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Towards A Completely Softwareized Optical Network [Invited]

Reza Nejabati, Shuping Peng, Bingli Gou, Mayur Channegowda, Dimitra Simeonidou

Abstract— **There is no denying the tremendous success of the current optical network technologies. However, the existing optical network infrastructures are not able to support independent evolution and innovation at physical, transport and network layer functionalities, protocols, and services, while at same time supporting the increasing bandwidth demands of evolving applications and their heterogeneous resource usage and QoS requirements.**

This paper addresses this problem by proposing a completely softwareized optical network infrastructure and its key technology enablers including open and programmable optical white box, optical transport and switching technology abstraction as well as a compute-aware optical network virtualization mechanism. Furthermore, these technology enablers are evaluated by experimental demonstration and simulation.

Index Terms—**Virtualization, Optical White Box, Optical SDN**

I. INTRODUCTION

There is no denying the tremendous success of the current Internet. However, the classical Internet is facing two major challenges [1,2,3]:

- Internet infrastructure rigidity caused by fixed architecture and highly specialized network devices creating a major bottleneck for innovation and independent evolution at physical layer, Internet protocols, transport layer functions and network services.
- Emergence of bandwidth intensive Internet applications characterized by heterogeneous networks resource usage patterns and diverse quality of service (QoS) requirements.

There are two main limiting factors for addressing these challenges:

- The deployed network devices in the network infrastructure of the Internet each includes a fixed amount of standard resources such as network processing, switching/routing and communication interfaces. These resources are tightly integrated together at hardware and software levels making the devices suitable for performing specific networking tasks and protocols.
- At the network level, these devices are interconnected together tightly at hardware (interfaces), software and control mechanisms by well defined and fixed network topology, connectivity as well as control and management protocols.

Therefore, it is becoming technically complex and impossible to create a single network infrastructure that can support independent evolution and innovation at physical, transport and network layers functionalities, protocols, and services while at same time supports both increasing bandwidth demands of the evolving Internet applications and also their heterogeneous resource usage and Quality of Service (QoS) requirements.

In order to address these limitations and challenges, there is an increasing need for a highly flexible, programmable, protocol and function agnostic optical network infrastructure. Such an infrastructure can be realized by programmable optical nodes performing both transport and network computing functions and interconnected by a flexible high performance optical network. This is further motivated by the facts that many networking functions are being generalized for the execution over commodity hardware, allowing distribution of functions to the most suitable resources in the network.

This paper extends the work presented in [4] and proposes new architectural and technological solutions based on SDN and virtualization for softwareization of the optical network infrastructure. The rest of this paper is organized in 5 main sections. Section 2 provides an overview of existing related research works. Section 3 describes an architectural framework for softwareization of optical networks. Section 4, 5 and 6 each proposes new technology enablers for realization of the proposed architecture. They include: the new concept of open and programmable optical white box, novel concept of SDN based optical transport and switching abstraction and a compute-aware optical network virtualization. Finally, section 6 evaluates these technology enablers by simulation and experimental demonstration.

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II. BACKGROUND & RESEARCH GAP

A. *Flexible Internet Architecture:*

The notion of ultimate flexibility of the network at the architectural level has been studied mainly within context of Service Orient Architecture (SOA) [5]. It adopts concept of software engineering in order to create a modular network architecture where the required architectural building blocks can be composed and deployed, as they are needed. Applying the SOA concept to the network infrastructure enables creation of Network As a Service (NAS) paradigm. The NAS allows delivery of the network connectivity services to user and applications similar to delivery of cloud computing services and often coordinated with them. However, all the existing solutions are technology dependent and focusing on specific network technology and protocol. Even for a single network technology such as optical they focus only on specific transport format among many existing ones. Furthermore, they consider network comprised of nodes with fixed and predefined standard functionalities i.e. routing and/switching supporting predefined network connectivity services.

B. *Network Functions and Protocols Customization:*

The inability of the current network infrastructure to support customized and arbitrary network functions and protocol based on applications and users requirements is well recognized fact and has been subjects of many studies [6,7]. Among the most advanced solutions proposed so far is the dynamic protocol and network function composition leveraging on cognitive networks technologies [8]. However the major shortcomings of this solution is on its application for IP packet networks only, and also its limitation on supporting only the network functions and protocols that can be build using its predefined simple function blocks. Another initiative to support arbitrary network function composition was first presented in [9], which is based on that some of network functions can be performed over commodity computing hardware and therefore transferred to the edge of network and supported by commodity servers. This allows flexible composition and deployment of customized network functions as a software running on a generic commodity server at the edge of the network. These functions can be easily updated and copied on demand and based on applications requirements. This approach can only support customization of high level (close to applications and services) such as firewalling or load balancing. It doesn't provide any solution for customization of network protocols or network functions that are close to transport layer and specifically optical layer.

C. *Flexible Infrastructure Hardware:*

The classical approach on design and implementation of network devices follows a historical rule of thumb that the hardware is designed for specific network function and transport technologies and also the software that is tightly bundled with the hardware. Current research focusing on developing new network devices is also keeping this rule in mind. Recently there have been new research ideas based on utilizing new advances in programmable hardware for network devices in order to bring flexibility on supported network functions performed by the devices. The most notable published research is proposing a new approach for implementing a reconfigurable data plane based on Field Programmable Gate Arrays (FPGAs) [10]. It uses a combination of FPGA hardware and software to create a function programmable network data plane.

D. *Infrastructure Softwareization and Virtualization:*

Infrastructure softwarization means building a mechanism on top of the physical infrastructure that abstracts network elements as software modules that can be programmed universally like a computer using an operating system. Infrastructure virtualization means creating multiple parallel network infrastructures sharing same physical infrastructure. Virtualization can be achieved by partitioning and/or aggregation of infrastructure resources into virtual resources and then interconnecting them to compose multiple parallel and autonomous virtual infrastructures. Recently, Software Defined Networking (SDN) technology has been introduced as an engineering solution for softwarization and virtualization of network. All the existing work focus on specific transport technologies and there very few researches on mechanisms that address virtualization and softwarization of network that comprises both programmable and heterogeneous optical switching technologies, and computing elements [11,12].

E. *Programmable Networks:*

There has been substantial research on programmable network both at the node level as well as network control and management levels mainly inspired by well-researched area of Active Networking. Recently, there have been new research studies leveraging on principle of SDN for creating functional programmable network nodes [13,14]. However all these works are mainly focused on providing programmable packet processing function and are based on mainly standard layer 2 transport and/or SDN protocols. Also, there has been few innovative works in using cognitive mechanism for creating reconfigurable and programmable networks and nodes. These are mainly focused on protection and selfhealing. These works don't provide any mechanism for creation and deployments programmable optical networks.

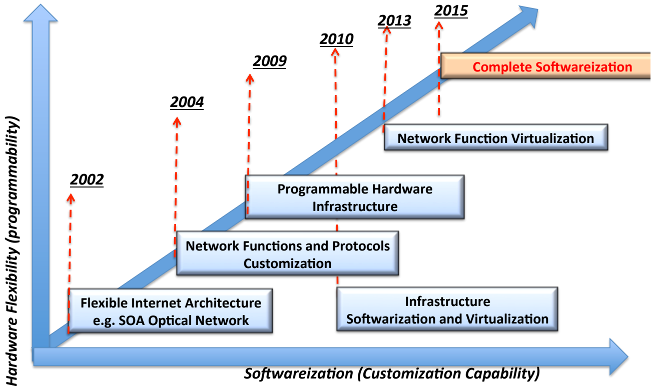


Figure 1: Evolution of network infrastructure flexibility and programmability.

F. *Sever & Datacenter Disaggregation:*

Facebook has recently pioneered the concept of server disaggregation for application in Datacenters through its Open Compute project. The project aims to create a new server architecture for datacenters which is completely disaggregated, modular, interchangeable and distributed (across data center). More recently, Facebook has taken then same concept into the network by pioneering development of the first white box packet switch (i.e. 6-pack switch) utilising open, programmable and modular hardware platform, that is deployed in an SDN controlled network within Facebook data centres [15]. While this solution is only applicable to the closed and controlled environments of Datacenters, it is failing to cover optical networks technologies.

Based on aforementioned background review, Figure 1 shows the evolution of the network in term of hardware programmability and softwareization. It shows that the time and technology advances are right for the next major step change which is complete softwareization of the optical network. To achieve this, there is a clear and urgent need to make a step change in the development of network infrastructure technologies in order to realize a radically new, flexible and deeply programmable optical network infrastructure that can be shaped and programed to support any functions, protocol sand applications from classical to completely new.

III. SOFTWAREIZED OPTICAL NETWORK ARCHITECTURE

An architectural framework for realization of a softwareized optical network is shown in **Figure 2**. This architecture comprises three main technology enablers:

A. *Open & Programmable Optical Switching Nodes:*

The first essential requirement for a softwareized optical network is to utilize optical nodes (switching or cross connects) that are architecturally flexible and open for configuration and/or programming by any external (third party) control algorithms and software. Unlike a traditional optical switching node, an open and programmable optical node includes hardware only, which are fully open and programmable via well-defined interfaces. This allows any network control and management software and algorithms to configure individual nodes to perform specific networking tasks and therefore create a customized or application specific optical network networks.

B. *Switching and Transport Technology Abstraction:*

In order to truly softwareize an optical network infrastructure with all its heterogeneous switching and transmission technologies, an abstraction solution must be developed to hide its technological details and complexity in order to uniformly presents capability of various optical transport and switching technologies. Such an abstraction mechanism will open up the complex optical infrastructure for network application and program developers without any specific knowledge of optical transport network technologies.

C. *Network Infrastructure Virtualization:*

Another important principle to achieve optical network softwareization is the capability for sharing the infrastructure as well as the capability to customize the infrastructure based on the application requirements. The classical optical networks have started to suffer from ossification and hardly can support these capabilities in a scalable manner. A key challenge is deployment of a dynamic infrastructure capable of supporting diverse network-based applications with heterogeneous network resource usage patterns. Optical network virtualization is a promising solution for addressing this challenge. It enables partitioning of an optical network into multiple application/service specific and customized virtual networks without significant investment or change in the physical infrastructure.

The following sections aim to provide a detailed insight about the aforementioned technology enablers and propose a solution for their realization.

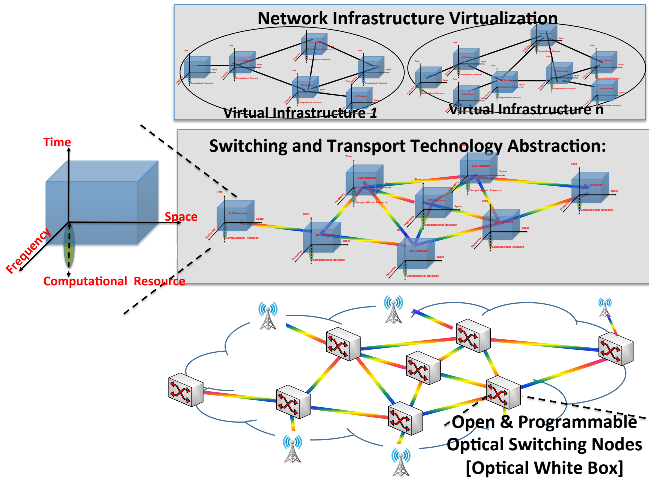


Figure 2 : Architectural framework for a softwareized optical network infrastructure

IV. OPTICAL WHITE BOX : OPEN & PROGRAMMABLE OPTICAL SWITCHING NODES

To achieve full softwareization of the optical physical layer, there is a need for an optical white box. An optical white box is an ultimately programmable and architecturally flexible optical switch that is build on commodity optical hardware components. It is completely open and programmable both architecturally and also at individual components level by an external controller and through well defined interfaces. Here for the first time, we propose a new optical white box utilising open and modular commodity and programmable optical and electronic hardware platforms. It is based on completely new concept, principles and architecture providing an ultimately flexible, programmable, extensible and technology agnostic optical node that progress beyond the current state-of-the-art. It takes the flexibility to a completely new level to the extend that both node physical architecture and functionalities can be reshaped and programmed to support any network architecture, protocols, functions and transport formats. An optical switching node in order to become a white box must be able to support the following features:

- Disaggregate-able, extensible and loosely connected optical switch: An optical white box comprises loosely interconnected elements where these elements can be used independently or aggregated together in an arbitrary architecture. Furthermore the node architecture must be pluggable supporting addition and removal of new hardware elements.
- Programmable network and compute functions: An optical white box comprises a pool of programmable and pluggable hardware elements supporting a broad range of networking functions, computing and transport capabilities including optical, analogue and digital processing as well as computing tasks from signal processing to computationally intensive calculations.

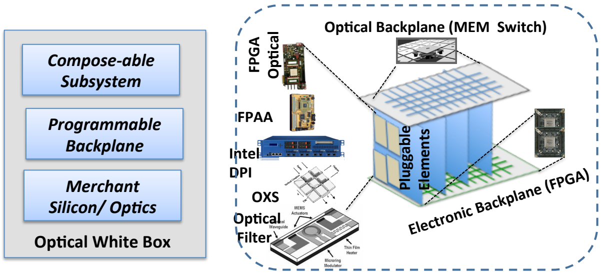


Figure 3: Optical white box architecture and its technology enablers

Figure 3 shows an architectural block diagram of a novel optical white box supporting the aforementioned features. It includes:

A. *Programmable Two-Sliver Backplane*

The backplane flexibility and in a programmable way interconnects all individual elements (see below) of the white box. It also allows different node elements to be added and removed/replaced within a white box. The backplane is a two-sliver backplane including optical and electronic slivers. These slivers are completely protocol and transmission format agnostic to allow any arbitrarily connectivity between different node elements. They are also based on optical and electronic switching technologies with at least millisecond switching regime, in order to support run time architectural reconfiguration of the white box (i.e. connectivity between different elements). Example of a suitable technology for the optical sliver is a Micro-Electro-Mechanical (MEM) based switch [16]. For the electronic sliver, programmable electronic hardware based on Field Programmable Gate Array (FPGA) technology that is programmed as a cross-point switch, is the most suitable technology [17].

B. *Programmable and Pluggable Node Elements:*

The proposed optical white box comprises a set of essential programmable elements required for a generic optical switching node as described below:

- Programmable Interfaces: The basic assumption is that the optical white boxes are interconnected with each other via high-speed optical links and also connected to external devices or network via optical connectivity where transmission format, protocol and bit rate are programmable in both cases. To achieve this capability, the node utilizes a set of programmable transponders based on FPGA that includes high-speed optical interfaces supporting any arbitrary and user defined optical transport format. Example of such an interface is programmable bandwidth variable transponder [18].
- Protocol Agnostic Switching: The proposed node utilizes transport format agnostic optical and electronic switching . The optical switching is proposed to be based on high-speed space switching technology (e.g. Semiconductor based cross point cross point switching [19]) to support both optical space and time slot switching. If it is combined with optical and/or digital filtering capability of the node (see below), it can support frequency switching. For a protocol agnostic electronic switching a protocol independent and programmable packet switch must be used e.g. a solution based on Intel DPDK processor technology which is a generic processor with specific instruction for packet processing [20] (an optical white box for interface with electronic packet switched domain and wireless as well as deep packet inspection at optical layer requires a high speed packet processor).
- Digital Processing Hardware: The optical white box must be able to support physical layer signal processing and network processing functions. To achieve this in a programmable way, an array of two types of FPGAs including Network Processing FPGA and Signal Processing FPGA must be utilized. An optical white box may also include computing resources such as storage and memory for hosting and executing local network functions and algorithms.
- Analogue Processing Hardware: Many network functions specially the ones that are related to optical physical layer require complex analogue processing often based on filtering. To satisfy these requirements, the node includes advanced Field Programmable Analogue Arrays (FPAAs) [21]. They can support electronic analogue and filtering functions. In order to address optical analogue and filtering requirements, the node also includes high-resolution optical tunable filters.

An optical white box utilising the proposed two-sliver backplane provides the flexibility for adding and removing aforementioned elements or adding any new elements (as long as it can interface with one or both slivers of the backplane), as required by the network. Early work on feasibility and scalability study, as well as prototype implementation of a reconfigurable optical switch utilising an optical backplane interconnecting multiple optical elements has been carried out by the High-Performance Network Group in the University of Bristol [22].

V. SDN BASED OPTICAL TRANSPORT TECHNOLOGY ABSTRACTION

The proposed optical white box aims to strip all the intelligent and control out of the node and fully expose the node hardware for external control, operation and configuration. Although this is an essential first step for full softwareization of an optical network, however this is impractical as the control plane of the network is exposed to a heterogeneous and technically complex network physical layer. To overcome this issue and create a homogeneous view of the technologically heterogeneous optical network nodes, we propose a radically novel optical node abstraction model. It completely hides all the technological details of an underlying optical node by creating a generic programming, configuration and operational model for the node.

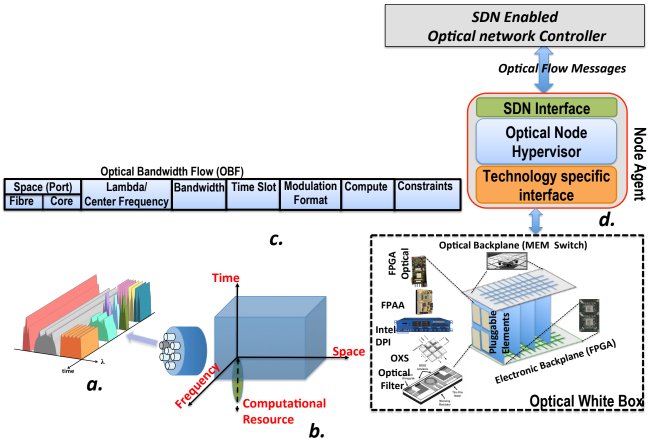


Figure 4: Multi-dimensional abstraction model (a,b), structure of the optical bandwidth flow (c), Architecture of the SDN based node agent enabling technology abstraction (d).

As shown in **Figure** 4.a an optical connectivity can be characterized in three dimensions i.e. time, space and frequency. Based on this, a new multi-dimensional abstraction model is proposed representing capability and operation range of an optical white box in these three main dimensions (as shown in **Figure** 4.b). The model also includes the fourth dimension representing computing capability. An optical white box depending on its utilized technology can have the capability to be programmed and/or operated in one or more of these dimensions. For example a Wavelength Division Multiplexing (WDM) switch or a flexi-grid wavelength selective switch operates in both space and frequency (with different granularities on frequency domain), or a time slotted and frequency selective fast switch operates in all three dimensions (space, time and frequency). Utilising this method an optical node can be modelled as a generic processing node with the capability for both bandwidth processing (i.e. switching in different dimensions) and network computing. Based on this abstraction model an Optical Bandwidth Flow (OBF) is defined as a unit of transport resource (**Figure** 4.c) that can be manipulated and switched by optical nodes.

A. *SDN Agent*

The abstracted model of each optical white box is created by an SDN agent. It sits on top of each optical node as described in previous section. **Figure** 4.d shows the functional architecture of the proposed agent. It comprises three parts:

- Technology Specific Interface: This is specific to each node and support programming, operation, control and monitoring of the specific technologies and elements within an optical node. As such this part of the agent has to be developed specifically for each node.
- Optical Node Hypervisor: This part is responsible to build a model of the device functionalities, capabilities and constraints in space, frequency and time domains as well as its computing capabilities based the proposed abstraction model.
- SDN Interface: This part will act as the interface between the agent and the network control and management (i.e. SDN/network controller) utilising a SDN based protocol.

The proposed agent utilises the concept of OpenFlow (OF), which is an open standard, vendor and technology agnostic protocol and interface that allows separation of data and control plane and therefore it is a suitable candidate for realization of the SDN [23]. It is based on flow switching with the capability to execute software/user defined flow based routing, control and management in a controller (i.e. OF controller) outside the data path. In OF protocol, a flow is the basic switching entity in the network and is defined as any arbitrary combination of the header fields in a standard packet [23]. As such a flow in an OF enabled packet switched network comprises any packets that their header fields match the flow definition. In a modern optical network where digital switching doesn't exist and due to analogue nature of the optical signal, the concept of packet flow is not applicable. To overcome this problem, we introduce the new concept of OBF taking into account the proposed abstraction model. The OBF definition is shown in **Figure** 4.c and extends the concept of flow as defined in OF protocol to the optical layer. Based on the proposed OBF concept, we can define an optical flow as a connectivity that its bandwidth is defined by any arbitrary combination of the proposed OBF fields. As such, a flow in an OF enabled optical network comprises any connectivity that its bandwidth match the flow definition. As shown in **Figure** 4.c, the OBF fields include:

- Space: This field refers to space multiplexing capability of an optical network. For an optical connectivity, this field defines its space dimension i.e. number of fibres, cores per fibre or modes per fibre.
- Lambda, center frequency and bandwidth: Modern optical networks are categorized as either fixed WDM or flexi WDM optical networks. For an optical connectivity, these fields together define lambda and channel spacing in case of fixed WDM or center frequency and bandwidth in case of flexi WDM.
- Timeslot: In time-slotted optical networks, this field defines timeslots used for an optical connectivity
- Modulation format: This field defines modulation formats used for an optical connectivity
- Compute: In emerging cloud computing and content distribution networks the computing and processing resources are being distributed across the network and often co-located (integrated) with network nodes (specially at the edge). In such an optical network a connectivity is defined not only by its bandwidth but also by its computing requirements. This field defines the computing resource requirements of a connectivity

i.e. processing and storage requirements.

- Constraints: This field defines optical or switching constraints e.g. optical power range, delay or impairments sensitivities associated with an optical connectivity.

The proposed OBF with specific value in each field define a signal optical flow. If OBF fields refer to a range rather than specific values then an OBF defines a range of flows or a flow space or set of bandwidth connectivities.

Finally an OBF can also be utilised to define capabilities, operational range and dimension of an optical switching node based on the proposed multidimensional abstraction model. An optical node can be modelled as an entity that its inputs and output operation range and characteristics are defined by their OBF flow spaces while its switching function is modelled as mapping between input flow spaces and out put flow spaces defined by the switch flow table (see below).

The OF protocol defines two types of messages i.e. " flow feature" messages and " flow mode" messages for operation and configurations of an OF enabled SDN switch [23]. These messages are used by the network control pane (SDN controller) to control individual nodes. Following the same principles, the SDN interface in the proposed agent uses two new messages i.e. "optical flow feature" messages and "optical flow mode" messages to interconnect the proposed agent and its associated optical device to the controller. The feature messages utilise the proposed abstraction model to communicate capabilities, features, operational range and constraints of an optical node. The mode messages utilise the proposed OBF to configure an optical node for specific switching action. To support optical flow mode messages, the optical node hypervisor holds an optical flow table that store actions that the optical node must perform on each incoming OBF e.g. cross connection. The SDN controller, update flow tables of each optical node using the flow mode messages and based on outcome of its network applications and algorithms that are running on the network controller. The optical node hypervisor also creates a model of the node based on the proposed abstraction model. It also map the abstracted model of the node into specific flow messages for communication with the controller (**Figure 4**).

Furthermore, the hypervisor holds a set of preloaded atomic network functionalities (simplest and most basic function that a programmable element of a node can perform) that can be used to configure programmable elements of the white box e.g. transponder FPGAs.

Each optical white box includes a pool of elements and utilizing the backplane, they are interconnected independently to support several nodes i.e. virtual nodes (see next section). The hypervisor is responsible for creating and operating these virtual nodes by configuring the backplane and programming node resources under control of algorithms and mechanism described in next section.

The proposed agent is device and technology specific only at its Technology Specific Interface layer. Therefore for any new device or technology just the specific technology interface of the agent must be developed and the rest i.e. the hypervisor and SDN interface remain the same.

VI. VIRTUALIZATION

Network virtualization technology provides a mechanism for partitioning or aggregating network resources into virtual resources and connecting them together in any arbitrary topology to create multiple coexisting but isolated virtual networks running in parallel over a shared physical infrastructure. When network virtualization is applied into a network utilising white boxes, it completely softwareizes the network by enabling full control over physical layer as well as virtual network composition, control and operation.

However, compared to other network technologies (i.e. Layer 2 and Layer 3), optical network has its unique analogue features such as spectrum continuity constraint. The optical layer specific features impact composition of Virtual Optical Networks (VONs). Therefore, when virtualizing an optical network infrastructure, the optical layer characteristics need to be taken into account. Furthermore, in an optical network utilising the proposed white box, the virtualization becomes even more complex since both the node architecture and its elements are programmable and also they may include computing resources to host network functions. In this section the required algorithms in order to create multiple parallel and independent VONs in an optical network utilising the proposed optical white box and the abstraction mechanism are described. A VON, as such, comprises a set of virtual nodes interconnected by virtual links with specific bandwidth-QoS attributes. As shown in Figure1.e , node virtualization is achieved through slicing of the network nodes (note that we don't show virtualization by aggregation here). However, as the optical network is abstracted with the novel concept of optical flow space and OBF, the slicing is applied to the flow space. Based on the requirements of a VON , each virtual node is allocated a slice of the flow space (i.e. range of flows) of the corresponding abstracted physical node. The flow space slicing can be applied in one or multiple dimensions (i.e. space, time and frequency). Moreover, the slicing can also be applied to computing resource of an optical node.

A. Virtualization of Optical Network Utilizing Optical White Boxes

In [12], the authors have conducted extensive studies on the virtual infrastructure provisioning over single-line-rate and mixed-line-rate optical WDM networks. Since the proposed optical white boxes support bandwidth flexible and multi-dimensional optical transport as well as processing and computing capabilities, a coordinated virtualization of bandwidth flexible optical network and computing resources is essential in the designing of the VON composition method.

Here for the development of the virtualization algorithm we consider OFDM-based optical transport technology due to the flexibility and granularity that this technology can provide in frequency dimension. This is further supported by capability of the optical white box that includes programmable and bandwidth-variable transponders (BVTs) as well as bandwidth-variable switching (see pervious section). For the simplicity we also consider only space and frequency dimension in the proposed virtualization algorithm.

In a VON, the requested bandwidth can be satisfied by a combination of OBFs with various line rates and modulation formats. The line rates supported by OBFs depends on the transponders' capability of the optical white box that is reserved for implementation of individual OBFs. To provision an end-to-end connectivity, a BVT in an optical white box (at the edge) will generate optical signals (OBFs) with just enough number of subcarriers and appropriate modulation format, while each optical white box along the route will allocate a switching window with corresponding optical filter width to establish an end-to-end lightpath for each OBF with suitable and sufficient spectrum (optical layer constraints e.g. the spectrum continuity should be also taken into account).

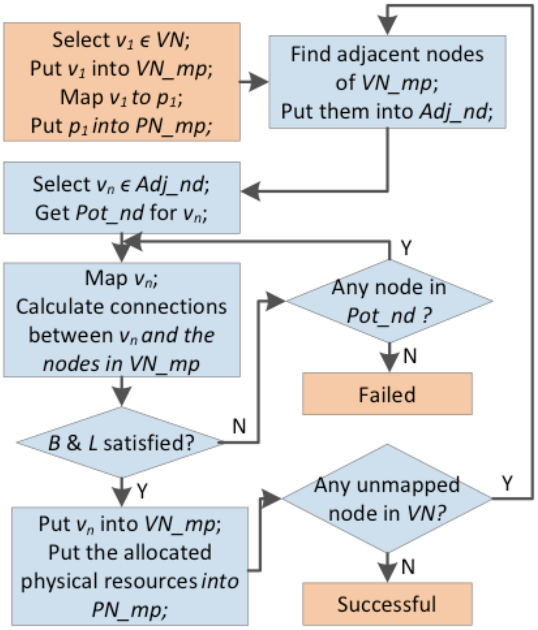


Figure 5: Workflow for compute-aware & multi-dimensional optical network virtualization

Generally, a VON is defined by its topology, attributes and functionalities of virtual nodes, the requested bandwidths and latencies of virtual links. In the VON composition process, virtual nodes are mapped to physical nodes, while virtual links are mapped to physical paths by virtual link mapping methods [24]. Here, we proposed a VON composition method enabled by coordinated virtualization of optical and compute resources over the proposed softwareized optical network as illustrated in **Figure 5** as described below:

- Among all the virtual nodes of a VON request, the one that requests the most compute resources will be selected first and mapped to a physical white box that has the most available resources.
- The mapped virtual nodes will be put into VN_mp list, while the allocated physical resources will be put into PN_mp lsit.
- The adjacent virtual nodes (form the request) of the already mapped virtual node in VN_mp list will be put into Adj_nd list. Again the node that requests the most computing resources are selected (we call this vn), and all the potential nodes for its mapping are put in Pot_nd list.
- The connections between the mapped virtual node (vn) and the nodes in VN_mp will be calculated, and the requirements on bandwidth (B) and latency (L) need to be satisfied as well as the spectrum continuity and contiguity constraints. The modulation format will also be properly selected.
- If all the connections can be established with enough resources and satisfied performance, vn will be put into VN_mp list, while the physical resources will be put into PN_mp llist. If the mapped node is the last one in the VON request, the VON composition is successful.
- If the connections between vn and VN_mp list cannot be found, the next node in Pot_nd list will be checked and goes through the path calculation and allocation process. If there is no node left in Pot_nd list, the provisioning is failed.

It is important to note that the proposed composition method enables the virtual compute and network resources to be mapped in a single step.

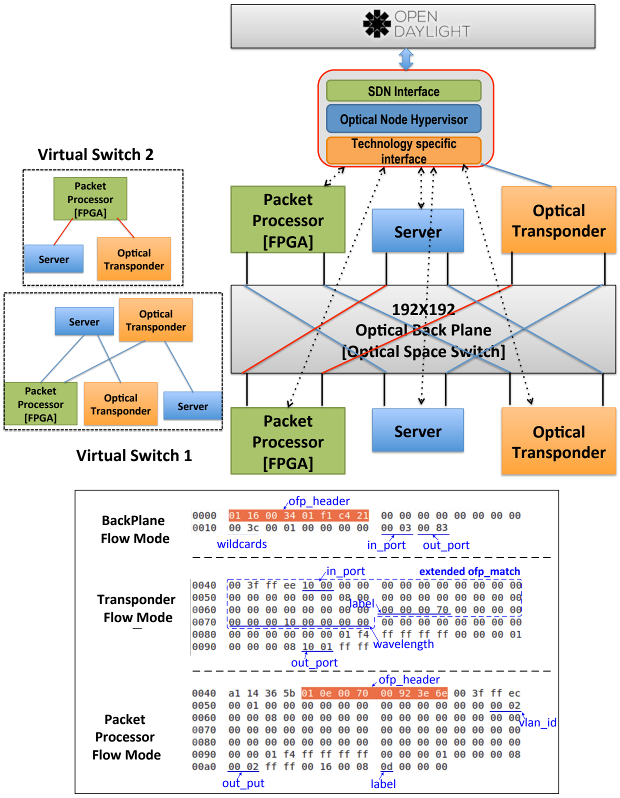
VII. EXPERIMENTAL EVALUATION & SIMULATION

In this section, a proof of concept implementation of the proposed optical white box and the SDN agent is experimentally demonstrated based on work reported on [26]. Furthermore, the proposed impairment-aware and compute-aware optical network virtualization algorithms are evaluated by simulation based on work reported on [27].

A. *Experimental Evaluation*

We have experimentally demonstrated the proposed agent over an optical white box with limited functionalities. In this experiment we implemented an optical white box, which comprises a space switch with 192X192 ports as an optical backplane (in this experiment, for simplicity we don't use any electronic backplane). Two FPGA based packet-processing elements, each with two 10GE optical interfaces are plugged into the backplane. Two Servers are connected into the backplane via two 10GE optical interfaces. Finally, two bandwidth variable and programmable transponders with two 10Gpbs optical interfaces are plugged into the backplane. Individual elements of the optical white box are connected via 1GE management interfaces to a computer that runs the proposed Agent. The agent is also connected to an OpenDaylight SDN controller running in a separate computer. The experimental set up is shown in Figure 7.

A program in the controller randomly generate requests for optical nodes (virtual nodes) and communicate them with the agent in order to implement them in the white box. Figure 7 shows a snap shot of two random requests. The first request first is for a virtual optical switch (virtual switch 1) comprising a packet processor, two servers and two optical transponders with the architecture shown in the Figure 7. The second request is for a virtual optical switch (virtual switch 2) comprising a packet processor, a server and an optical transponder with the architecture shown in the Figure 7. After processing the requests, the SDN controller will push the devices' configurations via the proposed agent. These are then translated into technology specific control messages by the agents of the node elements. Figure 7 shows flow mode messages generated by controller and processed by the agent for configuration of various elements of the optical white box (the required backplane configuration arrangement to support these two requests are marked blue and red in Figure 7). The breakdown of the timing for successful configuration and deployment of a node request are: Node Hypervisor to build the model and the node (35.12ms), information processing and message exchanges in the OpenDaylight SDN controller (195ms),Information processing and message exchanges in the agent (158ms), and device configurations (25ms) .



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0040   00 3f ff ee 10 00 00 00  00 00 00 00 00 00 00 00
0050   00 00 00 00 00 00 08 00  00 00 00 00 00 00 00 00
0060   00 00 00 00 00 00 00 00  00 00 00 70 00 00 00 00
0070   00 00 00 10 00 00 00 00  00 00 00 00 00 00 00 00
0080   00 00 00 00 00 00 01 f4  ff ff ff ff 00 00 00 01
0090   00 00 00 08 10 01 ff ff
```

```
0040   a1 14 36 5b 01 0e 00 70  00 92 3e 6e 00 3f ff ec
0050   00 01 00 00 00 00 00 00  00 00 00 00 00 00 00 02
0060   00 00 08 00 00 00 00 00  00 00 00 00 00 00 00 00
0070   00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
0080   00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
0090   00 00 01 f4 ff ff ff ff  00 00 00 01 00 00 00 08
00a0   00 02 ff ff 00 16 00 08  0d 00 00 00
```

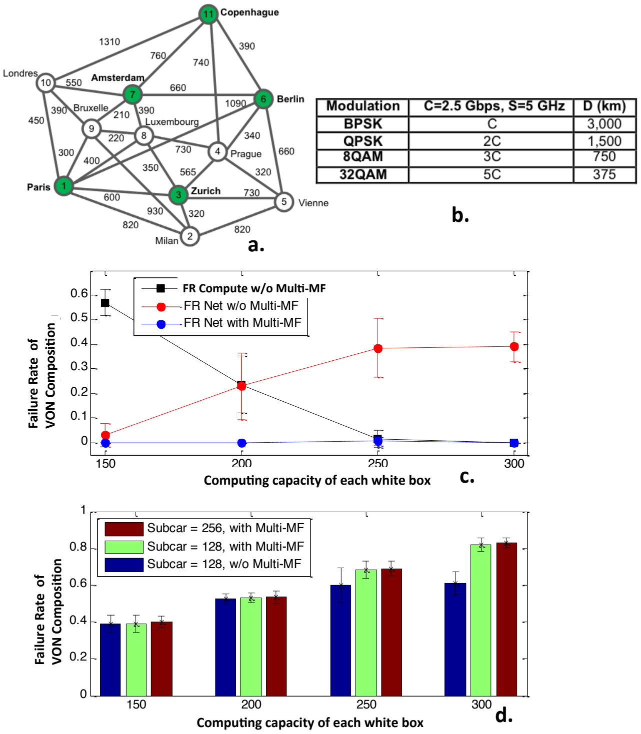
Figure 7 : Experimental set up for an optical white box and an agent showing SDN controller messages and Configuration of virtual optical switches

B. Simulation

In this section, the performance of the proposed compute-aware & multi-dimensional optical network virtualization method is evaluated using simulation.

The COST239 European Optical Network (EON) topology is used as the physical topology. We assume two types of optical white boxes are deployed: the white boxes with computing resources (computing capacity is set 150 to 300 units) and the white boxes without computing resources as shown in Figure 6.a. The number of subcarriers per link is 128 or 256.

The VON topologies are randomly generated (20 in total) with controllable parameters: the number of virtual nodes (3 or 4), the network degree (2 or 3), the probability of interconnecting virtual nodes (0.5), the bandwidth of virtual links (10 to 75 Gbps), and the requested capacity of each virtual node (20 to 30 units). In this study, we adopted four modulation formats, i.e. BPSK, QPSK, 8QAM, and 32QAM. The parameters such as subcarrier capacity (C) and spectrum (S) and the maximum transmission distance (D) with acceptable quality of transmission are given in Table Figure 6.b.



Modulation	C=2.5 Gbps, S=5 GHz	D (km)
BPSK	C	3,000
QPSK	2C	1,500
8QAM	3C	750
32QAM	5C	375

Figure 6: a: COST239 EON with 11 nodes and 26 links. White boxes with computing capability are marked in green, b: Parameters of different modulation formats The length of each physical link is labeled, and the unit is km, c & d: the result of compute-aware virtualization

We evaluated the performance of the proposed virtualization in terms of the failure rate (FR) of VON provisioning caused by lack of computing resources in nodes (“FR compute” in Figure 6.c) or available spectrum (“FR Net”), and the acceptance rate affected by the total number of subcarriers (“Subcar”) and multiple modulation formats (“Multi-MF”) availability (Figure 6.d). We can see that as the computing capacities increase, the constraints coming from the limited computing resources becomes relieved (black), while the network capacity becomes the dominant factor for damaging the overall performance (red). However, as we can see from the results, after the capability for choosing modulation format is enabled, the bottleneck arisen from the network is almost eliminated (blue). In Figure 6, it shows that the overall acceptance rate is increasing as the computing capacities grow, and the Multi-MF capability push the improvements forward, while the effect of the further increased network capacity is negligible under the given bandwidth demands. The results proved a key point which is essential in VON composition, that is, the computing and network need to be coordinately taken into account, since they may alternately become the performance bottleneck.

VIII. CONCLUSION

This paper introduced the concept of network infrastructure softwareization as a solution to address the rigidity of the existing optical networks. To create a softwareized optical network, the paper proposed a set of key technological enablers. These are: the optical white box as an ultimate open and programmable optical switch, SDN based optical transport and switching technology abstraction, and a compute aware optical network virtualization. A proof of concept implementation of the proposed optical white box and the SDN abstraction mechanism was experimentally demonstrated while performance of the proposed virtualization mechanism was evaluated with simulation.

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