# Optical datacenter network employing slotted (TDMA) operation for dynamic resource allocation

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## ABSTRACT

The soaring traffic demands in datacenter networks (DCNs) are outpacing progresses in CMOS technology, challenging the bandwidth and energy scalability of currently established technologies. Optical switching is gaining traction as a promising path for sustaining the explosive growth of DCNs; however, its practical deployment necessitates extensive modifications to the network architecture and operation, tailored to the technological particularities of optical switches (i.e. no buffering, limitations in radix size and speed). European project NEPHELE is developing an optical network infrastructure that leverages optical switching within a software-defined networking (SDN) framework to overcome the bandwidth and energy scaling challenges of datacenter networks. An experimental validation of the NEPHELE data plane is reported based on commercial off-the-shelf optical components controlled by FPGA boards. To facilitate dynamic allocation of the network resources and perform collision-free routing in a lossless network environment, slotted operation is employed (i.e. using time-division multiple-access - TDMA). Error-free operation of the NEPHELE data plane is verified for 200 μs slots in various scenarios that involve communication between Ethernet hosts connected to custom-designed top-of-rack (ToR) switches, located in the same or in different datacenter pods. Control of the slotted data plane is obtained through an SDN framework comprising an OpenDaylight controller with appropriate add-ons. Communication between servers in the optical-ToR is demonstrated with various routing scenarios, concerning communication between hosts located in the same rack or in different racks, within the same or different datacenter pods. Error-free operation is confirmed for all evaluated scenarios, underpinning the feasibility of the NEPHELE architecture.

**Keywords:** datacenter network, optical switching, slotted network, scheduling, software-defined networking

## 1. INTRODUCTION

Datacenters are at the vanguard of our data-centric Internet infrastructure, providing IT services to a growing number of networked devices, users, and business processes in general. The proliferation of datacenters has led to the fast uptake of new value-added services spanning from high definition video streaming to cloud storage as well as sensor networks in the Internet of Things (IoT), which in turn are calling for larger and more efficient datacenters. We have currently reached the point where the amount of new data generated is larger than our processing capabilities, a situation that is often referred to as the "data deluge". This sheer amount of data is posing inordinate challenges to the datacenter network infrastructure. Datacenter traffic is riding on a steep growth curve reaching 27% annually[1] and the industry grapples to keep pace with this soaring demand. So far equipment providers have effectively relied on Moore's law and Dennard scaling to upgrade DCN infrastructure; however, with traffic growth expectations outpacing silicon scaling rates, increasing concerns are being expressed as to the sustainability of this approach[2]. In this backdrop, new technologies are investigated in order to avoid an imminent capacity crunch and improve power efficiency in the DCN.

Optical switching is gaining traction as a strong contender for gracefully scaling datacenter networks by virtue of the technology's potential for high speed and low power consumption. Optical switching has become the norm in core and metro telecom networks in the shape of reconfigurable add-drop multiplexers (ROADMs) and its application in DCNs is investigated in order to reap the technology's benefits inside the datacenter. Considerable progress is being made not only on the optical switch hardware, but also on the supporting network architectures and management schemes. Alas, application of optical switching inside the datacenter is not a straightforward undertaking, owing to the fundamental differences between optical and electronic switches in terms of port count, buffering capabilities and technological maturity, as well as the larger scale and higher dynamicity of datacenter traffic compared to core and metro networks, as well as the different target cost envelope. One of the most salient challenges towards scalable optically-switched datacenter architectures is the trade-off between switching speed and number of ports, which is faced by current optical switch technologies: Although large switches with hundreds of ports exist, their speed is typically in the millisecond regime and cannot follow the dynamic fluctuations of datacenter traffic. On the other hand, very fast (nanosecond-scale) switches are constrained to a few tens of I/O ports. While efforts to develop switching components with fast reconfiguration speed and large number of I/Os are underway[3,4], particular focus is given on new architectures that can make the most out of existing, well-established technologies, allowing rapid deployment in real networks. These architectures should also tackle the challenge of adapting to the changing nature of datacenter traffic: communications between servers and storage inside the datacenter (intra-datacenter), following an east-west traffic profile, are dwarfing north-south traffic from/to the Internet[1], thus putting more stress on legacy DCN architectures that are inherently more appropriate for north-south flows (notably fat-tree topologies).

Amidst these challenges, several DCN architectures have been investigated tailored to the capabilities and limitations of the most prominent optical switching technologies, such as micro-electro-mechanical systems (MEMS)[5,6], semiconductor optical amplifier (SOA) switches[7,8], tunable lasers combined with arrayed-waveguide-grating routers (AWGRs)[9,10] and wavelength-selective switches (WSSs)[11,12]. These works have proven the concept of optical switching for datacenters, yet several open issues remain as to the scalability of these architectures for serving a large number of hosts. In addition, an outright challenge concerns the control and management of the optical data plane, towards its integration in a fully functional system suitable for practical deployment. Recently considerable efforts were made towards a combined data- and control-plane optical DCN solution, relying on an SDN-controlled switch and interface cards implementing the optical Architecture-on-Demand concept[13] as well as on silicon photonic WSSs combined with tunable lasers and controlled by a custom SDN framework assisted by a dedicated control channel[14]. Still, an end-to-end optical DCN with a scalable data plane architecture and controlled by an SDN framework with packet-level granularity is yet to be demonstrated. To this end we introduced the concept of the NEPHELE European project that is developing an end-to-end infrastructure for disaggregated datacenters. NEPHELE relies on commercial off the shelf (COTS) photonic components for its data plane in order to expedite its deployment cycle and leverages open source control plane frameworks to maximize compatibility with existing infrastructures. In this paper we summarize our recent achievements towards an end-to-end experimental validation of the NEPHELE DCN approach.

## 2. NEPHELE DCN ARCHITECTURE AND OPERATION

The NEPHELE data plane architecture is shown schematically in Figure 1. The NEPHELE DCN consists of pods, with each pod accommodating a number of racks. Each rack is administered by a top-of-rack (ToR) switch and consists of several hosts (i.e. disaggregated storage and compute resources, placed in "innovation zones"). The ToRs are connected to the POD switch in a star topology. Each ToR is equipped with a tunable laser and can reach the remaining ToRs in its pod by properly tuning the wavelength of its transmitted data. Routing of the intra-pod traffic is performed in the POD switch by means of an AWGR. Scaling the dimensions of the network to more racks is achieved by interconnecting multiple pods through a dense wavelength-division multiplexing (DWDM) ring, consisting of multiple fibers to deliver full bisection bandwidth. Inter-pod traffic is handled by fast WSSs placed at the input of each POD switch, serving to drop the wavelengths destined to the specific pod and forward the remaining wavelengths to the next pod through the DWDM ring. Distribution of the dropped traffic to the destination ToRs inside the pod is performed using another AWGR, serving inter-pod traffic. This combination of passive wavelength switching for intra-pod traffic and WSS switching for inter-pod flows allows wavelength reuse among pods, and thus enables network scalability beyond the typical wavelength count of DWDM systems. Further scaling of the NEPHELE network to higher bandwidth (e.g. more hosts per rack) is obtained with the addition of parallel DCN planes. Each plane comprises an independent DWDM ring and is addressed by additional transceivers at the ToRs, i.e. at each ToR, transceiver #1 is connected to plane #1, transceiver #2 is connected to plane #2 etc.

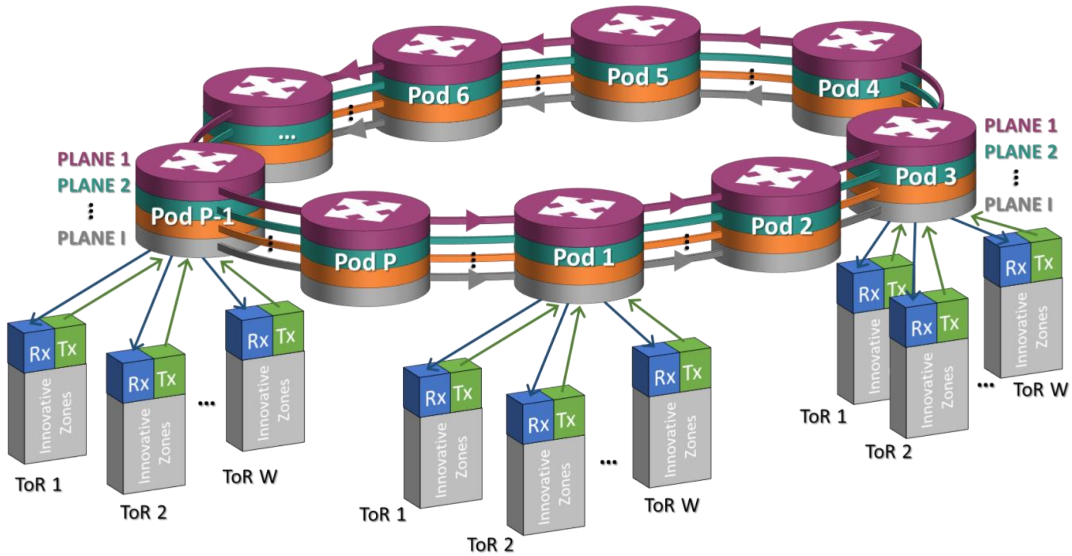


Figure 1: Schematic of NEPHELE data plane network architecture.

Dynamic and efficient sharing of network resources and collision-free routing are facilitated with slotted operation of the network (i.e. using time-division multiple-access - TDMA). Ethernet packets from the source hosts are collected at the ToR where they are encapsulated in the NEPHELE TDMA frames. After routing in the slotted optical DCN, the frames are received at the destination ToR where they are decapsulated; the constituent Ethernet packets are parsed and then routed to the destination host. As such, the NEPHELE ToR demarcates the slotted DCN from the legacy Ethernet data plane, allowing standard Ethernet hosts to be connected to the NEPHELE infrastructure transparently to its optical operation. The ToR distributes upstream traffic from the hosts to the NEPHELE planes making optimal use of the available bandwidth in each plane; for example, a host in ToR *i* of pod *k* can communicate with a host in ToR *j* of pod *l* through all the available planes *I*. This functionality of the ToR distributes the load among planes and maximizes utilization of network resources in the network. In our experimental demonstration, the NEPHELE ToR is implemented with a commercial Mellanox switch interconnected with off-the-shelf FPGA boards that perform the extra custom functionalities required, such as packet encapsulation and decapsulation in the NEPHELE slots and control of the optical hardware. More details on the NEPHELE data plane architecture can be found in ref[15] along with network dimensioning studies, whereas a preliminary validation of the ToR and POD switches is presented in ref[16].

### 2.1 NEPHELE control and orchestration framework

The NEPHELE DCN is controlled through OCEANiA (OptiCal Electrical ApplicatioN Aware data centre network controller), an SDN controller prototype implemented in the project that extends the open source OpenDaylight controller, Lithium version, with SDN applications, algorithms and OpenFlow protocol extensions to efficiently operate a NEPHELE network. OCEANiA is released as open source software under the Eclipse Public License (EPL) version 1.0 and is publicly available[17]. The main service provided by OCEANiA is the on-demand provisioning and tear-down of intra-DC network connections between hosts located in a single datacenter and attached to the NEPHELE ToR switches. This controller interacts on its southbound with NEPHELE OpenFlow Agents that operate at the data plane and are responsible for the translation of the OpenFlow messages received by the controller into the corresponding proprietary messages used to configure the data plane hardware. On the northbound of the controller a set of SDN applications, implemented as external stand-alone applications, implement the logic of the DCN configuration algorithms and network provisioning workflows, offering also a REST-based entry point to request the dynamic and on-demand setup and teardown of network paths between two servers attached to NEPHELE ToR switches. This entry point is typically used by external entities such as a cloud orchestrator that triggers the configuration of the NEPHELE DCN.

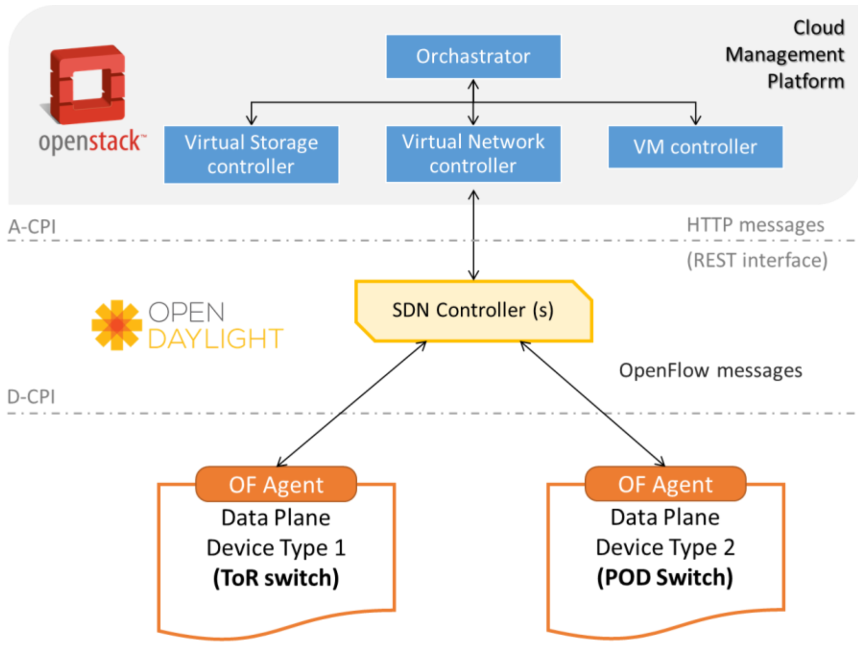


Figure 2: Overall architecture of the NEPHELE datacenter control and orchestration framework.

The NEPHELE OCEANiA controller offers a NorthBound Interface (NBI) to the NEPHELE cloud orchestrator which is based on OpenStack, extended to interface with the NEPHELE SDN controller. The NEPHELE cloud orchestrator requests the creation of reserved network paths dedicated to the delivery of QoS-enabled traffic between VMs deployed in different servers within a single datacenter in an application-aware DCN configuration, employing NEPHELE technologies. Based on the requests received at the NBI, the controller continuously updates the expected DCN traffic matrix and computes an efficient resource allocation solution exploiting the TDMA paradigm of the NEPHELE DCN. The Application Affinity service at the NEPHELE SDN controller is triggered through a REST API, requesting connections with different profiles between source and destination virtual machines residing in the Innovation Zones. The Traffic Matrix Engine aggregates such requests into a Traffic Matrix, representing the global load of traffic that the DCN should carry. The Scheduling Engine then applies a global optimization algorithm to allocate the DCN resources in terms of time slots and planes for that communication (and all traffic represented in the traffic matrix) taking into account the topology and the capabilities of the DCN. Several scheduling algorithms have been investigated in NEPHELE[18] and the experimental implementation is based on the incremental greedy heuristic, which was shown through simulations to experience good throughput performance and low execution time. Finally, the Flow Translator translates the Scheduling Engine's result into a set of OpenFlow (OF) rules and sends them to configure the devices (PODs and ToRs) according to the resource allocation determined by the Scheduling Engine. The SDN agent receives the OF commands, translates them and forwards them to the related data plane device.

## 3. NEPHELE DCN TESTBED AND DEMONSTRATION

### 3.1 Experimental setup of NEPHELE testbed

A DCN testbed was assembled to evaluate the NEPHELE dataplane and demonstrate TDMA slotted operation. The testbed is shown schematically in Figure 3 and comprises two POD and four ToR switches, so as to cover all possible switching and routing scenarios (both intra-pod and inter-pod). The greyed-out areas in Figure 3 serve to enable bidirectional communication between the ToRs and were not used in the current set of experiments; they will be instantiated and validated in follow-up studies. In the current demonstration POD 1 hosts two ToR switches; ToR 1 operates as transmitter while ToR 4 serves as receiver. On the other side, POD 2 hosts two receiver ToR switches and serves both incoming and pass-through optical traffic to a potential next pod (not implemented here). All ToR switches

are equipped with FPGA boards that are mainly responsible for the encapsulation and decapsulation of the Ethernet packets into NEPHELE frames but also facilitate the control of all the optical components and provide an interface with the SDN agent.
In the implemented scenarios, ToR 1 sends slotted TDMA optical traffic to all the receiver ToRs using its tunable transmitter. The ToR 1 FPGA board generates 200 μs NEPHELE frames containing Ethernet packets, followed by 20 μs guard time sections. The electrical data is introduced to a DC-coupled RF driver for amplification and is consequently fed to a 10 Gb/s optical modulator. Through a parallel path, the FPGA controls a FINISAR modulated grating Y-branch (MG-Y) tunable laser through a Texas Instruments digital to analog converter (DAC). The laser is controlled through three currents that are provided from the DAC and control its active elements, i.e. the left and right reflectors as well as the phase section. Additionally, the laser is fed with two constant currents that keep the gain and SOA sections in a predefined stable condition. Through the DAC, the FPGA varies the three control currents fed to the laser during the guard time, thus tuning the wavelength of the laser to the desired wavelength for the subsequent NEPHELE frame, implementing a simple look-up table. The optical traffic generated in ToR 1 is guided through POD 1 according to the desired TDMA schedule towards a destination either within the same POD (ToR 4) or POD 2 (ToRs 2 and 3). Accordingly, all the receiver ToRs are equipped with commercial 10 Gb/s photoreceivers converting the received optical traffic into electrical signals that are fed to the ToR FPGA boards. All network elements (PODs, ToRs) in the testbed are administered by their dedicated SDN agent, running on a PC and communicating with the FPGAs of the PODs and ToRs through PCI/e connections. The SDN agent is responsible for interpreting the schedule coming from the NEPHELE SDN controller into routing and switching commands for the specific network element, setting e.g. the tunable laser's wavelength at the ToRs and the WSS configuration at the PODs for each slot, according to the TDMA schedule. The SDN agents are controlled by NEPHELE's OCEANiA SDN controller, running in a virtual machine (VM) and communicating with the agents through the OpenFlow-based NEPHELE southbound interface (SBI).

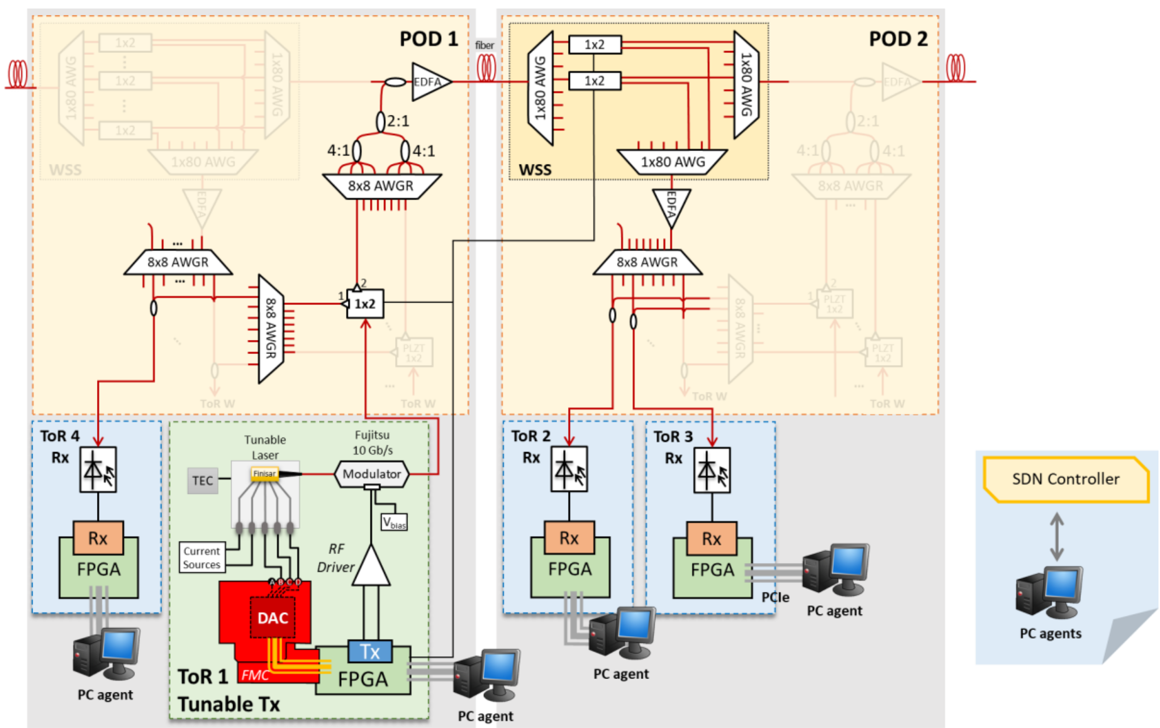


Figure 3: Testbed assembly for the evaluation of the NEPHELE dataplane and the dynamic slotted operation (the red lines are the optical datapaths while the black lines are the electrical control signals).

### 3.2 Slotted TDMA operation of NEPHELE testbed

Slotted operation in NEPHELE entails the dynamic control of all the optical switches and network elements of the NEPHELE architecture, thus enabling dynamic allocation of resources. In the implemented setup four wavelengths were used by the ToR tunable laser to address different destination ToRs; $\lambda_1$= 1546.917 nm, $\lambda_2$= 1547.715 nm, $\lambda_3$= 1548.515 nm and $\lambda_4$= 1549.315 nm. As described in section 2, routing is performed through passive wavelength-switching in the case of intra-pod traffic (by means of AWGs and AWGRs shown in Figure 3) and with a combination of wavelength- and space switching for inter-pod communication (involving also the WSS shown in Figure 3). The data plane elements are controlled by the SDN controller through their corresponding SDN agent.

When a NEPHELE frame is generated in ToR 1, it is introduced into a BATi fast 1×2 optical switch that is controlled by the transmitter's FPGA board. This switch is responsible for separating intra-pod from inter-pod traffic, according to the location of the destination ToR. If the destination is within POD 1 (ToR 4 receiver in this case), the optical traffic is fed into an 8×8 AWGR and depending on its wavelength it is directed to the specific destination ToR. Incoming traffic from different POD switches (not implemented here) is in principle guided through a different AWGR and combined with the intra-pod traffic before reaching the destination ToR. In a similar rationale, the NEPHELE frames that are destined to a ToR in a different POD (POD 2 in this case) will pass through the 1×2 switch and will be guided through an AWGR that handles the POD's outgoing traffic. This AWGR splits the traffic into different planes (one plane was implemented in this demonstration) and circulates the optical frames between the PODs through multiple optical fibers. Before exiting POD 1, the outgoing optical signals are amplified through an Erbium-doped fiber amplifier (EDFA). When entering POD 2, the optical traffic is fed to a WSS. The implemented WSS is based on the demultiplex-switch-multiplex approach and consists of three 1x80 AWGs and 1×2 switches, serving as a result up to 80 wavelengths and destination ToRs. Given that the implemented setup involved two ToRs per pod, the WSS in the experiments was populated with two 1×2 switches. Traffic entering the WSS is demultiplexed in the west AWG and each wavelength is introduced to a 1×2 switch that is responsible for dynamically switching the corresponding wavelength's frames according to the TDMA schedule; it drops the traffic if the destination is in the current POD or passes it through the ring towards the final destination POD. The dropped optical frames are multiplexed again through the relevant AWG and fed to an AWGR that guides the frames based on their wavelength to the destination ToR.

### 3.3 Experimental evaluation

In order to evaluate the performance of the implemented experimental testbed, all possible routing and switching scenarios were carried out and tested. Screenshots of the optical frames captured in a real-time oscilloscope are shown in Figure 4, showing how the optical TDMA traffic progresses after each of the switches in the testbed. In the leftmost figure, the optical signals are captured right after the first 1×2 switch that is responsible for separating the intra- from inter-pod traffic. The red trace packets correspond to intra-pod traffic destined for ToR 4 while the green and blue traces are optical frames destined for ToRs in POD 2. The red dotted line represents the switch control signal coming from the transmitter FPGA board that dynamically configures the switch according to the schedule. In this first scenario, eight NEPHELE frames are guided inside POD 1 towards ToR 4 with the transmitting wavelength being $\lambda_4$= 1549.315 nm. Similarly, eight frames are guided towards POD 2; four frames with destination ToR 2 transmitted at $\lambda_2$= 1547.715 nm and four frames with destination ToR 3 transmitted at $\lambda_3$= 1548.515 nm. In the middle figure, cascaded intra/inter and drop/pass-through switching is shown. The intra-pod scenario remains the same while the 1×2 switches in the WSS behave in a different way. As far as the inter-pod traffic is concerned, the scenario that was carried out is based on a schedule where three frames of $\lambda_3$= 1548.515 nm are destined for POD 2 while the fourth one was destined to an assumed next POD (not included in our setup). Since the traffic for ToR 2 and ToR 3 is on different wavelengths they are wavelength-demultiplexed in the first AWG of the WSS. The green trace illustrates the traffic with destination ToR 2 and in the absence of a control signal all frames are dropped through the WSS and guided to the ToR switch. On the contrary, the blue dotted line represents the control signal of the second 1×2 switch that drops only three out of the four incoming packets to POD 2 while the remaining one would be directed back to the ring and towards its final destination in a different POD. This way, it becomes evident that the dynamic control of the switches allows for slotted operation and switching on a frame level. Following a similar rationale, the rightmost figure illustrates dynamic switching of both WSS switches. The red dotted line is again the signal that controls the switching between intra- and inter-pod traffic, while the green and blue dotted lines represent the control signals of the WSS. In this last scenario, two out of four frames at $\lambda_2$= 1547.715 nm and $\lambda_3$= 1548.515 nm are to be dropped in POD 2. The $\lambda_2$ packets to be dropped are the first and second of the four that were transmitted while the $\lambda_3$ packets to be dropped are the first and third one.

All the aforementioned scenarios where successfully validated (measured bit-error-rate at the FPGA receiver better than 1E-12 in all cases), covering different switching and routing options and validating the dynamicity of the NEPHELE network.

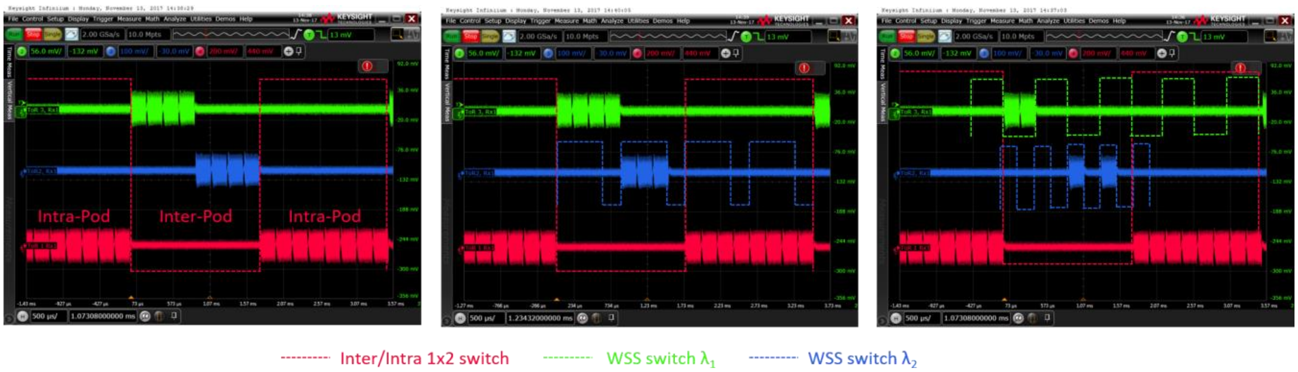


Figure 4: Screenshots of the optical frames propagating through the testbed assembly after each of the three fast switches; the dotted lines represent the relevant control signals for each switch.

## 4. CONCLUSIONS

We reported recent progress in the NEPHELE optical DCN towards end-to-end integration of the developed slotted data plane and SDN control plane. An experimental testbed was developed comprising two POD and four ToR switches with their corresponding SDN agents and SDN controller and various routing scenarios were demonstrated successfully.

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