-rate streams into high-rate streams and launch them into optical networks as shown in Fig. 2.2.4.3. The generated optical signal operates in the windows of 850 nm or 1310 nm and it is transmitted over low-cost multimode fibers. This short optical signal is sent to a device called a transponder, whose purpose is to receive the optical signal generated by low-cost lasers and prepare the information for long-distance transmission. This preparation includes the encapsulation of data in transport protocol, the insertion of Forward Error Correction (FEC), and optical domain conversion using high-quality laser operating at 1550 nm [5].

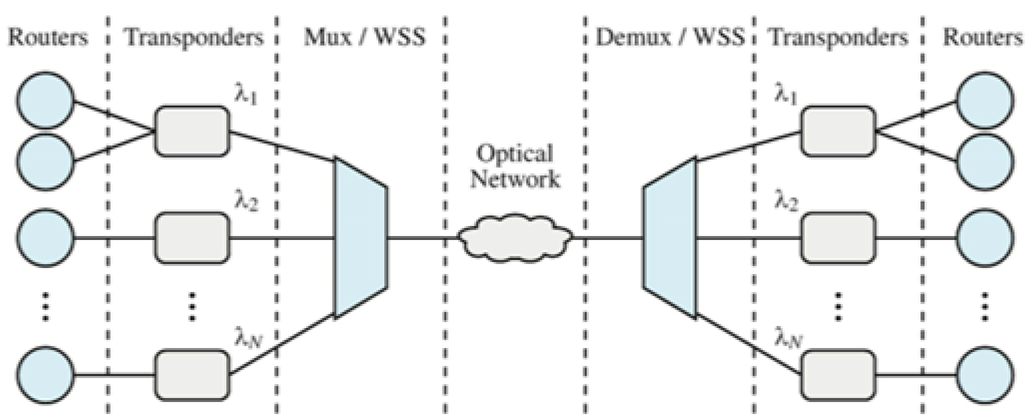


Figure 2.2.4.3 Transponder and WDM signal generation [5].

After the high-quality optical signal is generated by the transponder, it is frequency multiplexed using an optical multiplexer. Wavelength assignment involves determining a path in the network between two nodes and allocating a free wavelength on all links of the path. The transponder is tuned to generate an optical signal at a certain wavelength that remains fixed up to the receiver. At the receiver, the reverse process is carried out by an optical demultiplexer [5].

2.2.5 Fiber Propagation

The optical communication channel is the result of several interactions between optical signals and matter. These effects can occur in various fiber-optic sections of the link or in the devices traversed by the optical signal. An optical fiber is basically a cylindrical dielectric waveguide made up essentially of two layers, called the core and the cladding. There are two types of propagation mode in the fiber optical cable which are multi-mode and single-mode: the single-mode fiber provides robust performance at higher cost.

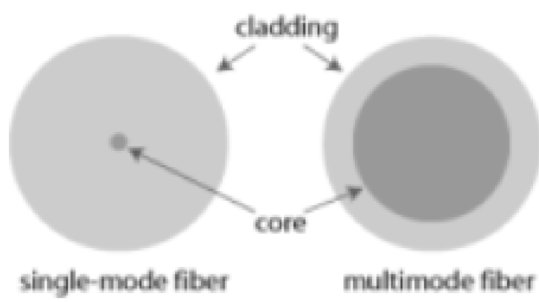


Figure 2.2.5.1 Examples of optical fiber for telecom applications [5]

In single-mode the refractive index n_2 of the cladding layer is slightly lower than n_1 of the core layer to facilitate the total internal refraction. Single-mode optical waveguides are a solution to reduce modal dispersion. Single-mode optical waveguides are designed so that they prevent the existence of higher-order waveguide modes. Properly selecting waveguide parameters is critical to cutting off the higher-order waveguide modes in optical waveguides. The cut-off frequency is the frequency above which the waveguide offers minimum attenuation to the propagation of the signal. Frequencies below the cut-off frequency are attenuated by the waveguide. To avoid signal attenuation and power loss from multiple active modes, waveguides should be constructed with their cut-off frequency in mind. When trying to pass signals of lower frequency than the cut-off frequency, the waveguide develops mechanical constraints [5].

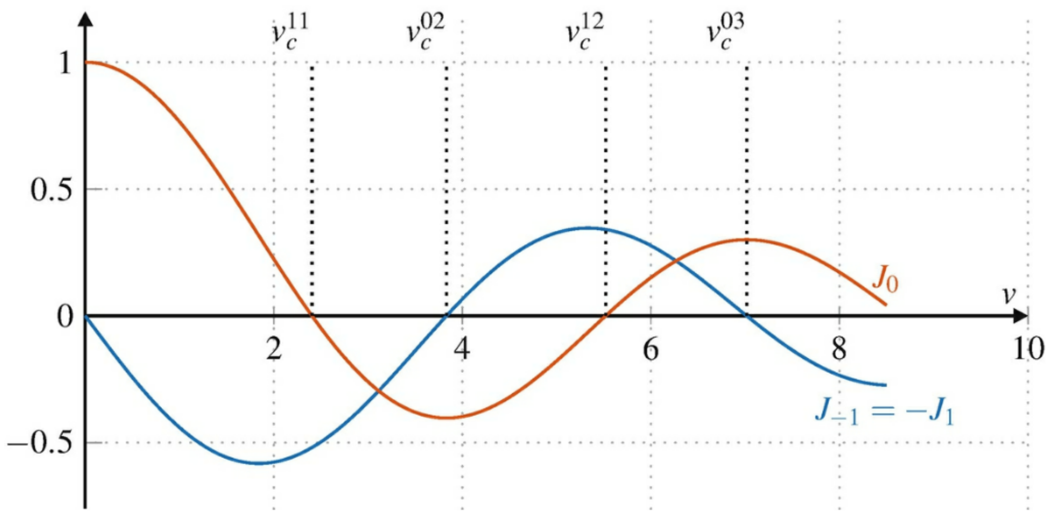


Figure 2.2.5.2 Cut-off frequencies of LP for l=0 and l=1 [5].

For $v < v_c^{11}$ is the single-mode condition required ($v_c^{11} = 2.405$)

The cut-off frequency v determines the number of propagation modes:

$v = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2}$ with a is core radius

Each mode is characterized by a specific propagation constant $\beta = \frac{2\pi n_{eff}}{\lambda}$ The propagation constant β is usually obtained by setting the boundary conditions of tangential fields at core-cladding in Maxwell's equation [5].

2.2.5.1 Chromatic Dispersion

Phase velocity is the speed of wave crests of a propagating wave. Phase velocity does not indicate the speed of energy or information transfer, but only the speed of a wave pattern. For a mode with propagation constant β, the phase velocity v_p of a sinusoidal signal with frequency ω is given by $v_p = \frac{\omega}{\beta}$. The optical waveguide is not a plane wave so the definition of phase velocity becomes $v_g = \frac{\partial\omega}{\partial\beta}$. If the propagation constant has linear dependency as in plane waves with frequency, $v_p = v_g$ any group of propagating frequencies have the same group velocity, and pulses are not distorted. In the optical waveguides the propagation constant β has a nonlinear dependence on ω.. Thus, different spectral components of a guided mode propagate with distinct group velocities, giving rise to the phenomenon known as CD . If left uncompensated, CD broadens the propagating pulses and leads to inter symbol interference (ISI), as shown in Fig. 2.2.5.1.1. In optical fibers, CD is generated by two main contributions. The first one, called material dispersion , is related to the material from which the fiber is made. The second one, called waveguide dispersion , arises from the fact that part of the energy of the transmitted signal propagates in the fiber core, and another part in the fiber cladding. As a consequence, the effective refractive index of the mode has an intermediate value, which depends on the energy distribution between the core and the cladding. As this distribution depends on the wavelength, CD is generated. The CD β_2 gives the spreading of pulses (in seconds) per unit of fiber length (in meters) and per unit of spectral bandwidth (in radians per seconds). In specification of optical fibers, however, dispersion is usually quantified by group velocity dispersion (GVD) parameter, D, in unit of s/m^2, $D = \frac{2\pi c}{\lambda^2}\beta_2$ with λ operating wavelength and c speed of light. The fact that different spectral components of an optical signal propagate with different group velocities leads to the temporal broadening of pulses.

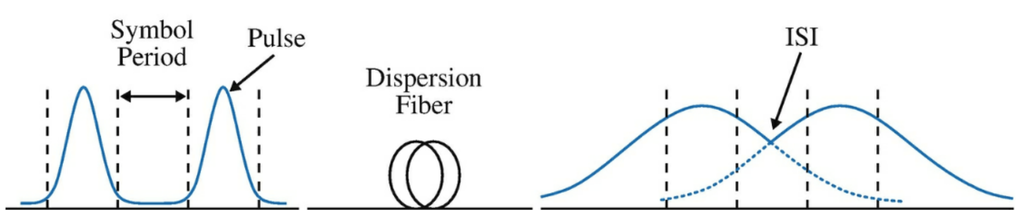


Figure 2.2.5.1.1 Effects of Chromatic Dispersion on signal propagation [5].

2.2.5.2 Kerr Effect

The nonlinearity effects in the optical fiber are due to an electro-optic effect, referred to as the Kerr effect, which arises from the dependence of the optical fiber refractive index on the transmit signal power. That makes the optical fiber channel different from other transmission media used for information transfer. In a linear transmission medium, the information signals are usually perturbed by the additive noise, which generally results in channel capacities monotonically increasing with transmit power and a corresponding increase in the SNR. However, the detrimental effects of Kerr-induced signal nonlinear distortions grow at a faster rate than the SNR capacity gain at higher launch powers. That in turn leads the channel capacity to be a nonmonotonic function of the transmit launch power with a maximum value at a particular launch power termed as optimum launch power. The achievable transmission rate decreases rapidly beyond the optimal power point as the launch power increases due to the corresponding increase in the Kerr-induced signal nonlinear distortion. The transmission performance of the single-channel optical communication systems is mainly limited by the intra-channel Kerr nonlinearity effect [5].

The intra-channel nonlinear interactions can be categorized into three types:

- self-phase modulation (SPM) : the refractive index is modulated by the intensity of the electrical field. In amplitude modulated signals the phase of the optical signal is also modulated causing spectral broadening;

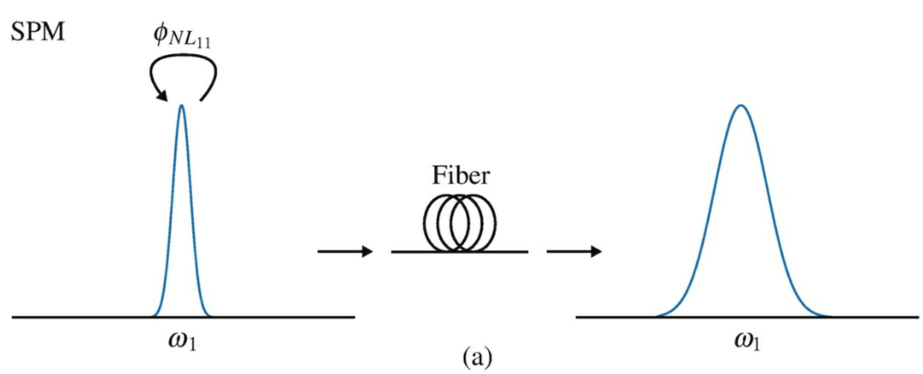


Figure 2.2.5.2.1 (a) Intra-Channel SPM [5].

- intra-channel cross-phase modulation (XPM) : amplitude variation of signal in frequency ω_1 (or ω_2) generate a pattern-dependent non-linear phase shift Φ_{NL12} (or Φ_{NL21}) on a second signal of frequency ω_2 (or ω_1) causing spectral broadening and impairing transmission.

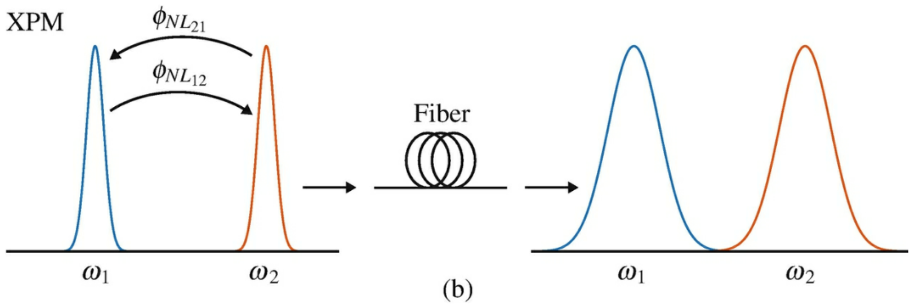


Figure 2.2.5.2.2 (b) Intra-Channel XPM [5].

- intra-channel four-wave mixing (FWM) : three signals in frequency ω_i, ω_j, ω_k generate a fourth signal in frequency $\omega_{ijk} = \omega_i + \omega_j - \omega_k$ with $k \neq i, j$. If $i = j$, the products are called degenerate, while $i \neq j$, they are called non-degenerate.

In the recent history of optical fiber communications, the Kerr effect has been studied in the given settings in accordance with its outcomes as SPM, XPM, or FWM, depending on the number of mixing frequencies. The study of these effects enabled the dimensioning of several generations of optical fiber systems based on on–off keying modulation and dispersion management. However, modern communication systems with Nyquist pulse shaping and electronic dispersion compensation have properties that favor other approaches for the study of nonlinearities. These approaches are based on the observation that, in long-distance dispersion-uncompensated systems, the nonlinear interference can be modeled as AWGN for the purpose of system modeling. [5]

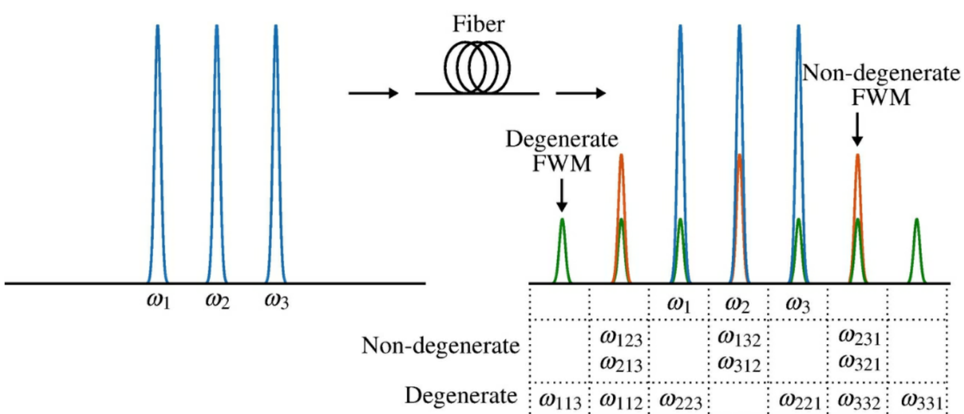


Figure 2.2.5.2.3 (c) Intra-Channel FWM [5].

It is important to mention that the SPM, XPM, and FWM can be compensated well using digital nonlinearity compensation (NLC) techniques referred to as coherent detection. The coherent detection also enables the implementation of the advanced forward error-correction coding techniques and the adaptive digital signal processing (DSP) algorithms to combat time-varying transmission impairments [5].

2.2.5.3 Attenuation

Attenuation reduces the power of an optical signal propagation through the fiber. Attenuation occurs due to several phenomena, such as material absorption, which is intrinsic to the material used in the production of the fiber and its impurities, scattering of light, imperfection in the waveguide geometry and curvatures in the fiber [5].

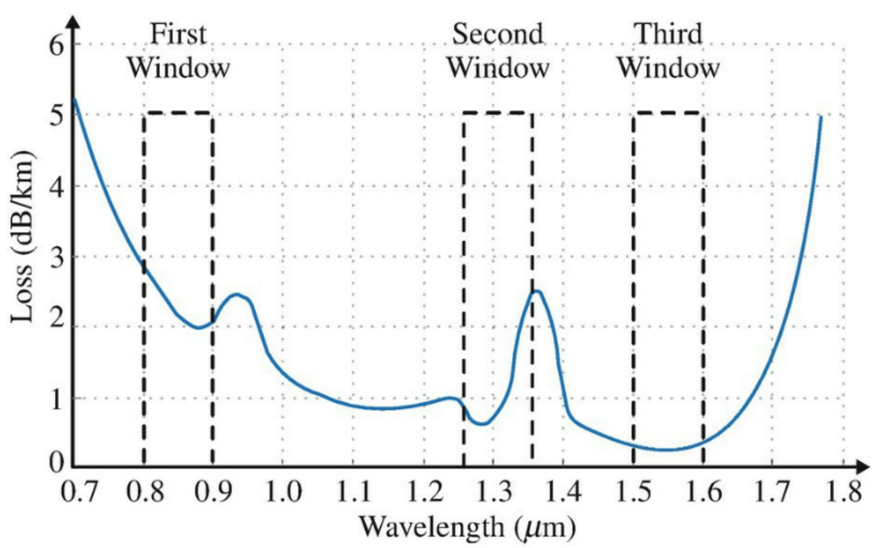


Figure 2.2.5.3.1 Attenuation Profile Of An Fiber [5].

The attenuation profile of an optical fiber shows the dependence of attenuation on the wavelength. It has three main low-attenuation windows that are typically used for optical communications, around 850, 1310 and 1350 nm. The step increase of attenuation in wavelengths shorter than 850 nm is mainly caused by Rayleigh scattering due to random fluctuation in refractive index. On the other side of the spectrum, the high increase in attenuation in wavelengths longer than 1600 nm appears because of absorption in the infrared region. The third window, around 1550 nm, exhibits an attenuation of approximately 0.2 db/km, which is considerably lower than that for the other two, and it is therefore widely used for long-distance transmission [5].

2.2.6 Transmission Technique

The electrical field of the optical carrier is given in terms of the complex envelope:

$$E(t) = \hat{e}Ae^{-j(\omega t+\phi)}$$

where

ê	is polarization vector of the laser source
A	is the amplitude of optical field
ϕ	is the phase of the optical field
ω	is the optical angular frequency

All four properties of the optical signal can be modulated by an electrical binary baseband signal $q(t)$:

$$q(t) = \sum_{i=-\infty}^{\infty} I_i q(t - iT_b)$$

where

I	can be 0 or 1
$q(t - iT_b)$	is the baseband pulse shape q(t) delayed by multiples of bit period T_b

Depending on which parameter of the laser source is modulated the modulation is mainly differentiated as Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK). Coherent detection and Digital Signal Processing (DSP) are now essential building blocks of modern optical communications. Until mid-2000 the On Off Keyring (OOK) amplitude modulation with direct detection was practically the only modulation format used. The reason for which the multilevel modulation format was late adoption was that the bandwidth in WDM systems was sufficient to guarantee good transmission and there was no pressure for improving spectral efficiency. As this pressure appeared in the mid-2000s, the optical communications community moved fast to develop technologies for spectral efficiency transmission. Nowadays, phase and amplitude modulation formats are extensively used in optical communication systems, especially Quadrature Amplitude Modulation (QAM) formats [5].

In the transmission by optical fiber the intensity and the phase of an approximately sinusoidal carrier are modified to convey data information. The modulated signal can be represented as *passband signal representation* :

$$x(t) = \sqrt{2}\, A(t)\, cos(2\pi f_c t + \phi(t))$$

where f_c is the carrier frequency,

A(t) and φ(t) are the amplitude and phase modulation components.

The $\sqrt{2}$ factors normalize the energy of the cosine function. The modulated signal can be also represented as :

$$x(t) = \sqrt{2}\, x_I(t)\, cos(2\pi f_c t) - \sqrt{2}\, x_Q(t)\, sin(2\pi f_c t)$$

where $x_I(t) = A(t)\, cos(\varphi(t))$ and $x_Q(t) = A(t)\, sin(\varphi(t))$, are in-phase and quadrature components

It is possible to adopt another representation of transmitted signals that suppress the dependence on the carrier frequency using complex numbers, called *baseband representation* :

$$x_b(t) = x_I(t) + jx_Q(t)$$

In digital transmission system with passband Pulse Amplitude Modulation (PAM), the continuous-time signals $x_I(t)$ and $x_Q(t)$ can be expressed as a sum of time-delayed continuous waveforms :

$$x_I(t) = \sum_{k=-\infty}^{\infty} x_k^I\, g(t - kT_s)$$

$$x_Q(t) = \sum_{k=-\infty}^{\infty} x_k^Q\, g(t - kT_s)$$

where T_s is the symbol period

Assuming that both signals $x_I(t)$ and $x_Q(t)$ have the same pulse shape g(t) and discrete in-phase and quadrature components x_k^I and x_k^Q. Depending on the choice of x_k^I and x_k^Q various modulation formats, represented by their constellations, are implemented. Fig. 1.2.6.2 shows common constellations used in digital communication. The OOK constellation (Fig. 2.2.6.2(a)) is the simplest and has been the most used throughout the history of optical communications, from its conception to the present day. It has only two symbols, one with amplitude 0 and the other with amplitude A. However, this scenario is changing quickly, and simplified coherent transceivers with multilevel modulation formats should become popular in short-reach applications as coherent transceivers [5].

The second simplest modulation format is binary phase-shift keying (BPSK), shown in Fig. 2.2.6.2(b). In BPSK , the two transmitted constellation symbols are in symmetric position with respect to the origin. At reception, coherent detection is required for polarity discrimination. Differential detection , with modulation formats such as differential phase-shift keying (DPSK), has also been briefly investigated in optical communications but was replaced by coherent detection because of advantages such as seamless chromatic dispersion and polarization mode dispersion compensation. BPSK uses only one degree of freedom, i.e., the modulation of the in-phase component. The simplest modulation format that exploits the two degrees of freedom provided by the complex plane is the quadrature phase-shift keying (QPSK) format, whose constellation is shown in Fig. 2.2.6.2(c). The QPSK constellation consists of the sum of two BPSK constellations in quadrature. QPSK and BPSK are considered phase modulation formats because their amplitude is kept constant for all the constellation symbols. A widely used family of modulation formats that achieves excellent performance is the M-ary quadrature amplitude modulation (M-QAM). In M-QAM, $\sqrt{M}$ amplitude levels of the in-phase and quadrature components are uniformly distributed and independently modulated. Fig. 2.2.6.2(d) shows M-QAM modulation formats, for M=4, 16 and 64. Other non-square M-QAM constellations can also be defined, such as 8-QAM in Fig. 2.2.6.2(e) and 32-QAM in Fig. 2.2.6.2(f) [5].

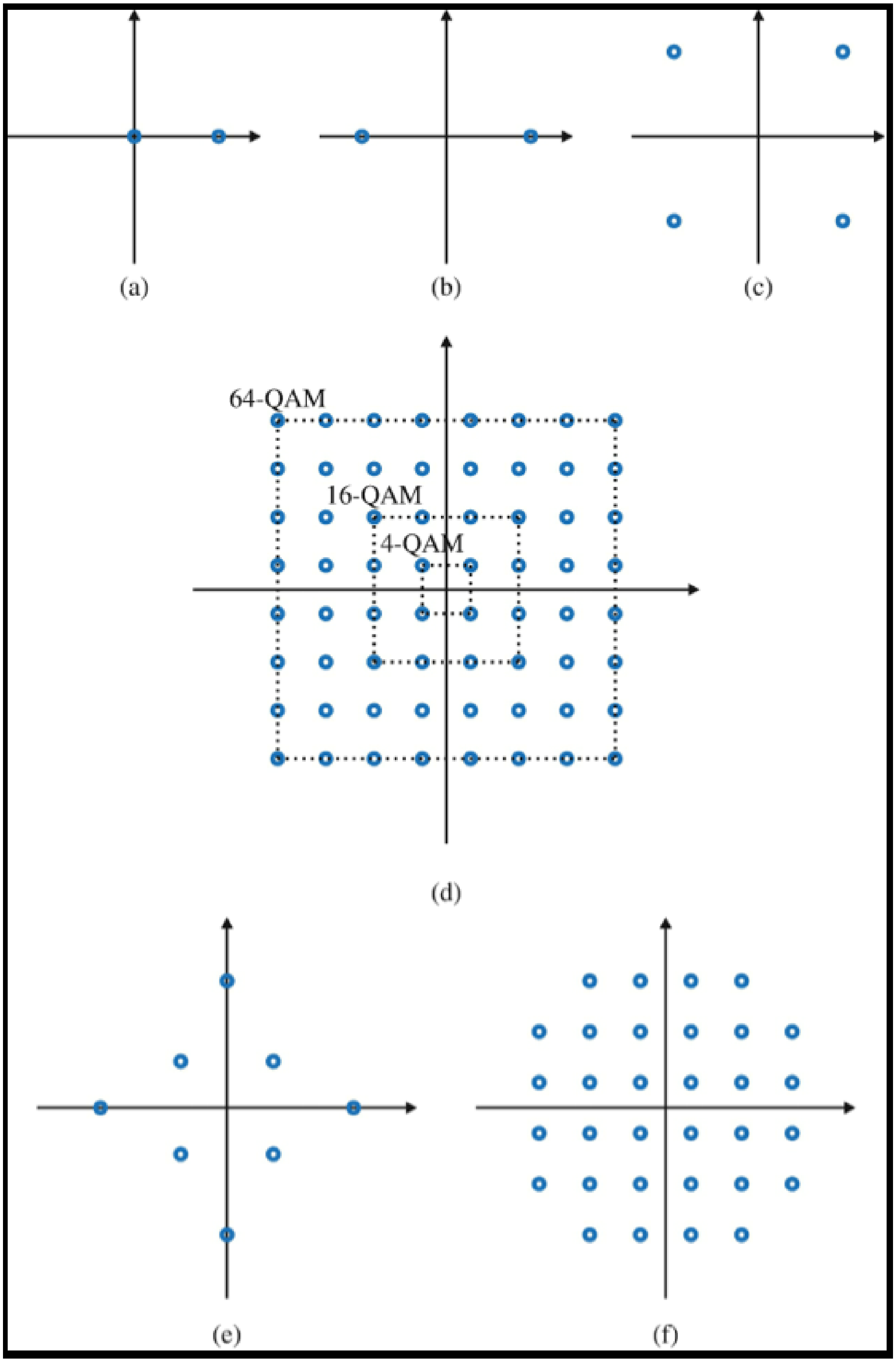


Figure 2.2.6.2 Common constellation used in digital communications [5]

Another important issue is how to map bits into constellation symbols. It is desirable that adjacent symbols are mapped to code words that differ by a small number of bits, ideally only one. In this way, even if one symbol conveys m = log_2(M) bits, most symbol errors cause only one bit error. This is achieved by an approach known as Gray mapping as represented in Fig. 2.2.6.3 for QPSK and 16-QAM modulation formats [5].

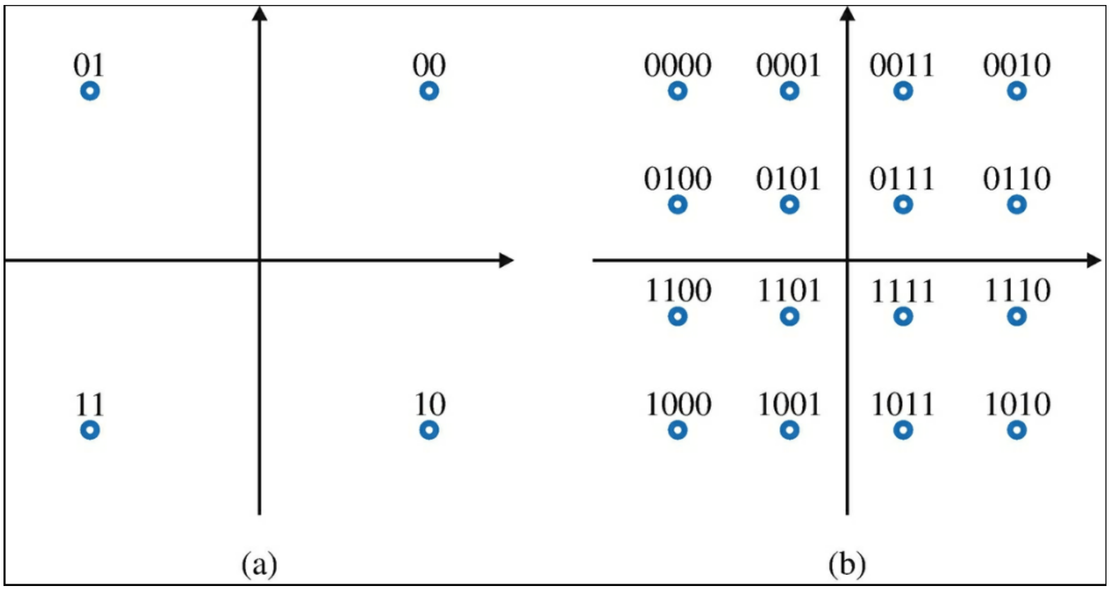


Figure 2.2.6.3 Gray mapping for (a) QPSK (b) 16-QAM [5].

As the QAM order increases, so the distance between the different points on the constellation diagram decreases and there is a higher possibility of data errors being introduced. There are several metrics to evaluate the performance of a modulation format, one of them is spectral efficiency (SE). SE itself can be defined in several ways, but it can be defined as the ratio between the conveyed net bit rate R_b and the bandwidth required to support this rate, W: $SE = \frac{R_b}{W}$. The spectral support W of the channel depends directly on the pulse shape g(t). The Nyquist criterion determines the existence of a family of pulse shape g(t) for which transmission is carried out free of Intersymbol Interference (ISI). This condition for ISI-free transmission can be expressed as:

$$\frac{1}{T_s} = \sum_{m=-\infty}^{\infty} G\left(f - \frac{m}{T_s}\right) = 1$$

where G(f) is the Fourier transform of g(t) [5].

ISI-free transmission is achieved if the sum of frequency shifted versions of G(f) add up to a constant. Pulses satisfying this condition are called Nyquist pulses. The Nyquist pulse shape with minimum transmission bandwidth, $\frac{1}{2T_s}$, is obtained by sinc pulse shape :

$$g(t) = \frac{sin(\pi t/T_s)}{\pi t/T_s}$$

Pulses based on the sinc function have infinite duration, which hinders their practical application. Alternatively, raised cosine pulse are Nyquist pulse whose spectral duration and support are controlled by a roll-off factor β^{RC} ($0 \le \beta^{RC} \le 1$). The frequency response of the RC shaping filter in given by :

$$H_{RC}(f) = \begin{cases} 1, \ if \ |f| < \frac{1-\beta^{RC}}{2T_s} \\ 0, \ if \ |f| > \frac{1+\beta^{RC}}{2T_s} \\ \frac{1}{2} + \frac{1}{2}cos\left(\frac{\pi T_s}{\beta^{RC}}\left(|f| - \frac{1-\beta^{RC}}{2T_s}\right)\right), \ if \ \frac{1+\beta^{RC}}{2T_s} > |f| > \frac{1-\beta^{RC}}{2T_s} \end{cases}$$

The transfer function $H_{RC}(f)$ is shown in Fig. 2.2.6.4(a), as well as the corresponding impulse response $h_{RC}(t)$ is shown in Fig. 2.2.6.4(b).

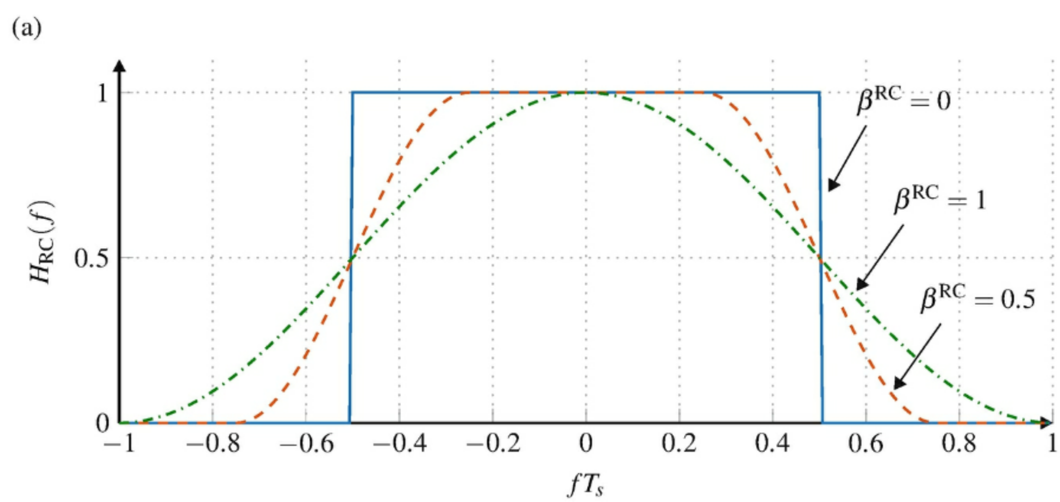


Fig. 2.2.6.4 (a) Raised cosine (RC) filter for different β^{RC} and T_s - Frequency response [5].

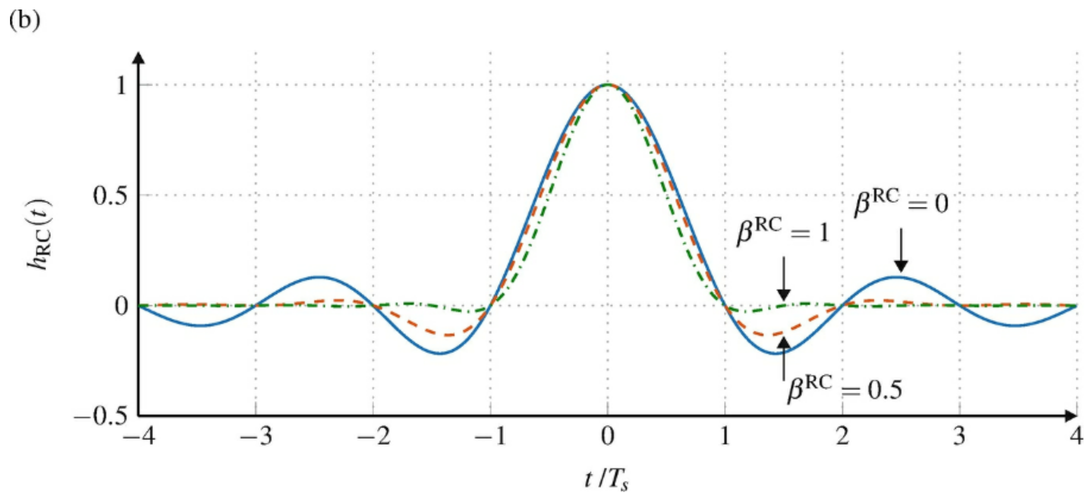


Figure 2.2.6.4 (b) Raised cosine (RC) filter for different β^{RC} and T_s - Impulse response [5].

For $\beta^{RC} = 0$, the signal has a rectangular frequency response and an infinite duration in time. By increasing β^{RC}, the frequency response widens, but the pulse becomes more time-constrained. Coherent optical systems can work with fairly low roll-off factors, ranging from 0.01 to 0.1, implementing a pulse near the rectangular spectrum. However the generation of pulse with such roll-off is complex, requiring shaping filters with hundreds of coefficients.

2.2.7 Digital Signal Processing

The symbiotic combination of DSP, spectrally efficient modulation formats and coherent detection led to the advent of actual digital coherent transceivers. Most of the DSP algorithms for polarization division multiplexed QPSK (PMD-QPSK) are derived from the wireless communication system. However, necessary modifications are required in order to apply them on the fiber optic channel. The DSP design becomes more challenging as the modulation format evolves from PMD-QPSK to multilevel quadrature amplitude modulation (QAM) formats [13]. The usual configuration of a coherent transceiver utilizing advanced vector modulation and DSP techniques is shown :

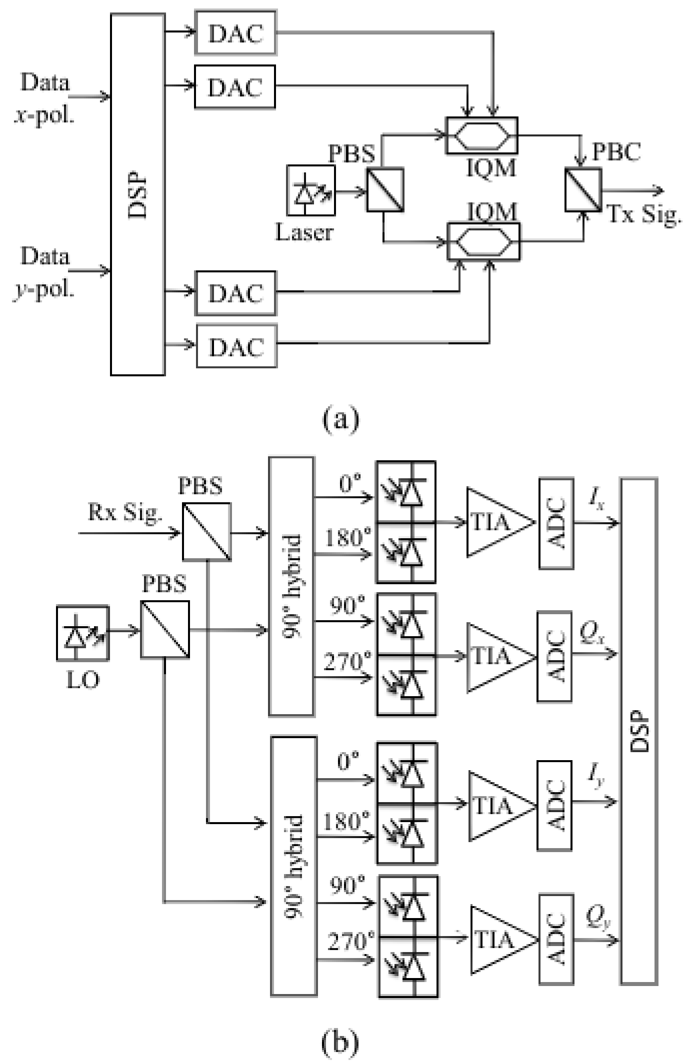


Figure 2.2.7.1 DSP configuration on transceiver [13]

(a) at the transmitter (b) at the receiver

DAC	Digital To Analog converter	IQM	IQ modulator
PBS	Polarization Beam Splitter	PBC	Polarization Beam Combiner
LO	Local Oscillator	TIA	Trans-impedence Amplifier
ADC	Analog To Digital converter	DSP	Digital Signal Processing

At the transmitter, first two independent data sequences for x- and y-polarizations are processed in the DSP which may include encoding, modulation, pre-compensation of linear and nonlinear transmission impairments and pulse shaping filtering. Such digitally processed signals are converted to analog signals using four digital-to-analog converters (DACs) corresponding to the in-phase (I) and quadrature (Q) components of signals for x- and y- polarizations which are then used to drive two IQ modulators

(IQMs). A single laser output split by polarization beam splitter (PBS) is used for two IQMs. Outputs of IQMs are then combined by polarization beam combiner (PBC) and transmitted through fiber. At the receiver, the received polarization-multiplexed optical signal $E_r(t)$ with the local oscillator $E_{LO}(t)$ produced four digital signals corresponding to the in-phase and quadrature fields components for the two orthogonal polarization orientations. polarizations. These four electrical currents are $i_{PV}(t)$, $i_{QV}(t)$, $i_{PH}(t)$, $i_{QH}(t)$ and are converted to voltage by a set of TIAs and digitized by a set of ADCs, generating the digital signals ($r_{PV}(t)$, $r_{QV}(t)$, $r_{PH}(t)$, $r_{QH}(t)$). The resulting signals are sent to a second subsystem, consisting of a chain of Digital Signal Processing (DSP) algorithms.[13]

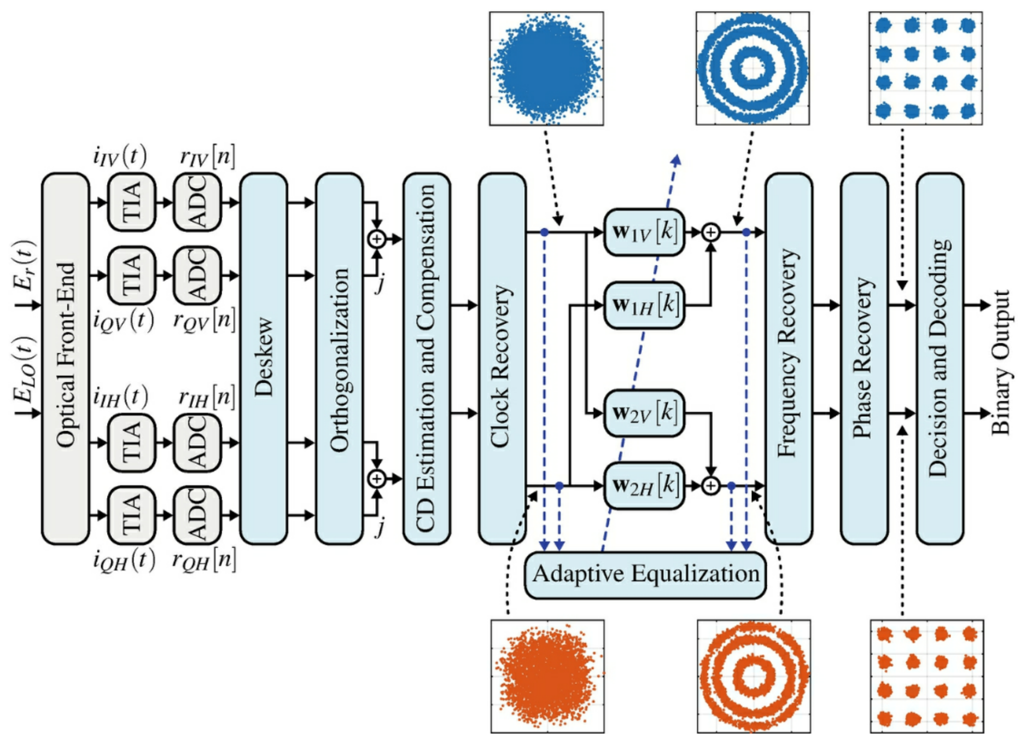


Figure 2.2.7.2 Digital Coherent Receiver [5].

The first DSP block is that of deskew , responsible for compensating for possible temporal mismatches in the alignment of the four received components. The parameters of the deskew block are typically static and factory-characterized. After the temporal alignment carried out by the deskew block, the in-phase and quadrature components of the received signals can be combined, producing two complex signals, corresponding to the V and H polarization orientations. The next DSP block is that of orthogonalization , which compensates for the mismatches on the receiver front-end that are not related to temporal misalignments, such as slightly unbalanced photodetectors or power splitters. Then, two static filters perform chromatic dispersion (CD) compensation. The vast majority of current optical coherent systems operate without any optical CD compensation, resulting in high inter symbol interference (ISI) to be dealt with at the receiver. Therefore, these filters are the longest of the coherent receiver, and their length can reach thousands of taps. Fortunately, CD is a practically time-invariant effect, and its compensation does not require temporal adaptability. The following block is that of symbol synchronization, also known as clock recovery. Although it is placed after CD compensation in Fig. 2.2.7.2, it can also be implemented in other positions of the DSP chain, such as after adaptive equalization, or even within the CD compensation block. Clock recovery detects possible mismatches between the symbol rate and the ADC sampling rate, and implements a control loop that corrects this mismatch digitally using time-varying interpolators, or actuating directly on the ADC reference oscillator. Following clock recovery, an adaptive equalizer with two inputs and two outputs interconnected in butterfly structure compensates for polarization effects and other eventual residual linear distortions. The adaptive equalizer also separates the polarization-multiplexed signals. Fig. 2.2.7.2 shows the constellations before and after adaptive equalization. The equalizer inputs are linear combinations of the transmitted symbols, resulting in constellations with a circular shape. At the equalizer outputs the signals are separated. The resulting constellations have multiple rings, corresponding to the transmitted constellation affected by phase rotations. After the adaptive equalizer, a frequency recovery block compensates for the frequency mismatch between transmission and local oscillator lasers. Phase noise effects are mitigated by a phase recovery block. After phase and frequency recovery, the shape of the transmitted constellation is recovered. Finally the decision block retrieves the decoded bit sequence [5].

3. Challenges in the Architecture Development

The first mission of telecom operators is to provide capacity and coverage for trusted, resilient and secure connectivity. The pandemic showed just how important that mission actually is. As a result, in 2021 many operators in Europe and the rest of the world have shifted some of their investment focus back onto their core service, connectivity, by accelerating their deployment of fit-for-purpose infrastructure in the form of 5G and fiber. This is not simply a matter of capacity and coverage for ever higher traffic demands from consumers and businesses; it is also about making the networks greener, more resilient, predictable, flexible and adaptable, and fit for new kinds of demand.

3.1 Digital Society

The Digital Decade infrastructure targets advance the European Gigabit Society 2025 targets by aiming to provide gigabit connectivity for every European household and 100% 5G coverage of populated areas by 2030 [6].
They also, for the first time, include the establishment of edge nodes (10000 to be deployed in the EU by 2030) as an infrastructure target :

Connectivity for a European Gigabit Society (2025)	Digital Decade (2030)
● Access to download speeds of at least 100 Mbit/s (using gigabit-upgradeable technology) for all European households ● Uninterrupted 5G wireless broadband coverage for all urban areas and major roads and railways ● Access to 1Gbit/s speeds for all schools, transport hubs, major providers of public services and digitally intensive enterprises	● Full coverage of populated areas with 5G ● All households covered by a gigabit-capable network ● 10 000 climate-neutral, highly secure edge nodes will be deployed in the EU

The Digital Decade is about more than just enablement through infrastructure. The project also aims to make Europe a hub of technological innovation, rather than having to rely on outsourced services and products. This will bring additional economic benefits and new job opportunities. It is also about digital transformation and the human capital required for that to occur: encouraging citizens to become digitally competent, training highly skilled ICT specialists, supporting businesses and the public sector with their digital transformations. The Digital Economy and Society Index (DESI), which tracks the progress of EU digitalization, has adapted to reflect the Digital Decade's new set of targets. The infrastructure targets are the targets that apply directly to telecoms. They are challenging because there remains a great disparity across Europe in terms of connectivity and in terms of the demand for, or ability to take advantage of, the services that require such connectivity. Strong collaboration is required between upstream suppliers (such as network operators and infrastructure owners) and public administrations in order to achieve the Digital Decade infrastructure targets. A win/win approach is required, which involves more flexibility in network-sharing, in joint-venture initiatives or in other horizontal agreements to bridge connectivity gaps and achieve the desired outcomes. In addition, the issue of building scale both in country and across countries remains currently unsolved, with highly fragmented European markets [6].

Fixed networks continue to be the workhorse of the digital ecosystem and carry about 90% of all data traffic. There is a consensus that FTTH is the best fixed technology in terms of capacity, reliability and operational efficiency. FTTH is also the most energy-efficient access technology essentially because it decouples rising demand from the requirement for increasing density of powered elements in networks. According to Telefónica, it has the potential to reduce the energy consumption of fixed access network equipment by around 85%. Being the most energy-efficient technology also makes it the greenest available technology [6].

5G plays a vital role underpinning operators' broader ambitions of helping to achieve digital transformation in the economic and social spheres. The operators are key local players in the creation of industrial ecosystems in the 5G era where digital business and industry solutions will be boosted [6].

Initially 5G launches involved relying on existing 4G LTE networks to enable 5G capabilities. However, 5G standalone (5G SA) is a step further; it involves rolling out completely new network architecture with, potentially, a new, cloud-native, 5G core. This advanced 5G architecture provides increased network capabilities and device capacity. It also enables more efficiency and automation in the running networks, which will enhance the quality of service for consumers and businesses alike [6].

What is particularly important about 5G SA is that it opens up new possibilities in terms of what 5G is capable of achieving. Slices of the 5G SA network can be defined for specific use cases without the capex burden of having to create dedicated networks. This opens up myriad new possibilities for businesses, and it also enables more-efficient digitalization of public services [6].

While it is true that mobile network data traffic has historically grown at an extraordinary rate, fixed networks still account for about nine tenths of data traffic in Europe. Fixed traffic growth-rates actually outstripped mobile traffic growth-rates in many countries worldwide in 2020. The picture in Europe was mixed. Mobile traffic growth surged in some countries, but fell back in others. Where it rose and where it fell demonstrated that the rate of mobile data traffic growth is largely determined by the size of the cohort of users that do not have recourse to a fixed connection [6].

The move to 5G is particularly challenging for operators: the business case remains unproven, especially when considering the range of new services that 5G is envisioned to support in future, and the investments required are large. Improved network cost efficiency is key to making these investments possible, in particular through infrastructure sharing, carve-out of passive infrastructure and radio access network (RAN) sharing models, including innovations such as network-as-a-service [9].

Telecom stakeholders are also coming together in a number of industry initiatives to open up and standardize interfaces between different network components, which would allow solutions from different vendors to work together or ‘interoperate’. Traditional networks today are mostly supplied by one main vendor for each operator, while a network that is made up of numerous interoperable components from multiple vendors is referred to as a disaggregated network. These disaggregated networks could allow operators to deploy new network functions more quickly and flexibly to support new and improved services [9].

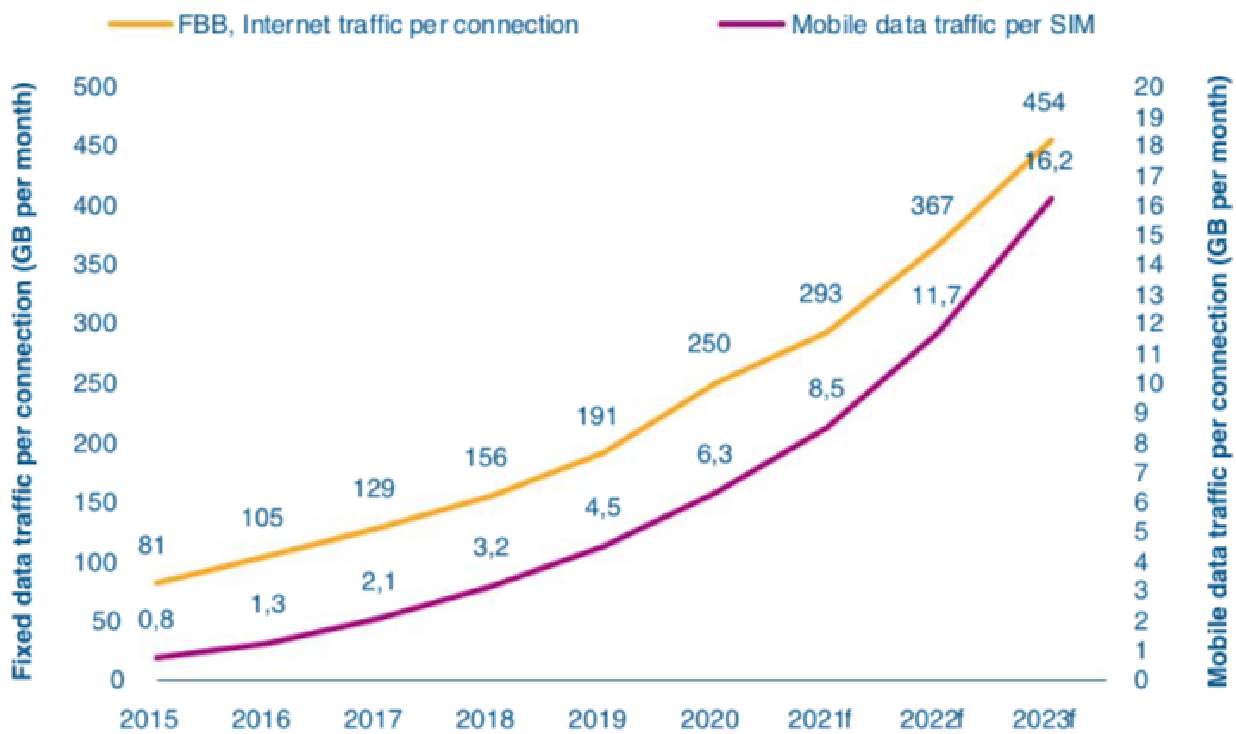


Figure 3.1.1 Fixed And Mobile data traffic [9].

Consumer fixed data use has long been dominated by large-screen devices, particularly TVs; this remains the case even as lockdown restrictions ease. Indeed, it is the popularity of video streaming services such as Netflix, Amazon Prime, Apple TV+ and Disney+ that has sustained fixed data traffic growth. It is salient to remember that the greater part of smartphone traffic in Europe (>60%) is actually on Wi-Fi/fixed broadband rather than on mobile networks [6].

When we look into the future, there are plenty of emerging network applications very sensitive to latency, jitter, loss rate, and/or flow completion time. Unlike today's web applications, the new applications are expected to serve some new "consumers," which lack capability in dealing with service degradation as do humans. For example, industrial applications are very sensitive to latency, jitter, and loss. Vehicle-to-everything (V2X) networks require guaranteed network services with low latency and loss rate. Even with human consumers, emerging multimedia applications, such as holographic communication, immersive virtual reality (VR), augmented reality (AR), and extended reality (XR), telemedicine, remote surgery, and cloud gaming, require much more stringent network quality of service (QoS), including bounded latency and ultra-high throughput [18].

There are significant research challenges in satisfying these requirements. Research progress in multiple aspects of the network needs to be coordinated in a systematic way, including the control plane orchestration and planning algorithms, data plane packet and flow scheduling algorithms, network architectures, and protocols that coordinate endpoints and network devices. Extensive research has been dedicated to satisfying time-sensitive applications. 5G and beyond-5G network architecture and air interface technologies are optimized for ultra-reliable low-latency communication (URLLC) in the 3rd Generation Partnership Project (3GPP). The Time-Sensitive Network Task Force in IEEE and the Deterministic Networking Working Group in the Internet Engineering Task Force (IETF) are solving bounded latency problems in wired networks on layer 2 and layer 3,respectively. Edge computing architecture has been proposed to reduce latency by putting services close to clients. New transport layer protocols and algorithms are proposed to optimize flow completion time. Low latency and lossless flow and congestion control mechanisms are studied in data centers for high-performance computing, artificial intelligence, and big data analysis [18].

Ocean researchers contribute to a clear understanding of global climate change, biodiversity protection, ocean resource development, and intelligent maritime transportation. With the development of sensing and communication technologies, ocean research is widely enhanced by emerging maritime applications, ranging from deep sea sensing to on-water maritime service, such as marine pollution monitoring, search and rescue (SAR) at sea, remote piloting, intelligent traffic management at ports, and infotainment services for vessels' passengers [19].

IEEE 802.1 time-sensitive networking (TSN) is able to provide deterministic communication of time-critical and mission-critical applications over a bridged Ethernet network, which is shared by various kinds of applications having different quality of service (QoS) requirements, that is, time- and/or mission-critical traffic and best effort traffic [20].

Industrial Internet, or Industry 4.0, has presented strict requirements for deterministic transmission capability over a shared network of multiple applications. Time-sensitive networking (TSN) is recognized as an efficient networking solution for the features of bounded delay, low delay variation, and zero congestion loss. However, the benefits of

TSN are limited to closed networks now. The interconnection of several TSN networks through non-TSN networks is a main upcoming challenge for emerging applications [21].

Cloud computing has revolutionized the way businesses use computing infrastructure. Instead of building their own data centers, companies rent computing resources from cloud providers (e.g., Amazon AWS, Google Cloud Platform, and Microsoft Azure), and deploy their applications on cloud provider hardware. Network latency variability is still common in multi-tenant data centers, and even small amounts of delay, on the order of tens of microseconds, may lead to significant drops in application performance. An important factor in achieving predictable application performance is understanding the networking requirements of the application in terms of bandwidth and latency. By measuring dynamically the network latency in the data center and having a model of the application performance dependent upon network latency, the relationship between network latency and application performance can help cloud customers to determine the performance their application can achieve under certain network conditions and can guide cloud operators in selecting the network latency ranges that best suit the needs of their customers [22].

Industrial wireless control systems are mainly designed on the premise of time-sensitive ultra-reliable low-latency communications (URLLC). With the introduction of survival time to the quality of service requirements of such systems, the design paradigm has evolved from typical link reliability (i.e., minimizing packet error rate), to service availability, that is, minimizing the chance of burst errors, which can cause loss of communication for longer than survival time. The wireless transformation will, in particular, reduce bulk and cost of installation, while enabling a highly flexible and dynamically reconfigurable industrial environment. Such a vision covers various use cases, including the Industrial Internet of Things (IIoT), smart grid, mobility and traffic control, healthcare, entertainment, and gaming. In manufacturing environments, thanks to time-sensitive wireless networking, production stations may be seamlessly re-arranged according to production requirements. For this, wireless communication has to be as dependable as a wired connection, providing extremely high reliability, while guaranteeing anytime/everywhere service. This is the promise of the fifth generation (5G) [16].

An emerging use case of 5G is augmented reality (AR)-assisted surgery. Surgeons depend on surgical AR to target surgical resection in a more accurate and objective process, thus minimizing the risk of relapse. Furthermore, AR-assisted surgery enables surgeons to carry out surgical and diagnostic procedures remotely through a combination of robotic arms and sensors. Data transmitted as instruction for robots must be highly reliable. A slight delay or latency may mean harm to the patient. Doctors use virtual reality (VR) headsets to view the inside of the human body. Surgeons may also require patients to use VR headsets when taking them through their surgical plan. There is usually a high latency between action and response (head movements in particular) for VR headsets users. 5G URLLC helps overcome this issue, allowing a more expansive VR experience in the medical field [16].

5G URLLC is applied in drone-based delivery to estimate traffic density in real-time, in self-driven cars, and in substation control to synchronize systems and manage traffic. Some of these applications entail network communication, involving broadcast from vehicle-to-everything (V2X) servers, that include vehicles and everything around the traffic system. Such communications modes are significant to route discovery and collision avoidance in real-time. In predictive vehicle maintenance, 5G URLLC provides a secure, highly reliable wireless connectivity that supports a high density of devices to provide real-time data analytics based on defined metrics. The metrics, including vibration and temperature, are registered from multiple wireless sensors connected to a cellular network and integrated into the vehicle management system. The data analytics results from this system help avoid potential issues, keep the vehicle maintained, decrease maintenance costs, and improve downtime [16].

Data Center networks have an important role to play in effectively managing the increasing and unpredictable traffic trend as bandwidth intensive applications such as internet video are hosted. Due to the rapid growth of businesses such as e-commerce, cloud computing, and e-entertainment, data center networks grow very fast, with Data Center Interconnect traffic doubling almost every year. To cope with fast-growing traffic and fast-changing businesses, most companies as Alibaba have been embracing the idea of open and disaggregated optical transport networks since 2016 [1].

3.2 New Evolution of Internet Infrastructure

The inability of the current Internet infrastructure to cope with the wide variety and ever-growing number of users, emerging networked applications, usage patterns, and business models is increasingly being recognized worldwide. New applications require networks with well-known and predictable characteristics and behavior, which the current best-effort Internet intrinsically cannot deliver. These considerations are triggering network models that can potentially transform the established technology content and business models of the Internet [23].

There are many challenges seen as driving forces towards the New Evolution Of Internet. The most important challenges are listed below:

The available bandwidth per user/device will continue to grow: Dial-up has been completely replaced in most countries with broadband connections. The expected wide deployment of optical access networks and fiber-to-the-home (FTTH) solutions will further increase the bandwidth capabilities at the edges of the Internet enabling Gb/s delivery to the user. The routing and transport schemes in the existing Internet will not scale to the Gb/s transmission rates that will be made available to future applications [23].

Heavy increase in content and quality of content: There will be an enormous increase in online content offered by the Future Internet. Digital photos and videos will not only increase in number, but also in size, due to increases in resolution and the ease of creation and manipulation. As the quality of media content increases, the demand to provide and sustain a high quality of service (QoS) also increases proportionally. Processing, transmission, and presentation errors that were acceptable at lower resolutions become intolerable in high-definition and ultra-high-definition (HD/UHD) video. For such high-quality content, distribution over IP "best-effort" networks is not possible without a substantial deterioration of the QoS [23].

Huge increase in the number of users: Much like the growth of telephony in the 20th century, the number of Internet users will continue to increase as the digital divide narrows in various countries. Furthermore with the increased Internet availability and security, the business community moves towards the use of the Internet via VPN rather than private data networks [23].

Large data flow transfers between users, remote instrumentation, and computing/data centers: Several new applications require transfer of very large data flows between users and/or data centers. Examples include financial, e-science, content distribution, and large remote sensor and instrumentation applications, which appear to generate large data flows that need to be delivered to computing/storage centers that can be far away. Furthermore, Moore's law will continue to drive the need for higher bandwidth connectivity through the increase of the computational power (teraflops) and memory (terabytes) of devices. Solutions such as grid and cloud computing have identified that for the Internet to support these applications, it is important to enable dynamic high-bandwidth secure services over a physical (L1/L2) infrastructure [23].

The growth of cloud computing has placed a lot of pressure on data centers in recent years. Likewise, the evolution and development of the internet of things (IoT), including 5G, has contributed to the requirements imposed on data centers. Then, these data centers will have to boost their network capacities to respond to the impulsiveness of traffic patterns : the DCI now can be at 400 Gb/sec, 600 Gb/sec or 800 Gb/sec

Energy-efficient networking: Recently there is increasing attention on energy saving in telecommunication networks. Although today the total energy consumption of the Internet is very small compared with the levels of power consumption required by other industries, it is rapidly expanding and is predicted to become an important contributor. The power consumed by large routers is increasing with their overall capacity increase and has become one of the most stringent limits in the design of IP routers. The expected increase of line rates to 100 Gb /s will further stress these limits. It is important to identify switching technologies, architectures, and protocols to minimize network power consumption. Optical technologies offer significant advantages with respect to power consumption when information is transmitted and/or switched at increasing bit rates and at longer distances [23].

Network Application requires constraints about latency and bandwidth: see chapter 3.1 Digital Society in order to view details about application. Crowdsourced live video streaming challenges operators' infrastructure with tides of users attending major sport or public events that demand high bandwidth and low latency jointly with computing capabilities at network edge. The Optical Access Network and 5G Wireless Infrastructure must be reviewed in order to support new application requirements.

C-band in WDM exhausted: increasing the Wavelength Division Multiplexing (WDM) systems capacity, which nowadays usually exploit the C-band only, is becoming increasingly more important. Alternatively, a translucent network design (i.e., doing the regeneration of the optical signal in the intermediate nodes) can also be explored as a solution to cope with this traffic demand [17].

The above challenges can be satisfied with the below strategies in order to implement new Network Infrastructure that must support emerging applications, fulfill 5G requirements, and respond to the sudden increase of societal need for communications.

Optical Network Access: The optical access network will change in order to migrate the xDSL connections to FTTH. FTTH fibers use less power than copper and FTTH has the potential to reduce telecom operator's fixed access energy consumption by 85% as long as older and less-efficiency technologies are retired.

5G RAN Network Integrated Into Wired Optical Network Access: 5G networking deployment requires ultra-high-capacity Radio Access Network (RANs) exploiting Multiple Input Multiple Output and beam-forming technologies in order to support a very large amount of traffic per antenna.

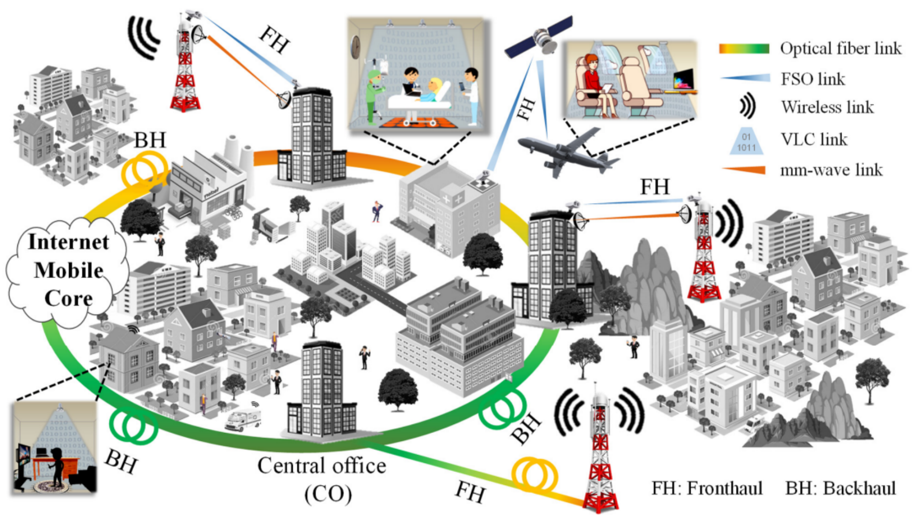


Figure 3.2.1 Optical Wireless communications integration [32].

The New Evolution Of Internet drives the challenges also in telco operator environment:

Enable NFV: such an evolution needs the full virtualization of network functions and hardware control to enable virtual slicing and programmable and dynamic adaptation of virtualized network operations to traffic and service requests. The virtualization paradigm requires the disaggregation of telecommunications infrastructures into programmable multi-vendor network elements (NEs) and subsystems operated by open application program interfaces (APIs) and protocols within a hierarchical multi-layer network controller. The industrial consortium Telecom Infra Project (TIP) is one of the consortia and standardization agencies operating with the purpose to develop open networking solutions. The TIP consortium groups most of the network operators and vendors to develop open software and hardware solutions for open networking. The TIP Open Optical and Packet Transport (OOPT) working group (WG) targets multi-layer solutions for open optical networking (OON) according to the partially disaggregated network architecture [24].

Enable QoT: Optical networking is based on WDM optical circuits deployed and routed on the transparent optical infrastructure, so the Open Optical Network needs a full virtualization of the physical layer to enable the optimal, dynamic, and software-defined exploitation of optical networks. The OOPT project GNPy is an open source software project based on approximating as additive white Gaussian noise (AWGN) channels the transparent optical circuits—lightpaths (LPs)—operated by state-of-the-art dual-polarization coherent optical technologies. So, the physical layer is fully abstracted by the LP quality of transmission (QoT) summarized by the generalized signal-to-noise ratio (GSNR) including the effects of amplified spontaneous emission (ASE) noise from amplifiers and nonlinear interference (NLI) from fiber propagation. The GNPy core is the QoT estimator that operates on the network topological graph and computes the GSNR on the selected wavelength on the given route—the selected LP—by accumulating the QoT impairments of each crossed NE. [24]

Implementing Linux OS: The linux-based platform has facilitated the evolution of open-source software and operational automation tools are now being used and operators have been able to reduce their operational cost. Open source software has proven itself over the years both as a feasible de-facto standard for software development and a successful business case for companies willing to provide support and extra features on top of it.

Enable SDN: The practices of SDN in the past decade and its successful deployment in real networks have given network operators experience with, and confidence in, open network technologies.

Business Model : The traditional telecom model is based on a vertically integrated business model in which one entity delivers the service, operates the network and owns the network infrastructure. Technology has evolved dramatically and today the amount of available services is booming : from telephony (mobile or fixed), web access, emailing, television (standard quality and HDTV) to rapidly growing ones such video conference, video, music streaming and sharing, on-line gaming, e-health etc. For all these services the data information is stored and transmitted digitally and it is increasingly delivered using IP protocol. Moreover, the end-user is no-longer just a consumer of contents, but has also become a producer of material using a variety of applications. A vertically integrated model with a dedicated network infrastructure for each service is therefore highly inefficient. The open network model, in which services are provided on a fair and non-discriminatory basis to the network users, is enabled by conceptually serating the role of service provider and the network and the communication operator. Due to the different technical and economic nature of different parts of the network, different roles and actors can be identified. An optical network consists of a passive infrastructure (implying right-of-way acquisition, trenching, cable duct laying, local-office premises), and active equipment (transponders, ROADMs, routers and switches, control and management servers). The CAPEX are major purchases a company makes that are designed to be used over a long term. The OPEX are the costs that a company incurs for running its day-to-day operation. The passive infrastructure is typically characterized by high CAPEX, low OPEX, low economies of scale and is highly local, hard to duplicate or inherently subject to regulation. The active equipment is characterized by high OPEX, economies of scale, and is subject to regulation. These factors justify a further role separation between the network owner which owns and maintains the passive infrastructure and the communication operator which operates the active equipment [25].

Optical Components Diversification: Recent innovations in optical components, such as coherent DSPs and silicon photonic, have shortened the technology development cycle. As a result the next generation of devices are quickly being brought to market. In addition there has been a significant increase in types and generations of form factor pluggable, octal SFP. C form-factor pluggable, intensity-modulation direct-detection,.. This is primarily due to an increase in the number of operator type building and operating optical networks with different transceiver requirements. Therefore it is important to efficiently accommodate a wide variety of form factors in terms of type and generation to reduce procurement and operation costs.

A new network architecture that enables efficient deployment of network, computing and storage resources and automatic operation control require the following :

- Defining an open interface to eliminate hardware complexity
- Defining vendor-to-vendor interconnection modes between coherent DSPs
- Implementing a Linux-based platform that can accelerate the use of Open Source Software
- Defining application programmable interface (APIs) procedures and monitoring techniques for automatic operation.

- Software-Defined network (SDN) entered the scene decoupling the data plane forwarding actions from the control-plane decisions, hence boosting network programmability and innovation.

When deploying open optical networks, operators are looking to eliminate vendor lock-in, lowering capital and operational expenses. **Vendor lock-in** is the relationship of dependence established between a customer and a supplier of goods or services, such as to prevent the customer from purchasing similar goods or services from an alternative supplier without incurring high costs or significant risks.

3.3 Evolution towards Disaggregated Optical Networks

The shift of the optical transport network paradigm to openness and disaggregation is mainly due to the following reasons :

- The advent of digital coherent technology, which not only increases the spectral efficiency and receiver sensitivity but also significantly simplifies the design of optical communication systems. This simplification enables the decoupling of the Optical Line System from Optical Terminal Transponder.
- Faster innovation and flexibility in adopting the latest technology is the top driver leading operators to adopt disaggregate networks. Telco operator's infrastructure is undergoing high pressure to keep pace with traffic demand generated by the societal need of remote communications, bandwidth-hungry applications and the fulfillment of 5G requirements. The communication network after 4G fully introduces IT technology, and the telecom cloud is generally used as the infrastructure. In the actual telecom cloud landing process, technologies such as NFV (Network Functions Virtualization), containers, SDN (Software Defined Network), and API (Application Programming Interface)-based system capability exposure have all received commercial verification.
- An alternative approach to effectively increase the capacity of an optical transport network is to increase network efficiency. This can be reasonably achieved with open and disaggregated networks as network operators can effectively control and reconfigure their network and have end-to-end optimization of their networks according to their needs.
- Open Disaggregate Optical Network will enable a white box optical device that enables multiple components to be combined together. Vendors can focus on

building a specific optical component without having to build a complete optical network leading to accelerated innovation and lower costing. Telco operators will have the freedom to select best-in-class components and avoid vendor lock-in, gaining in flexibility as their network needs grow.

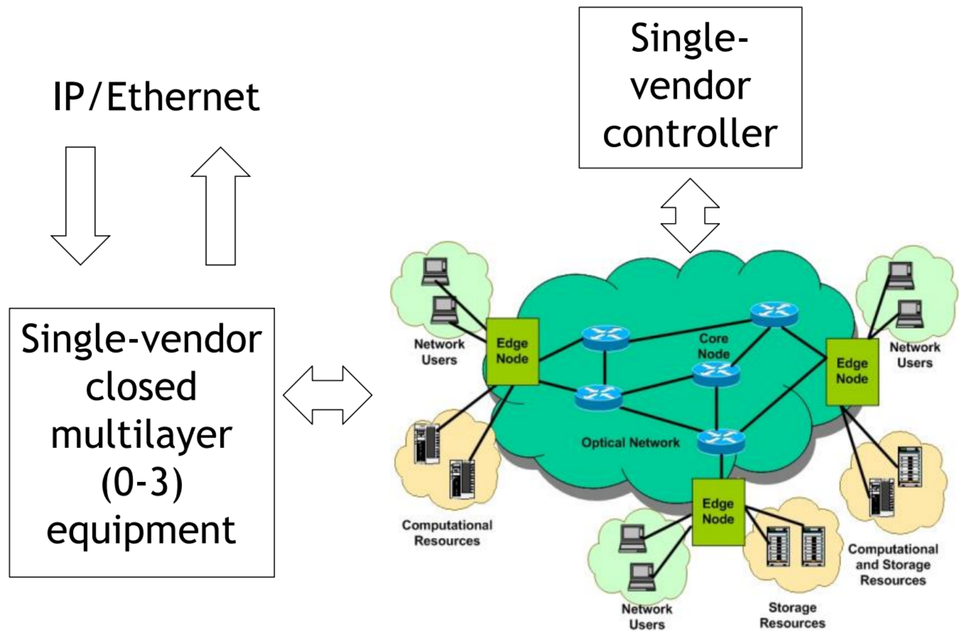


Figure 3.3.1 Closed Optical Network

Disaggregation implies that TELCOs are directly or indirectly involved in the process of design, assembly, integration and testing of a whole Optical Transport System. The evolution toward programmable networks and virtualization paradigm needs the disaggregation of network architectures into independent and possibly multi-vendor network elements (NEs) and subsystems operated by Open Application Program Interfaces (APIs) and protocols within hierarchical multi-layer network controllers. [24]
Each disaggregated NE is a programmable white box exposing open models for its control and granting the virtualized access to its functionalities. NEs are controlled by a centralized multi-layer hierarchical network controller. The main optical network elements are fibers, optical amplifiers (OAs), reconfigurable optical add/drop multiplexers (ROADM) performing the optical switching operations, and transponders for deployment of optical circuits.[24]
Disaggregated optical networks can be classified as :

- **fully disaggregated optical networks** where each NE is independently controlled. All NE (also OA and ROADM) are vendor-neutral NETCONF/YANG controls.

- **partially disaggregated optical networks** where the amplified lines are managed as aggregated subsystems. The OLS (including OA and ROADM) is managed by a single vendor while transponders are vendor-neutral NETCONF/YANG control.

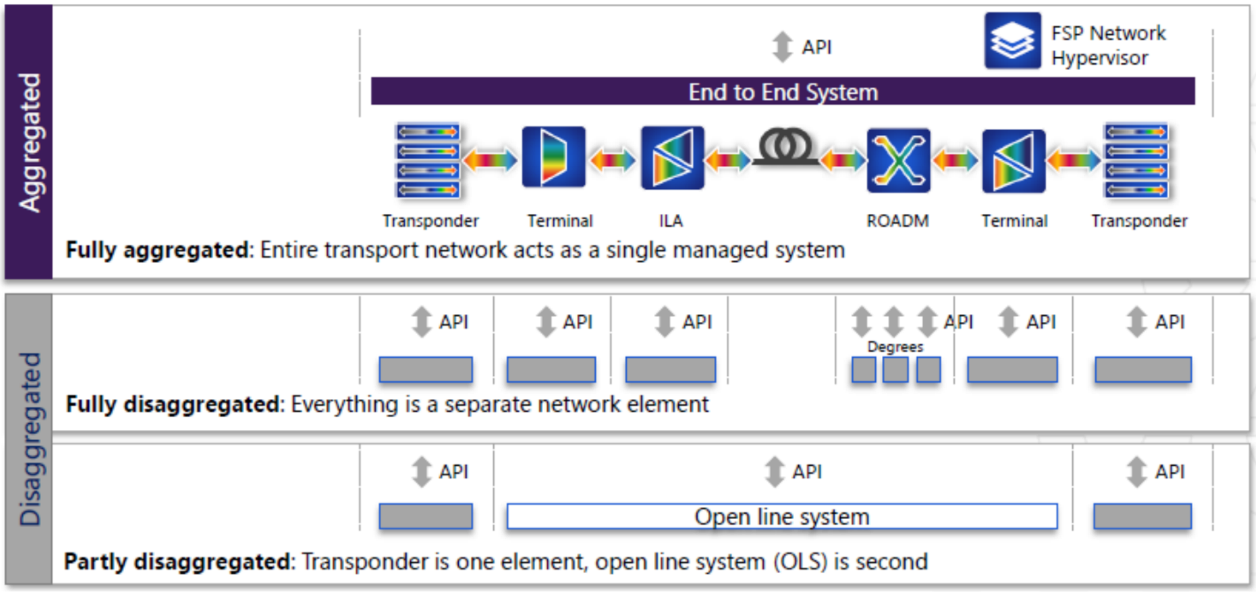


Figure 3.3.2 Optical Network Classification[34]

The partly disaggregated model remains stable despite technological evolutions and capable of including proprietary advanced transmission solutions maximizing throughput performance. As a drawback, this approach requires definition and implementation of specific workflows to manage the OP modes that go beyond the model itself. Partial disaggregation has attracted significant interest from operators and vendors, since it neglects most of the optical data plane complexity without significantly compromising on transmission performance. Indeed, transponders are provided in pairs and can implement even proprietary transmission solutions by defining specific operational modes. The business model that drives partial disaggregation considers that optical transport (i.e., OLS) is a mature technology that, once deployed, can last for more than ten years without relevant upgrades. Moreover, OLS is an analog complex system and disaggregating it may lead to critical implementation, control and management, particularly considering the entire lifecycle of the system. On the other hand, transmission technology is evolving at an extremely high pace, with an impressive and continuous increase of the symbol rate. In some network scenarios, to cope with the continuous increase of data traffic, transponders can be replaced with higher rate

versions even every three years. Thus, partial disaggregation enables Operators not to be bound to a single vendor for new transponder deployments, still enabling a single vendor to have full responsibility of the OLS. In order to be practical and sustainable, typical partial disaggregated deployments are expected to involve, at least in the first phase, just two vendors per metro network: the one providing the OLS and most of the transponders and a second vendor providing the remaining percentage of transponders (e.g., 20-30%). The control and maintenance will be in charge of the first OLS vendor, which will have to take, from the operator perspective, full responsibility of the entire optical metro network operations. This approach would not require the Telco to have internal skills and effort to manage the disaggregated optical network, relaxing one of the most relevant aspects that concerned the Operators about disaggregation [37].
In the fully disaggregated model, devices such as transponders and ROADMs and amplifiers are fully detailed in the YANG model using a tree structure. The business model that drives full disaggregation appears to be less evident at the moment, and potentially beneficial only as a long term approach [37].
The closed and single-vendor optical network become a disaggregated optical network and the role of SDN is important. In May 2022, Heavy Reading conducted the inaugural **Open, Automated & Programmable Transport Networks Market Leadership Survey** with project partners Ciena, Fujitsu, Infinera and Juniper. The 2022 survey attracted 78 qualified network operator responses from around the world, sharing their views on optical line systems.

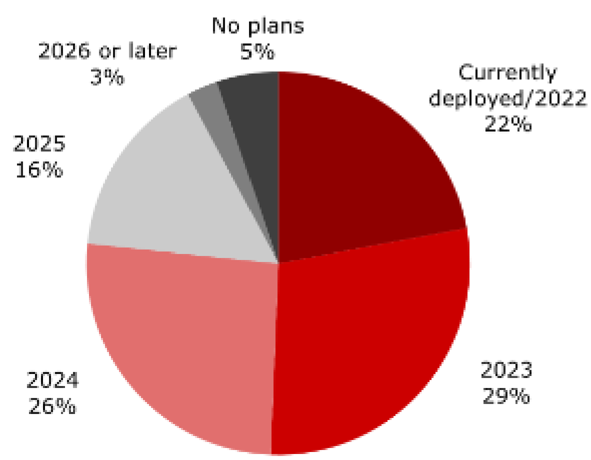


Figure 3.3.3 Result of survey about timeline [Source Heavy Reading] [33]

Heavy Reading's latest survey indicates that just over one-fifth of operators intend to have in place disaggregated, multi-vendor optical line systems by the end of 2022. An additional 29% plan such deployments in 2023. Thus, by year-end 2023, exactly half of the operators surveyed expect disaggregated line deployments. Still, the results as shown in figure 3.3.3 indicate a clear intent and direction toward truly disaggregated open optical networks. In the survey, as shown in figure 3.3.4, the telecom operators have answered the factors that drive the choices versus disaggregate optical networks..

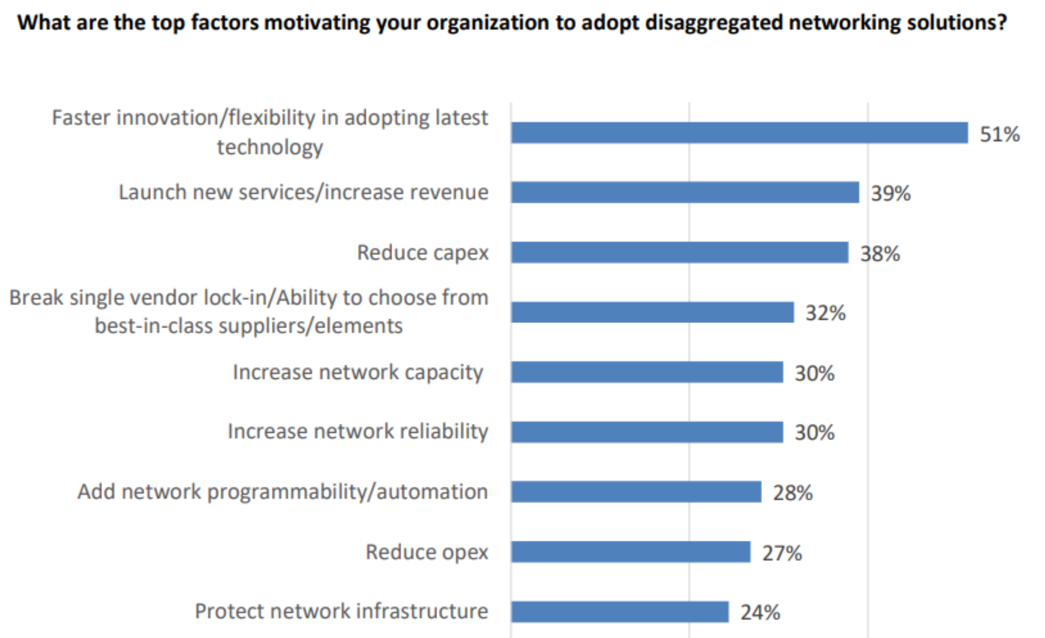


Figure 3.3.4 Result of survey about reason of adopting disaggregate optical network [Source Heavy Reading] [33]

Heavy Reading survey indicates two principal reasons for adopting a disaggregated optical network : the innovation and flexibility inside the architecture of the disaggregated optical network and new services/revenue lowering the OPEX.

4. Physical Layer Abstraction

A transparent optical network is a circuit-switched network where circuits are transparent lightpaths (LP) from a defined source *s* to a defined destination *d*. When the optical signal transmits through the fiber links and optical devices, the quality of transmission (QoT) degrades due to various physical layer impairments (PLIs), including linear and nonlinear impairments. QoT is an important metric that determines the availability of a connection. Therefore, the QoT guarantee is the premise of successful connection establishment in optical networks. QoT prediction before connection establishment can provide guidance for the routing and resources allocation of connections [36].

The signal propagated along light-path/light-tree travels through a number of optical devices EDFAs, ROADMs, etc.) and fiber segments. There are many factors that may degrade the QoT, such as the burst of failure or destruction, hardware aging, and various PLIs, as shown in Fig. 4.1 PLIs are the main factors that degrade QoT, when no fault occurs in fiber links and devices of the connection. PLIs mainly include fiber attenuation, dispersion, four-wave mixing (FWM), self-phase modulation (SPM) and cross-phase modulation (XPM)-induced nonlinear interferences (NLIs), amplified spontaneous emission (ASE) noise of amplifiers, as well as insert noises. Among them, the ASE is more prominent, it is twice the NLI when the system operates at optimal power. Remarkably, it is also the toughest to measure. The ASE noise power depends on the working point of amplifiers, which eventually depends on the spectral load. EDFAs are the dominant ASE noise source . The ASE noise power is related to the noise figure (NF) and gains a ripple of EDFA. The greater the ASE noise, the less the EDFA amplifiers. ROADM based on wavelength selective switches (WSSs) is a key element in optical networks. The WSSs of the ROADM are essentially strong filters. Filter penalty becomes severer as the number of ROADMs are cascaded over long paths. In addition, the nonlinearities of fiber is another influence factor for QoT. SPM produces self-channel interference (SC-NLI) of the channel on itself, and XPM induced nonlinear distortions affect the neighboring channels, thus the signal to noise ratio (SNR) of one channel is still actually related to the signal power of all other channels. When the frequency spectrum of the interference channel with higher power is closer to that of the target estimation channel, the NLI introduced into the target estimation channel is stronger. The connector loss at the input of each fiber span is a crucial value that impacts QoT, because it is related to nonlinear interference and spectra tilt. The impairments discussed above are analytically intractable since they cannot be easily measured and may vary in time because of equipment aging, update or maintenance [36].

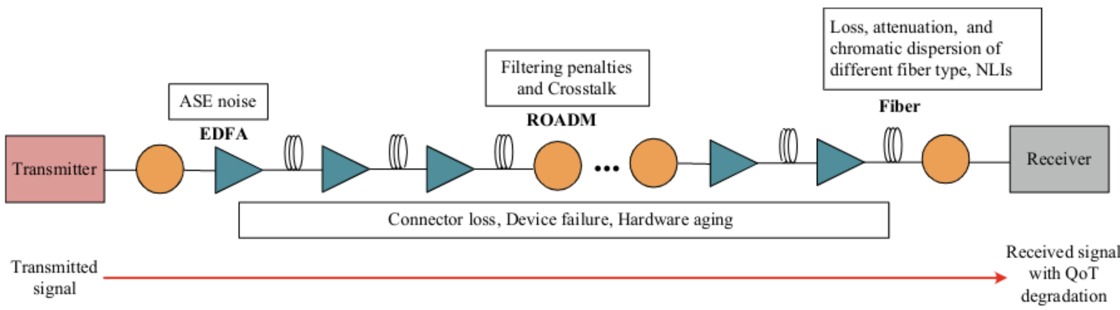


Figure 4.1 Signal transmission suffering impairment in light-path [36]

In transparent optical networks operated by coherent optical technologies, it has been extensively proven that the QoT is defined by the generalized SNR (GSNR). GSNR includes both the effects of ASE noise and NLI accumulation, which are the main sources of noise accounted for in QoT estimators [36].

4.1 Open Software GNPy

In 2017, the Open Optical & Packet Transport-Physical Simulation Environment (OOPT-PSE) group with Telecom Infra Project started to define and develop a common open source and vendor-neutral set of algorithms to assess the optical impairments in an optical line system. The core software developed by OOPT-PSE is called Gaussian Noise Simulation in Python (GNPy). It relies on a Quality Of Transmission (QoT) estimator that, given the network status, calculates the generalized Signal-To-Noise ratio (GSNR) over a dedicated network route. Furthermore, applications have been developed to describe, design, and optimize optical networks based on it. In essence, it allows a user to determine the feasibility of modulation and capacity allocation in a fully coherent wavelength division multiplexed (WDM) network with vendor-independent software. The computational time is a few seconds per Lightpath (LP), with a future target of well below one second per LP. [26]

The Fig. 4.1.1 is a schematic depicting the software-defined optical network application for a partially disaggregated optical network. Every ROADM-to-ROADM OLS is controlled by an independent OLC that sets the operational point of OAs. The OLC has a local ROADM-to-ROADM vision and is traffic agnostic. The related OLS may be either open or closed. In the case of an open OLS, the OLC controls devices and exposes the line model as a white box to the ONC. The OLC has full access to each device and implements the control algorithm specified by the ONC to set the operational point of OAs. On the contrary, in closed OLSs, the OLC exposes to the ONC the line as a black box providing only the metrics required for the line abstraction within the digital twin: GSNR degradation, accumulated CD, PMD, PDL, and propagation latency. The control algorithm implemented in the OLC is not exposed. The optical network controller has a global vision of the transparent network infrastructure and, besides interacting with the OLC, needs full control of the network elements in charge of optical circuit management. These are transceivers and ROADMs that must be open white boxes enabling full control of the device functionalities. The ONC, when a source-to-destination optical circuit is requested, finds the proper route and wavelength, performs the optical path computation on the LP QoT, sets the switching matrices, and deploys the optical circuit by setting the TRX operational mode.[26]

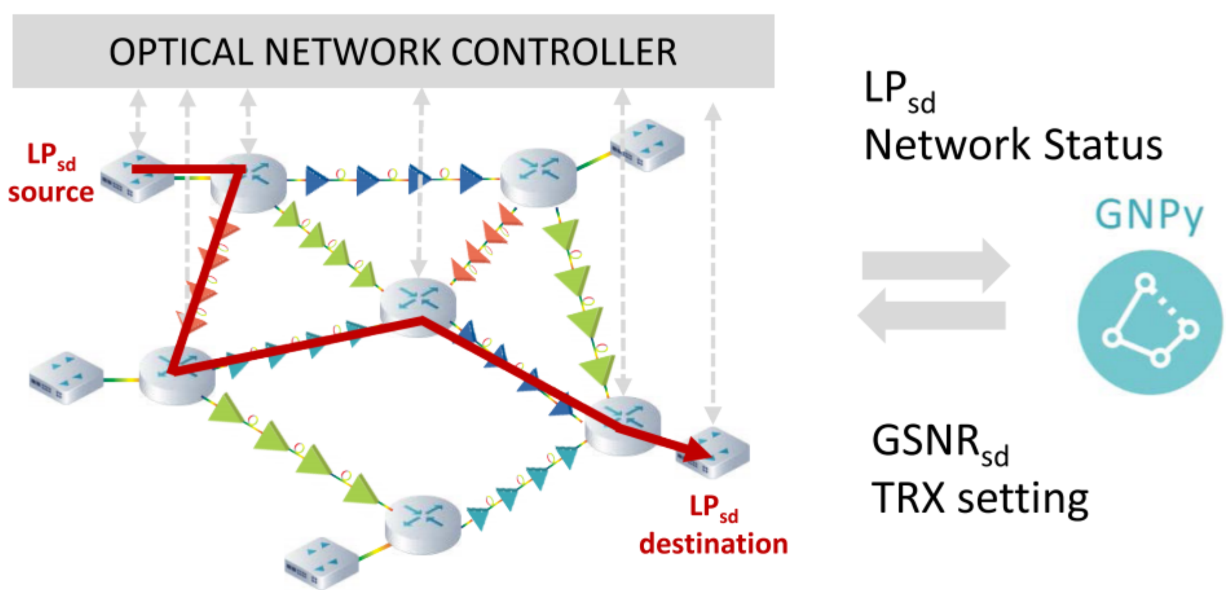


Figure 4.1.1 Architecture for the optical path computation using GNPy [24]

The QoT estimator of GNPy requires a description of the network through a JSON file. It is abstracted as an optical impairment-aware topology as shown in Figure 4.1.2

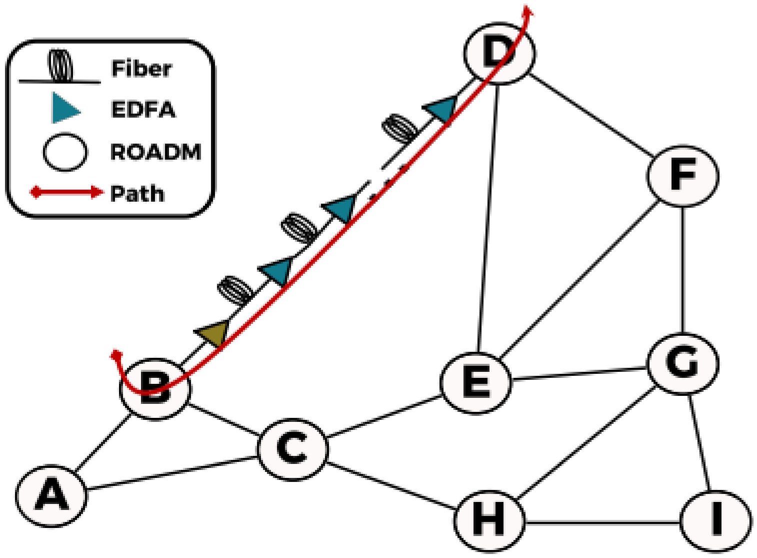


Figure 4.1.2 Path propagation on GNPy to asses the QoT [26]

in which each Network Element is properly connected to others, and it returns the GSNR for each channel at the end of the path. A network element can be a fiber, an optical amplifier, a reconfigurable optical add-drop multiplexer (ROADM) node, or a transceiver. [26]

Given the description of the physical layer, the GSNR between a source transceiver and destination transceiver is assessed through the path under analysis by using the so-called spectral information. The aim of spectral information is to maintain all of the information related to WDM, such as power of each channel, the symbol rate, the central frequency, the amount of ASE noise and NLI that affects the channel. Such spectral information is generated by source transceiver and it is propagated through each Network Element belonging to the path under analysis. These Network Elements update the spectral information by properly attenuating or amplifying each power value and by adding new ASE and NLI noise contributions on the spectral information if it is warranted. In particular a ROADM node may add some noise in the add/drop channels and it equalizes the power per channel of the spectral information. The amplifier properly amplifies the spectral information and introduces some new ASE noise, taking into account the possible frequency variation of the gain and the NF. [26]

The ASE noise power contribution, as a function of the frequency f, is computed as

$$P_{ASE}(f) \; = \; h\, f\, NF(f)\, G(f)\, B_{ref}$$

where h is the Planck constant,
G(f) is the amplifier gain,
B_{ref} is the reference bandwidth in which the GSNR is evaluated.

The fiber propagation attenuates the power levels and properly introduces the NLI generated by the Kerr effect, also taking into account the stimulated Raman scattering (SRS). The SRS is assessed by implementing a Raman solver that numerically computes the solution of the set of ordinary differential equations (ODEs) that describe the SRS effect, also including the two-point boundary value problem in the presence of counter-propagating Raman pumps. Thanks to the Raman solver, it is possible to assess the interchannel SRS, the SRS excited by the presence of co-and counter-propagating Raman pumps generated by Raman amplifiers, and also the spontaneous Raman scattering that is fundamental to assess the ASE noise generated by Raman amplifiers. Then, the NLI contribution of each fiber span is treated as an additive white Gaussian noise disturbance that takes into account the SRS according to the generalized Gaussian noise (GGN) model. This contribution is evaluated as

$$P_{NLI}(f) = G_{NLI}(f)\, B_{ref}$$

where $G_{NLI}(f)$ is the NLI power spectral density
B_{ref} is the reference bandwidth in which the GSNR is evaluated.

The $G_{NLI}(f)$ depends on the fiber parameters and on the WDM spectral occupancy. $G_{NLI}(f)$ is decomposed into self-channel interference (SCI), cross-channel interference (XCI) and multi-channel interference. While the SCI and the XCI are computed via the GGN model, the multichannel interference (MCI) is not computed because it is negligible. This reduces the computational time as the complexity of the problem moves from quadratic with respect to the number of channels to linear. Finally, the transceiver at the end of the path receives the spectral information and returns the propagation performances of each channel by computing the GSNR, which includes both the optical signal-to-noise ratio (OSNR) and the nonlinear signal-to-noise ratio (SNR_{NL}). Those quantities are defined and computed on the i_{th} channel as

$$OSNR_i = \frac{P_{S,i}}{P_{ASE}(f_i)}$$

$$SNR_{NL,i} = \frac{P_{S,i}}{P_{NLI}(f_i)}$$

$$GSNR_i = \frac{P_{S,i}}{P_{ASE}(f_i) + P_{NLI}(f_i)} = \left(OSNR_i^{-1} + SNR_{NL,i}^{-1}\right)^{-1}$$

where $P_{S,i}$ is the signal power of the i_{th} channel and f_i is its central frequency

The network topology must be schematized in a JSON file where each NE and its own parameters are described with YANG data structure language and each NE parameter can be retrieved with a REpresentational State Transfer (REST) query or other methods, such as using Network Configuration Protocol (NETCONF). Each ROADM node requires a target output power per channel that can be retrieved from the total power measured by the photodiode before the booster amplifier divided by the number of channels. Then, each amplifier requires a gain target and a tilt target, and this information can be provided by the network equipment. Furthermore, the amplifier NF must be derived to properly assess the ASE noise level. To do this, the data model of GNPy for EDFA is fed with the gain-versus-NF characterization from the documentation of the amplifier. Because this curve also depends on the input power, it is necessary to use the proper curve, depending on the output power (P_{out}) level that is measured by the amplifier photodiode [26].

A qualitative example of NF-versus-gain and P_{out} characterization is shown in Figure 4.1.3.

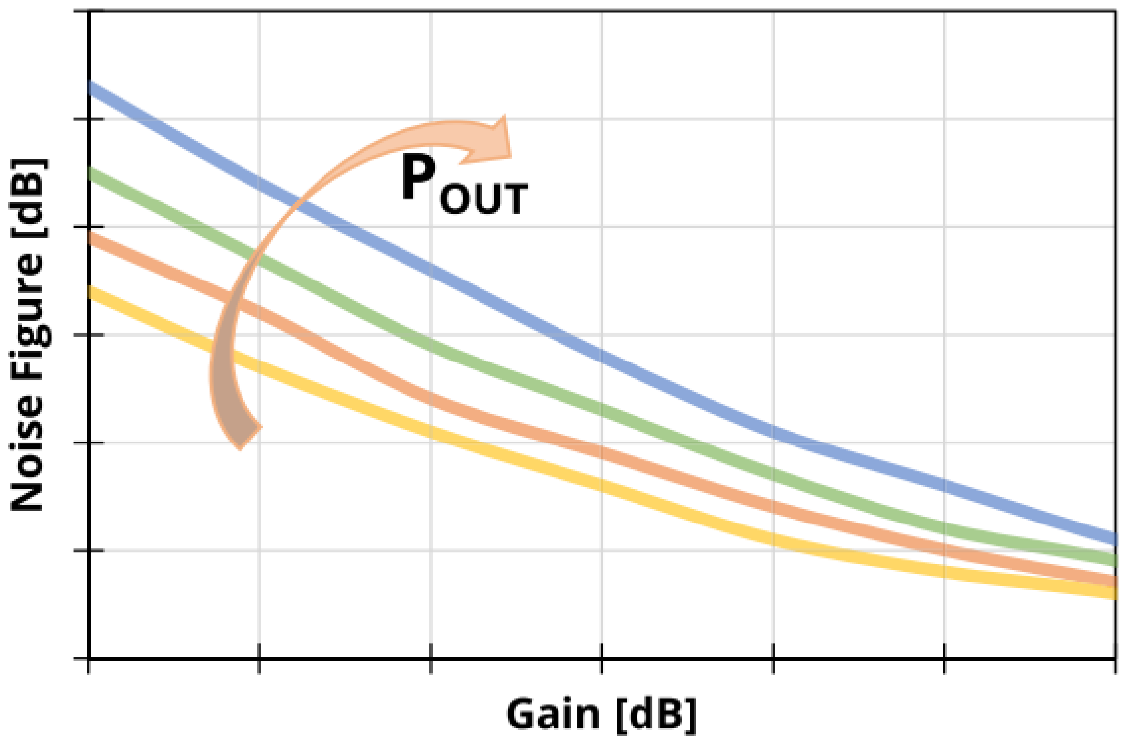


Figure 4.1.3 Qualitative example of the noise-figure-versus-gain and P_{out} curve of amplifier [26]

To describe a fiber span, it is necessary to input the fiber type, the fiber length (L_F), the attenuation coefficient (α), and the connector losses. Furthermore, when Raman pumps are injected into the fiber by Raman amplifiers, the parameters related to the Raman pumps and the temperature of the fiber also are needed. The fiber types already available in GNPy are standard single-mode fiber (SSMF), non zero dispersion-shifted fiber (NZDSF), and large effective area fiber (LEAF). It also is possible to define custom fiber types. To define a custom fiber type, it is enough to know the dispersion, the nonlinear coefficient, and the Raman efficiency. The length L_F can be retrieved by computing the distance between the locations of the amplification sites or it can be obtained by the network equipment by measuring the propagation time between two amplifiers. For each fiber type we use the specified attenuation coefficient from the data sheet. Then, the connector losses can be estimated if you know the overall span loss (A_S) : it can be derived by computing the difference between the total power measured by photodiodes placed at the output of the previous amplifier and at the input of the following amplifier. Thus, the overall splice-plus-connector loss (A_C) can be derived knowing A_S and the fiber loss (A_F), so:

$$A_C = A_S - A_F = A_S - (\alpha L_F)$$

The proper partition of this loss is crucial because the input connector loss determines the amount of NLI generated by that fiber span. As the optical time domain reflectometer (OTDR) trace is not always available, it may be impossible to retrieve the concentrated loss distribution along the fiber [26].

(a)

```
"Fiber":[{
    "type_variety": "SSMF",
    "dispersion": 1.67e-05,
    "effective_area": 83e-12,
    "pmd_coef": 1.265e-15
    }
]
```

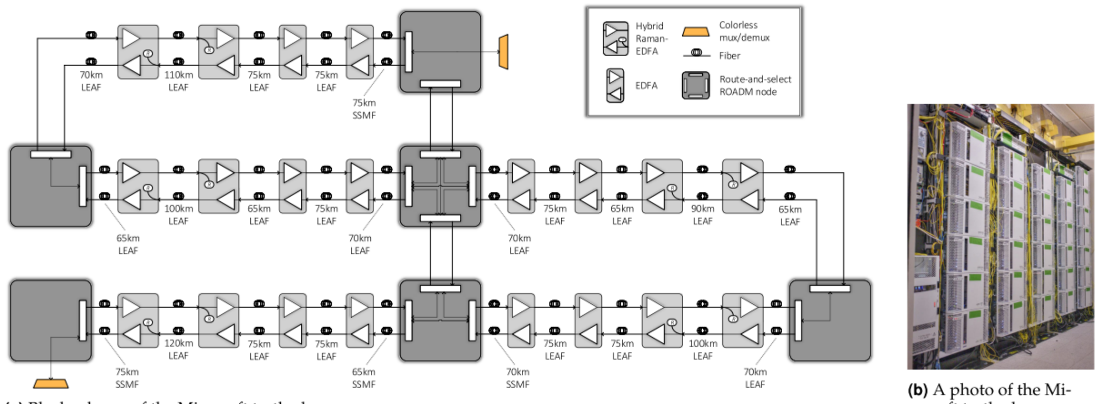
(b)

```
"Edfa":[{
        "type_variety": "Juniper_BoosterHG",
        "type_def": "advanced_model",
        "gain_flatmax": 25,
        "gain_min": 10,
        "p_max": 21,
        "out_voa_auto": false,
      }
    ]
```

Figure 4.1.4 Example of JSON file (a) Fiber description, (b) EDFA amplifier

The tool GNPy has been tested emulating a commercial network with six ROADM nodes and five amplified optical segments, and the longest bidirectional path in the network is 2000 km long. The transponders come from three different vendors, whereas all the ROADM nodes and the amplifiers are from a fourth vendor. Each node degree of each ROADM node has a booster amplifier and a pre-amplifier. Each line segment is roughly 400 km long, and it includes four in-line amplifiers (ILA): three lumped EDFAs and one hybrid Raman–EDFA amplifier with Raman amplification operating in the moderate pumping regime [28]. The length of the fiber spans varies from 65 km to 120 km, and the fiber types are G.652 standard SSMF and G.655 LEAF. The exact network topology, including the detailed length of each fiber span, the fiber type, and the position of each

EDFA and hybrid Raman–EDFA amplifier, is shown in Fig. 4.1.5 (a). The line system has been properly configured by a vendor proprietary controller.



(a) Block scheme of the Microsoft testbed.

(b) A photo of the Microsoft testbed.

Figure 4.1.5 (a) Block schema and (b) photo of Microsoft testbed [26]

To collect and prepare the information, the state of the network was probed by querying it using a Microsoft software-defined network (SDN) line system monitoring tool that is based on REST : comparing the estimated GSNR against the measured value relying only on the data obtained querying the network equipment and data present in equipment documentation, it is possible to obtain excellent accuracy [26].

5. NETCONF Protocol

NETCONF is an important component of SDN (Software Defined Networking) architecture (as defined in RFC 7426) and network programmability and automation. ETF has defined the NETCONF (Network Configuration Protocol) standard in RFC 4741 in December 2006 and improved it in June 2011 in RFC 6241 (which is the currently active standard). NETCONF was created based on the requests of the network operators (defined in RFC 3535 in June 2002) for a standard protocol for the configuration of network devices. NETCONF defines the mechanisms of installing, manipulating, and deleting the network device configurations. NETCONF uses RPC messages, SSH for the transfer of messages between the server and the client; it has its defined set of operations and it uses YANG for data modeling. NETCONF defines the initial basic set of operations and additional capabilities. Capabilities are additional functions of the NETCONF device (of client and server) that may but do not have to be implemented by the network devices.[7]

NETCONF protocol contains two parts :

- NETCONF manager : mainly act as a client in the network, runs on the server and manage the devices interacting with NETCONF agent
- NETCONF agent : mainly serves as the server in the network. NETCONF agent sends configuration management by accepting NETCONF manager. NETCONF agent parses the request and manages the configuration of the device with the help of configuration management components.

NETCONF protocol is divided into four layers:

- secure transport layer: provides secure and reliable transmission of messages between the client and the server.
- messages layer: describes the coding mechanism of remote procedure call (RPC) and notification.
- operations layer: defines a group of basic operations of the protocol that allow retrieval and editing of configuration data. Table 5.1 presents the basic operations of NETCONF protocol.
- content layer: consists of configuration data and notification data. NETCONF protocol does not deal with the contents layer in its RFC documents, but

rather a separated protocol has been made, titled YANG. YANG is defined in RFC 6020, and RFC 6021 presents the types of data.

Basic NETCONF functionalities can be expanded by defining additional possibilities (NETCONF capabilities) while establishing the session between the client and the server. NETCONF allows a client to discover the set of protocol extensions supported by a server. These capabilities permit the client to adjust its behavior to take advantage of the features exposed by the device. The capability definitions can be easily extended in non centralized manner.[7]

Operation	Description
<get>	Retrieve running configuration and device state information
<get-config>	Retrieve all or part of a specified configuration datastore
<edit-config>	Edit a configuration datastore by creating, deleting, merging or replacing content
<copy-config>	Copy an entire configuration datastore to another configuration datastore
<delete-config>	Delete a configuration datastore
<lock>	Lock an entire configuration datastore of a device
<unlock>	Release a configuration datastore lock previously obtained with the <lock> operation
<close-session>	Request graceful termination of a NETCONF session
<kill-session>	Force the termination of a NETCONF session

Table 5.1 NETCONF Operation

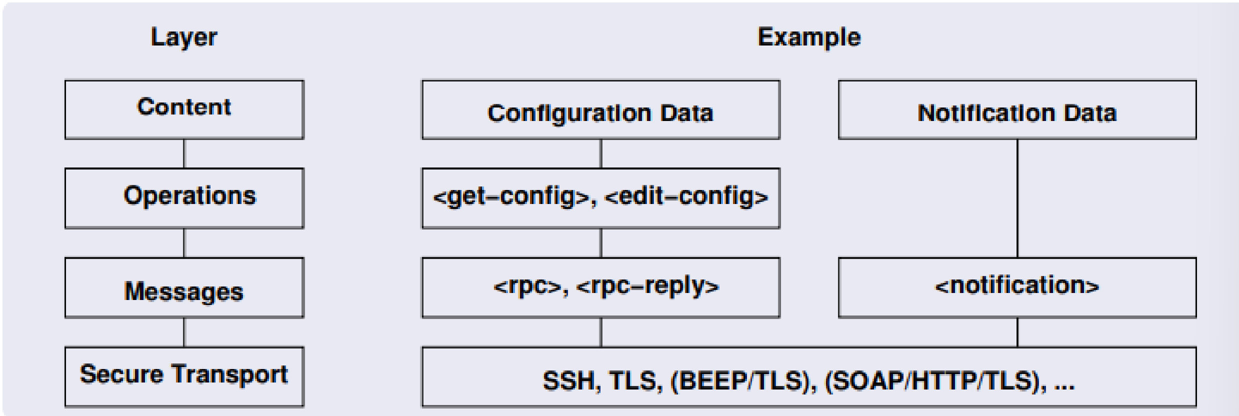


Figure 5.1 NETCONF Layer Model [RFC 6241]

The NETCONF protocol provides a small set of low-level operations to manage device configurations and retrieve device state information. The base protocol provides operations to retrieve, configure, copy, and delete configuration datastores. Additional operations are provided, based on the capabilities advertised by the device [3]. A NETCONF capability is a set of functionality that supplements the base NETCONF specification. Capabilities augment the base operations of the device, describing both additional operations and the content allowed inside operations. The client can discover the server's capabilities and use any additional operations, parameters, and content defined by those capabilities [3].

5.1 Capabilities

The NETCONF protocol provides a small set of low level operations to manage device configurations and retrieve device state information. The base protocol provides operations to retrieve, configure, copy, and delete configuration datastores. Additional operations are provided, based on the capabilities advertised by the device [3]. A NETCONF capability is a set of functionality that supplements the base NETCONF specification. Capabilities augment the base operations of the device, describing both additional operations and the content allowed inside operations. The client can discover the server's capabilities and use any additional operations, parameters, and content defined by those capabilities. [7]

The base capabilities are defined using URNs following the method described in RFC3553 and have the following format:

urn:ietf:params:netconf:capability:{name}:1.x

where {name} is the name of the capability.
Capabilities are often referenced using the shorthand :{name}. Capabilities are advertised in messages sent by each peer during NETCONF session establishment. When the NETCONF session is opened, each peer (both client and server) must send a <hello> element containing a list of that peer's capabilities. Each peer (client and server) advertises its capabilities by sending them during this initial capabilities exchange. Each peer needs to understand only those capabilities that it might use and must ignore any capability received from the other peer that it does not require or does not understand. Additional capabilities can be defined using the template in RFC6241. Future capability definitions can be published as standards by standards bodies or published as proprietary extensions.[7]

5.2 Advantages And Possibilities

NETCONF standard offers the following possibilities and advantages :

1. NETCONF is a standard-based solution for configuration management over remote IP access to R/S devices because the structure of commands and data is the same for all vendors.
2. NETCONF as a standard-based solution for configuration management because of providing the automated and programmable network operations which replaces the process of manual configuration and so significantly decreases the possibility of human error.
3. NETCONF because of making a clear distinction between configuration and operational data.
4. Possibility of partial configuration of a network device that is offered by NETCONF. NETCONF achieves this by using XML language and "XML subtree filtering" function.

5. Possibility of validation of a configuration prior to implementation that is offered by NETCONF. NETCONF achieves validation of the configuration datastore by using the capability <validate>
6. Possibility of locking a configuration datastore offered by NETCONF. NETCONF operations “lock” and “unlock” protect from simultaneous change of configuration datastore from several sources (for example by access of other user with NETCONF session, CLI or SNMP protocol).
7. “Backup & Restore” option offered by NETCONF. NETCONF achieves by (1) manipulation of different configuration datastores (<running>, <candidate>, <startup> and backup) and (2) by using the “Rollback-on-Error” capability.
8. Possibility of network-wide configuration offered by NETCONF. NETCONF achieves this by using different configuration datastore (<running>, <candidate>, <startup> and backup) and with operations “lock” and “unlock”.

Most of the above listed NETCONF advantages and possibilities are obtained by using NETCONF capabilities [7].

5.3 NETCONF in Disaggregate Optical Networks

The NETCONF protocol offers primitives to view and manipulate data, providing a suitable encoding as defined by the data-model. Data is arranged into one or multiple configuration datastores (set of configuration information that is required to get a device from its initial default state into a desired operational state). The protocol thus enables remote access to a device, and provides the set of rules by which multiple clients may access and modify a datastore within a NETCONF server (e.g., device). The protocol is, in simple terms, based on the exchange of XML-encoded RPC messages over a secure (commonly Secure Shell, SSH) connection. Out of the different messages and operations, the <get-config> allows retrieving part or the configuration data, the <edit-config> allows changing (creating, deleting, merging or replacing) that data (including adding elements to a container, or adding elements to a list, as allowed by the model) and, <get> allows to retrieve device state information and operational data. [27]

A common web/HTTP approach to design services is based on the Representational State Transfer (REST) paradigm, an architectural style that defines a set of constraints to be used for creating Web services. RESTful Web services allow their clients to access and manipulate textual representations of Web resources by using a uniform and predefined set of stateless operations. RESTCONF relies on REST and provides a HTTP based API to access the hierarchical data within the running datastore. RESTCONF thus maps NETCONF operations to HTTP operations (such as POST, PUT, and DELETE) used to create and replace resources in the web, and supports two main encodings: XML and JSON.[27]

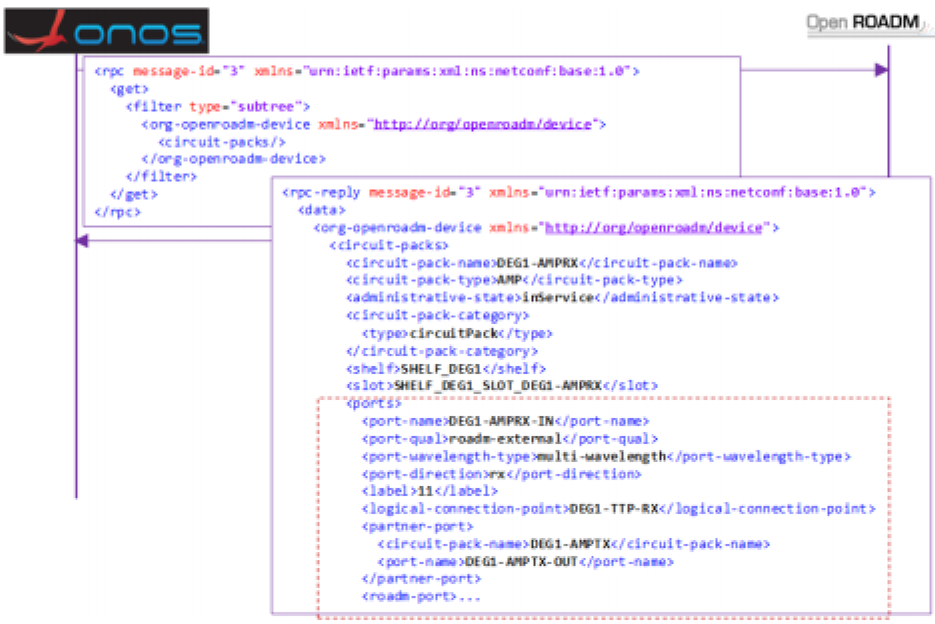


Figure 5.3.1 NETCONF <get> operation to retrieve list of circuits of ROADMs [27]

The YANG/NETCONF symbiosis provides the ideal breeding ground not only for the development of optical devices that facilitate the vendor interoperability but also for the development of software tools that emulate the real behavior of such devices [35].

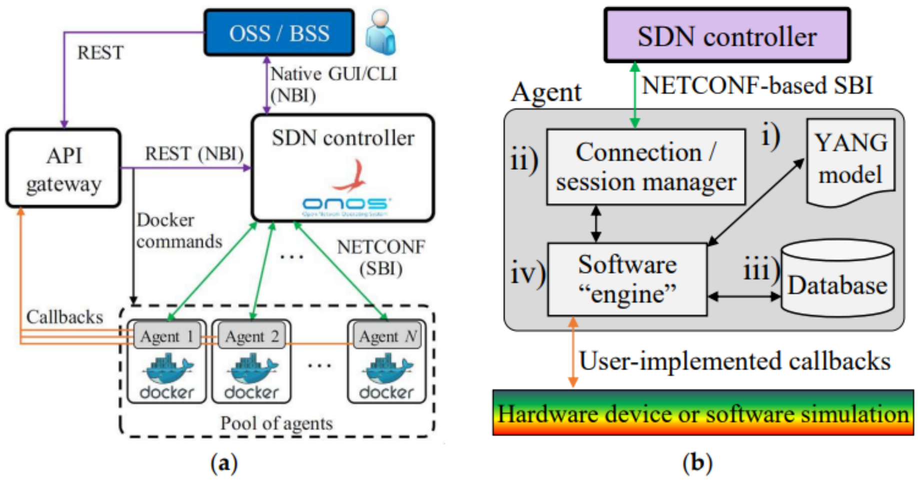


Figure 5.3.2 (a) Architecture (b) Detail agent view [35]

The figure 5.3.2(a) shows the architecture of an optical disaggregate network that comprises three main elements:

- ONOS SDN controller
- pool of software agents that emulate the interaction with optical devices (examples transponders)
- API gateway

ONOS is chosen to play the role of the SDN controller, and is configured with the required modules and YANG drivers to interact with the optical devices or agents in the data plane via NETCONF protocol. A pool of agents emulates a realistic environment of a Disaggregate Optical Network data plane; those agents are implemented in docker containers and they are created automatically by the API gateway REST-based interface according to the topology specification given by ONOS [35].

The figure 5.3.2(b) shows the structure of optical network agent : each agent includes four components:

- (i) YANG model of transponder
- (ii) Connection manager through NETCONF protocol that enables connectivity with the controller
- (iii) database to store the configuration file
- (iv) software engine to detect and interact with changes in the configuration files

6. YANG Data Model Language

Multi-vendor interoperability can be achieved at node and network levels by relying on standard data modeling. YANG represents an attractive data modeling solution for network component definition. Recently, network operators have shown interest in the deployment of data plane hardware providing multi-vendor interoperability. This way, operators can use systems of different vendors optimizing transmission performance (e.g., achievable transmission distance), network device reuse, and capital expenditure without the need for being tied to single-vendor equipment. Multi-vendor operability can be applied in two different contexts: network and node. The *White Boxes* is a node composed of components provided by different vendors and assembled under the same control system. To support control and management of multi-vendor networks and white boxes, standard operator-defined data models are required, so a common application programming interface (APIs) can be adopted for controlling/managing these multi-vendor optical systems. The candidate language to describe a standard-defined data model is YANG (Yet Another Next Generation). [8]

YANG is a data modeling language standardized by IETF. It has been developed and standardized as a language to model data into NETCONF messages : a YANG module can be translated into a XML representation called YIN. The main advantage of YANG is the XML representation, which makes YANG also adoptable by other protocols (as RESTCONF).

The YANG data model is a machine-oriented model interface, which defines data structures and constraints to provide more flexible and complete data description.

- YANG uses a compact syntax since human readability is highest priority
- YANG is an XML representation of YANG (lossless roundtrip conversion)

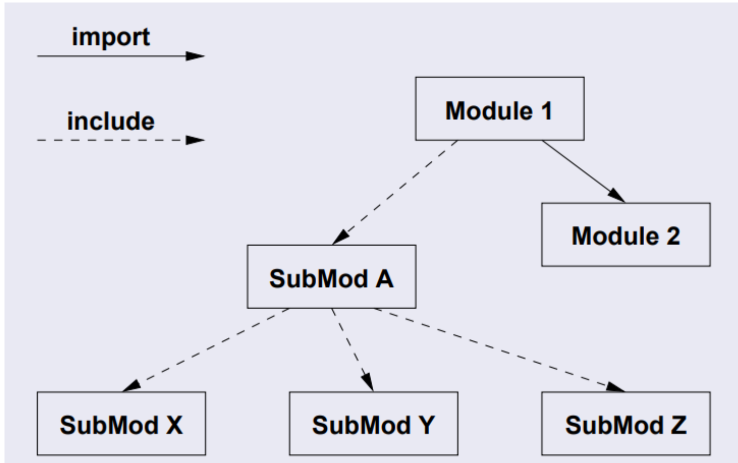


Figure 6.1 YANG data model

A module is a self-contained collection of YANG definitions
A submodule is a partial module definition which contributes derived types, grouping, data nodes, RPCs, and notification to a module
A YANG model file contains the following information:

- Module definition. Modules and submodules : YANG structures data models into modules and submodules. The hierarchy can be augmented, allowing one module to add data nodes to the hierarchy defined in another module. This augmentation is conditional with new nodes presented only if certain conditions are met. The **include** statement allow a module or submodule to reference materials in submodules, and the **import** statement allows references to materials defined in other modules
- Namespace of module, globally unique
- Version of module. The **revision** statement records the version change history of a module.
- Module description and introduction

```
module example {
        namespace "http://module.example.com/modules";
        prefix example;
        organization "Poli";
        description "Module Examples";
}
container system {
```

```
        leaf host-name {
                type string;
                description "Hostname";
        }
        leaf-list domain-search {
                type string;
                description "List Of Domain names";
        }
}
        typedef NEW-TYPE {
                type enumeration {
                        enum type-one;
                        enum type-two;
                }
}
```

Figure 6.2 Generic 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
```

Figure 6.3 Tree View Of ROADM model in YANG language

The end purpose of a ROADM is to facilitate Media Channel (MC) routing over a fiber 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 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 flex-grid ROADM, the OCM is typically also capable of flex-grid operation. An OCM can therefore measure the optical power being transmitted in a given media channel.

The structure of the YANG model for ROADM as shown in Fig. 6.2 consists of three blocks:

- A list of possible Media Channels which might be passing over ROADM.
- A subset of Media Channels defined above are realized over WSS. A desired attenuation is also set. These Media Channels might not be the same in both directions, but channels routed in one direction must not overlap.
- A possibly different set of Media Channels is selected for monitoring via an OCM

YANG data can be of two types: configuration or state. Configuration data is explicitly set by an external entity from the system (e.g., the centralized controller). State data cannot be set by the external entity, but they can be read. State data can be used for monitoring purposes. A further layer in the hierarchy indicating the list of configuration and state data can be defined, as detailed later. YANG also supports the definition of "Notification" to model the content of NETCONF Notification messages, which indicate that certain events have been recognized (e.g., a failed link). Moreover, although YANG is mostly considered as a data modeling language, it also provides the possibility to define executable functions through remote procedure calls (RPCs) that specify the name, the input, and the output parameters of a specific function, for example, switching on (off) a device inside a node.

```
rpc activate-software-image {
 input {
  leaf image-name {
   type string;
  }
 }
 output {
  leaf status {
   type string;
  }
 }
}
```

Figure 6.4 YANG RPC executable function

The operation name is **activate-software-image**. The input parameters are image-name and output value is **status**.

The corresponding NETCONF.xml example is :

```
<rpc message-id="101" xmlns="urn:ietf:params:xml:ns:netconf:base:1.0">
 <activate-software-image xmlns="http://acme.example.com/system">
  <image-name>acmefw-2.3</image-name>
 </activate-software-image>
</rpc>

<rpc-reply message-id="101" xmlns="urn:ietf:params:xml:ns:netconf:base:1.0">
 <status xmlns="http://acme.example.com/system">
  The image acmefw-2.3 is being installed.
 </status>
</rpc-reply>
```

Figure 6.5 YANG module translated into XML

YANG is a highly readable text language. This significantly simplifies management and troubleshooting operations compared to protocols relying on bit encoding, which require ad hoc software to parse encoded information. Nowadays, handling a text file instead of bit encoding does not represent a particular challenge. Moreover, in the case of bit encoding, the support of novel parameters at the data plane would imply redesigning the protocol messages' content, such as header and objects. On the contrary, thanks to the nature of YANG, when the model changes, the YANG model can be refined without redesigning the protocol, thus providing a much more effective solution with respect to bit encoding. Such an example has to be considered relevant given the continuous evolution of the technology at the data plane.

6.1 YANG in Disaggregated Optical Networks

The most relevant standardization initiative providing YANG models for partial disaggregation is OpenConfig, led by Google. In OpenConfig, transponders are described by the terminal-device YANG model, relying on the concept of logical channels to define the mapping among client ports and line ports [37].

The media channel is defined as a specific portion of the optical spectrum along an optical path between a source and a destination node. The media channel occupies a portion of the spectrum called frequency slot, defined by two parameters : central frequency and the width of the occupied spectrum portion. As an example of application of the YANG model for a vendor-neutral optical network on Fig. 6.1.1 there are portions of the trees of sub-modules node, link, and media channel. The interfaces leaf of the node is a list containing all interfaces in the node. Each element of this leaf has several sub-leaves defining attributes of the considered interface (or port) such as name, the number, two Boolean variables indicating if it is input or output port, and the IP address if it is present. The model also includes the "connectivity matrix" (not shown in the figure): a list of connected input/output ports in the node. Additional information may be added. This model can be further augmented by including information on the add/drop part of the node, in particular, to define the reachability of an add port (or a drop port) to an output interface (or an input interface). The link sub-module consists of five leaves: the availability of flex-grid technology for that link, the maximum value N of slices supported by that link (i.e., slices of 12.5 GHz), the nominal central frequency for the link, the spacing among channels' central frequency (i.e., 6.25 GHz), and the slot width granularity (i.e., 12.5 GHz). The media channel sub-module consists of four main leaves: the source and destination nodes of the media channel, the frequency slot, and a list of traversed links. Both source and destination nodes include two leaves: one defining a reference to the module of the node (i.e., the tree of Fig. 6.1.1) and the other one related to the used interface (port) in such a node. This model can be further augmented including a reference to the transponder used by the media channel, the used add/drop port, and also information on the adopted transmission technique (e.g., Nyquist wavelength-division multiplexing, NWDM).

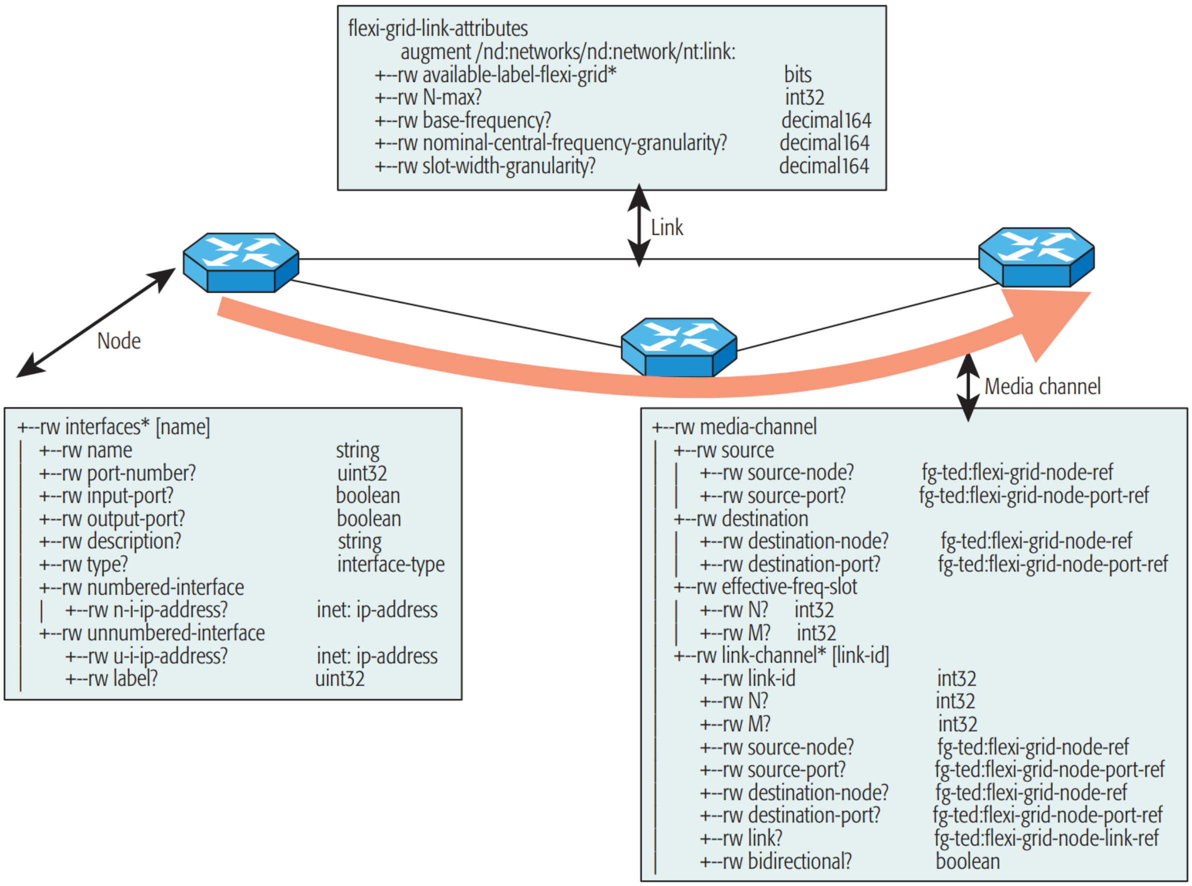


Figure 6.1.1 YANG model of node, link and media channel [8]

- With statement **augment** YANG allows extending data models : with **augment** YANG allows a model to insert additional nodes into data models. This is useful for helping vendors to add vendor-specific parameters to standard data models in an interoperable way.

A sliceable transponder is a transponder generating multiple independent optical flows that can be directed toward different destinations. The transponder is composed of a set of subcarrier modules. Each subcarrier module is devoted to generating (at the transmitter side) or detecting (at the receiver side) an optical subcarrier. Similarly, the YANG model is organized per subcarrier module.

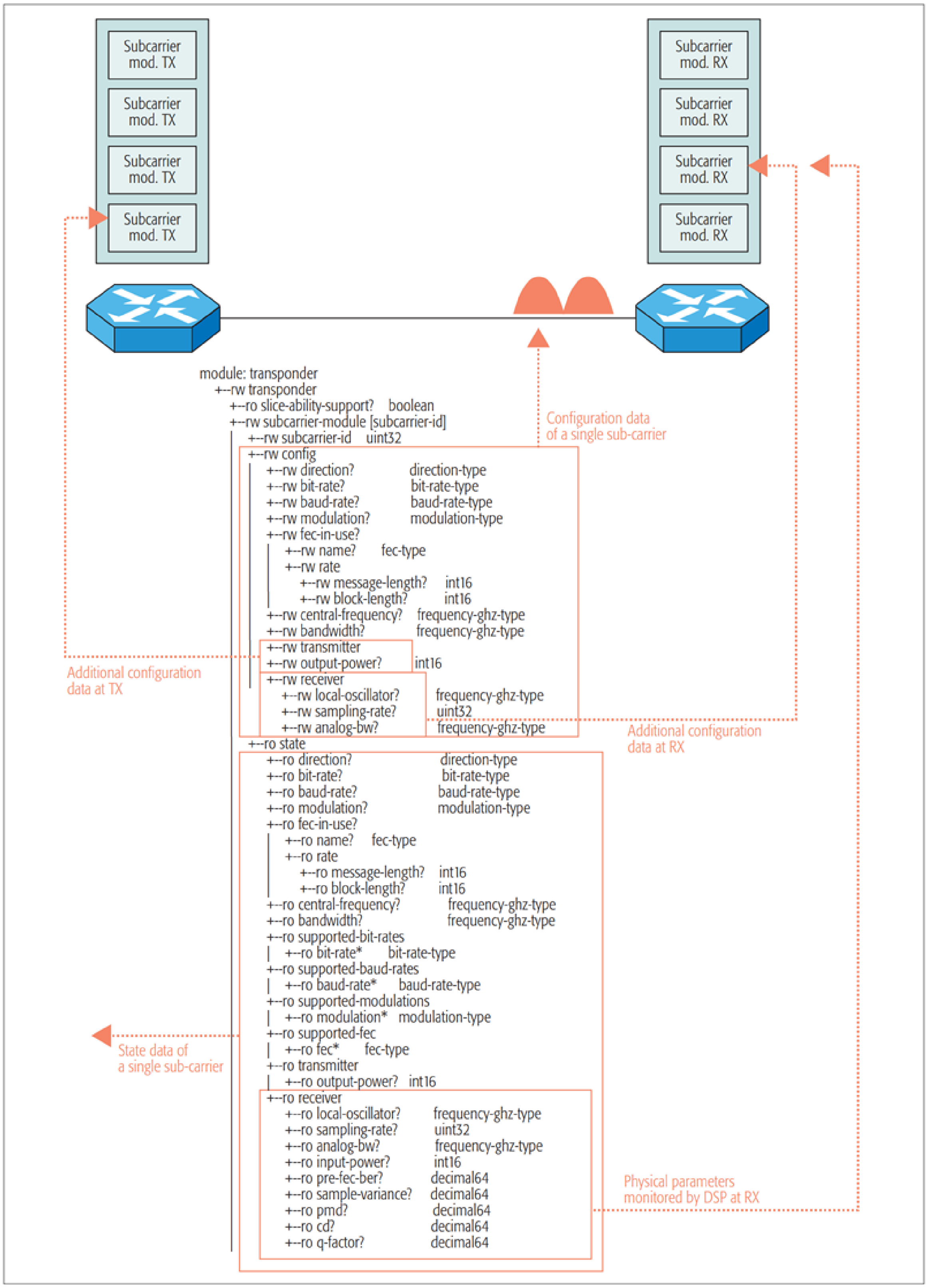


Fig. 6.1.2 YANG tree model representation of a sliceable transponder [8]

First, Boolean data indicates if slice-ability is supported or not. Then a list of subcarriers' sub-modules is modeled. As configuration data, different data are present if the "direction" is in transmission or detection (e.g., local oscillator configuration if the module is in detection). Other data has to be specified in both transmission and detection: for example, baud rate, bit rate, modulation format, FEC. Note that we defined the type "frequency-ghz-type". to discern between the central frequency of a subcarrier and that of a media channel. Indeed, while the central frequency of a media channel has to follow ITU-T specifications in steps of 6.25 GHz, and thus can be expressed as just an integer number, the central frequency of a subcarrier of a media channel composed of several subcarriers does not necessarily follow a grid. Thus, the central frequency of a subcarrier can be any number. For this reason, we defined the type "frequency-ghz-type" to express the frequency value in "GHz." Regarding state data, first, configuration data is replicated into state data to enable an operator to verify ("read") the actual configuration of the transponder. Then other data is included in the model, mainly related to the monitoring capabilities of coherent detection. Indeed, thanks to the digital signal processing (DSP) at the receiver, it is possible to monitor end-to-end parameters associated with each subcarrier. As an example, monitored parameters can be pre-FEC BER, Q-factor, chromatic dispersion (CD), and polarization mode dispersion (PMD), all expressed as decimal64. Other leaves of the subcarrier module comprise (not shown in the figure) the identification of the node and of the add/drop module, and a list of media channels that are using such a transponder. The "transmission scheme" is included to identify the adopted transmission technique [8].

The use of YANG and, in particular, finding common models for events and transceiver actions/functions can be considered relevant because of two main trends: network operators looking for common vendor-neutral solutions; and developing transponders supporting multiple transmission parameters (e.g., bit rate, coding, modulation format, baud rate) and monitoring capabilities. In a disaggregate optical network a NETCONF message is generated to configure the transmission parameters :

- Bandwidth, example at 100 Gb/sec
- Limit maximum of FEC, example 7 % of FEC
- Modulation Format, Example PM-QPSK

Fig. 6.1.3 shows the NETCONF message exchange between the centralized controller (example ONOS) and a transponder device. Similarly, message exchange has been performed with the controller at the receiver side. Initially, the centralized controller sends an <edit-config> message. Once the device controller has received the transmission parameters, an acknowledgment message (<ok> message) is sent to the remote centralized controller notifying that the operation has been concluded.

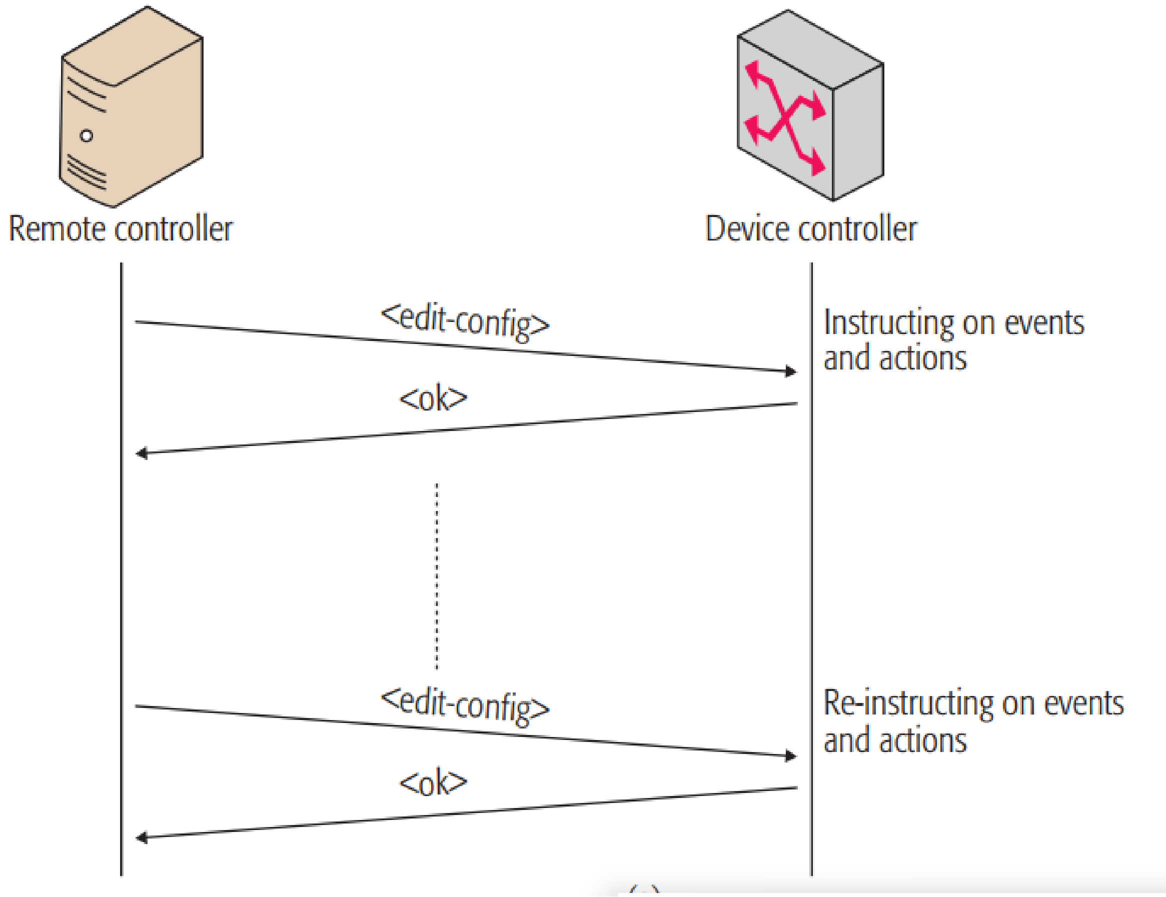


Figure 6.1.3 NETCONF exchange message where Remote Controller is centralized network controller (example ONOS) and Device Controller is the transponder device. [8]

7. SDN Software

The recent Software Defined Networking software offers the possibility to program the network and thus facilitates the introduction of automatic and adaptive control approaches by separating hardware (data plane) and software (control plane) enabling their independent evolution. SDN aims for the centralization of network control, offering an improved visibility and a clear flexibility to manage the network and optimize its performance. Research studies on feasibility of SDN deployment have revealed that the physical centralization of control planes in a single programmable software component, called controller, is constrained by several limitations such as issues of scalability, availability and reliability. Gradually it became inevitable to think about the control plane as a distributed system, where several SDN controllers are in charge of handling the whole network, while maintaining a logically centralized network view, Consequently several SDN controller solutions have been explored and many SDN projects have emerged.

Distributed platforms such as ONOS focus on building consistency models for their logically centralized control plane designs. The principal characteristics of a SDN Software are :

- Scalability

  As the network grows in size (numbers of switches, hosts…) the centralized SDN controller becomes highly solicited (in terms of events/requests) and thus overloaded (in terms of bandwidth, processing power and memory). Furthermore when the network scales up in terms of both size and diameter, communication delays between SDN controller and then network element may become high, thus affecting flow-setup latencies. This may also cause congestion in both the control and data planes and may generate longer failover time. Since control plane scalability in SDN is commonly assessed in terms of both **throughput** (numbers of flow requests handled per second) and **flow setup latency** (delay to respond flow requests), metrics, a single physically-centralized SDN controller may not particularly fulfill the performance requirements of large scale networks. To alleviate some of these scalability concerns some SDN controllers extend the responsibilities of the data plane in order to relieve the load of the SDN controller, other SDN controllers model the control plane in a way that mitigates scalability limitations. A physically distributed control model uses multiple controllers that maintain a logically centralized network view. To maintain the logically centralized view, a strongly-consistent model can be used to meet certain application requirements.

- Reliability

  The data to control plane decoupling has indeed a significant impact on the reliability of SDN control planes. In a centralized SDN-based network, the failure of the central controller may collapse the overall network. In contrast, the use of multiple controllers in a physically distributed (but logically centralized) controller architecture alleviates the issue of single point of failure.

- Controller state consistency

  Distributed SDN controller platforms face major consistency challenges. Clearly, physically distributed SDN controllers must exchange network information and handle the consistency of the network state being distributed across them and stored in their shared data structures in order to maintain a logically centralized network view that eases the development of control application. Achieving a convenient level of consistency while keeping good performance in software-defined networks facing network partition is a complex task.

7.1 **ONOS**

ONOS has been originally designed to operate on traditional SDN networks composed of electronic devices (layer2 switches), mainly utilizing the OpenFlow protocol. ONOS is one of the best candidates for control of optical networks. From a reliability view, ONOS is designed to run in a logically centralized but physically distributed fashion, where the controller functionalities are spread on a number of synchronized instances running on different physical machines. This approach together with an advanced multi-thread software architecture, strongly improves the system scalability because the mastership of devices can be balanced among the several instances. [28]

Optical communication systems based on SDN control are already available on the market and in the phase of deployment in the field. However, they typically implement fully aggregated systems, providing both transmission and switching functionality with proprietary software for control and configuration. The current challenge is therefore twofold: vertically, as in the most traditional SDN approach, to separate the control plane from the data plane opening the system to third-party controllers, and horizontally, aiming at decomposing the optical communication system in its single components, allowing best-of-breed selection during the deployment of optical networks, from a multi-vendor pool, breaking the vendor lock-in dependencies and achieving significant cost reduction. The first step for enabling vertical disaggregation is the standardization of well-defined interfaces between the SDN controller and the data plane to bypass proprietary control and management systems. This includes the choice of a reference communication protocol and the definition of a specific abstraction for each type of data plane device [2].

Regarding the communication protocol, a first attempt to enable SDN in optical networks has been made through NETCONF protocol which has the important advantage of using an extensible markup language (XML)-based data encoding, thus not requiring extension at the protocol level for transporting optical configuration. In order to define a standard abstraction of data plane devices, there is relevant work on the definition of multi-source agreements and YANG models (OpenROADMs, OpenConfig, Transport Application Programming Interface (TAPI), and Telecom Infra Project (TIP) initiatives). This way, an SDN controller can build on standard YANG models and procedures to consistently control, configure, and monitor the optical network. In this context, the most important network vendors are already selling their products, including in the documentation the adopted (not standard) YANG models. This enables third-party controllers to properly control the devices, and also reveals if the development of a specific driver would still be required for each new device to be supported. Thus, proprietary YANG models do not allow plug and play, but enable operators and service providers to start the innovation of the offered services through the implementation of specific applications on top of the controller. While waiting for commercial products to support standard YANG models, the research community started development of NETCONF based software agents (e.g., METRO-HAUL project) implementing those models to act as a translation point between the SDN controller and commercial or experimental optical devices, thus enabling accurate testing of controller features and performance. The horizontal disaggregation of the data plane is an ongoing process that is typically featured in three levels, as depicted in Fig. 7.1.1. Specifically, at the first level of disaggregation, the data plane is presented as a set of terminal devices (i.e., transponders) and optical line systems (OLSs) (Fig. 7.1.1(a)). With this solution, the operators can independently select and upgrade transponders, which typically have a shorter technological lifecycle with respect to line systems. Fig.

7.1.1(b) shown the second level of disaggregation where the data plane is seen as a number of transponders and reconfigurable optical add–drop multiplexers (ROADMs); in this scenario, the SDN controller is enabled to deploy third-party applications for using advanced traffic engineering solutions, i.e., routing and spectrum assignment (RSA) algorithms, which are not feasible, disaggregating only transponders from line systems. Finally, going deeper in the disaggregation process, each ROADM can be further decomposed into a set of ROADM degrees or even more elementary components (examples are optical filters and optical amplifiers) as illustrated in Fig. 7.1.1(c). From the control plane point of view, besides proprietary controllers typically owned by device vendors, several open-source initiatives recently emerged for the control of disaggregated optical networks, arising mainly from the traditional SDN community (example ONOS). Among them, the ONOS controller has been proposed by the Open Networking Foundation (ONF) with the support of many of the most important telecommunication vendors and operators [2].

ONOS is currently one of the best candidates for the control of optical networks, where reliability and scalability are key focus points. From the reliability point of view, ONOS is designed to run in a logically centralized but physically distributed fashion, where the controller functionalities are spread on a number of synchronized instances running on different physical machines. This approach, together with an advanced multi-thread software architecture, strongly improves the system scalability because the mastership of devices can be balanced among the several instances [28].

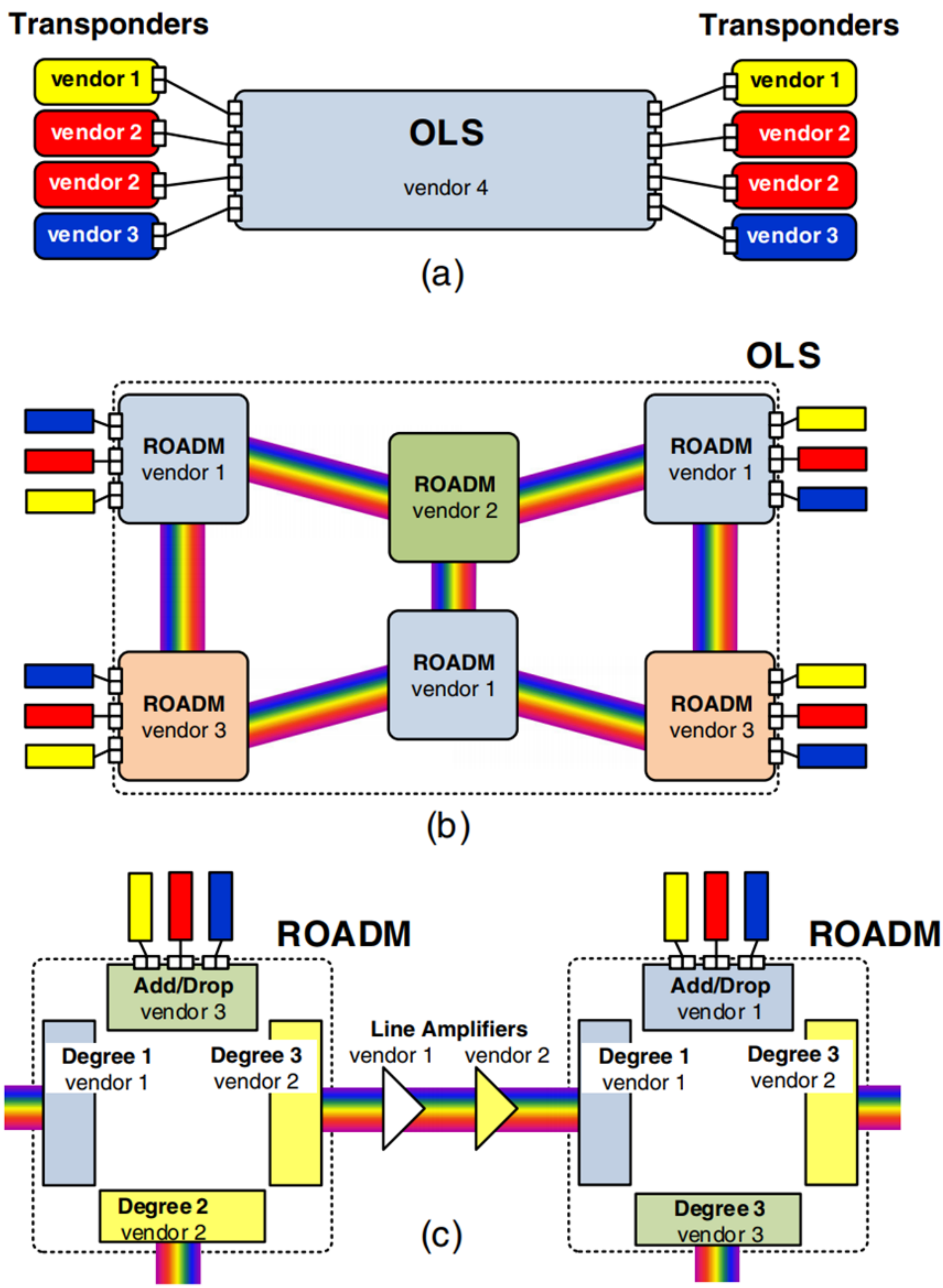


Figure 7.1.1 Optical Components Disaggregation levels [2]

7.2 ONOS Architecture

ONOS controller has a NBI and SBI interface as illustrated on Fig. 7.2.1

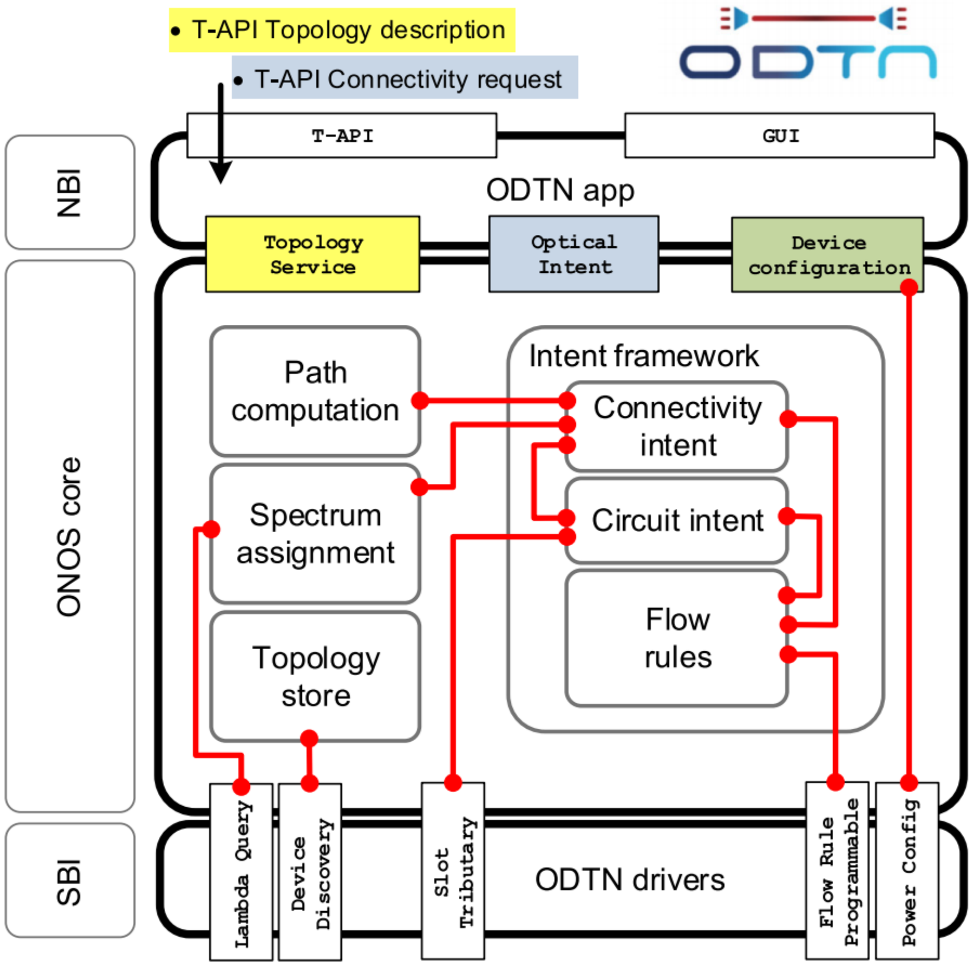


Figure 7.2.1 ONOS Architecture [2]

On the NBI, the ODTN working and developing group has been developed to expose a T-API, and most recently to implement a web-based graphical user interface (GUI) for direct interaction with the optical devices. Specifically, the NBI is already well defined, adopting T-API (version 2.0). The interface is implemented through the RESTCONF protocol and supports the reception of connectivity service requests, and the upload/download of the network topology description into/from the distributed topology store. Within the ONOS core, the adoption of the intent framework facilitates the reutilization of a set of already available ONOS features such as (elementary) RSA algorithms [2].

A connectivity service request can be issued between two client ports of a source and a destination transponder, or between two line ports. In the former case, the connectivity request is managed by the intent framework mapped into two separate intents, i.e., an optical connectivity intent and an optical circuit intent. In the latter case, only the optical connectivity intent is configured [2].

The optical connectivity intent encompasses the configuration of the optical layer (i.e., line side of the transponders and cross-connection of the traversed ROADMs or OLSs). Thus, after the execution of path computation and spectrum assignment, the optical connectivity intent is typically translated into a number of flow rules: one rule for each traversed ROADM and one rule for the source and the destination transponders. If an OLS is present, a single rule is generated and translated into a T-API connectivity service to be forwarded to the OLS on the SBI. ROADM and OLS rules include the input port, the output port, and the optical channel to be used. Transponder rules include the line port and the optical channel to be used. The optical circuit intent encompasses the association of the transponder client port to the transponder line port utilized for the associated optical connectivity intent. Thus, the circuit intent is mapped into two flow rules, one for the source transponder and one for the destination transponder. The rules include the client port, line port, and mapping information [2].

Once the intents have been compiled into a number of flow rules, those rules are forwarded to the device-specific drivers on the SBI (i.e., to the flow rule programmable behavior of the driver). A set of drivers has been developed and others are in phases of development within ODTN, supporting both proprietary and standard YANG models. Specifically, a different driver will be necessary for each type of device (e.g., transponders, ROADMs, OLSs) and for each considered YANG model (e.g., OpenConfig, OpenROADM, T-API). The driver essentially translates the flow rules into NETCONF/OpenConfig-OpenROADM or RESTCONF/T-API messages to be forwarded to the device for applying the required configuration. Besides the aforementioned flow rule programmable behavior, the drivers typically implement other behaviors, each one for employing a specific functionality. The device description discovery is called for when the device is pushed in the topology to load the device details, such as the number and the types of ports. The lambda query behavior is used during the spectrum assignment to retrieve the list of optical channels supported on each port. The tributary slot behavior is used to perform effective multiplexing from transponder client ports into transponder line ports (i.e., mapping multiple circuit intents into a single connectivity intent). The power config behavior is used by applications to retrieve information regarding target and current optical power information from each port of the devices. Finally, besides the work focused on the NBI and SBI, some aspects more inside the ONOS core have been extended for supporting specific requirements of optical devices. These extensions include support of multi-instance ONOS deployment with NETCONF-based devices, support of unidirectional ports of optical devices, and support of OLS-type devices [2].

In order to enable ONOS to control the disaggregate optical network it is necessary to facilitate the integration of ONOS with external tools, implementing advanced network planning, optical physical impairment modeling, data plane monitoring, and telemetry. An example of an external tool is the GNPy QoT estimation tool, modeling nonlinear optical impairments supported by the TIP consortium and the modular integration inside ONOS is shown in Fig. 7.2.2.

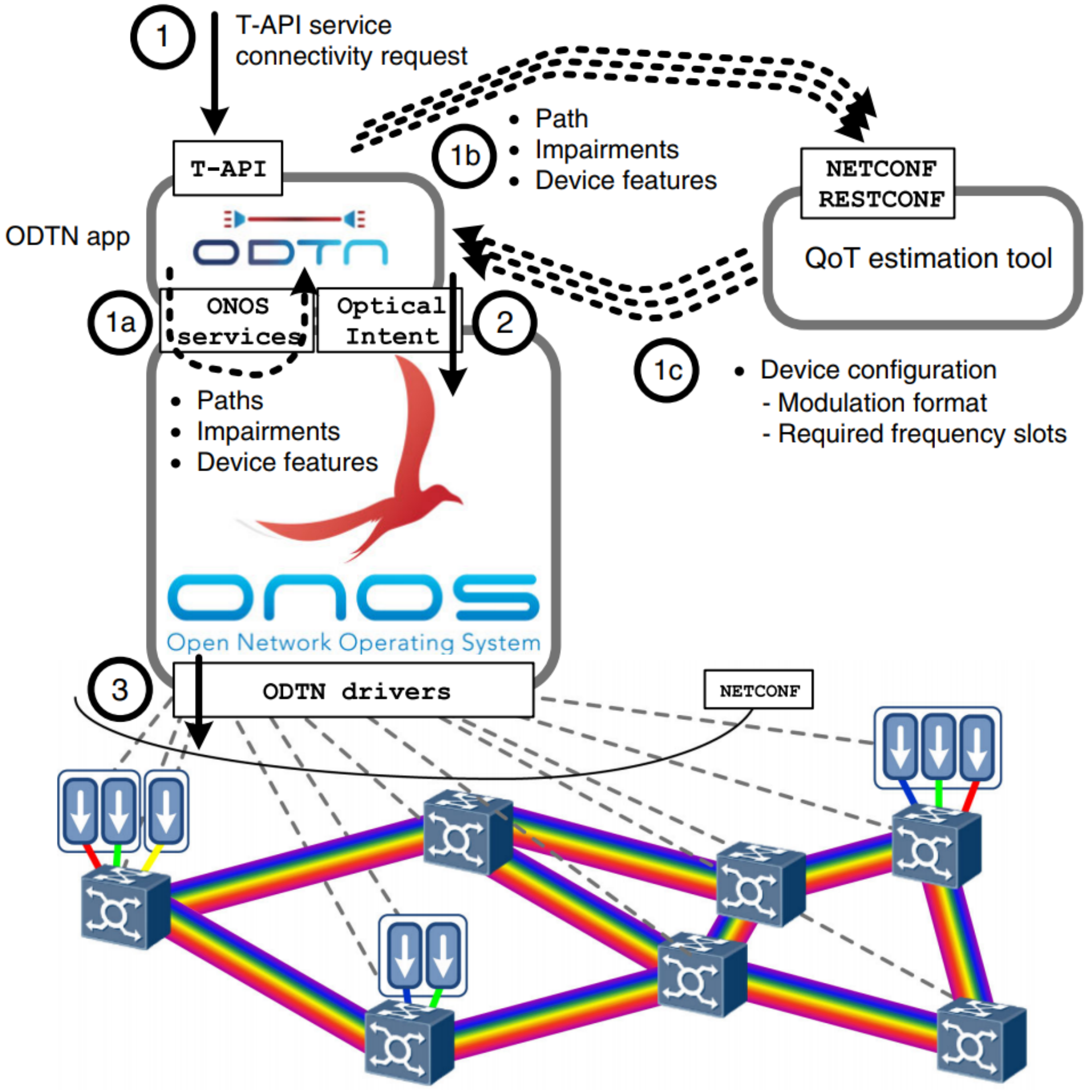


Figure 7.2.2 SDN reference architecture [2]

When a connectivity request is received by T-API (1), the intent framework is utilized to map the request into a number of flow rules (2), then the rules are translated into NETCONF configuration messages and sent to the data plane by using a specific driver (3). The proposed workflow to integrate an external QoT estimation tool (example., to evaluate the QoT on a set of candidate paths) is depicted in Fig. 7.2.2 with dashed lines. Specifically, the application on NBI is extended to execute steps 1a, 1b and 1c before invoking the intent framework. In step 1a the application utilizes the needed ONOS services for computing the set of candidate paths to be evaluated, retrieving also the information for estimating the physical impairments (e.g., fiber types, fiber lengths) and information about the features supported by the devices (e.g., modulation formats, transmission power). Step 1b is executed for each computed path; specifically, the paths are forwarded to the external tool using, for instance, RESTCONF or NETCONF protocols. For each path, the external tool provides a reply (step 1c), including the required details on device configuration (e.g., modulation format to be used at the transponders, number of frequency slots to be reserved on the ROADMs). Then, based on the received information, the application selects the best path (e.g., the path where the highest spectral efficiency can be reached) and triggers the intent deployment. To this extent, the intent framework has to be extended to take into account the data provided by the external tools and consequently deploy the network connectivity [2].

A further requirement of optical networks, where devices are characterized by a significant configuration time, is the ability of the controller to know when a Lightpath (i.e., an optical connectivity intent) has been completely configured on the data plane. In this regard, the utilization of NETCONF protocol is a good starting point because it features a confirmation message for each configuration request. The controller replies to the T-API request only when the data plane is totally configured; the intent is set as installed in the controller only when all the flow rules are in the ADDED state at the controller. Finally, each flow rule is set in the ADDED state immediately after the reception of the NETCONF confirmation message from the device [2].

8. Conclusions and Possible Future Scenarios

In the light of the above topics presented in the previous chapters, we can derive the conclusions from this thesis work summarizing with the following concepts and mentioning a possible future scenario in fiber optical networks.

The needs of users/applications to communicate and interact each can be summarized in these network requirements as mentioned in **section 3.2 New evolution of Internet infrastructure**:

- Huge increase in the number of users (Internet network is being available for all world users)
- New application constraints in latency, minimum bandwidth requirements need to have priority in the network, setting a QoS for each application
- In optical access networks, the available bandwidth per user/device will continue to grow
- Large data flow transfers between users, remote instrumentation, and computing/data centers require more bandwidth also in the metro/long-haul networks

The above requirements must be satisfied with strategies modifying the optical network infrastructure :

- Increase the bandwidth capacity in the network
- 5G RAN Network need to be integrated into Wired Optical Network Access
- Enable NFV to satisfy the needs of applications
- Enable QoT to select the correct path between source and destination
- Enable SDN that involves the easier operations over the network with the increase of the scalability and reliability.

To increase and control the bandwidth capacity in the network, the hardware/software components of the network need to be updated quickly with the current technologies : also these updates must be transparent for the users, and a possible future scenarios is to development the disaggregate optical networks with these advantages :

- The open source software not only covers the SDN controllers but also references implementations of NFV. Additionally, a large number of open source libraries (with different licensing models) are also available covering several building blocks in a complete software stack, supporting SSH connections, the NETCONF protocol, YANG model parsing, enabling the implementation of NETCONF servers and software agents. All NEs in an optical network must be configured with a common data model language, so each NE built from a hardware company is compatible with another NE built from a different hardware company. The common data model language can be YANG.

- Each single parameter of NE in an optical network must be synchronized with other NEs, and the network protocol that can be utilized to read/change these parameters is NETCONF.
- All NEs must be managed by a network software program that can read/change the configurations of each NE in order to control and organize the data transfer between source user/application and destination user/application allocating the hardware resources needed. The network software program SDN can be ONOS..
- But the business model of telecom operators must changes in :
    - **vertically** where software is decoupled from hardware. Software include NE management functions as well as critical Operations, Administrations and Maintenance tasks. This model creates great agility for service providers to develop their own business applications which can be applied to multiple different vendor deployment, but the data plane is serviced by a single vendor.
    - **horizontally** where the data plane is deployed with components from different vendors (example in long-haul network each NE component as transponder is from different vendors and the OLS is from another vendor).
- The optical disaggregation involves all the operational models in which telcos are actively involved in the design, assembly, testing and life-cycle management of data transport systems : this implies that different optical functionalities, traditionally integrated into a single device and interconnected by a back panel, are now performed by different boxes, interconnected by external cables. Furthermore, the introduction to the market of disaggregated optical HW from some vendors along with the rise of open source software initiatives, implementation and multi-source agreements as well as open and standard data models (such as OpenROADM or OpenConfig), enables a wide range of disaggregation options in the data transport systems with considerable potential cost savings.

In conclusion this work has shown as the optical networks are important nowadays in the architecture of the Internet infrastructure : for satisfy the continuous new request from the heterogeneous applications/users in terms of availability, performance, stability is necessary an flexibility in the network infrastructure for both utilization and management in order to reacts quickly also to the evolution of technology. The disaggregate optical network is a possible optimal scenario where the telcos can belt.