Chapter 11

High-Speed Optical In-House Networks Using Polymeric Fibers

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Additional information is available at the end of the chapter

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Abstract

Data communication over polymer optical fibers (POF) is a good alternative method for local area networks to use an optical medium to transmit data in short-range environments like cars or copper in-house networks on the basis of IEEE 802.3. Many companies offer transceivers for the area of Ethernet networks in the visible wavelength range. In the first part of the chapter, a system comparison of manufacturers with interoperability check is presented. Here, the real transfer rates within a manufacturer and between all manufacturers are measured as a cross-check. In the second part of the chapter, the limitation of bandwidth due to the use of only one wavelength channel is discussed. Wavelength Division Multiplexing (WDM) is a promising candidate to significantly increase bandwidth in POF to more than 40 Gbit/s. Here, the problems in the development and manufacture of a demultiplexer (DEMUX) for WDM over POF as well as the results of the optical separation of four wavelength channels are described. At least, the possible extension of a WDM grid of ITU G.694.2 is discussed, which seems to be a hopeful candidate to introduce a standardized WDM grid for POF in the visible range to reach data rates of 40 Gbit/s up to 50 m POF.

Keywords: polymeric fiber transmission, optical networks, WDM over POF, wavelength division multiplex, demultiplexer, injection molding

1. Introduction

Polymer optical fibers (POF) are used in various fields of applications. The core material consists of polymethylmethacrylate (PMMA), while the cover is made of fluorinated PMMA. The whole fiber has a diameter of 1 mm, which is depicted in **Figure 1**. POFs are used for optical data transmission based on the same principle as glass fiber. As a communication medium,

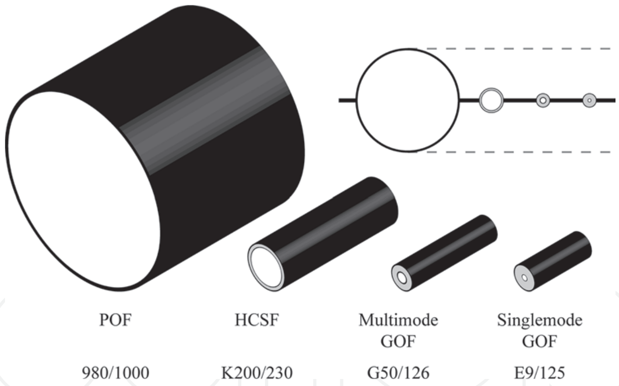

Figure 1. Comparison of optical fiber types.

they offer a couple of advantages related to other data communication systems such as copper cables, glass fibers and wireless systems and have great potential to replace them in different applications.

In comparison with glass optical fibers (GOF), POFs are easy to use in the field because of low bending losses and a large optical core of 980 μm. This makes the POF very insensitive to rough and dusty environments as well as losses on plugs in comparison with glass fibers [1]. However, one advantage of using glass fibers is their low attenuation, which is below 0.2 dB/km in the infrared range. The attenuation of polymeric fibers in the visible spectrum from 350 to 750 nm (see **Figure 2**) is much more higher with its minimum of 85 db/km at a wavelength of 570 nm. For this reason, the use of POF in communication systems is focused on short distance communication from 10 to 100 m. The larger core diameter of POFs leads to high-mode dispersion of more than 2.2 millions of optical modes. Additionally, the high attenuation at wavelengths higher than 700 nm limits the application of the POF to the visible spectrum of light (400–700 nm). Here, POFs can outperform the current standard of copper cable as a communication medium. On the one hand, they feature lower weight, low bending radius and space. On the other hand, POFs are not susceptible to electromagnetic interference [2, 3]. For these reasons, POFs are already used in various application domains, for example, in the automotive sector and for in-house communication [4–7].

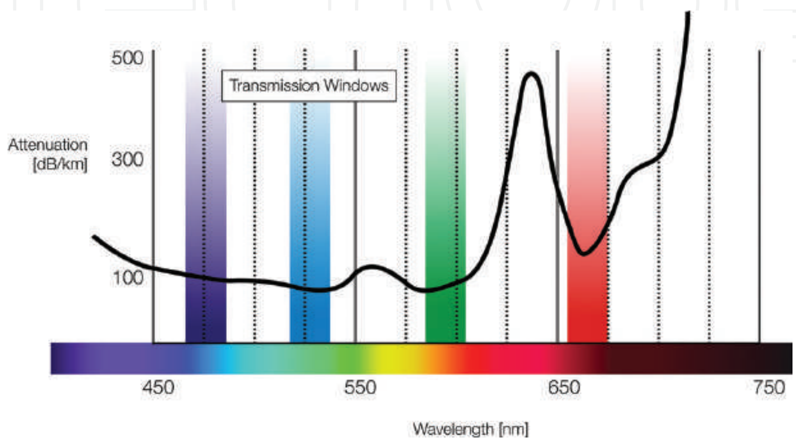

Figure 2. Attenuation of POF in the visible range [1].

1.1. POF in the automotive sector

Typically, copper-wired bus systems are used in the car environment. In the past 15 years, POF has replaced the electrical wiring in many types of car (see **Figure 3**). It was first introduced by BMW in the 7er series in 2001. Since then, not only high-class cars were equipped with POF, actually more than 200 types of volume cars benefit from the advantages of POF [4, 5]. The used bus is called **M**edia **O**riented **S**ystems **T**ransport (MOST), which is a multimedia network optimized for multimedia and infotainment applications. The bus was developed by the automotive industry. It works in three data rate levels with 25, 50 and 150 Mbit/s. MOST defines basically the physical interconnection between devices by using POF as a transport medium. Additionally, it specifies and standardizes a communication protocol to develop complete systems and applications to distribute multimedia content for the car.

The replacement of the communication technique from copper wires to POF leads to lower weight. The low melting temperature of PMMA (95°C) still prevents the use of POF in the engine compartment. However, new types of fiber in the development that have higher glass transition temperature will allow the use of high-temperature POF in the engine compartment in the near future [4]. Another application in the car, where POF most likely will be used in the future, is as sensors for measuring various in-car pressures or forces. Additionally, sides emitting polymeric fibers are interesting devices for future applications for ambient lighting in the passenger cabin.

1.2. POF for in-house communication systems

Another sector where POF displaces the traditional communication medium is in-house communication [6, 7], although the possibilities of application are not confined to the inside of the house itself. In the future, POF can possibly displace copper cables for the so-called last mile between the last distribution box of the telecommunication company and the end consumer. Today, copper cables are the most significant bottleneck for high-speed Internet.

"Triple Play" is called the combination of IPTV, VoIP and the data Internet. The combination is currently introduced into the telecom market; therefore, high-speed connections are essential. It is highly expensive and bandwidth limiting to use Ethernet in-house system using copper components, thus the future will be FTTH, in combination with optical in-house wires of POF or GOF (see **Figure 4**).

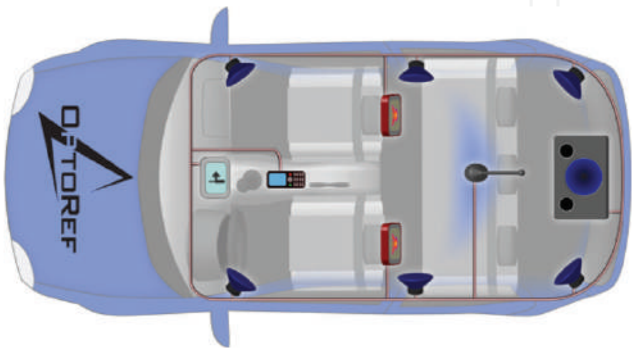

Figure 3. Multimedia bus system (MOST-bus) with POF.

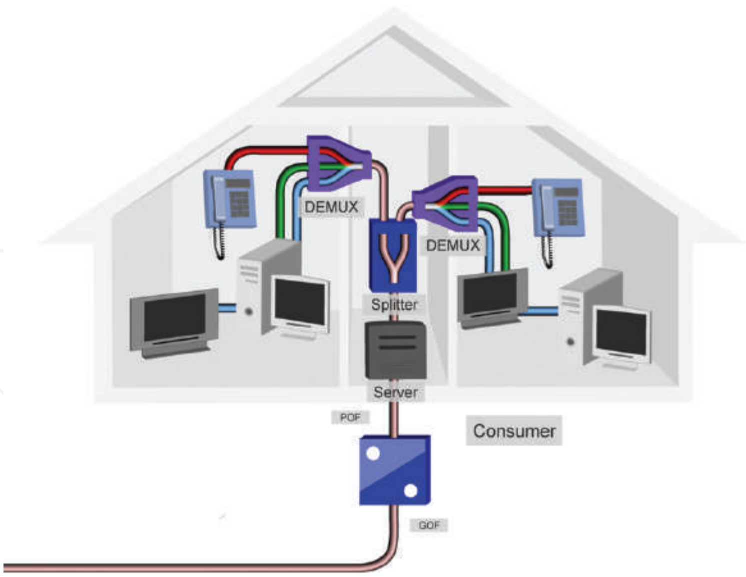

Figure 4. In-house communication with POF.

2. Studies on the interoperability of different transceivers for optical polymer fibers

In this chapter, various transceivers, which can be used for data home cabling with optical polymer fibers, are examined with respect to their interoperability. Eight different devices are tested for their effective data rate over length-varying POF transmission distances. Furthermore, the results are compared with the manufacturer's data regarding performance and the interoperability of all devices is checked.

The Photonic Communications Lab at the Harz University works closely together with manufacturers of various POF components in several projects. From this cooperation, the question of the compatibility of POF devices from different manufacturers among one another has become increasingly important. All devices tested comply with the IEEE 802.3u guidelines for Fast Ethernet. Fast Ethernet is mainly used in local networks and allows data transmission at 100 Mbit/s.

2.1. Devices under test

Table 1 shows the tested media converters or switches with specifications from the manufacturer:

As can be seen in **Table 1** and **Figure 5** devices from various companies are examined. Starting with media converters of German manufacturers (Siemens, Diemount and Rutenbeck) to transceiver-switches from Homefibre (Austria) and BSPCOM (China).

A USB media converter from the company BSPCOM could not be considered for investigations for reasons of problems with the USB driver software for Windows (**Figure 5**).

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Name	Wavelength (nm)	Transmission length (m)	Data transfer rate (Mbit/s)
Speedport OptoLAN	670	30	100
Diemount CS-116	470	70	100
Rutenbeck wall socket	660	70	100
Rutenbeck socket switch	660	50	100
Media converter Rutenbeck	660	50	100
Switch OMS 126S-150 Homefibre	650	50	100
Switch CP8016 BSPCOM	650	50	250

Table 1. Used POF-transceivers.

Figure 5. Tested media converter: Speedport, Diemount, BSPCOM, Rutenbeck and Homefibre.

All the devices tested, except the CS-116 from Diemount, operate at a wavelength in the visible red range. The device from Diemount transmits data at the wavelength of 470 nm in the visible blue range (see **Figure 2**).

2.2. Experimental setup

In the investigations of the POF devices, each existing one is combined with each, connected by a POF of 50 m length and put into operation. The measurements are carried out using a certification scheme developed in the Photonic Communications Lab of Harz University in accordance with the ETSI TS 105175–1 V1.1.1 (220010-01) standard, which establishes an in-house networking of the optical polymer fibers.

The optical polymer fibers are wound up with the aid of two cylinders. These cylinders have different diameters and thus offer different bending radii (see **Figure 6**) in order to apply the typical application conditions of a typical LAN network distribution in an apartment.

Several optical polymer fibers are wound onto this structure. These differ in length and outer cable diameter. However, all have a step index profile with a core diameter of 980/1000 μm. The cable diameter varies between 1.5 and 2.2 mm. The 2.2 mm fibers are being designed for simplex transmissions only. The 1.5 mm fibers are duplex fibers. The lengths of the optical polymer fibers are: 1, 15, 30 and 50 m.

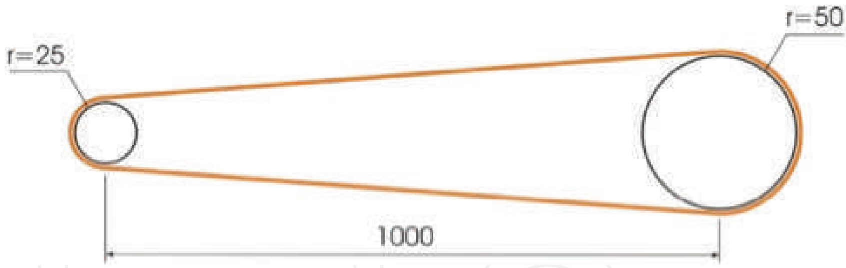

Figure 6. Setup for testing typical laying of a POF with a length of 30 m in an apartment with 15 bends of different radii (in mm).

2.3. Transmission speed measurement with Jperf 2.0.2

Iperf is a command line utility for measuring the performance of networks. Jperf is a graphical interface developed in Java for Jperf. This program is started on two PCs, one of which is the function of the server and the other is assigned to the client (see **Figure 7**). The server accepts connections on TCP port 5001. Data are transferred from the client to the server for the duration of the measurement. Thus, unidirectional data transmission always takes place.

Iperf offers different, adjustable parameters for throughput measurements. Examples of this are the selection of the transmission protocol (TCP/IP or UDP) as well as the modification of the measurement duration. In addition, the buffer size can be changed. The measurements are carried out in transmission control protocol (TCP) [8].

2.4. Transfer rates

At a transmission distance of only 1 m (back to back), all media converters and switches are working together with transmission speeds in the range of 90 Mbit/s (see **Figures 8** and **9**). However, in some combinations, the quality of the transmission rate is lower for this short distance than for a longer distance such as 30 or 50 m. Overdriving at the photodiode due to the excessive light intensity may cause this.

All the transceivers of the different manufacturers have been able to communicate with each other easily and also over the distances of 15 and 30 m, and all tests have been positive. The data rate fluctuates ±1–2 Mbit/s in the range of 92 Mbit/s. A 50 m transmission cannot be positively tested in combinations in which the Diemount CS-116 media converter is used as a client and with a blue transmit diode. This can be explained by the fact that the tolerance window of the photodiodes of the other devices is setup in the red range to this range by 650 nm. However, it should be noted that the light output up to 30 m was still intense enough to achieve a functionality of the two wavelengths without problems.

Figure 7. Measurement setup with Jperf (MC (media converter)—DUT.

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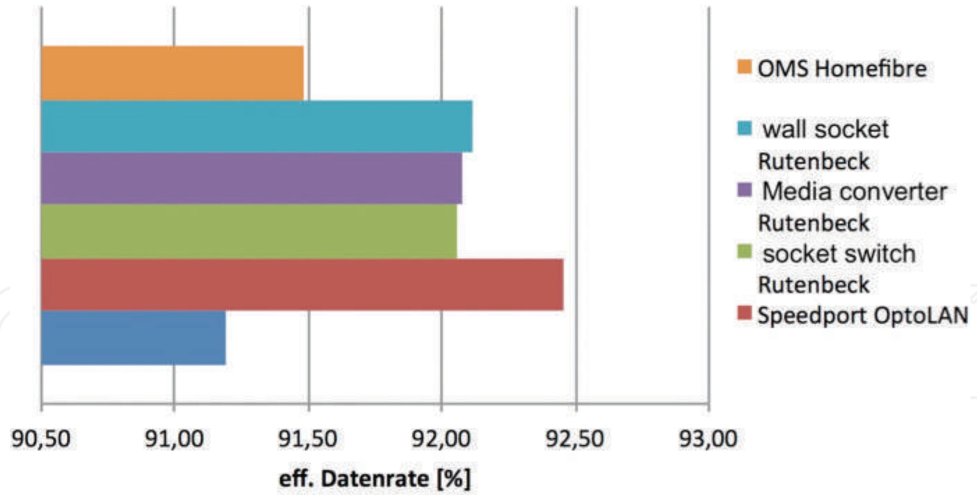

Figure 8. Effective measured data rates within one manufacturer.

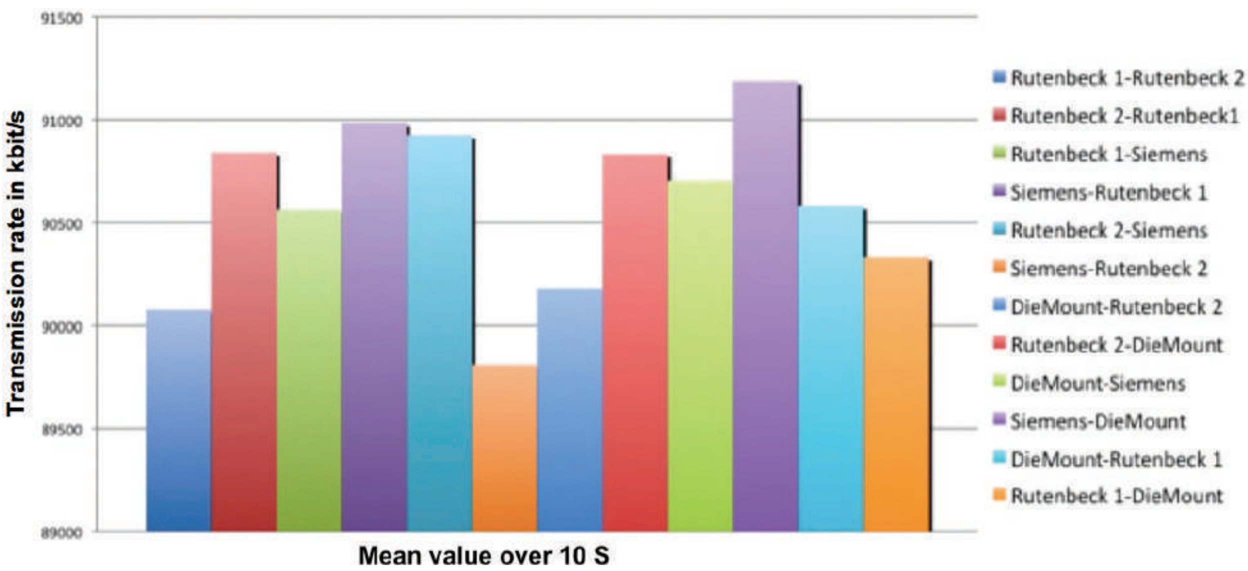

Figure 9. Measured effective data rates with 15 m POF length between different manufacturers.

In addition, the Speedport OptoLAN from Siemens is able to achieve 50 m transmission distances in almost all combinations. In general, it should be mentioned that the data rates reported by the manufacturers of 100 Mbit/s were not achieved by any system. On the other hand, all manufacturers did not provide a minimum data rate to be compared with the measurement results. The POF switch from BSPCOM from China shows the most stable transmission in all combinations and transmission lengths.

2.4.1. Measurement errors in Jperf

During the use of Jperf as a tool for recording the data rate, some points must be noted. On the one hand, higher transmission data values are always detected when the duration of the measurement is set to longer sampling values. This can be explained by the fact that the measuring interval is longer during a longer measuring period than in the case of a shorter measuring duration. Consequently, a mean value formation takes place. The reason is that the output format of Jperf of Mbit/s calculates large rounding errors. In addition, there is an error in the calculation of the average bandwidth over the whole measurement period by recalculation in Excel. The mean bandwidth was always larger than calculated externally. Therefore, the external calculated values are used in the evaluation.

3. WDM over POF

3.1. WDM over POF basics

At present, the great potential of the POF is not available as the alternative techniques offer transmission rates up to 10 Gbit/s over copper and up to 40 Gbit/s over glass fibers in the network area. The WDM technique offers an approach to achieve these high data rates also in the POF range. A sketch of the basic principle is shown in **Figure 10**.

Wavelength division multiplex systems need two basic components of a multiplexer and a demultiplexer (see **Figure 10**). To realize a working DEMUX for POF, several preconditions must be fulfilled. The basic component is a mirror, which focuses a divergent light beam coming from the input fiber. The shape of this mirror must be a toric shape to prevent spherical aberrations [9–11].

To separate the different incoming wavelength channels, a diffraction grating is used. This principle is illustrated in **Figure 11**. The light is split into different orders of diffraction. The first order is the important one to regain all information. There, the outgoing fibers with the different wavelengths channels must be arranged.

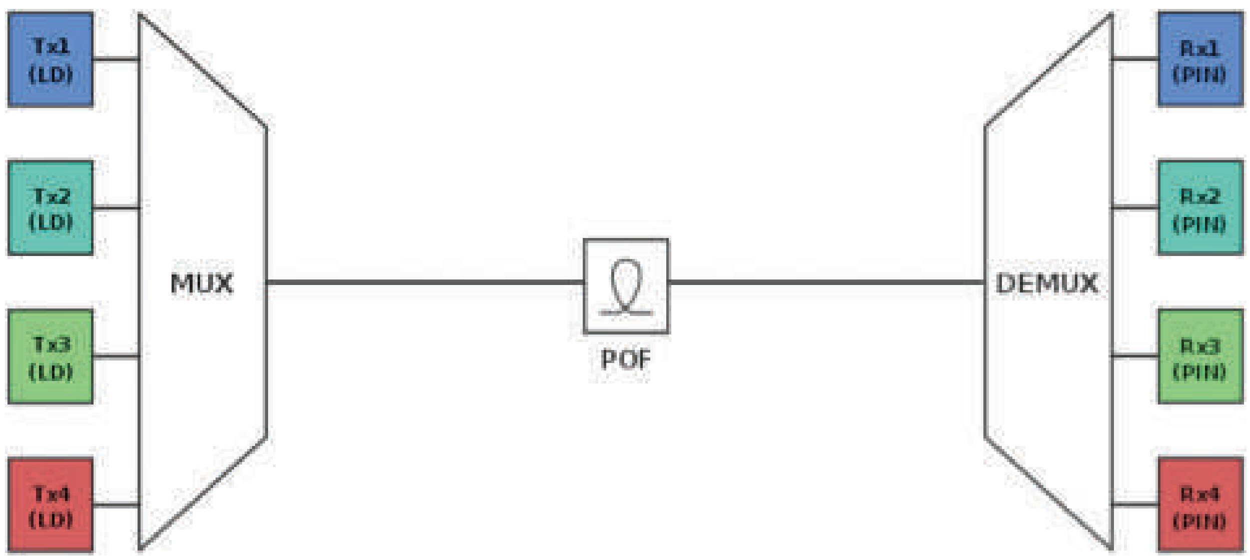

Figure 10. Schematic of the WDM over POF structure.

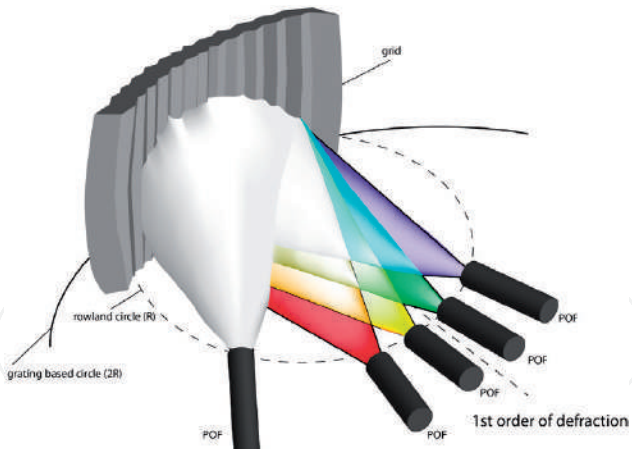

Figure 11. Rowland setup of demultiplexer.

The development of the injection-molding process starts with the production of a master for the imprint of the entire component. This master is milled in micrometer precision by means of a diamond cutting process and created by the diamond turning process. Here, the PMMA material is processed directly. Both the moldings as well as the grid for wavelength separation can be made using this technique (see **Figure 12**). The last step is performed to validate the simulation results with the produced component.

For the injection-molding process, the production of the impression part is the most important factor. Due to the three-dimensional toric structure of the grating planar manufacturing methods like lithography, especially LIGA [a German acronym for Lithographie, Galvanoformung, Abformung (Lithography, Electroplating and Molding)] cannot be used. LIGA is used to manufacture planar spectrometers based on the glass fiber technology [12–15]. In the present approach for using a grating as a WDM element, it is necessary to manufacture the three-dimensional grating with its fine line structure and blaze precisely. In particular, the micro-structure of the grating and the exact shape of the toric surface require high precision. The

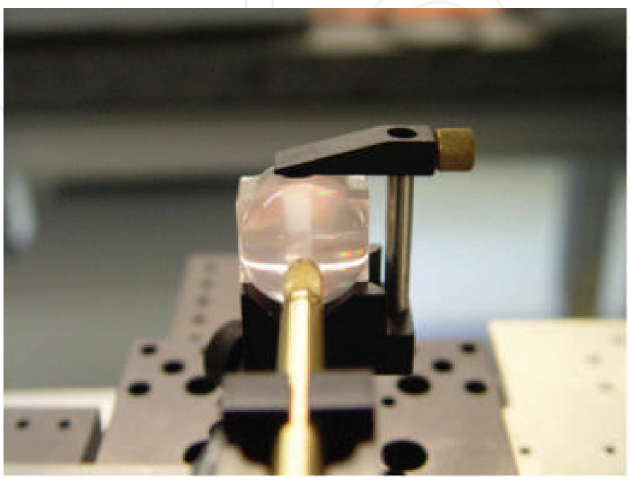

Figure 12. Integrated demultiplexer prototype.

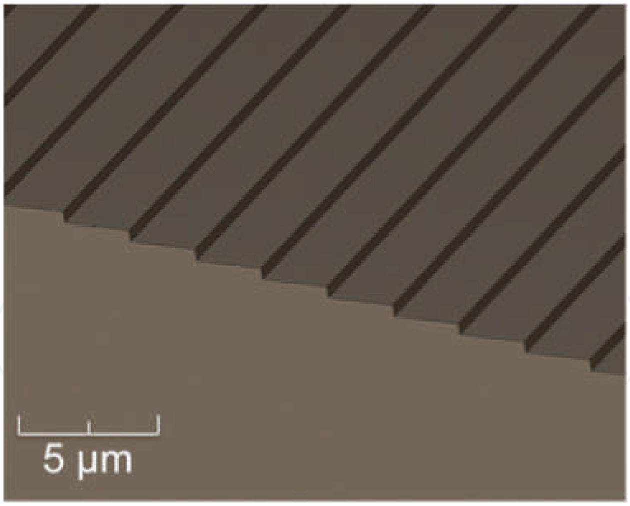

Figure 13. Grating of the demultiplexer.

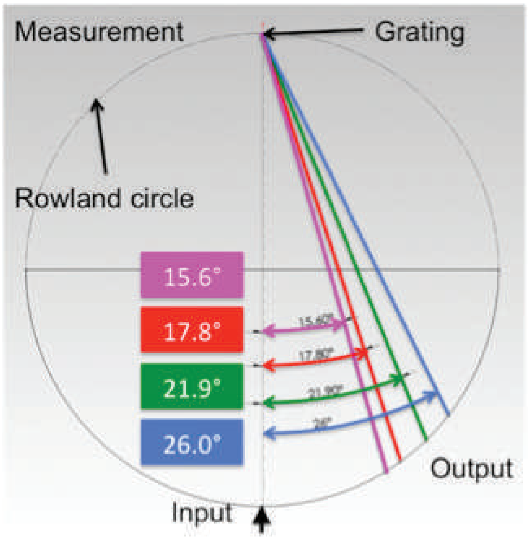

Figure 14. Measurement results of the focal points for different wavelengths (405 nm 15.6°, 450 nm 17.8°, 520 nm 21.9° and 650 nm 26.0°).

blaze with the grating lines is a microstructure in the form of a sawtooth with a distance between the teeth of 2.5 μm. **Figure 13** shows an enlarged 3D model of the grating. After analysis of other microtechnical machining processes to our knowledge, only the diamond turning meets the stringent requirements of the microstructured grating (**Figure 14**).

3.2. Design of the first demonstrator

The DEMUX elements must be manufactured in injection-molding technology. The capability of injection-molding technology for the cost-effective mass production of large volume and micrometer-accurate plastic components has made this technology the industrial standard production method for plastic parts. More and more high-quality optical components

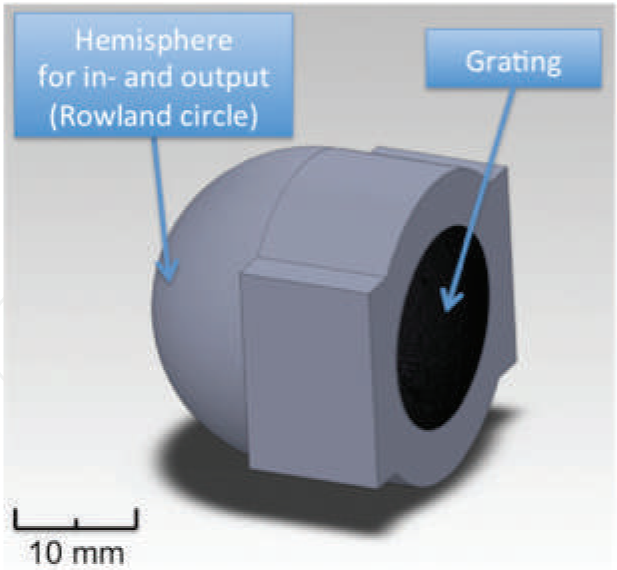

Figure 15. 3D model of the DEMUX demonstrator.

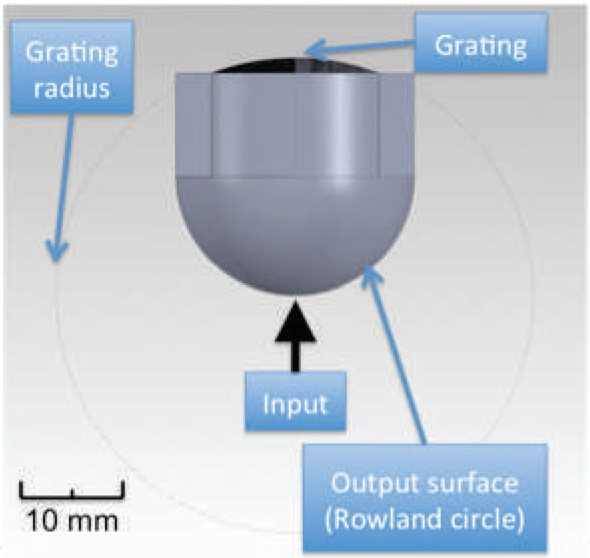

Figure 16. Cross-section view of the DEMUX demonstrator.

are produced with injection molding. With the aid of the injection molding, dimensionally stable and stress-free molded parts can be produced. In particular, the reduction of internal mechanical stress makes this technique ideal for optical mold components [12]. With this cost-effective production, the components for WDM can be made available via POF for a very wide application market. To further reduce the production costs, a self-adjustment of the individual optical components of the DEMUX such as fiber, grating, focusing mirror is necessary. This is why the various functions are combined in a molded part. However, this makes DEMUX technologically more difficult to implement, and therefore the individual process steps are discussed in detail.

In the first step, a demonstrator was produced. In order to verify the concept of the demultiplexer and to compare the simulation results with the real setup, it is necessary to proceed step by step. For this reason, a special optomechanical design was chosen. **Figure 15** shows the new design where a hemisphere at the output of the DEMUX represents the radius of the Rowland circle. This is shown in the cross-sectional view in **Figure 16**. The light reflected from the grating and emanating from the circle is focused on this radius. Therefore, the light is coupled into the center of the hemisphere, and the separated wavelengths can be detected on the surface of the hemispheres. This is illustrated in **Figure 14**. For detection, scanning of the surface is performed to determine the positions of the outgoing, separated light for each wavelength.

4. Materials and methods

Prior to the production of the DEMUX, some preliminary investigations have taken place to find the best suitable material for the demultiplexer. Therefore, both the processability of the material and the optical parameters had to be considered in detail. The injection-molding process was tested with a thick-walled mold. This test tool had the same shape as the final DEMUX, except for the grid. The test runs were carried out with an injection-molding machine from Babyplast 6-10P. This device was able to inject precisely small parts. **Table 1** lists all the materials used for the study. Further, parameters such as the respective melt volume rate (MVR) and light transmittance (according to the manufacturer's specification) are depicted. The test was additionally used to find the optimized injection-molding process parameters for the material.

In addition, the optical quality of the polymer materials must be investigated. Therefore, a mold for injection-molding test plates was designed. The test plates had a thickness of 2 mm. The mold is used to make samples from each material listed in **Table 2**. The DIN EN ISO 13468–2 standard describes the measurement of the optical transmission of polymer materials. Therefore, the test plates are designed to meet this standard.

Transmission measurements were carried out with all test plates. The results are shown for 405 nm in **Figure 17**. It can be seen that both ZEONEX types and PMMA POQ62 show the highest value for the light transmission. PMMA POQ62 is a polymer grade with high purity of polymer granulates. The measurement is made at a wavelength of 405 nm because it is one of the wavelengths used for the WDM system.

4.1. Manufacturing of the demonstrator

By using the injection-molding process, the manufacturing of the mold insert is the most important factor. Due to the three-dimensional toric structure of the grating planar manufacturing methods like lithography, especially LIGA cannot be used [15].

In our case, however, the three-dimensional grating requires a different processing method. The microstructure of the grating and the exact shape of the toric surface require a particularly

Name	Type	MVR [cm^3/10 min]	Transmission [%]
Plexiglas 6 N	PMMA	12	92
Plexiglas POQ62	PMMA	21	92
Topas 5013 L-10	COC	48	91.4
Topas 6013 M-07	COC	14	91
ZEONEX F52R	COP	22	92
ZEONEX 350R	COP	26	92
Makrolon LED2245	PC	35	90

Table 2. Injection-molding materials for MUX/DEMUX-element.

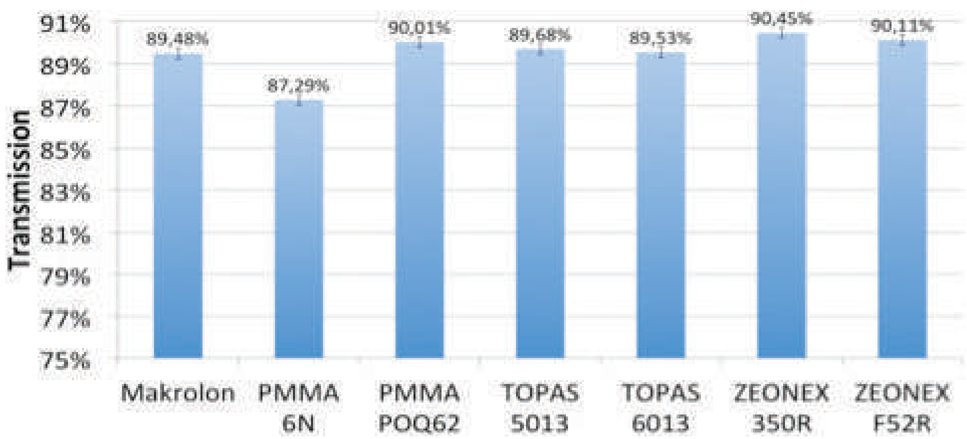

Figure 17. Transmission of different material at 405 nm.

high precision of manufacture. The microstructure has the shape of a sawtooth with a distance between the teeth of 2.5 μm. **Figure 13** shows an enlarged 3D model of the grating. An in-depth investigation of various processing methods has shown that only the diamond turning fulfills the high requirements of the production of the microstructural lattice. The diamond twisting technique is a special machining method using a single crystal diamond cutting tool. It is also possible to produce a surface with an optical quality at the edge of the optical component. It offers several advantages:

- True three-dimensional contour generation.
- Accuracy of one part in 106 with absolute accuracy of 1 part in 108 on a single axis for ideal conditions.
- Surface finish of 5 nm Rz for a range of materials and as good as 1 nm Ra.
- Ability to generate surfaces with variable aspect ratios and
- Feature sizes that exceed the limits of optical microscopy [14, 15].

A metallization process was used to analyze the surface of the lattice. The surface was sputtered with a thin aluminum layer depicted in **Figure 18**. It is now possible to measure the shape of the surface with a white light interferometer and to examine the lattice structure under the scanning electron microscope (SEM). The metallized surface of the grating is shown in **Figure 18**. It can be seen that the structure on the left side has a dull and mat surface instead of the glossy residue of the surface. This is a first indication that the surface roughness in this part is higher and does not meet the requirements for the component precision. The first visual impression was then confirmed by the analysis under the SEM.

The cause of the degradation of the grating quality is the change in the strain as the milling tool passes the highest point in the center of the surface. It changes the way the force is exerted by a pushing movement on the surface. This results in a coarse structure on the other half of the surface. From the measurement of the structure size in **Figure 19**, a width of 2.55 μm can be determined, which is within the tolerances of the reference of 2.5 μm.

In addition to the structural quality, the dimensions of the surface are also important for the functionality of the DEMUX and must be considered in detail. The shape of the radius of the

Figure 18. High-quality structures of the grating.

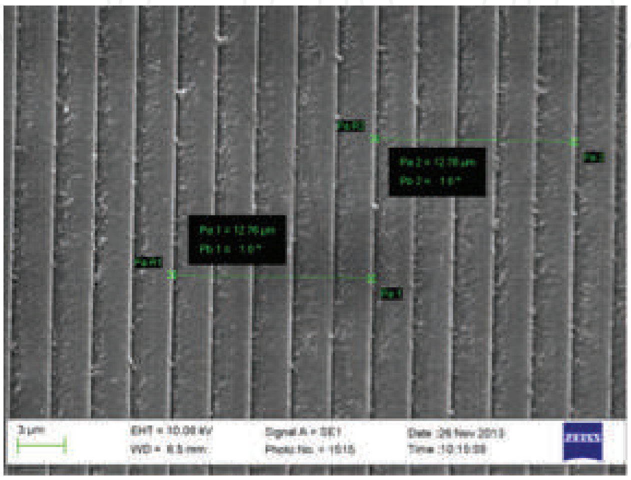

Figure 19. Metallized grating surface of the DEMUX.

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toric surface was designed to focus the colored light beams on the Rowland circle. Therefore, it was analyzed using a white light interferometer (FRT MicroProf). The cross-section of the toric surface was measured. The measurement shows that the dimensions of the surface correspond to the tolerances of the DEMUX. An exception can be seen in the diameter in the x-axis, which is somewhat out of tolerance (**Table 3**).

Several parameters have to be optimized in order to correct the manufacturing errors. This is performed in several iterations in close cooperation with the manufacturer. For example, the adjustment of the force applied to the surface was varied and optimized by the diamond tip. The next part with optimized parameters is now in production and is then analyzed in the same way to check the adjustments of the parameters.

4.2. Optical measurements

In order to measure the position of the focal points of the different separated wavelengths on the Rowland circuit, a special measurement setup was chosen. It uses a parallel kinematic precision alignment system to align a POF on the surface of the hemispheres. An input fiber firmly bonded to index matching is used to couple white light into the DEMUX, as shown in **Figure 16**. In this figure, it can be seen that the separated wavelengths are focused on a ring on the hemisphere. This ring is scanned by the fiber on the alignment system. The light from the scanning fiber is analyzed by using a spectrometer.

From the spectra along the Rowland ring, the location of the maxima of the wavelengths is determined. For the first component, the entire measurement was performed and compared with the simulation results. Four different wavelengths that were used to analyze the wavelength separation are as follows: 405, 450, 520 and 650 nm.

The positions of the wavelengths measured by the setup are also depicted in **Figure 14**. In comparison to the simulation, a shift of the positions of 2,3° are found. Nevertheless, the separation of the wavelengths was measured and confirmed the functionality of the demultiplexer.

The derivations to the simulation could be caused through the following reasons:

- Derivation of the blaze angle of the sawtooth grating
- Inhomogeneous structure of the grating
- Manufacturing tolerances

These depend strongly on the precision of the manufacturing process. As mentioned in the previous section, the production of such complex structures on a toric surface is a major

Dimension	Measurement (mm)	Reference (mm)
Diameter x-axis	15.869	>16.000 ± 0.1
Diameter y-axis	15.887	>15.170 ± 0.1
Height of grating	1.862	1.872 ± 0.05

Table 3. Measurement results of the DEMUX dimensions.

challenge. Therefore, the process parameters must be improved and optimized to fully meet the optical requirements of the demultiplexer component.

5. Spectral grids in the visible spectrum for POF WDM applications

Besides developing low-IL cost-effective POF WDM components and fast POF WDM transmission systems, it is also important to allocate a unique set of WDM transmission channels in the visible spectrum to support WDM applications over SI-POF. To evaluate the applicability of a spectral grid to support visible spectrum WDM applications over SI-POF, the appropriate criteria were first established. Those criteria refer to:

- Channel distribution with respect to the spectral attenuation of SI-POF;
- Performances of different demultiplexing techniques;
- Availability of laser diodes in the visible spectrum.

5.1. Extension of ITU-T G.694.2 CWDM grid into the visible spectrum

If ITU-T G.694.2 CWDM wavelength grid would be extended into the visible spectrum, 15 equidistant channels between 400 and 700 nm would be obtained, as shown in **Figure 14**. The parameters of the grid including the nominal central wavelengths are depicted with arrows in **Figure 20**.

The channel spacing of 20 nm makes good utilization of the available spectral range. In the red window, the extension has a channel at 651 nm, which is very close to the attenuation minimum at 650 nm. The channel distribution also corresponds well to three other attenuation windows. The channels experiencing the highest attenuation are those at 611, 631, 671

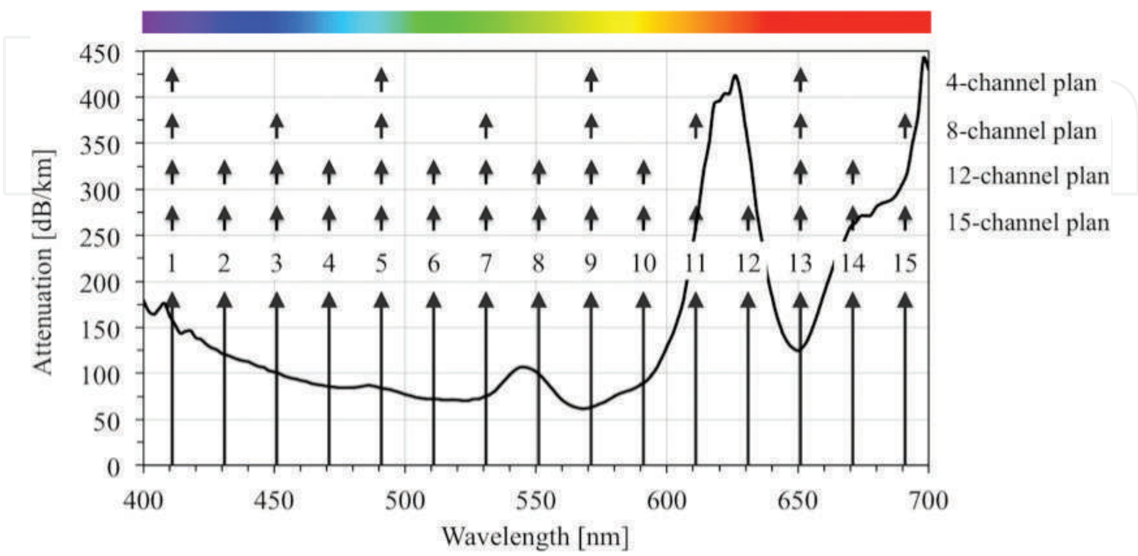

Figure 20. Extension of CWDM wavelength grid into the visible spectrum and channel plans for 4-, 8-, 12- and 15-channel applications.

and 691 nm. Those channels could be used for distances up to 20 m since they would experience approximately the same attenuation as 651 nm channel over 50 m, but lower intermodal dispersion. Good channel allocation, sufficient channel spacing, high channel count and good availability of the transmitters make the extension of CWDM grid very suitable to support WDM applications over SI-POF.

6. Conclusions

Currently, commercially available POF transmission systems are able to fulfill the needs of IEEE 802.3 requirements with a data rate of 100 Mbit/s. The interoperability between the devices of the different manufacturers is also in a good condition.

To realize higher bitrates WDM over POF will be an interesting application. We produced a DEMUX by injection molding.

The realization of this DEMUX element for POF presents several challenges, in particular the microstructure of the grating on the three-dimensional surface. It is shown that it is possible to realize the structure size and the exact radius for the DEMUX with the current optimized production process. The high challenge of producing the blazed grating leads to some errors in the milling process, which still needs to be improved. This will be done in the future by optimizing the process parameters. The next parts will be produced and analyzed with the optimized parameters.

This hopeful result shows that WDM applications over SI-POF with high Gbit/s transmission are a realistic aim for the next future. The technique will be able to extend the bandwidth in POF systems strongly. It seems to be possible to transmit 40 Gbit/s via 15 channels and a channel rate of 2,7 Gbit/s data rate with WDM over POF. This opens the range of POF applications to existing cloud centers and future in-house networks with to link length up to 100 m.

Acknowledgements

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Content Defined Optical Network

Hui Yang

Additional information is available at the end of the chapter

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Abstract

Optical interconnection has become one of the key technologies to adapt the needs of large-scale data center networking with the advantages of large capacity, high bandwidth, and high efficiency. Data center optical interconnection has the characteristics of resource and technology heterogeneity. Its networking and control face enormous challenges for the increasing number of users with a high level quality of service requirements. Around different scenarios, there are a series of key networking and control problems in data center optical interconnection, such as multiple layers and stratums resources optimization in inter-data center, and time-aware resource scheduling in intra-data center. To solve these problems and challenges, this chapter mainly researches on content defined optical networking and integrated control for data center. For networking of vertical “multi-layer-carried” and horizontal “heterogeneous-cross-stratum”, the chapter launches research work around application scenarios about inter-data center optical interconnection with optical network, and intra-data center. The model architecture, implementation mechanism and control strategy are analyzed and demonstrated on the experiment and simulation platform of data center optical interconnection. This chapter will provide important references for future diverse applications of data center optical interconnection and software defined networking and control in practice.

Keywords: software defined optical network, content, data center, optical interconnect, OpenFlow

1. Introduction

With the rapid development of cloud computing and high rate services, data center services have attracted a great deal of attention from network service providers. With the variety and massiveness of applications, the high-performance network-based datacenter applications have the features of high burstiness and wide-bandwidth, particularly for the super-wavelength services [1]. Flexi-grid optical networking with big capacity, low power density and distance adaption, provides a promising solution for the new datacenter network bottlenecks. A novel optical orthogonal frequency division multiplexing (OFDM)-based architecture with high spectral efficiency and high energy efficiency is presented for data center networks [2]. Networking architecture, algorithm and control plane for inter-datacenter network is also addressed in flexi-grid optical networks [3]. Lower power, improved scalability and port density which is the advantages of software defined optical networking for highly virtualized datacenters are studied [4].

Compared with optical interconnect networks between datacenters, optical interconnect networks in a datacenter is a more imperative requirement and respective case to serve the services in a flexible and high-efficient way [5]. Besides, miscellaneous datacenter services have a lower delay and higher availability requirements whose quality of service (QoS) can be guaranteed in corresponding levels [6]. Many studies focus on the architecture and equipment in datacenter interconnection [7–9]. For instance in Ref. [7], arrayed waveguide grating router (AWGR)-based interconnect architecture is proposed. A distributed all-optical control plane is designed with low latency and high-throughput at high traffic load in the case of sufficient packet transmission time. The authors in [8] achieve the hitless adaptation between Ethernet and time shared optical network (TSON) by designing a novel network on-and-off chip approach for highly efficient and transparent intra-datacenter communications. The work [9] make the datacenter offloads heavy inter-pod traffic onto an optical multi-ring burst network by proposing efficient scheme to all-optically inter-networking the pods. However, the time feature of application to guarantee the services delivery with various QoS in intra-datacenter networks from the view of service is relatively unexplored. Recently, as a centralized software control architecture, the software defined networking (SDN) enabled by OpenFlow protocol has become a focus of study by making the network functions and protocols programmable [10–13], where maximum flexibility is provided for the network operators and the integrated optimization of services can be achieved in a centralized control over multi-dimensional resource [14–17]. Hence, to introduce SDN method to centrally control network and application resources in optical interconnect of intra-datacenter has a great significance.

In our previous study, the network architecture with cross stratum optimization (CSO) based on SDN including muti-stratums resources in inter-datacenter networks has been designed to partially satisfy the QoS requirement [18–21]. Even in the edge of the network, the similar architectures with CSO based on SDN have been studied for improving the performance of cloud-based radio access network, which is similar as the inter-datacenter networks [22–24]. Based on the previous work, this paper proposes a Content Defined Optical Network (CDON) architecture in OpenFlow-based datacenter optical networks for service migration, in which a time-aware service scheduling (TaSS) strategy is introduced. CDON considers the time factor, in which the applications with required QoS can be arranged and accommodated to enhance the responsiveness to quickly provide for datacenter demand. By the experimental implementation on our testbed with OpenFlow-based intra-datacenter and inter-datacenter optical networks and the statistics collection of blocking probability and resource occupation rate, the overall feasibility and efficiency of the proposed architecture are verified. Intra-datacenter and inter-datacenter networks are considered in this paper. Based on the unified and flexible control advantages, SDN is deployed in both two networks.

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The rest of this paper is organized as follows. In Section II, we propose the novel datacenter-network-based CDON and builds functional models. Then intra-datacenter optical interconnection architecture and inter-datacenter optical network architecture are designed. Section III describe the TaSS strategy. Finally, we describe the testbed and present the experimental results and analysis in section IV and section V conclude the paper.

2. Datacenter-network-CDON

In order to promote the control efficiency of datacenter networks, control architecture based on CDON is described as shown in **Figure 1**. Different OpenFlow controllers for different resources including intra-datacenter computing recourse and inter-datacenter communication resources have been developed. The latter is mainly flexi-grid optical network resource in this work. All resources are software-defined with OpenFlow and support datacenter application. Then OpenFlow-enabled network controller and OpenFlow-enabled application controller can work together. By using user and application interface (UAI), application plane which is served through application and controller interface (ANI) can provide users with various services. The architecture of intra-datacenter and inter-datacenter networks is discussed in detail as follows.

2.1. Intra-datacenter optical interconnection architecture

The CDON architecture for OpenFlow-based intra-datacenter optical interconnect is shown in **Figure 2(a)**. Top-of-rack (ToR), aggregation and core optical switches three kinds of optical switches are used to interconnect datacenter servers with the deployment of application stratum resources (e.g., CPU and storage). Application controller (AC) and network controller (NC) respectively centrally control each stratum resources which are software defined with OpenFlow. To control intra-datacenter networks for service migration with

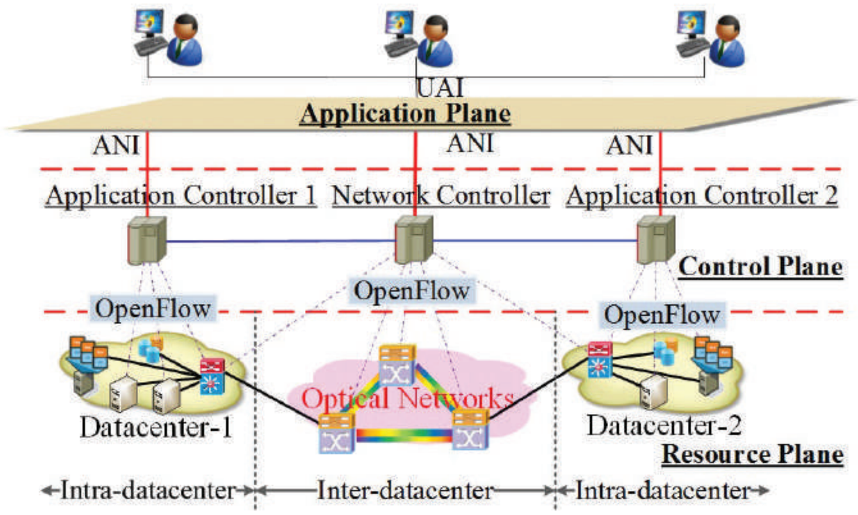

Figure 1. Datacentre-network-based CDON.

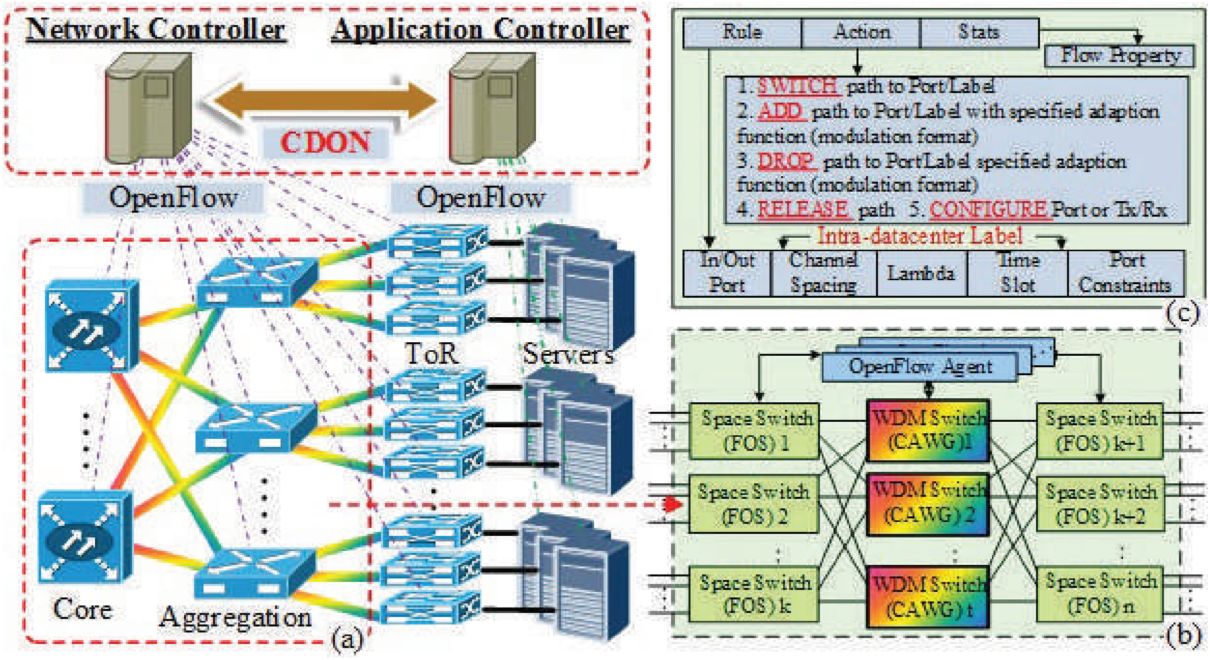

Figure 2. (a) The SDN-based intra-datacenter network architecture of CDON. (b) The SDN-based switching fabric of intra-datacenter. (c) The extension of protocol for CDON.

extended OpenFlow protocol (OFP), OpenFlow-enabled optical switches with the OFP agent software (OF-OS) is used. The CDON architecture in intra-datacenter networks have twofold motivations. Firstly, CDON can highlight the cooperation between AC and NC for supporting TaSS strategy to schedule datacenter applications based on different time sensitivity requirements reasonably and optimize application and network stratum resources efficiency. Secondly, considering the burstiness, burst applications fast provisioning with unified CDON control and process can be supported.

Figure 2(b) describes the OpenFlow-switching structure of intra-datacenter. The functions and interaction descriptions of relevant functional modules are described below. The AC is responsible for monitoring and maintaining the resources of application stratum for CDON, NC supports abstraction of the network information from physical stratum and lightpath provisioning of optical networks in intra-datacenter. When request arrives, AC processes it by using TaSS strategy considering the requirements of delay sensitivity and achieving CSO of the computing and storage in an internal database and sent the decision to NC. The control of virtual and physical network are concerned in NC. The former controls the virtual network and send abstracted network information to AC, the responsibilities of latter is to monitor and control the programmable physical modules. With the extended OFP, the lightpath can be built according to the request from AC. It is noteworthy that burst traffic can be correspondingly serviced by the high level optical switch by fast tunable laser (FTL) and burst mode receiver (BMR) in ToR switch. The aggregation and core switching fabrics are built based on space and wavelength circuit-switching technologies, fast optical switch (FOS) and cyclic arrayed waveguide grating (CAWG) respectively. The OFP agent software embedded in optical module has four functions which are maintaining flow table, modeling the information of node with programmability, mapping the content to configure and controlling hardware.

In connection to networks control of intra-datacenter, **Figure 2(c)** shows extended flow entry of OFP. The rule is added with the main characteristics of intra-datacenter including the in/out port, intra-datacenter label (e.g., channel space, lambda and time slot) and port constraints The action is extended as five types: add, switch, drop and configure to set up a path, and release a path. Using combinations of rule and action, the control of optical node is realized. The responsibility of stats function is monitoring the flow property to provide service provisioning for CDON.

2.2. Optical network architecture of inter-datacenter

Flexi-grid optical networks are the promising technology for inter-datacenter networks as these networks can satisfy the requirement of burstiness. The CDON architecture is built and shown in **Figure 3(a)**. The distributed datacenters are interconnected through the flexi-grid optical networks. The network architecture mainly consists of the optical resources stratum and application resources stratum. In a unified manner, network controller and application controller can control each resource stratum which is software defined with OpenFlow. Software defined OTN (SD-OTN) is necessary to control the flexi-grid optical networks for inter-datacenter network with extended OFP. SD-OTNs are essentially OpenFlow-enabled elastic optical device nodes with OFP agent software. It has twofold motivations to design the CDON architecture over inter-datacenter optical network. Firstly, the CDON can realize the global interworking of cross stratum resources that the physical

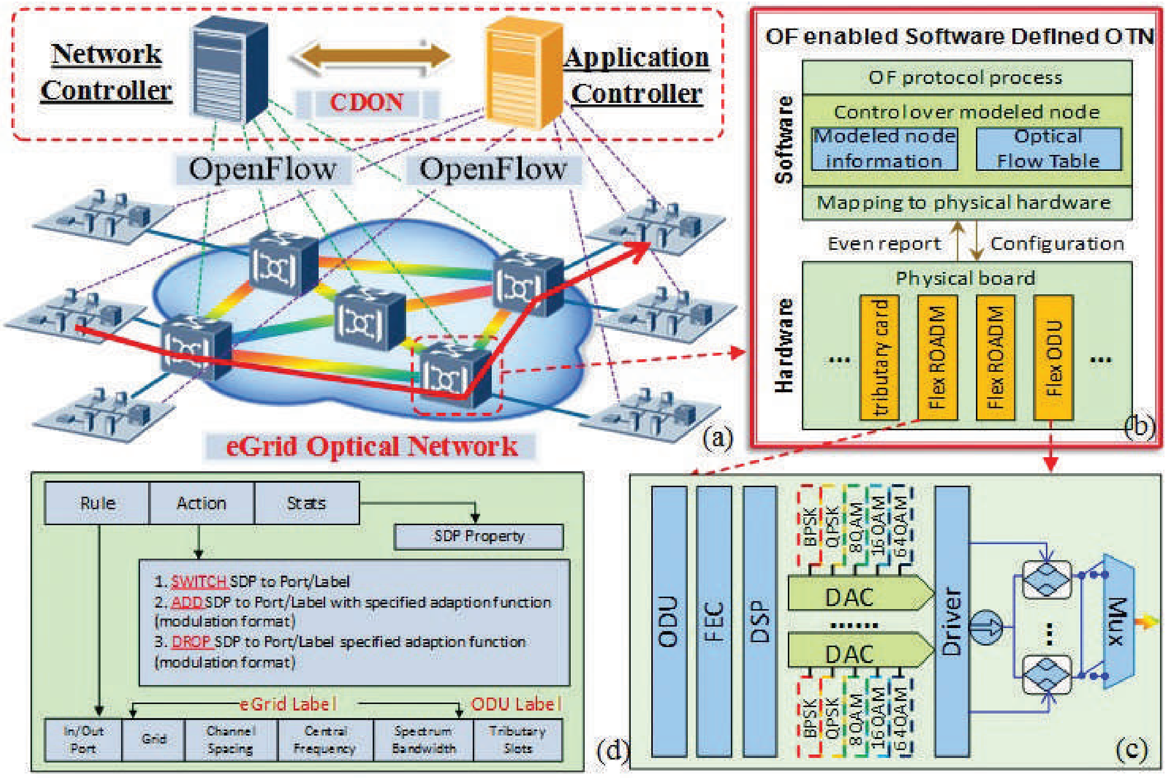

Figure 3. (a) The architecture of CDON in OpenFlow-based inter-datacenter networks. (b) OF-enabled SD-OTN functional models. (c) Flex ODU. (d) The extension of protocol for CDON in inter-datacenter.

layer parameter (e.g., bandwidth and modulation format) can be adjusted. So the cooperation between AC and NC is emphasized to realize software defined path (SDP) with application and spectrum elasticity. Secondly, the different time sensitivity requirements of services can be considered reasonably through scheduling data center services with time elasticity to optimize the application and network resources utilization further. Based on functional architecture described above, TaSS scheme is proposed in the AC and it can arranging the start time, transport time and corresponding transport bandwidth for services for realizing the application and network stratums resources optimization.

The functional modules of AC and NC and the coupling relationship between different modules are shown as follow. NC is responsible for the control in physical and virtual network. The former includes controlling spectrum resource and modulation format. The latter is responsible for managing the virtual network and sending virtual resource information to AC. While a request arrives, AC runs TaSS strategy based on muti-stratum resource information and sent the decision to NC through application-transport interface (ATI). The SDP can be found out and built up based on extended OFP according to the request from AC. It is noteworthy that, the length of SDP decides the modulation format of service (e.g., QPSK and 16QAM). In the case of short distance, spectrum bandwidth which is more precious than other resource can be economized by using high-level modulation format. In SD-OTN, OpenFlow-enabled agent software is embedded to realize the communication between NC and optical node. The SD-OTN maintains optical flow table and modeled node information as software. The physical hardware which contains flexible ROADM and ODU boards shown in **Figure 3(b)** and **(c)** respectively is configured and controlled through the content mapping. In the side of the control of flexi-grid optical networks in inter-datacenter, flow entry of OFP is extended and shown in **Figure 3(d)**. In this architecture, the rule is extended as the main characteristics of flexi-grid optical networks which including the in/out port, flexi-grid label (e.g., central frequency and spectrum bandwidth) and ODU label (e.g., tributary slots). The action of optical node mainly includes three types: add, switch and drop. Through combining rule and action, the control of flexi-grid node can be realized. The responsibility of stats function is monitoring the flow property to provide SDP provisioning.

3. Service scheduling strategy

In the side of the service accommodation of datacenter optical networks, the traditional strategy can.

allocate the optimal datacenter server application and corresponding lightpath network resources when a request arrives. That may satisfy the following conditions, which are shown in **Figures 4** and **5**. We assume that two datacenter servers are deployed in the candidate destination node. The storage utilization of server #1 and server #2 are 80% and 85% respectively when service arrives. After a relatively short time, the services which are provided by the two servers have changed, i.e., some services are released when they are complete and new ones arrive. It leads that the storage utilization of server #1 increases to 95%, while that in server #2 is down to 25%. The server #1 (80% at arriving time) would be chosen as the destination

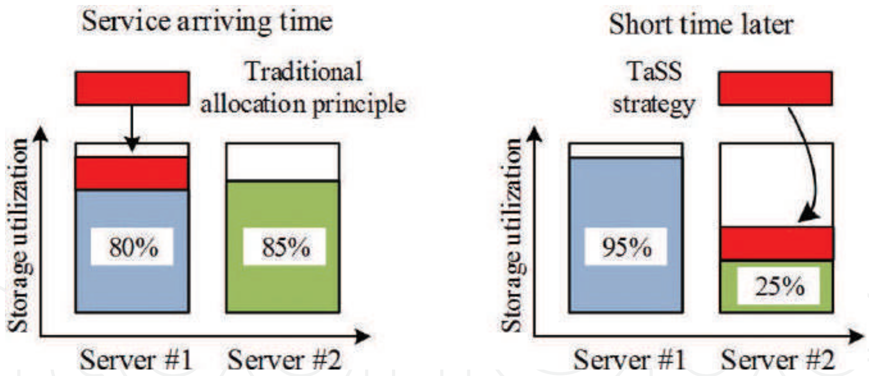

Figure 4. Illustration of time-aware datacenter application resource allocation.

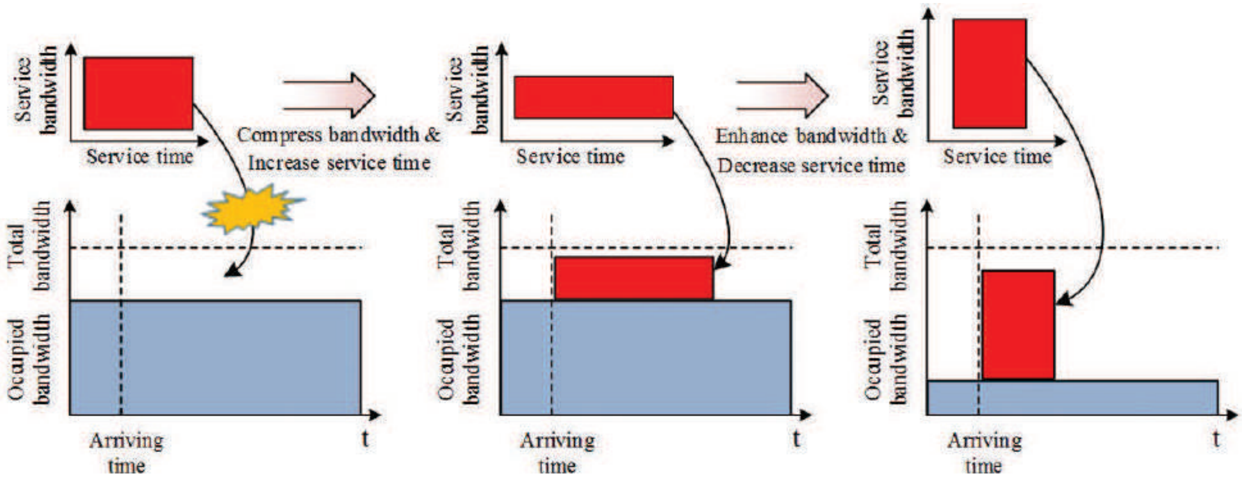

Figure 5. Illustration of time-aware network resource allocation.

node When the traditional allocation principle is used. However, if the resource is allocated after a short time (within delay tolerance of user), the better optimization and more effective resource utilization may be realized. The other instance is about the service bandwidth. The bandwidth which most of datacenter services use is specified and the time to transmit service is fixed for achieving the overall data volume of service. If the bandwidth is fixed with traditional methods, the service cannot be provided with enough resource in case of less available bandwidth. With compressing the bandwidth to adapt the available bandwidth and increasing the service time (overall data volume of service is constant), the allocation scheme can be feasible. Similarly, by enhancing the provide bandwidth, the service can be completed as soon as possible with relatively abundant resources. The time factor of datacenter service is considered in the two issues. Therefore, we propose the time-aware service scheduling strategy.

3.1. Network modeling

G (*V, L, F, A*) denotes the OpenFlow-based datacenter interconnect with optical networks, where $\boldsymbol{V} = \{v_1, v_2, \ldots, v_n\}$ is represented as the set of SDN-based optical switching nodes, $\boldsymbol{L} = \{l_1, l_2, \ldots, l_n\}$ denotes the set of optical fiber links connecting nodes in $\boldsymbol{V}$. $\boldsymbol{F} = \{\omega_1, \omega_2, \ldots, \omega_F\}$

indicate the set of wavelengths of optical fiber and ***A*** is the set of servers in datacenter. While source node *s sends* a service request, the request contains total data volume of service *D* and storage space *S*. The services are classified with latency-sensitive and delay-tolerant service. The former requires immediate service process and its *i*th request is denoted as $SR_i(s, D, S)$, and the latter incluces the arriving time t_c and tolerant delay *T*, and we denote its *i*th service request as $SR_i(s, D, S, t_c, T)$. The request SR_{i+1} will be the next request in time order when the connection demand SR_i arrives. In addition, **Table 1** shows some requisite notations and their definitions.

3.2. Time-aware service schedule strategy

Developing on the functional architecture, we present a novel time-aware service scheduling (TaSS) strategy which is implemented in application controller to schedule datacenter service with time sensitivity requirement. For the requirements of the arriving service, we classify them as burst latency-sensitive and delay-tolerant service including flow volume and tolerant latency, based on the delay sensitivity of each service. For the delay-tolerant service, we search servers and lightpaths of datacenter to judge whether the volume of S_r, B_r and *t is enough* to satisfy the incoming service. If the $S_r \geq S$ and $B_r{*}t \geq D$, by comparing CSO factor [16], the minimum one would be chosen to provision. If the resources for accommodating is not enough, the service would wait until maximum tolerant delay arrives, i.e., $t = T - D/B_a - t_G$, which considers B_a and t_G. New lightpath will be allocated with CSO to accommodate the service. In the side of delay-sensitive requests, by searching the existing candidate with the same method, the available resources are decided. The path which has minimum propagation delay obtained from candidate paths can be prepared to provision. When an available built path is found, the TaSS.

Strategy builds new lightpath for the service immediately. In order to realize the quick response for service provisioning, service time is used to reckon the release lightpath procedure immediately. The flowchart of TaSS strategy is shown in **Figure 6**.

Symbol	Definitions
$\cdot S$	The total capacity of storage space in target data center
$\cdot S_r$	The residual storage space in target data center
$\cdot D$	The total data volume of service
$\cdot B_r$	The product of available bandwidth of lightpath
$\cdot T$	The tolerant delay of delay sensitive service
$\cdot t$	The lightpath duration
$\cdot B_a$	The network average transmission bandwidth
$\cdot t_G$	The guard time
N	The number of network nodes
L	The number of links
F	The number of wavelengths
A	The number of datacenter nodes

Table 1. Symbols and definitions.

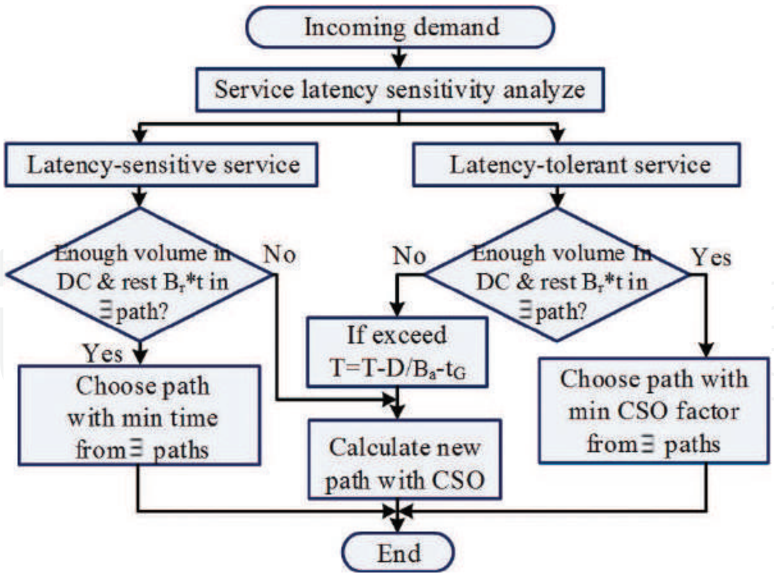

Figure 6. Flowchart of TaSS strategy.

4. Experimental demonstration and results discussion

A testbed of datacenter networks consisting of intra-datacenter and inter-datacenter is built. SDN is deployed on the two parts together. The following is a detailed description of the testbed demonstrations.

For experimentally evaluating CDON architecture, we deploy it into optical intra-datacenter networks and realize the service migration in this architecture on our testbed as shown in **Figure 7(a)**. In data plane, it contains 4 optical switches with FOS, Two CAWG cards in the core side, BMR embed into burst mode transceiver (BMT) card with FTL and the software OFP agent. The switching time of optical switches is 25 ns and the insert loss is lower than 4.5 dB. The frequency deviation of CAWG cards is 12.5GHz and the insert loss is 10.5 dB. The receiving power sensitivity of BMR is -25 dBm. The switching time of FTL has 98 ns and the frequency deviation is 2.5GHz according to ITU-T standard. The software OFP agent use PI to control the hardware through OFP. We use VMware software to build groups of virtual machines to realize Datacenters. Each virtual machine model a real node with the independent operation system, CPU and storage resource. In control plane, NC is realized with optical module control function, PCE computation function and resource abstraction function corresponding to three servers, database server is deployed to maintain transmission resources and the database of traffic engineering. AC server is used to carry TaSS strategy and monitoring the computing resources in servers. User plane is built in a server for running the required service.

We have designed experiment to verify the lightpath provisioning in CDON architecture for datacenter service migration. AC runs TaSS strategy to determine the path and schedule for service migration based on various application utilizations among datacenters and current network resource, then setup the path from source to destination node chosen by CSO. **Figure 7(b)-(d)** show the eye diagram and tuning waveform of FTL and spectrum of CAWG port reflected on the filter profile. The experimental results are further

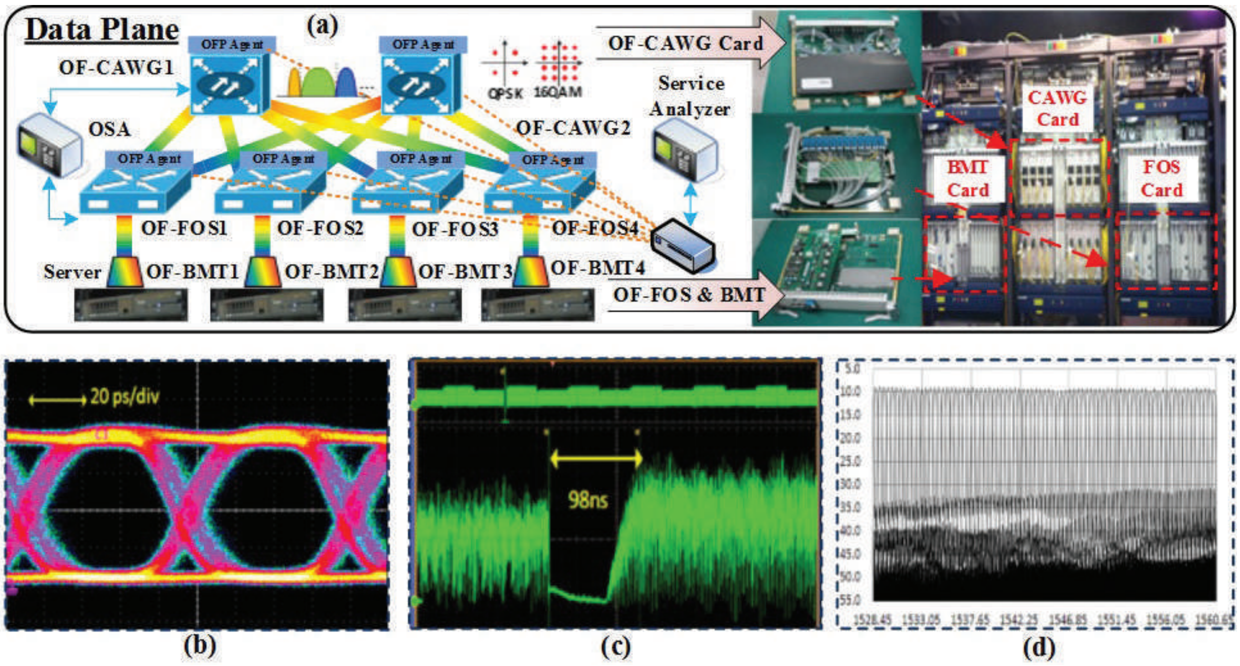

Figure 7. (a) Experimental testbed and demonstrator setup. (b, c) eye diagram and tuning waveform of FTL. (d) Spectrum of CAWG port.

shown in **Figure 8(a)** and **(b)**. **Figure 8(a)** demonstrates the OpenFlow message exchange sequence for CDON by capturing in NC with Wireshark. In **Figure 8**, 10.108.50.74 denotes AC and 10.108.65.249 denotes NC, OF-OS nodes are 10.108.50.21 and 10.108.51.22. AC performs TaSS strategy and NC control all OF-OS via flow mod message through the allocated lighpath to provide the path. Then the path releasing information is sent via flow mod message, and keep synchronization by updating the application usage with UDP to. **Figure 8(b)** verifies OPF extensions for CDON in intra-datacenter networks with a snapshot of the extended flow table modification message for lightpath provisioning. We also evaluate the performance of CDON in intra-datacenter networks under the condition of heavy traffic load through simulation by comparing TaSS with traditional CSO (TCSO) strategy [16]. The migration data volumes from datacenter node following a Poisson process are randomly from 50Gbit to 400Gbit. **Figure 9(a)** and **(b)** compare the performances of two strategies. Comparing to TCSO, TaSS can reduce blocking probability effectively, especially when the network is under heavy load. We can also find that TaSS outperforms TCSO in the resource occupation rate significantly. The reason is TaSS realizes global optimization considering the time schedule with various delay sensitivity requirements and adjusts the service bandwidth according to the distribution of network resources.

in order to evaluate the proposed architecture in experiments, we build CDON including both control and data planes based on testbed, as shown in **Figure 10(a)**. In data plane, SDN-based flexible optical nodes are deployed, each of which including flex ROADM and ODU boards.

Datacenters and the other nodes are also implemented on virtual machines created by VMware software on servers. As each virtual machine has independent operation system, IP address, CPU and memory resource, it can be regarded as a real node. The virtual OS technology can set up experiment topology including 14 nodes and 21 links which is similar to the backbone of US. For OpenFlow-based CDON control plane, the NC is set up to support the proposed architecture and deployed in three servers corresponding to elastic spectrum control, physical layer parameter adjustment, PCE computation and resource abstraction, while the database server work for maintaining traffic engineering database, management information base, connection status and the configuration of the database and transport resources. The AC server support CSO agent and monitoring the application resources from datacenter networks with TaSS strategy. User plane is set up in a server for running the required application.

We have designed experiment to verify SDPs provisioning in CDON over flexi-grid optical networks for datacenter service migration whose results are shown in **Figure 10(b)-(d)**. AC runs TaSS strategy to determine the destination datacenter based on various application utilizations among datacenters and current network resource, and then set up SDP for the service migration along the lighpath from source to destination node. Moreover, for different SDP distances, the spectrum bandwidth and corresponding modulation format is tunable. **Figure 10(b)** and **(c)** show the spectrum of SDPs on the flexible link between two SD-OTNs which is reflected on the filter profile. The setup/release time of end-to-end SDP is evaluated and shown in **Figure 10(d)** by collecting the statistics of the strategy processing time, OFP transmission delay and device handle times of software and hardware.

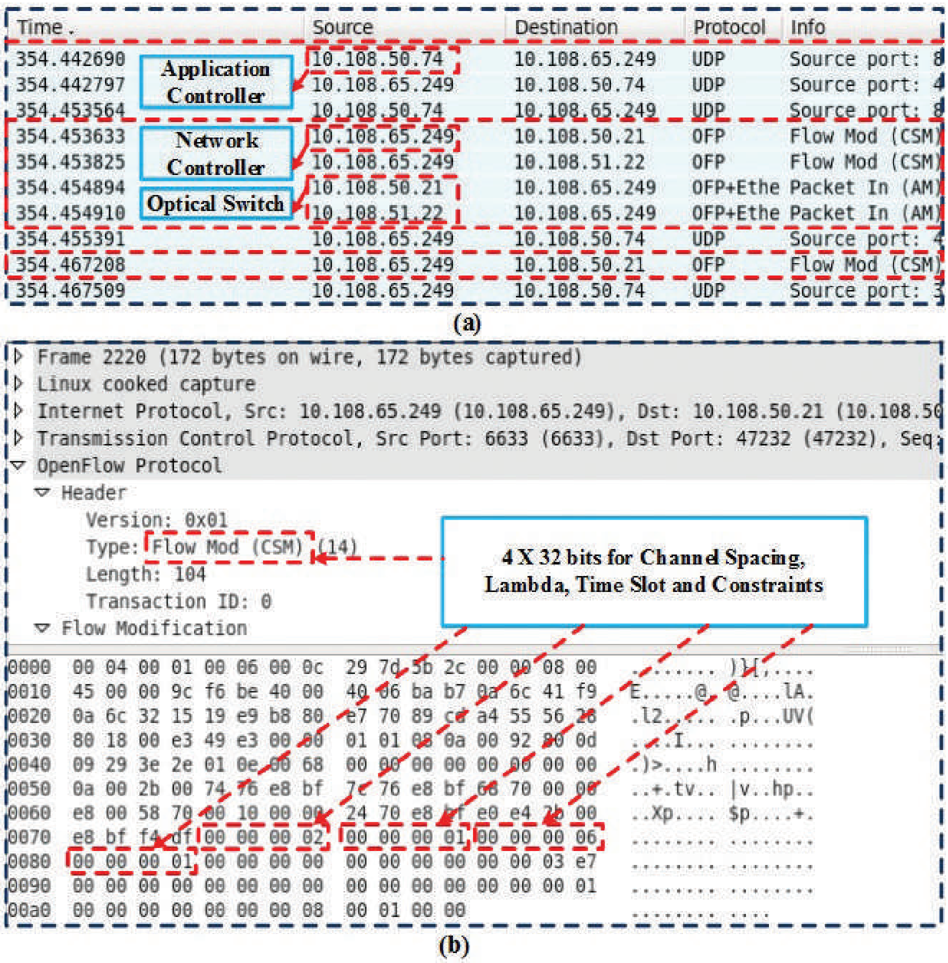

Figure 8. (a)The capture of the OpenFlow message sequence and (b) extended flow mod message for CDON.

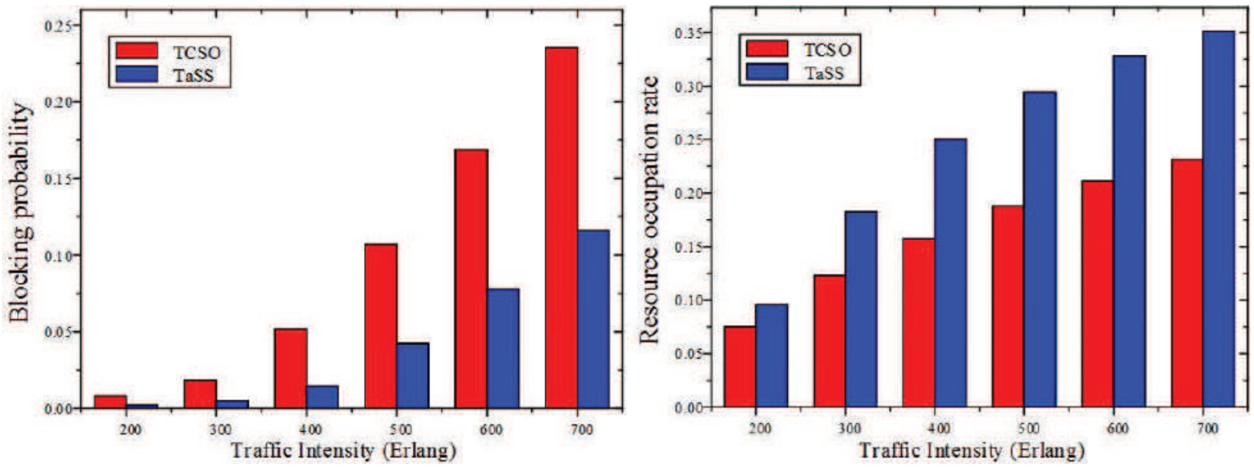

Figure 9. Comparisons on (a) blocking probability and (b) resource occupation rate between two strategies in heavy traffic load scenario.

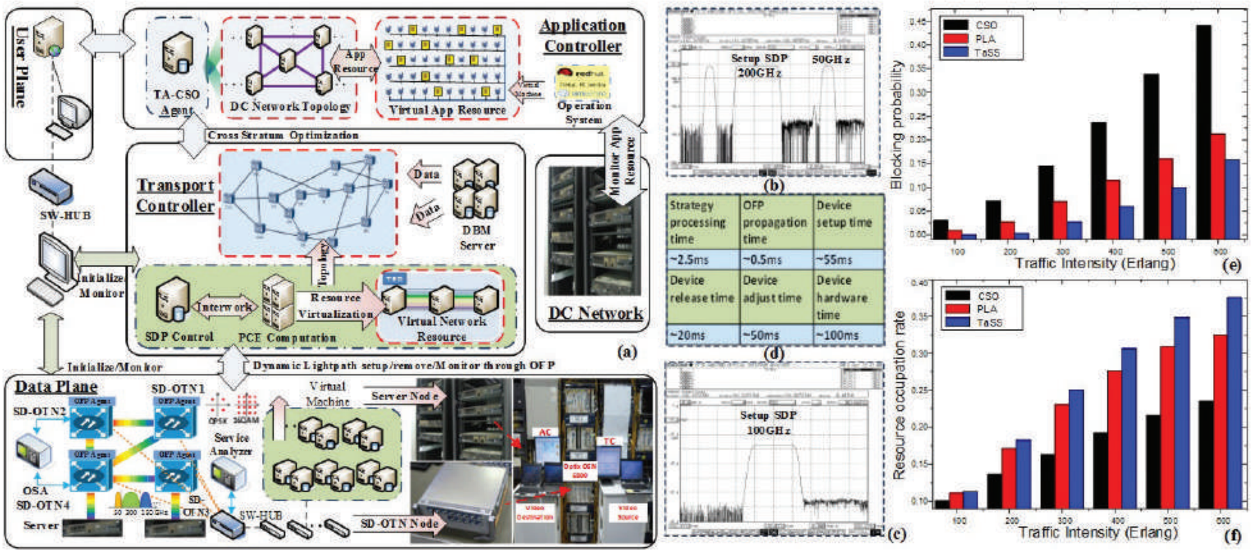

Figure 10. (a) Experimental testbed. (b, c) optical Spectrum of SDPs. (d) SDP setup/release delay. (e) Blocking probability (f) resource occupation rate under heavy load.

We test the performance of CDON by collecting the performance statistics in TaSS with CSO and physical layer adjustment strategies (PLA) under the condition of heavy load. The spectrum bandwidth of requests are randomly from 50GHz to 400GHz and the adjustable minimal frequency slot is 12.5GHz. All the destination nodes are datacentre in this network. These requests follow a Poisson process and statistics have been collected through the generation of 1×10^5 requests per execution. **Figure 10(e)** and **(f)** compare blocking probability and resource occupation rate of three strategies. In the figure, TaSS has a lower blocking probability than CSO and PLA, especially when the network is under the condition of heavy load. We can also find that TaSS can provide a better resource occupation rate than the other strategies. That is because both application and network resources can be considered in TaSS integrally and global optimization can be realized. Furthermore on the basis of it, by choosing high-level modulation format the spectrum resource is economized again. These results are further emphasized in **Figure 11(a)-(c)**.

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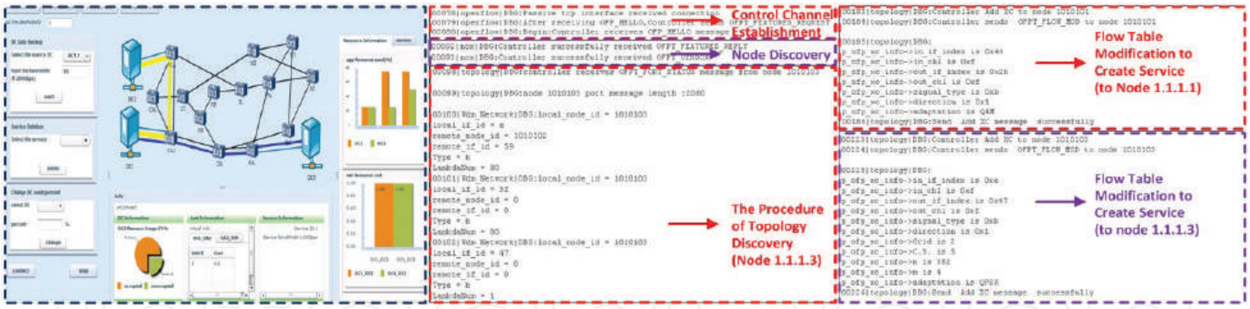

Figure 11. (a)Application graphical user interface (GUI) of testbed. (b) The capture of the OF messages for network discovery. (c) The capture of extended flow table message for SDP setup.

Figure 11(a) shows the application interface of CDON with status and destination node choice of datacenter service migration and various bandwidths of SDP. **Figure 11(b)** illustrates the OpenFlow message exchange for CDON with the capture in TC. **Figure 11(c)** shows a capture of the extended flow table modification message for SDP setup to verify the OPF extensions for CDON over flexi-grid optical networks.

5. Conclusion

Datacenter server resources will become more and more important in the future information society. It will be the main decision factor for reducing cost to allocate the resources efficiently. Considering the high capacity and low energy consumption requirements, Optical networking is regarded as promising technology for both intra-datacenter and inter-datacenter networks. The SDN technology can improve the resource utilization of application and network efficiently. In this chapter, we provide a CDON architecture in SDN-based datacenter optical network for service migration. Besides, we design the TaSS strategy for CDON and the extended OFP further. Based on our intra-datacenter and inter-datacenter networks testbed, we verify the feasibility and efficiency of CDON. The blocking probability and resource occupation rate of our approach under the condition of heavy traffic load are collected and compared with TaSS strategy. The experimental results indicate that the service with time sensitivity can be scheduled effectively and cross stratum resources utilization efficiency is improved in the CDON with TaSS strategy.

Our future works for CDON are to improve TaSS performance with dynamic parameters and consider the scalability in optical network. Then we will realize the network virtualization in datacenter optical network on our OpenFlow-based testbed.

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Chapter 13

An Integrated SDN-Based Architecture for Passive Optical Networks

Hamzeh Khalili, David Rincón, Sebastià Sallent and José Ramón Piney

Additional information is available at the end of the chapter

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Abstract

Passive optical network (PON) are often managed by non-flexible, proprietary network management systems. Software defined networking (SDN) opens the way for a more efficient operation and management of networks. We describe a new SDN-based architecture for Ethernet passive optical networks (EPON), in which some functions of the optical line terminal (OLT) are virtualized and located in an external controller, while keeping the rest of the passive optical network (PON) functionality around an OpenFlow switch. This opens the way for an improved management of the resource usage, bandwidth allocation, quality-of-service (QoS) monitoring and enforcement, or power consumption management, among other possibilities. In order to maintain the time-sensitive nature of the EPON operations, synchronous ports are added to the switch. OpenFlow messages are extended in order to cope with the PON-related parameters. Results based on simulations demonstrate that our proposal performs similarly or better than legacy architectures, in terms of delay and throughput.

Keywords: software defined networking (SDN), OpenFlow protocol, passive optical network (PON), Ethernet passive optical network (EPON), service interoperability for EPON (SIEPON)

1. Introduction

1.1. Ethernet passive optical networks

Passive optical networks technologies (among them, Ethernet passive optical network (EPON) [1] and GPON [2]) are currently used in access networks. As shown in **Figure 1**, passive optical network (PON) is composed of a central office (optical line terminal, OLT), passive optical splitters, and one terminal (optical network unit, ONU) at each one of the customer premises, in a tree topology. First-generation PONs use time division multiplexing (TDM) for sharing the medium in a point-to-multipoint scenario. In the downstream, the OLT broadcasts the data frames towards the ONUs, while in the upstream an arbitration mechanism is needed in order to avoid collisions when ONUs send frames to the OLT. The EPON standard, which will be the focus of this work, uses the Ethernet format for the data frames.

A key piece in EPON is the concept of dynamic bandwidth allocation (DBA) algorithms, which allow the OLT to orchestrate the access to the shared medium and to dynamically adapt to the changing requests from the ONUs. In the EPON architecture, an entity called multi point control protocol (MPCP) manages the upstream channel and harmonizes the transmission of data from ONUs to OLTs. In addition, it manages operations such as terminal discovery, registration, and bandwidth allocation. MPCP uses two standard messages for DBA operations, namely GATE and REPORT. REPORTs are used by ONUs to request transmission opportunities, and GATEs are sent by the OLT to grant a transmission slot (time and length) to a specific ONU.

1.2. EPON service interoperability

In order to ensure service interoperability in a multivendor scenario, IEEE developed the 1904.1 Service Interoperability for Ethernet passive optical networks standard (SIEPON) [3–5]. One of the key concepts in SIEPON is the definition of a unified data path architecture to ensure that data services can be managed, provisioned and monitored across the EPON. SIEPON covers the physical (PHY), medium access control (MAC), and upper layers to manage tasks related to the data path, such as multicast delivery, tunnels, VLANs, and quality-of-service (QoS) enforcement.

EPON service pathways (ESPs) are defined as the path that a data frame follows through the media access control (MAC) client functional blocks, specifying both the connectivity and QoS of the frame. Connectivity is defined by classifying the frame according to header fields (VLAN tag, MAC address, IP address, to name a few possibilities), while QoS parameters can

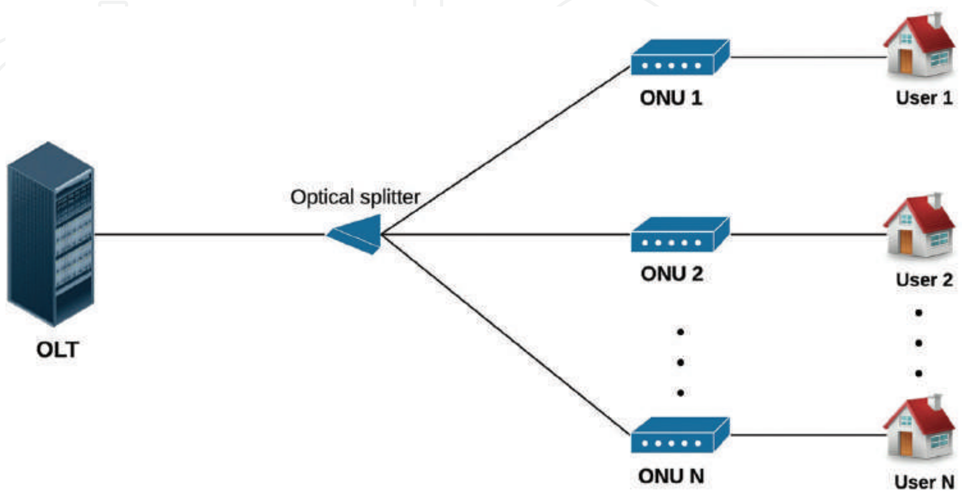

Figure 1. PON topology.

be enforced by queues with priorities and scheduling. **Figure 2** shows the SIEPON architecture in both the OLT and the ONUs, and specifically the ESP-related blocks: the Input block [I] is the ingress port that receives frames from user-network interface (UNI) or network-network interface (NNI); the classifier block [C] classifies incoming frames; the modifier block [M] is able to modify frame fields; the Policer/Shaper block [PS] enforces conformance to the service contract; the Cross-connect block [X] is used to direct a frame to the proper queue; the Queue block [Q] holds frames until they are selected by the scheduler for transmission; the Scheduler block [S] transmits the frames from the queue block to the output block using a predefined scheduler algorithm; and finally Output block [O] is the egress port that receives frames from a scheduler and forwards them to the UNI or NNI. Each one of the ESP blocks can involve several independent instances operating on various flows of traffic.

1.3. Software defined networking

Software defined networking (SDN) [6] is a new paradigm for network management that introduces network programmability and separation of the data and control planes, migrating the complex, "intelligent" functions from the network devices to a centralized controller. These characteristics allow the SDN controller to obtain a centralized and accurate view of the state of the network, thus opening the way for the optimization in several ways (bandwidth assignment, QoS guarantees, minimization of power consumption, or resilience, to name a few possibilities).

The SDN architecture defines two interfaces in the controller. The northbound interface defines an API that allows network management systems (NMS) or ad-hoc applications to communicate with the controller. The southbound interface communicates the control

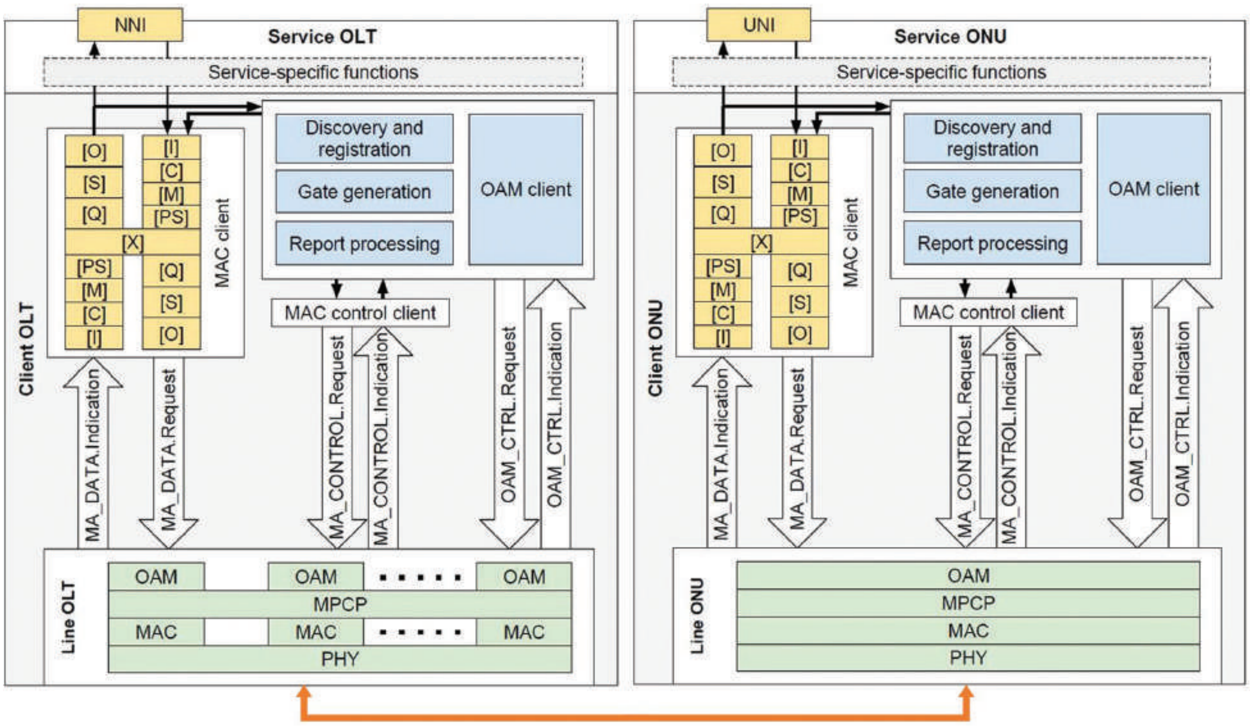

Figure 2. SIEPON architecture, OLT (left) and ONU (right).

plane that runs in the controller with the data plane that resides in the network equipment (switch). The original southbound API, and probably the most popular, is OpenFlow (OF). The OpenFlow protocol [7] defines a standardized instruction set that allows the controller to manage any OpenFlow-enabled device and specify the path to be followed by traffic flows through the network of switches, by means of the definition of matching rules (based on packet header fields) and operations to be performed (e.g., forwarding to a specified port, modifying the headers, or dropping the packet).

1.4. SDN-based PON networks

The management of access and backbone optical networks is becoming more and more important in the research literature [8], and how to apply SDN is being now intensively investigated. In the specific case of PON networks, given its centralized nature (the OLT manages almost all the operations), applying the centralized control envisioned by SDN makes even more sense. However, the aspects related to service interoperability, or a detailed SDN architecture (including extensions of OpenFlow messages and actions), are relatively unexplored. The authors of [9] provide a useful and up-to-date survey on the contributions on SDN-based optical networks. Here, we discuss the most relevant works in the field of SDN and optical access.

In [10, 11], authors envision a scenario where each optical switching node is virtualized, in order to obtain a unified control plane. Each physical interface is mapped to a virtual interface. In order to ensure a smooth transition from legacy equipment, an extra layer would translate the messages between the controller and the switches [12], at the cost of adding latency by using message proxies. The authors of [13] developed an architecture for PON networks based on SDN including an OpenFlow extension for traffic mapping and forwarding capabilities, with no effect on data link layer latency. In [14] an architecture control plane for converged metro-access networks under SDN is described. Reference [15] presents a novel software-defined optical access network (SDOAN) architecture. The purpose of developing a Service-Aware Flow Scheduling (SA-FS) strategy is to assign network bandwidth resources in an efficient and flexible way. In order to operate PONs coordinated with a core SDN-based network, Ref. [16] describes an architecture for a Software-Defined Edge Network (SDEN) able to control end-to-end the traffic flows. In [17], authors propose a new SDN- and NFV- (Network Function Virtualization) based architecture for EPON networks; in this scheme, OLTs and ONUs are partially virtualized and moved to a central controller. Reference [18] describes, at a high level, an EPON architecture based on SDN that replaces the hardware-based DBA with a software-based one, residing in the controller. The authors of [19] describe a GPON architecture where an OpenFlow agent is located in the OLT to communicate with the SDN controller, claiming that the approach can connect several sites in different locations in a cost effective manner.

Central office re-architected as a datacenter (CORD) is a novel architecture developed in [20] aimed at substituting the telephone exchange hardware with software-based equipment, converting central offices into datacenters, with the purpose of speeding the deployment and increasing the efficiency of services. CORD decouples the control and data planes, using the open network operating system (ONOS) [21] SDN controller, and virtual machines running on top of OpenStack. CORD is currently supported by service providers such as AT&T and NTT Communications.

To the best of our knowledge, Refs. [22, 23] are the only works that tackle the topic of how to adapt the SIEPON standard to the SDN architecture. Reference [22] describes methods for enabling nodes to exchange information between a management protocol and other protocols, including control plane and data plane interfaces to support SDN. Reference [23] expands the work presented in [17], converting the OLT into an OpenFlow switch, and describes the extensions to make it compatible with the SIEPON architecture, and thus reach the goal of having a virtualized, simplified and centralized management system migrated to the SDN controller.

The remainder of this chapter is organized as follows: In Section 2, we describe the SDN-based EPON architecture and the OLT functions. Section 3 expands the description by defining the new elements and modifications, together with details of its operation and implementation. Section 4 presents the validation of the proposal, together with results obtained with a simulator and a reference implementation. Section 5 concludes the chapter.

2. SDN-SIEPON architecture

This work builds on [17] and expands [23] with more details and results. We present a novel SDN-SIEPON architecture based able to decouple, virtualize, and simplify the management and operation of the OLT and OAM functions, and opens the way for multi-tenant and multi-provider optical access networks, where various service providers use the same basic infrastructure.

Our architecture is based on the principle that the OLT is built around an OpenFlow switch that takes care of the forwarding plane and carries out the functions related to the EPON service path, while some of the control plane-related functions are migrated to an OpenFlow controller. The OpenFlow switch performs the following functions: (1) classifies incoming packets following the matching rules; (2) modifies packet header fields if required; (3) schedules and ensures QoS for each flow; and (4) forwards packets towards their destination ports. In order to do so, the OpenFlow switch emulates some of the EPON functionalities defined in the OLT, such as control multiplexer (CM), control parser (CP), and multipoint transmission control (MPTC). Many of these functionalities work in real time, and therefore we need to define synchronous ports and make it compatible with the SDN architecture by defining a set of registers. The operations that must be executed in real-time are kept in the switch, while those that work at longer time scales can be migrated to the SDN controller.

As shown in **Figure 3**, the SDN-SIEPON architecture includes three main elements: an SDN-based OLT; an SDN controller; and the EPON network, including the passive splitters, the fibers and the ONUs. We focus here on the redesign of the OLT, and although the partial virtualization of the ONUs might be of interest (for example, in the context of energy saving or QoS management), it is out of the scope of this work and left for future research.

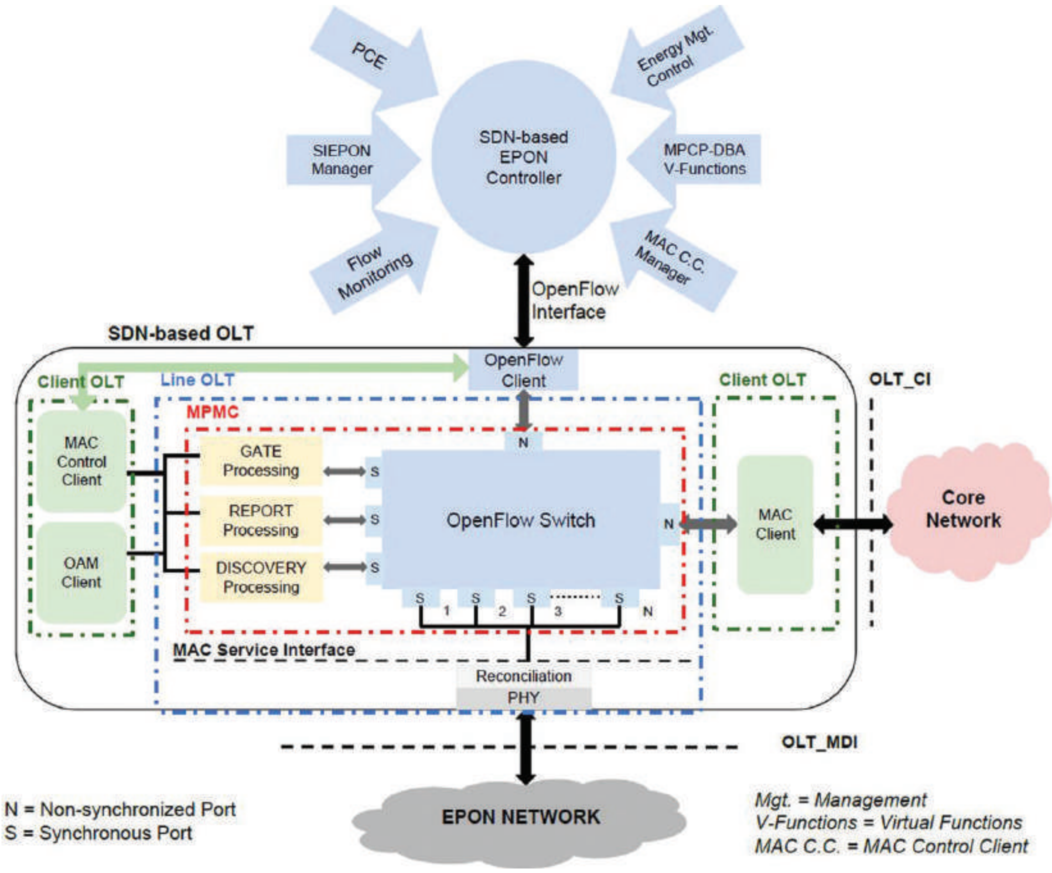

Figure 3. Elements of the SDN-SIEPON architecture.

2.1. SDN-OLT

The SDN-based OLT is built around an OpenFlow switch, and its tasks include the forwarding functions of the MPMC sub-layer and the operations of the Control Multiplexer, Control Parser, and Multipoint Transmission Control elements of the EPON architecture.

A non-synchronous port is in charge of the connection of the SDN-OLT to the SDN controller, while a set of synchronous logical ports link the ONUs and the operations of the SDN-OLT (among them the processing of the GATE and REPORT messages, the discovery process, and the DBA management). There is a synchronous port per ONU (with a maximum of 64 ONUs per OLT), attached to a specific MPMC instance running in the SDN-OLT, plus one extra logical port for broadcasting messages to all ONUs. The 64 port-instance pairs are activated on demand, depending on the number of active ONUs. Whenever an ONU is activated, the SDN controller creates a MPMC instance and links its three logical ports to the DISCOVERY, GATE, and REPORT processing modules. In parallel, the controller creates a unicast MAC service logical port and connects it with the recently started up instance. While legacy OLTs require several complex entities with multiple coordinating entities, our design simplifies the architecture by setting the OpenFlow switch as the single coordinator of all the entities, thus arbitrating the access to the downstream and upstream channels, as illustrated in **Figure 4**.

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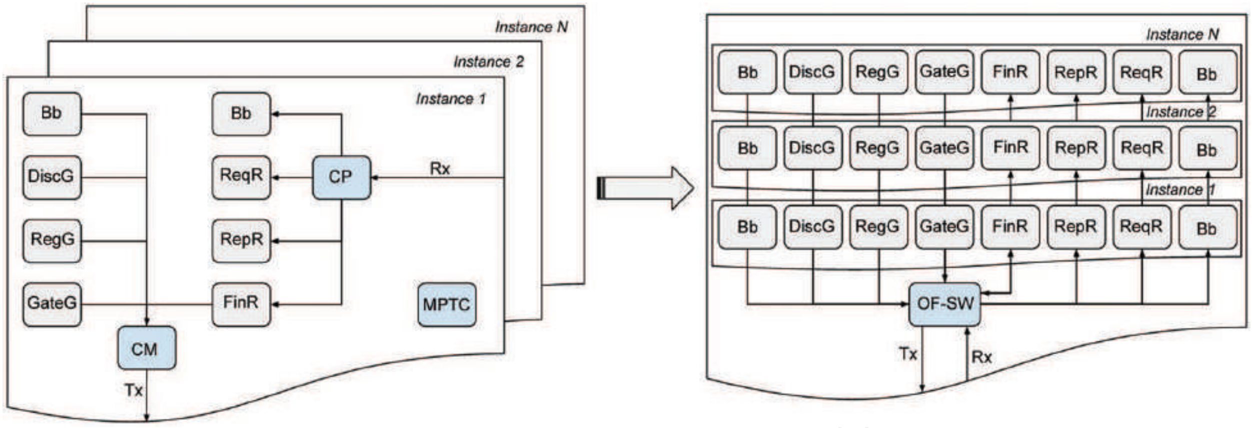

Figure 4. Left: architecture of a legacy OLT with several complex MPMC instances. Right: the simplified SDN-OLT architecture. Acronyms of the processing entities: OF-SW (OpenFlow switch); Bb (backbone), DiscG (discovery gate generation); RegG (register generation); GateG (gate generation); FinR (final registration); RepR (report reception); and ReqR (request reception).

2.2. SDN controller

The SDN controller is a piece of software that manages one or several SDN-OLTs, and runs the complex, non-real time functions that compose the control plane of the EPON network. It is usually run on virtual machines in a datacenter, and has a centralized view of the network. One key aspect of our design is the decoupling of the virtualizable functions that work in longer timescales and can be migrated to the controller from the functions that work at shorter timescales and have to be kept at the switch. To name a few cases, the controller manages the parameters of the MAC control client; the policies of the MAC client; or the translation of the linking the high-level SIEPON QoS class definition to the low-level MAC QoS parameters.

An important SIEPON module that is also migrated to the controller is the ESP manager of the MAC client, responsible of aspects such as provisioning, QoS policies, flow management, bandwidth assignment policy, time-related decisions, addition of unregistered ONUs to the network, and data forwarding services through the SDN-OLT. It is also in charge of handling and configuring the initial parameters of the MAC control client in the OpenFlow switch, and the processing of GATE, REPORT, and DISCOVERY messages as well. It also provides a database for the OpenFlow switch to keep information regarding logical link identifiers (LLIDs), status of logical port, and ONU MAC address so as to configure flow tables for the switch.

The MPCP-DBA virtual module handles the overall network policy function and allows the controller to communicate with SDN-based OLT to alter parameters and policies of DBA, ONU priority in DBA, or shift between several available DBA algorithms.

3. Extensions and modifications of OpenFlow

This section describes the extensions and additions to the OpenFlow architecture that are needed for our proposal. OpenFlow messages and actions will have to be extended to support

EPON operations, and synchronous ports will be needed in the switch in order to keep the synchronous nature of EPON. Another aspect to tackle is how to implement the ESP functional block of SIEPON. Finally, a new and simpler MPMC sub-layer will be described.

3.1. Extension of OpenFlow messages

The original OpenFlow messages lack specific headers and parameters needed to execute some of the SIEPON-related operations. Basically, we need:

1. A way to determine whether the OF switch is a SDN-OLT type or not. This is solved with an extension of the OFPT_FEATURES_REPLY message sent in response to the controller query.

2. Maintain correspondence of the logical link identifier (LLID) of the port and the MAC address of the ONU. This is done by extending the OFPT_PORT_STATUS message.

3. Set up the initial parameters of the MAC control client and MAC client (for example, setting the LLIDs) during the initial phase of the dialog between the SDN-OLT and the SDN controller. This can be done by extending OFPT_SET_CONFIG message.

4. Transport the set of synchronous rules, matching fields and actions. This information is carried in an extension of the OFPT_FLOW_MOD message.

OpenFlow match fields must also be extended in order to support the new SIEPON-related functionalities. A PDU_type field is created to maintain the type of received packet (a MAC control frame or a data frame). An opcode type distinguishes the control frames as a DISCOVERY GATE, REGISTER_REQ, REGISTER, REGISTER_ACK, GATE or REPORT message. Flag is used to classify the type of GATE packet (DISCOVERY GATE or normal GATE). LLID contains the port's LLID number, which is given by the controller and allocated by the MAC control client. Finally, a Grants_number stores how many grants have produced as result of the processing of the GATE message. It can range from 0 to 4, where 0 signals a periodic GATE packet and 1 to 4 are related to the bandwidth allocation by a normal GATE.

3.2. Synchronous ports

The synchronous nature of PON networks requires the SDN-OLT to be able to handle real-time operations in synchronous ports, through which packets are sent or received in specific times specified by the synchronous flow entries. We developed a MPMC sub-layer extension that retains synchronicity and allows us to replace control parser, control multiplexer, and multipoint transmission control components of a legacy OLT with the OpenFlow switch.

The synchronous operations related with a newly added ONU include:

- Setting an instance_ID in the OpenFlow switch for the respective MPMC instance.
- Allocating three synchronized logical ports to each gate, report, and discovery processing instance.

- Allocating an input/output synchronized logical port with an associated LLID so the port is linked with the MAC address of the newly connected ONU.
- Timestamping of packets delivered to/received from the ONUs. The timestamps are obtained from the local clock of the OpenFlow switch.
- Computing and monitoring the round trip time (RTT) of the packets received from the ONUs.
- Assigning bandwidth and transmission time slots in the upstream direction (packet forwarding strategy), in cooperation with the SIEPON manager (based on its QoS policies).
- Creating and destroying flow entries in the OpenFlow switch.

Several registers are used to emulate the synchronous operation:

- P (transmitPending), I (transmitInProgress), and E (transmitEnable) are employed to synchronize the MPMC instances with the DBA (thus allowing the packets from the instances to share the channel in an arbitrated way). The OpenFlow switch controls the transmission of packets towards the Reconciliation Sub-layer (RS) by activating the transmitEnable signal.
- Two additional registers are used for round-trip-time (RTT) calculation and packet timestamping. RTT calculation is used for synchronization between OLT and ONU.

Figure 5 illustrates the extension of the MPMC sub-layer of the SDN-OLT.

3.3. ESP functional block

The aforementioned extension of the Flow-Mod message allows us to introduce the functionality of the SIEPON ESP functional blocks in the SDN-OLT. **Figure 6** describes an example of an OpenFlow flow entry extended with the new matching fields and actions. The actions related with the ESP functional blocks are:

1. Set-Field: it is consistent with the Modifier block [M] and implements all the set-field actions in the packet. It modifies the value of the packet header fields (e.g., Ethernet/IPV4/IPV6 source and destination addresses, VLAN ID and VLAN priority, for example).
2. Apply meter: it is consistent with the Policer/Shaper block [PS] and allows packets' rate measurement and control (setting rate limit), and implement DiffServ-like policy. In addition, meters can assist per-port queues in scheduling packet on an output port with respect to their priority, thus ensuring QoS.
3. Set-Queue: it is consistent with the Queues block [Q], and sets the queue_id for a packet when it is delivered to the port. It is used for packet scheduling and forwarding.
4. The Scheduler block [S] controls the actions related with the transmitPending, transmitInProgress and transmitEnable actions by altering their associated registers P, I, E.

5. Output port: it is consistent with the Output block [O]. Packets are allocated to a physical port (i.e., controller) or a logical port (either unicast or broadcast, depending on the ONUs targeted).

6. Operations performed by the Classifier [C] and Cross-connect [X] blocks are executed via rule matching and actions in the flow table. Incoming packets are compared and classified based on their matching fields with the existing rules, and packets are later sent to the destination based on the associated action.

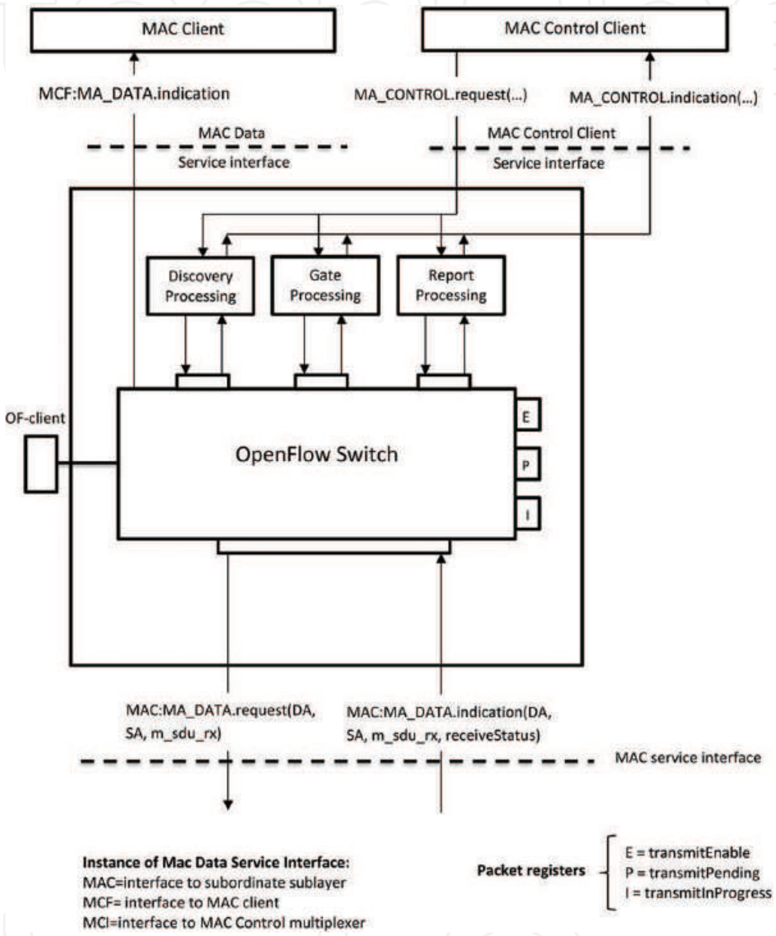

Figure 5. MultiPoint MAC Control functional blocks, from [23].

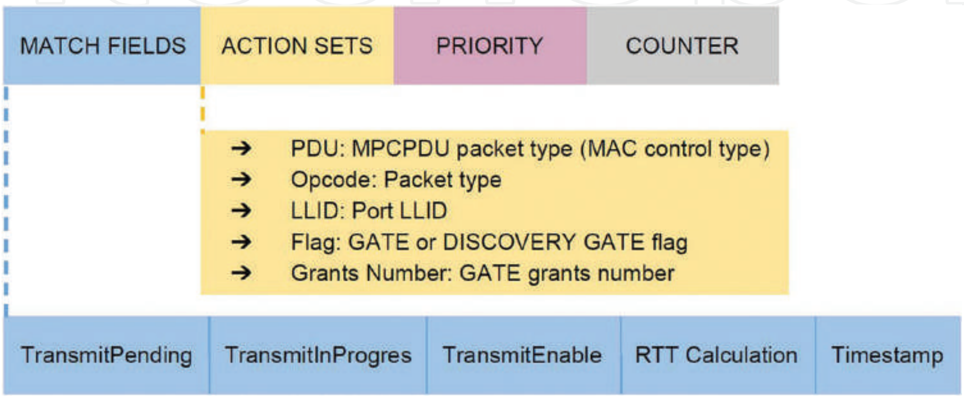

Figure 6. Example of extended match fields and actions.

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3.4. MPMC sub-layer

In the legacy OLT the MPMC sub-layer is quite complex: a MPTC module synchronizes multiple instances of MPMC (one for each ONU, with a control multiplexer and a control parser entity). Our proposal simplifies this by introducing three single entities of MPTC, CM, and CP, implemented as rules and flow entries in the OpenFlow switch. Therefore, the switch's task is to coordinate with different MAC instances of the OLT and coordinate their requests for sending or receiving packets.

Figure 7 illustrates the main blocks that compose an OpenFlow switch: OF agent; control path; and data path. The OpenFlow agent interacts with the SDN controller in order to manage both the control and data paths. The control path is responsible of emulating the OLT functionality through the set of rules and actions in the flow entries. The data path task is to match the received packets with respect to the matching rules, and execute the attributed actions (e.g., frame forwarding and scheduling for transmission).

The MPMC sub-layer carries out the following functions: after receiving a frame from the underlying MAC, forwards it to the OpenFlow switch flow table in which the frame is analyzed based on its opcode. The REPORT and data frames coming from ONUs are analyzed by CP functions. In **Figure 7** each data path flow entry related to the control path element is shown in the same color. The MPMC also coordinates the processing of DISCOVERY GATE, GATE, and data frames created by the MAC instances and forwards them to the RS layer (shown in green in **Figure 7**), and manages the transmission of data frames using the three registries (i.e., P, I, and E) defined in the OpenFlow switch control path.

3.5. An example of operations

We now provide an example to illustrate the procedure for generating a new flow entry in the SDN-OLT for processing a DISCOVERY GATE, GATE and REPORT messages. Let us recall that a GATE message tells a specific ONU when to send data (start time) and how

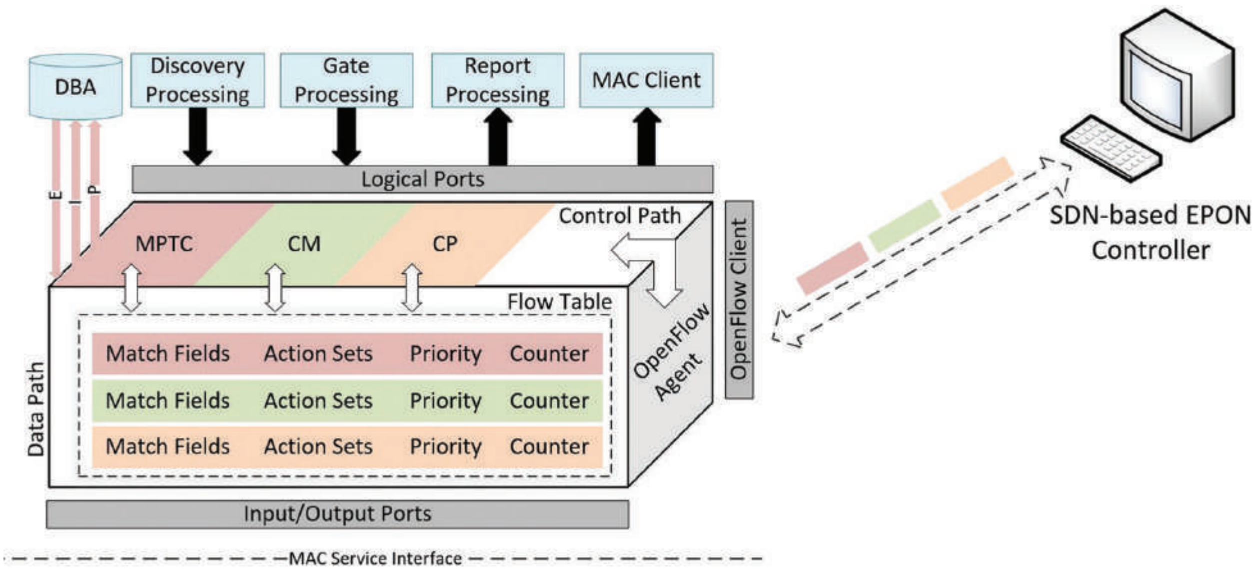

Figure 7. MPMC sub-layer design.

much data to send, in response to a previous REPORT message from the ONU requesting a transmission opportunity. Regarding the discovery process, DISCOVERY GATE messages are broadcasted periodically to all ONUs, and are replied by the newly connected ONU with a REGISTER REQUEST (randomly delayed in order to minimize collision with other ONUs). The OLT confirms by sending a REGISTER message immediately followed by a GATE that grants and schedules an ONU response in the form of a REGISTER-ACK message, finishing the discovery and register process. **Figure 8** illustrates the state diagram for the actions related to processing the aforementioned messages.

When the SDN-OLT establishes the communication with the SDN controller, the latter sends a series of FlowMod messages with pre-defined rules to be inserted in the flow table of the OpenFlow switch. These rules define how to process the DISCOVERY GATE, REGISTER_REQ, REGISTER, REGISTER_ACK, GATE, and REPORT messages. The MAC control client sends a request to a discovery processing entity of an instance to creates a DISCOVERY GATE message with the required fields (discovery information and policy to use by the ONU) and sends it through the appropriate synchronous logical OpenFlow switch port. After receiving a packet, a flow table lookup is performed by comparing the packet header fields with the matching fields of the installed rules by following a priority order. When the packet is matched, the associated counter for the chosen flow entry is increased and the actions linked with the flow entry are performed.

When, later on, the controller receives a request (through Packet-In) from the SDN-OLT, for processing a GATE message, it gathers and analyses the received packet data (source and destination MAC addresses, PDU type, opcode, flag, grant number, LLID and VLAN IDs) to set a rule in the OF switch for determining the grants' number and establish the QoS policy, and

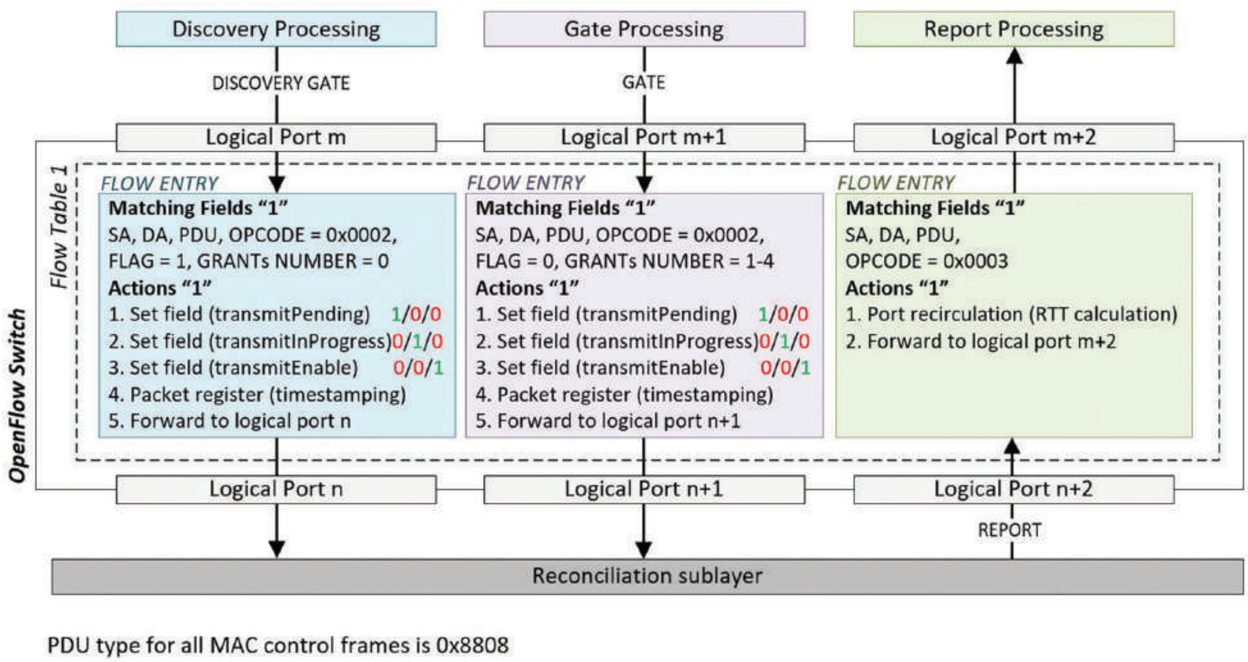

Figure 8. Operations related to the processing of DISCOVERY GATE, GATE and REPORT messages.

prioritize packet delivery towards an output port. The rule is transmitted through a FlowMod and a Packet-Out messages to the OpenFlow switch, and the received GATE message is processed accordingly.

For both the DISCOVERY GATE (right side of **Figure 8**) and GATE (center of **Figure 8**) messages, when the packet is prepared for broadcasting, the packet is scheduled for transmission by setting register P (transmitPending). The packet, placed in the queue, might wait for higher priority packets to be processed by the DBA. The transmitInProgress action is performed by setting register I so as to alter transmission state of the packet to transmitInprogress (by setting I to 1 and transmitPending to 0). Then, transmitEnable action is performed when no more packets are available to be transmitted by setting register E, and the transmission state of the packet is altered to enable (E is set to 1 and transmitInProgress to 0). The next action is to send the packet towards a specified logical output port. A timestamp is then added to the frame and the packet is sent to the RS layer. In the case of REPORT message (at the left side of **Figure 8**), as soon as the REPORT message is received from an ONU and matched against a rule in the flow table, the action of calculating the RTT is executed on the packet (via port re-circulation and interacting with the packet registers) and the value is communicated to the DBA. Once the RTT is calculated, the packet is forwarded to the REPORT entity for further processing.

4. Evaluation

This section describes the simulation model and the performance evaluation of our proposal. We built models of both the legacy EPON architecture of the SDN-based EPON architecture using the OPNET Modeler package, and compared them in terms of delay, and throughput. The results expand our initial validation described in [23] with an evaluation of the influence of the traffic pattern, the number of active ONUs, and end users in the performance of the system.

4.1. Description of the scenario and delay analysis

A scenario with a SDN controller, a SDN-OLT, and a tree topology with 16 ONUs was built. The distance between the SDN controller and the OLT is initially set to 1 km, and the ONUs are at distances ranging from 16 to 18 km from the OLT. The link rate in both the downstream and upstream directions is 1 Gbit/s, the guard time is 1 μs, and the maximum cycle time is set to 1 ms. IPACT [24] is used as DBA algorithm, and the message processing delay in the SDN-OLT is set to 0.0164 ms [25].

Two traffic generators are used: constant bitrate and self-similar traffic [26, 27]. For CBR traffic, packets have a constant length of 791 bytes, while in the second case packet size is uniformly distributed between 64 and 1518 bytes (with a mean of 791 bytes, to compare with the CBR case), and the Hurst parameter (a measure of the long-range dependence of self-similar traffic) was set to 0.7, 0.8, and 0.9. In order to understand the delay analysis that follows,

Figure 9 shows the scenario and the delay measurement points, where the dashed path is used for calculating the round trip time (RTT) delay, and the DE path is used for evaluating the queuing delay and throughput of the system.

Table 1 shows the time it takes for the controller to process each type of packet, and the time for transmitting the packet through the logical output port in the SDN-OLT, for the cases of the six initial FlowMod messages (DISCOVERY GATE, REGISTER_REQ, REGISTER, REGISTER_ACK, GATE, and REPORT,) where the OpenFlow installs the flow rules at the

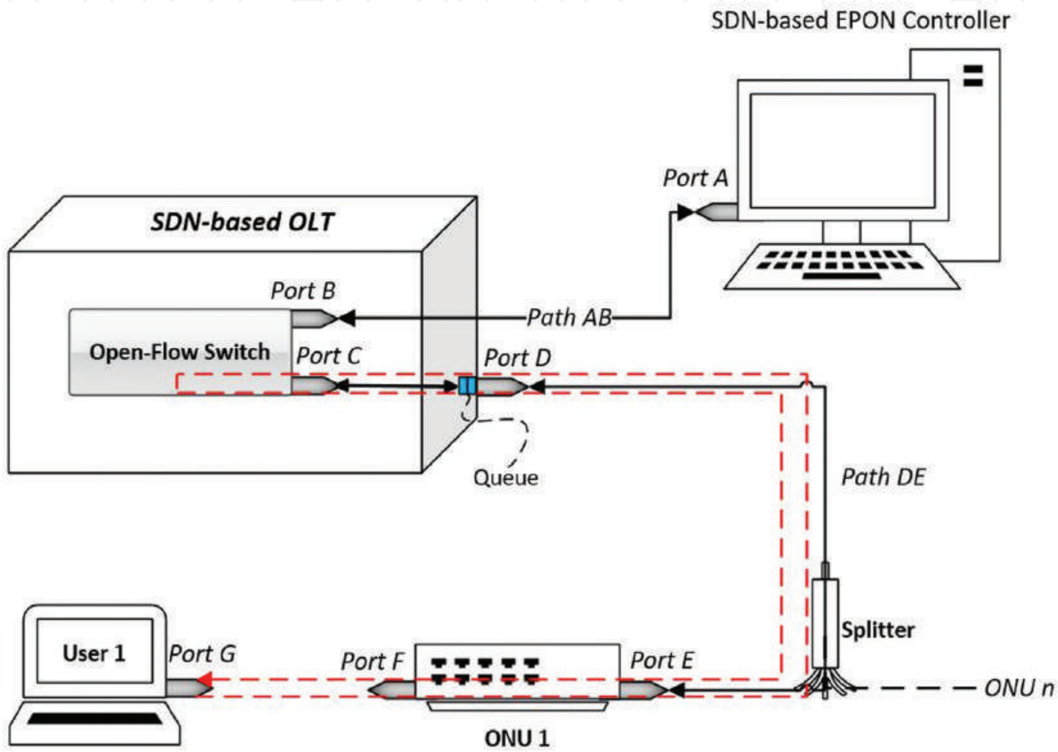

Figure 9. Measuring points in the SDN-based EPON scenario.

FlowMod	Tx delay in the controller (port A) (μs)	Rx delay in the switch (port B), d = 1 km (μs)	Rx delay in the switch (port B), d = 10 km (μs)	Tx delay through the path AB, d = 1 km (μs)	Tx delay through the path AB, d = 10 km (μs)
DISCOVERY GATE	0.52	5.76	51.66	5.243	51.14
REGISTER REQ	1.04	6.28	52.18	5.243	51.14
REGISTER	1.56	6.80	52.70	5.243	51.14
REGISTER_ACK	2.08	7.32	53.22	5.243	51.14
GATE	2.60	7.84	53.70	5.243	51.14
REPORT	3.12	8.36	54.26	5.243	51.14

Table 1. Average values of packet processing delays.

switch during the connection establishment. The average packet delay is measured for two different cases of distance between the controller and the SDN-OLT, 1 Km and 10 Km. Even for the longer distance, in which a single controller located in a datacenter could manage simultaneously several OLTs in a diameter of 20 Km (i.e., a medium-sized city), response times are almost negligible.

A metric of interest is the influence of the presence or absence of the flow processing rules in the performance of the SDN-OLT. In the first case we assume that the SDN controller has previously installed in the switch the rules for processing the control frames (DISCOVERY GATE, REGISTER_REQ, REGISTER, REGISTER_ACK GATE, and REPORT). The delay is evaluated from the moment a packet (such as control frame or data frame) enters the OpenFlow switch via a synchronous port, including the look-up for a rule in the flow table to match and perform a group of actions (such as read and write a register, and forward the packet to the output port). The average processing time in presence of the rules in the flow table is $T_{presence\ of\ rule} = 0.488\mu s$.

For the case when the rules are not yet installed in the switch, whenever a new packet arrives, the OpenFlow switch sends a Packet-In message to the controller, who in turn creates a FlowMod and a Packet-Out message to insert a rule in the flow table, followed by the look-up time and action execution. In this case, the average processing time can be described as the first look-up time ($T_{1st\ look-up} = 0.297\mu s$), plus forwarding time of the packet to the logical port B ($T_{forwarding-to-port-B} = 0.096\mu s$). In addition, the packet forwarding time from logical port B to a physical port A is, and the controller processing time for analyzing the incoming the Packet-In message, installing the rule, and issue a FlowMod and Packet-Out messages is $T_{controller\ processing} = 1.986\mu s$. The second look-up and actions execution times are, as in the first case, $T_{2nd\ look-up+actions} = 0.488\mu s$. Therefore, the average processing time in absence of the rules is $T_{absence\ of\ rule} = 13.353\mu s$. Since the look-up time process will vary depending on the length of the flow table and the number of flow entries, we carried some experiments. For both cases (in presence and absence of the rules) the average look-up time when 10 flow entries are present in the table is 0.294 μs, increasing to 0.398 μs, when 100 flow entries are present. Therefore, the influence of the number of flow rule entries does not play an important role in the delay performance of the system.

4.2. QoS performance evaluation

We now focus on the evaluation of the QoS in the path between the OpenFlow switch and the end users, shown as a dashed line in **Figure 9**. This path includes the look-up and rule matching times, registers read and write operations, and waiting time in the port queue (point D in the MAC service interface, queue in **Figure 9**). The results are obtained by averaging 50 values for each parameter.

Figure 10 shows the round-trip-time (RTT) delay against the offered load for both the SDN-based and legacy architectures. The RTT delay is evaluated for the data frames, which are generated and forwarded to the logical port C of the OpenFlow switch by the end user through the physical port G, and returned back. In a real situation, packets would actually ingress the core network, but since we are interested in the PON segment, we do not include this term. The results are presented using box plots, showing the average delay value (center of the box), the first and third quartiles (bottom and top of the box), lowermost and

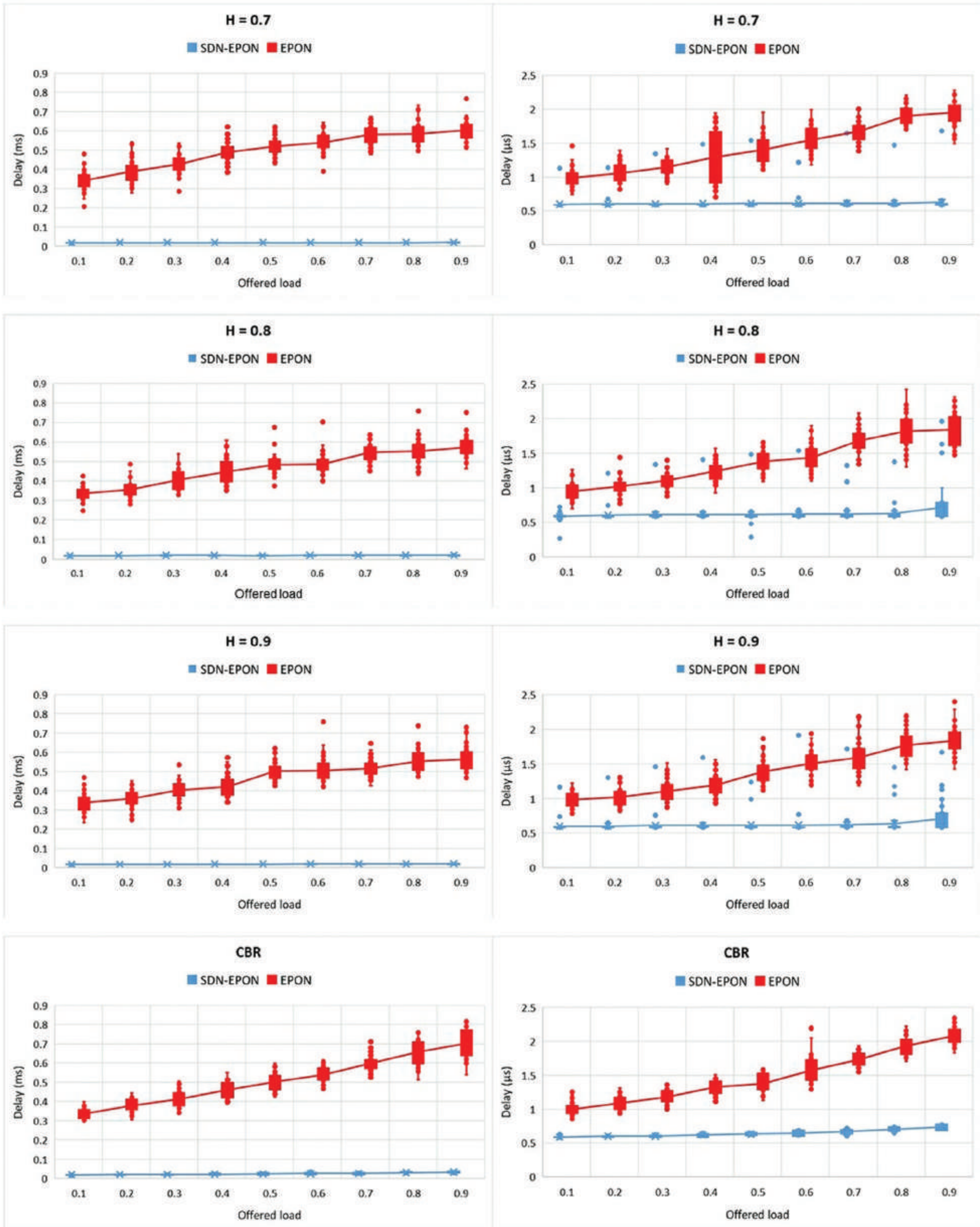

Figure 10. Comparison of RTT delay (left column) and downstream queuing delay (right column) in SDN-based EPON and legacy scenarios under different offered load, for CBR and self-similar traffic patterns and different Hurst parameter.

uppermost values (whiskers below and above the box) and the low min and high max values (red dots scattered). Please note that, although they are related to the same x-axis value, red dots not coincide with the blue dots at the same x-axis position in order to enhance visualization

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and avoid overlapping. Both SDN-based and legacy EPON architectures are evaluated in the same conditions (global offered load) and each blue or red dots in the figures relates to the average value obtained for all the ONUs. The offered load is expressed as 10% fractions of the maximum capacity of the system.

The main conclusion from the left column of **Figure 10** is that the delay performance is much better in the SDN-based architecture, particularly when the network load is high. The almost constant RTT in the SDN-OLT scenario is explained by to the presence of pre-defined rules in the flow table, thus ensuring almost constant processing time. In the SDN-based architecture the DBA procedures are highly simplified, while in the legacy EPON architecture, several Control Multiplexer and Control Parser entities (one per instance) are involved. This also explains the higher variability (red dots dispersion) in the legacy case, compared with the more deterministic behavior of the new architecture. The traffic pattern does not have a significant affect in the results. CBR and self-similar traffic offer the same average results, with less variance in the case of constant traffic. Long-range dependence characteristics of the traffic pattern do not seem to affect significantly the performance, with only a slight increase in the dispersion of the measurements when H is increased (probably related to the presence of more time-correlated traffic bursts when the Hurst parameter is increased).

The right column of **Figure 10** shows the queuing delay in the downstream direction against the offered load for both architectures and for different traffic sources (self-similar with different Hurst parameters and CBR). The queuing delay is evaluated for both control and data frames at the OLT physical port (port D of the MAC service interface), and correspond to measurements of the packet waiting times in the downstream direction of the queue. The delay is measured from the moment when a packet is forwarded to the transmitter channel queue and until the time the last bit of the packet is transmitted. Our goal here is to evaluate the possible impairments in the downstream transmission in the SDN-based architecture. As discussed earlier, the OpenFlow switch affects the downstream transmission by controlling the synchronous logical ports that communicate with the DBA entity. The results show a behavior similar to that of the RTT. In the legacy case, the queuing delay is very dependent on the load, while it almost does not vary in the case of the SDN-based architecture—and in this case the delay is much smaller. Again, this is caused by the simplified architecture of our proposal.

In the next set of experiments we vary the number of active ONUs (16 and 8), for different offered loads, and Hurst parameter 0.9. The case of 16 active ONUs is the base case already analyzed previously, while in the second scenario only 8 ONUs send and receive the total traffic of the network (we double the rate of each ONU, in order to maintain the global load equivalent) and the other eight ONUs do not generate any user-related traffic and only communicate with the OLT through the control frame messages. As **Figure 11** illustrates, in both architectures, the RTT delay increases with the input traffic, but as in the previous experiments, the delay for the legacy EPON case is much higher. The number of active ONUs has a limited influence, shown as a small increase in the delays experienced in both architectures. The increase is caused by the fact that we are averaging the delays experienced by the packets generated by ONUs that generate a rate that has been doubled, and therefore their packets experience increased waiting times.

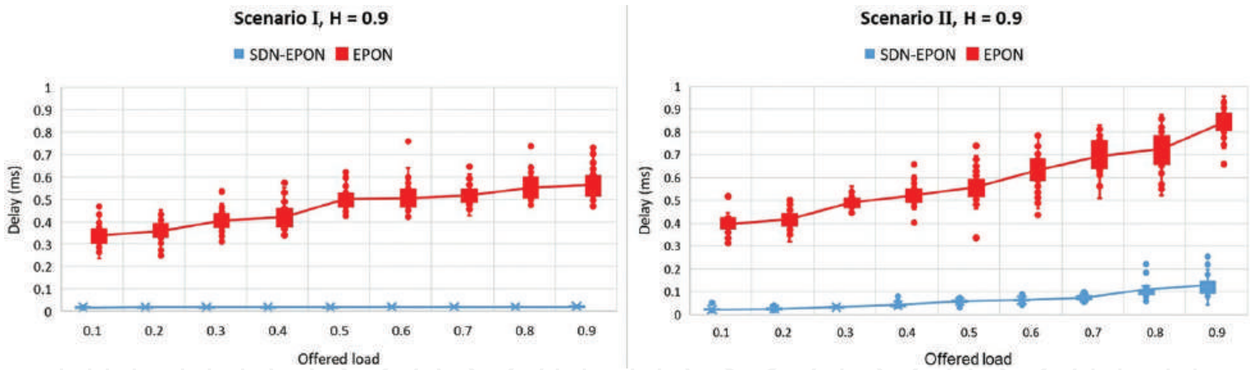

Figure 11. RTT delay in SDN-EPON and EPON architectures under different number of end users (16 active ONUs on the left, 8 active ONUs on the right), for different offered traffic load.

The same phenomenon is seen in the queuing delay analysis, whose results are shown in **Figure 12**. As the number of packets per second increases at each ONU, the queuing delay increases too, but much faster for the legacy EPON scenario, and both scenarios suffer a slightly higher delay when the load is concentrated in a few the ONUs.

Figure 13 shows the throughput of both the downstream (left column) and upstream (right column) channels against the offered load for total ONUs, for CBR and self-similar traffic sources, where self-similarity is evaluated under 16 and 8 active ONUs (scenarios I and II, respectively). As shown in **Figure 9**, the throughput is evaluated for the control and data frames traversed through path DE. As expected, the total throughput is very similar, although there is a small advantage for the SDN-based EPON architecture (3.7% better in the downstream, 2.9% better in the upstream), caused by a faster processing of packet is performed in existence of predefined rules, thus lowering the queuing delay. Results show the throughput for both architectures and scenarios (I and II) is quite similar no matter what configuration and Hurst parameters are used. As the number of packets is increased, the average transmission delay and the QoS will be degraded. Again, the traffic pattern does not have any relevant influence in the results.

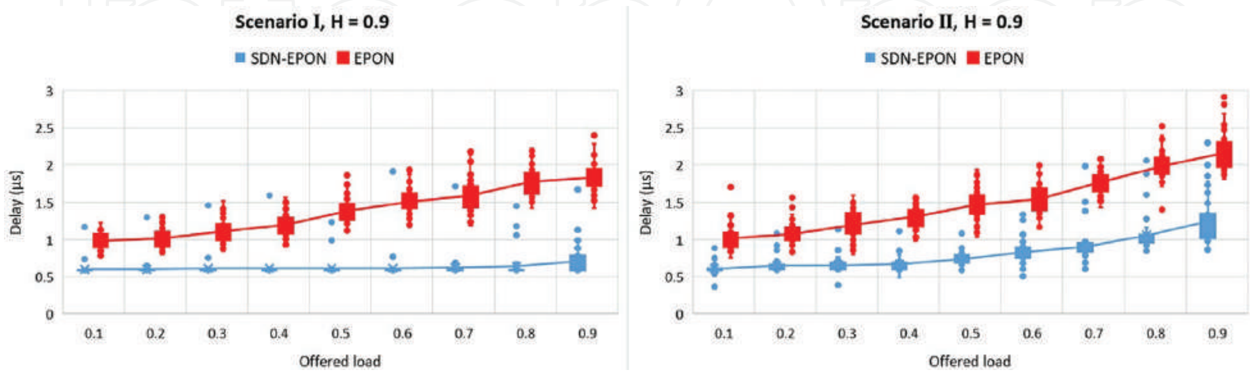

Figure 12. Queuing delay in SDN-EPON and EPON architectures under different number of end users (16 active ONUs on the left, 8 active ONUs on the right), for different offered traffic load.

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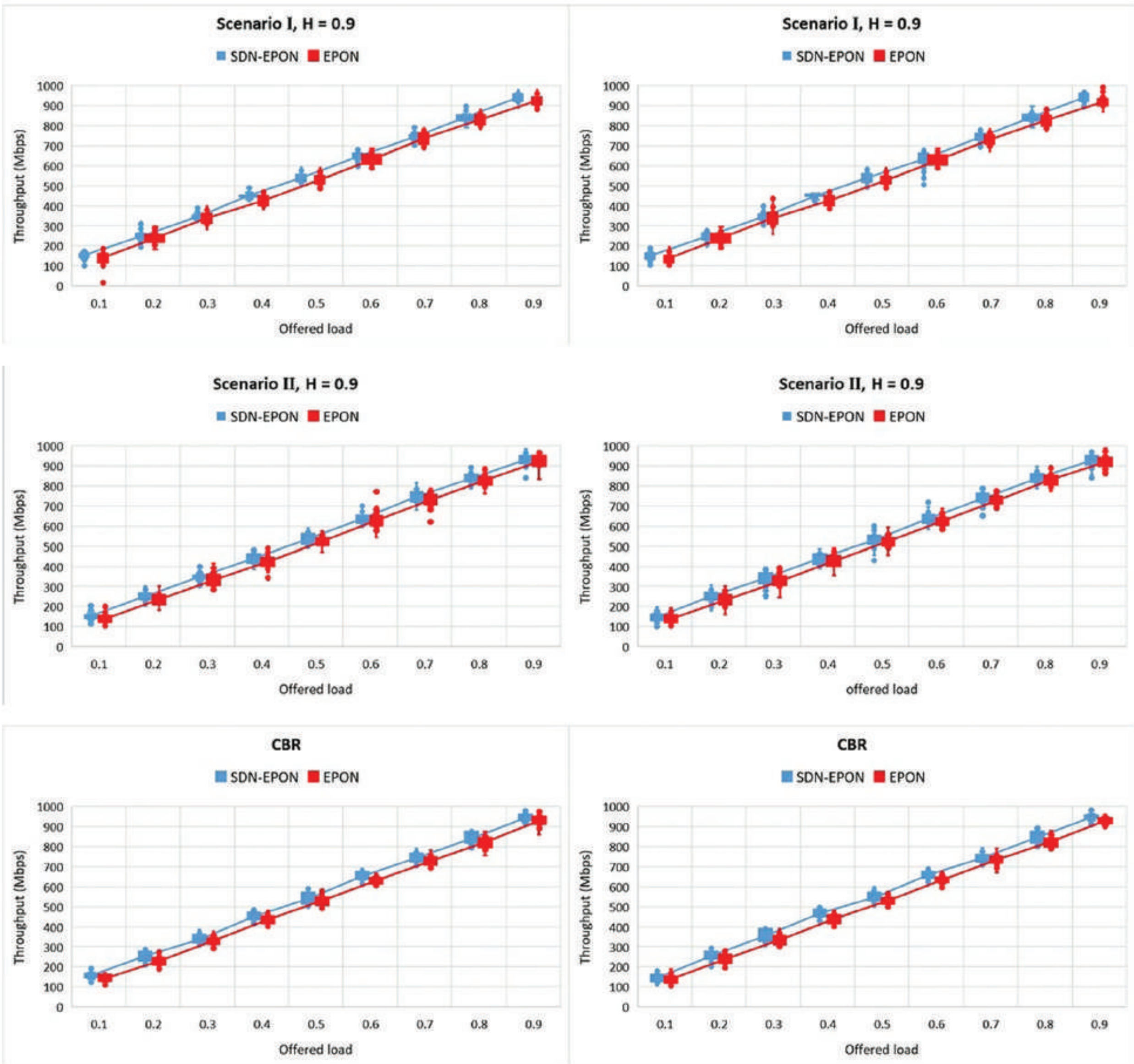

Figure 13. Downstream and upstream throughput in SDN-EPON and EPON architectures under different traffic sources and number of end users (16 active ONUs on the left, 8 on the right), for different traffic patterns (CBR and self-similar) and different offered traffic load.

5. Conclusions

We have described a novel architectural design for SDN-controlled EPON networks, together with system implementation details. Our architecture minimizes the management and operational complexity of the EPON, while optimizing the flexibility and controllability of the network. An extension of MultiPoint MAC Control sub-layer is defined in the OLT to decouple some of its functionalities and distribute them between the SDN controller and the SDN OLT. The management and control functionalities of the MAC client and MAC control client are migrated to the SDN controller, (an example of the operations that take place at longer time scales), and the main functional blocks kept in the SDN-based OLT to be integrated with the OpenFlow switch (operations that work at short time scales are kept at the OLT). Synchronous operations are introduced in the OpenFlow architecture by defining a group of synchronous and non-synchronous ports (via operation of registers), and extending the OpenFlow's rules and messages. Several simulations have demonstrated a significant improvement in data packet delay and downstream and upstream throughput when compared with the legacy EPON architecture.

Among the advantages of our approach we want to emphasize that it opens a lot of possibilities related to the optimization in the resource usage. For example, we envision end-to-end QoS by the coordination of the SDN controllers in charge of the access, metro and core networks. Another important feature of our architecture is the possibility of sharing the same EPON infrastructure among different service providers, by providing separate slices of resources to each provider, under the control and coordination of the SDN controller. This opens the way for multitenant, virtualized EPON networks, with a substantial reduction in OPEX and CAPEX, and the creation of new business models in the field of optical access networks.

Our work is currently focused in the development of power-saving algorithms in the OLT and the ONUs, and its management by the SDN control plane. Power saving can be obtained by setting the laser transmitters and the receivers of both the OLT and ONUs to a sleep state when there is no traffic [28]. The SDN controller could modify the behavior of the DBA and use the GATE/REPORT messages to switch the state of the ONU between sleep, doze, and active mode. The decision could be taken with the information transported in REPORT messages about the queue status of the ONU for the upstream channel, and the OLT queue information for the downstream channel. The action of setting off transmitters affects the traffic patterns by grouping the data frames in burst, thus introducing delays and jitter, and affecting the QoS. That is why a global approach in which the SDN controller has both the control over the QoS and the energy saving, and can reach an appropriate trade-off.

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