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Optical Network Democratization

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The current Internet infrastructure is not able to support independent evolution and innovation at physical and network layer functionalities, protocols, and services, while at same time supporting the increasing bandwidth demands of evolving and heterogeneous applications. This paper addresses this problem by proposing a completely democratized optical network infrastructure. It introduces the novel concepts of optical white box and bare metal optical switch as key technology enablers for democratizing optical networks. These are programmable optical switches that their hardware is loosely connected internally and completely separated from their control software. To alleviate their complexity, a multi-dimensional abstraction mechanism utilising software defined network technology is proposed. It creates a universal model of the proposed switches without exposing their technological details. It also enables a conventional network programmer to develop network applications for control of the optical network without specific technical knowledge of the physical layer. Furthermore, a novel optical network virtualization mechanism is proposed, enabling composition and operation of multiple co-existing and application specific virtual optical networks sharing the same physical infrastructure. Finally, the optical white box and the abstraction mechanism are experimentally evaluated, while the virtualization mechanism is evaluated with simulation.

1. Introduction

The Interment infrastructure democratization refers to the process by which the infrastructure moves away from traditionally closed, vendor specific and technologically monopolised to a completely open, accessible, vendor and technology agnostic infrastructure [1].

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An immediate and arguably the most important result of the infrastructure democratization is rapid innovation [1]. Internet infrastructure has benefited immensely from technology democratization. However, so far the effect has been mainly on user-end devices i.e. computers and mobile phones. Computer industry was the first to benefit from technology democratization by moving away from vendor specific, closed and tightly integrated hardware and software solutions. Today's computer technologies are based on solution where hardware is open, accessible and programmable via standard interfaces (i.e. drivers and Application Programmable Interfaces (APIs)) that abstract uniformly various hardware technologies within a computer. This has resulted major and rapid innovations in computer operating systems and applications during the past three decades. More recently, mobile industry, pioneered by Google and Apple has also immensely benefited from technology democratization with introduction of smart phones and operating systems that abstract and open up the mobile hardware to application programmers.

By observing the ongoing trends in computer and mobile phone technologies we can define a set of fundamental features required for democratization of Internet infrastructure technologies. These features include:

- Complete disaggregation of hardware from its control software
- Abstraction of hardware via well-defined interfaces and protocols in order to hide its technological details
- Enabling users and application developers to customise and program hardware without a detailed knowledge of the hardware technology
- Capability for development of software, applications and control mechanisms independent of the hardware (seamless porting of software and applications across different hardware platforms)
- Virtualization of hardware for independent sharing and customization by multiple co-exiting applications or users

The rapid and immense success of democratization of the computer and mobile device technologies has recently generated a wave of research and innovation pioneered by Software Defined Network (SDN) for democratization of communication network technologies [2]. SDN is defined as a control framework and technology that supports programmability of network functions and protocols by decoupling the data plane and the control plane, which are currently integrated vertically in most network equipments. The separation of control plane and data plane makes the SDN a suitable candidate for a control plane supporting multiple domains and multiple network technologies. Furthermore, the SDN technology when is combined with network virtualization allows manipulation of logical map of the network and creation of multiple co-existing network slices (virtual networks) independent of underlying transport technology and network protocols [3]. SDN and network virtualization together enable a network to support the aforementioned features and therefore they are the key technology enablers for democratization of the network infrastructure of the Internet.

New generation of Internet services are mainly characterized by global delivery of high-performance network-based applications such as cloud computing and (ultra) high definition video on demand streaming over a high-capacity network. As a result the network infrastructure of the Internet is undergoing a major evolution with deployment of high speed wireless driven by 5G technologies at the edge of the network back-hauled by high capacity and dynamic optical network driven by multi-dimensional and flexible optical network at the core. However, the existing SDN and virtualization technologies are mainly developed for electronic packet switched networks which makes them unsuitable for wireless and optical networks that are analogue in nature with highly non-linear and time varying transmission characteristics. Therefore, in order to achieve democratization of the network infrastructure of the Internet, both SDN and virtualization require major innovation in order to make them suitable for wireless and optical networks.

This paper aims to propose new architectural and technological solutions based on SDN and virtualization for democratization of the optical network infrastructure. Since modern optical networks (e.g. flexi grid optical network) and modern wireless networks (e.g. massive Multiple-input multiple-output (MIMO)) exhibits same features and characteristics, therefore similar approaches can be adopted for democratization of wireless networks. The rest of this paper is organised as follows: section 2 describes the architectural building blocks and technology enablers required for democratization of emerging optical networks. Section 3, introduces the new concept of optical white box and bare metal optical switch. Section 4, proposes an SDN based solution for abstraction of optical network elements. This section also includes an experimental evaluation of the proposed solution. Section 5, describes challenges and solutions for virtualization of an optical network. This section also reports on evaluation of the proposed virtualization methods.

2. Optical Network Architecture Supporting Democratization

The classical optical network is facing two major bottlenecks for democratization :

1. The deployed network devices in the optical network each includes a fixed amount of standard resources such as switching 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.
2. At network level, these devices are interconnected together tightly at hardware (interfaces) and software levels by well defined and fixed network topology and connectivity as well as control and management protocols.

Therefore, it is becoming technically complex and impossible to create an optical network infrastructure that can support independent evolution and innovation at physical and network layers functionalities, protocols, and services while at the same time supports the evolving Internet applications with their heterogeneous resource usage and 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. An architectural framework for realisation of such an optical network is shown in Figure 1. This architecture comprises three main technology enablers aiming to support the fundamental features of a democratised optical network infrastructure as mentioned in previous section:

- **Bare metal optical switch or optical white box:** the first essential requirement for democratising an optical network is to utilise 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 optical white box (or optical bare metal node) includes hardware only which are fully open and programmable via well defined interfaces. This allows any network control software and algorithm to configure individual nodes for specific networking tasks and therefore create a customised optical network.
- **Abstraction:** In order to truly democratise 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 technology will open up the complex optical infrastructure for network application and program developers without any specific knowledge of optical network technologies.
- **Virtualization:** Another important principle to achieve network infrastructure democratization is the capability for sharing the infrastructure as well as the capability to customise the infrastructure based on the application requirements. Classical optical networks has 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.

Both abstraction and virtualization constitute the main building blocks of a democratized network operating system that hide the complexity of underlying infrastructure. Such an operating system must also include functions to ensure reliability and stability of the infrastructure when is programmed and operated by applications and users. In this paper, these functions are discussed only within context of the virtualization and abstraction.

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

3. Bare Metal Optical Switch and Optical White Box

A major bottleneck for democratization of the optical network is the deployed network nodes that are tightly integrated together at hardware and software levels making the devices suitable only for performing specific networking tasks and protocols. In order to address this limitation, there is an increasing need for a highly flexible, programmable, protocol and function agnostic optical switching node capable to perform any transport functions and well as network functions and algorithms. 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.

(a) Bare Metal Optical Switch

The first step for design and development of an open and programmable optical node is to leverage on SDN technology to convert a classical optical switch to a bare metal optical switch that is fully open and can be programmed in an abstracted way by any external control mechanism. We define a bare metal optical switch, as a classical optical switch which is SDN enabled i.e. without any integrated control software and equipped with SDN enabled control interfaces. This allows configuration of the switch with any external (third party) controller. As shown in Figure 2.a, we propose a novel optical SDN agent (see details in section 4) that sits on top of any classical optical switch and makes the switch a bare metal optical switch i.e. provides a universal SDN enabled control interface that allows configuration of the switch irrespective of its comprising technologies or internal architecture. In an optical network comprising of bare metal optical switches equipped with the proposed SDN agent, networks applications and physical layer nodes can be developed and evolved independent of each other. More importantly, the powerful abstraction capability provided by the proposed SDN agent (see section 4) allows a conventional network programmers (i.e. common linux programmers) to develop network applications for control and management of optical network without specific technical knowledge of the optical physical layer.

(b) Optical White Box

Although the proposed bare metal optical switch is the first step towards the democratization of the optical network physical layer, however it still relies on the classical and off-the-shelf optical switching nodes that are equipped with an SDN agent such as the one proposed in section 4. A bare metal optical switch comprises specialised and often none-open hardware component that are tightly integrated with a fixed architecture. It can be configured via standard management interfaces which usually hide the internal architecture and details of the individual component of the switch.

To achieve full democratization of the 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. Facebook has pioneered the concept of the white box switch by 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 [4]. 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 and architecture providing an ultimately flexible, programmable, extensible and technology agnostic optical node that progress significantly 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 support the following features:

- **Disaggregate-able, extensible and loosely connected node:** 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 1.b and Figure 2.b show an architectural block diagram of a novel optical white box supporting the aforementioned features. It includes:

Programmable Two-Sliver Backplane: This 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 based. It 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 be 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 [5]. 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 [6].

Programmable and Pluggable Node Elements: The proposed optical white box comprises a set of essential programmable elements required for a generic optical 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 connectivities 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 FPGAs that include high-speed optical interfaces supporting any arbitrary and user defined optical transport format. Example of such an interface is a programmable bandwidth variable transponder [7].
- Protocol Agnostic Switching: The proposed node utilizes transport format agnostic optical and electronic switching . The optical switching must be based on high-speed space switching technology (e.g. Semiconductor based cross point cross point switching

[8]) 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 [9] (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 e.g. SDN agent (see next section).
- 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) [10]. 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. The programmable network elements when interconnected together via the two sliver-backplane constitute an advanced and programmable phonetics network possessor which is the key building block for the proposed optical white box.

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 reported by the High-Performance Network Group in the University of Bristol [11] as well as the Task Force Photonic Network Vision 2020 of the Photonic Internet Forum [12].

As shown in Figure 2 and similar to a bare metal optical switch, the optical white box also utilises an SDN agent (as described in section 4) that abstract its capability and functionality and provide an SDN compatible interface for its programming, configuration and operation.

4. Abstraction

Optical bare metal to some extent and optical white box to a full extent both aim 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 democratization of an optical network, however this is impractical as the control plane of the network is exposed with 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.

As shown in Figure 2.d an optical connectivity can be characterised 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 node (white box or bare metal as described in previous section) in these three main dimensions. This is shown in in Figure 1.c. 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 in 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 2.c) that can be manipulated and switched by optical nodes.

(a) SDN Agent

The abstracted model of each optical node is created by an SDN agent that sits on top of each optical node as described in previous section. Figure 2 shows the functional architecture of the proposed agent. It comprises three parts:

- **Technology Specific Interface:** This is specific to each node and supports programming, operation, control and monitoring of 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 an SDN based protocol.

The proposed agent utilises the concept of OpenFlow (OF), which is an open standard (standardized by of Open Networking Foundation (ONF)), 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 [13]. 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 [13]. 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 proposed abstraction model. The OBF definition is shown in Figure 2.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 is an OF enabled optical network comprises any connectivity that its bandwidth match the flow definition. As shown in Figure2.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 categorised 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 single 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 multi-dimensional 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 [13]. 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.

The most innovative part of the proposed agent is the optical node hypervisor. It holds an optical flow table that store actions that an 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 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 (Figure2).

The aforementioned hypervisor functionalities are common for both optical white boxes and bare metal optical switches. However, the hypervisor requires to perform extra functionalities for an optical white box, as described below:

- Function Library: this includes 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
- Node Composition: Each 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. node modeller and SDN interface remain the same.

(b) Experimental Evaluation of an Example Implementation

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 an optical 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 3.a.

A program in the controller randomly generates request for optical nodes (virtual nodes) and communicate them with the agent in order to implement them in the white box. Figure 3.c 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 3.c. 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 3.c. 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 3.b 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 Figyure 3.a). 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 SDN controller i.e. OpenDaylight (195ms),Information processing and message exchanges in the agent (158ms), and device configurations (25ms).

5. Virtualization

Since network applications are becoming increasingly diverse in terms of their network requirements and usage patterns, an important feature of a democratised network is the ability to support application specific networking. This can only be achieved by enabling each application to configure and operate the network based on its own requirements.

Network virtualization technology aims to address these requirement by providing a mechanism for partitioning or aggregating network resources into virtual resources and connect them together in any arbitrary topology to create multiple coexisting but isolated virtual networks running in parallel over a shared physical infrastructure. Network virtualization technology enables applications and services each to compose and control their own network slice. When network virtualization is applied into a network utilising white boxes, it completely democratises 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 wavelength and spectrum continuity constraints as well as linear and non-linear impairments. These optical layer features impact isolation between coexisting Virtual Optical Networks (VONs) and hence the VONs composition methods. Therefore, when virtualizing an optical network infrastructure, these inherent 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 node architecture and its elements are programmable and also they may include computing resources to host network functions. This is shown in Figure 1.e.

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 Figure 1.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 the OBF, the slicing is applied to the flow space. Based on the requirements of a VON , each virtual node is allocated a slice of a 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 via conventional compute virtualization methods.

(a) 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 [14]. In this paper, we propose a Multidimensional, Multi-rate and Computing-aware (MMC) optical network virtualization algorithm. It is designed to support the proposed democratised Multidimensional and Multi-Rate (MMR) optical network physical layer. Considering the unique features of the optical network, the proposed MMC algorithm comprises an impairment-aware VON mapping methods. A flowchart for the proposed method is given in Figure 4.a (for simplicity, in this section we don't consider the time dimension or time switching capability for optical node. The flowchart also doesn't include compute resource virtualization of the node. This will be considered in the next section).

In MMR optical networks, the requested bandwidth can be satisfied by a combination of OBFs with various line rates. The line rates supported by OBFs depends on the transponders' capability of the optical white box that is reserved for implementation of individual OBFs. The choice can affect the network resource utilization. For instance, for a 30Gbps OBF request, with optical white boxes that its transponder is programmable to either 40Gbps or 10Gpbs, two options are possible. We can consider either to utilise one 40Gbps transponder or three 10Gbps transponders. The first option can save two transponders, while the latter one provides zero residual bandwidth. The proposed VON composition method is resource-aware and chooses the combination of line rates considering the trade-off between the minimum number of channels and the least amount of residual resources in order to save resources for future VON requests.

In MMR networks, the impact of impairments such as Amplified Spontaneous Emission (ASE), Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) is similar to that in single line rate optical networks [14]. However, the impact of nonlinear impairments between different OBFs is asymmetric, particularly the Cross Phase Modulation (XPM). Low bit rate OBFs e.g. 10 Gbps severely impact the with higher bit rate OBFs e.g. 40 Gbps or 100 Gbps by a detrimental XPM impairment. Since, the XPM generated from the high-line-rate OBFs is not so harmful, and neither the XPM between the OBFs with the same line rate [15]. Therefore, in the proposed impairment-aware VON composition method, we assess the impact of impairments using the impairment model elaborated in [16], and select the transponders with suitable line rates and spectral separation in order to minimize the impact of non-linear impairments and guarantee the transmission quality and the isolation of coexisting VONs.

(b) Computing-aware Optical Network Virtualization

A virtual optical network infrastructure can be composed using the methods presented above. However, as it was mentioned earlier, an optical white box may also include computing resources and as such OBFs and therefore VONs may require computing resources (e.g. to perform complex network functions). Here we propose a coordinated computing and optical network infrastructure virtualization method. In this method, a physical infrastructure is modelled as a weighted undirected graph comprising a set of computing and optical network resources (including optical nodes and links). Each optical white box is associated with a set of common attributes such as geo-location and a set of technology dependent attributes such as CPU/storage capacity for computing resources and optical networking resources.The proposed method for mapping a VON to physical infrastructure performs the following steps:

(i) The geo-location requirements of virtual nodes in the requested VON are checked first (i.e. whether the locations of virtual nodes are specified) in order to reduce the potential search space.
(ii) During the mapping process, virtual node requests that require the most computing resources will always be mapped first. If there are more than one candidate physical nodes suitable for a particular requested virtual node, the physical node that has the most available capacity is selected for the purpose of load balancing.
(iii) After mapping each virtual node, the associated virtual links that interconnect the newly mapped virtual node and the already mapped nodes are considered for mapping by using step 4 and 5.
(iv) For mapping a virtual link, suitable physical paths that can satisfy the requirements of virtual links (i.e. bandwidth and latency) are found by using routing algorithm (e.g. k-Shortest Path).
(v) After a suitable physical path is found for a virtual link, which can satisfy all the requirements, taking into account the analogue features (e.g. impairments as described in previous section) in optical layer, the requested bandwidth of a virtual link is mapped within a physical path as stated in the previous section.

In the proposed method, a complete mapping step includes the mapping of a virtual node (i.e. network and computing) and the virtual links that interconnect the virtual node. If a mapping step is failed due to lack of resources, the algorithm can return back (i.e. this is a backtracking algorithm) to the last successful mapping step and continue mapping from there.

(c) Simulation of an Example Virtualization Scenario

In this section, the performance of the proposed infrastructure virtualization methods is evaluated using simulation. The NSF topology with 14 nodes and 21 links is adopted, as shown in Figure 4.b. The network is transparent and three types of OBFs (different in their bandwidths) per virtual link are requested: type I [10Gbps-40Gpbs] (50%), type II (40Gbps-120Gbps] (40%), and type III (120Gbps-360Gbps] (10%). k-Shortest Path routing algorithm is used to map virtual links to physical paths, where k = 2. The impairment assessment model in [15,16] is used to evaluate the impact of the impairments during the process of composing virtual optical networks. The fibre parameters used in the impairment assessment are given as follows: each fibre span consists of an Single Mode Fibre (SMF) and a Dispersion Compensating Fibre (DCF). SMF: D(dispersion parameter) is 17 ps/(nm*km), r(nonlinear coefficient) is 1.3/(W*km), attenuation parameter α is 0.2 dB/km, n2(nonlinear refractive index) is 2.6*10^{-20} m^2/W, Aeff(effective area) is 80*10^{-12} m^2; DCF: D is -92 ps/(nm*km), r is 6.0/(W*km), α is 0.6 dB/km, n2 is 3*10^{-20} m^2/W, Aeff is 20*10^{-12} m^2. Bit Error Rate Threshold (BERth) before Forward Error Correction (FEC) is set to 10^{-6}. Each simulation randomly generates 1000 VON requests. VON requests follow a Poisson process with average inter-arrival period of 20 time units, and each VON has an exponentially distributed holding time (life time) with mean value varying from 200 to 1000 time units. The failure rate of VON composition is taken as the performance comparison criteria, defined as the ratio of declined VON requests relative to the total.

Figure 4.c shows performance of the proposed virtualization algorithm with and without taking into account effect of the impairments. When the impairments are taken into account, during the selection of proper resources, the suitable spectral separation Δf is estimated by calculating the penalty introduced by XPM which is set at less than 0.1 dB and BER that is larger than BERth. To evaluate performance of the proposed computing-aware virtualization algorithm the same aforementioned NSF topology is used (Figure4.b). The number of computing resources of the infrastructure is randomly generated and attached to the randomly selected optical switches, and each node with computing resources has an initial processing capacity 100 units. Each pair of virtual nodes in a VON is randomly connected with a probability of 0.5. The network degree of the generated virtual topology is uniformly distributed between 2

and 3. The number of virtual computing resources is randomly generated and attached to the randomly selected virtual network nodes, and each virtual computing resource in virtual node has the capacity between 1 and 20 units. The requested bandwidth per virtual link is uniformly distributed between 10 and 100 Gbps. For simplicity, the geo-location requirement of virtual nodes was not considered. Each result presented as statistical values is collected by running simulation four times. As it was explained before, in computing-aware virtualization algorithm if a single mapping step is failed, the algorithm will call a backtracking function and return back to the last successful mapping step and continue finding a mapping solution. When a mapping solution cannot be found due to the size of a network, the backtracking attempt would make the mapping process traverse the whole search branches. It will severely effect the convergence time and performance of the VON mapping in large-scale networks. Therefore, we need to introduce a threshold on the backtracking to limit the maximum backtracking attempts. Here, we conducted simulation studies to evaluate the restriction. The threshold m on the backtracking attempt is determined according to the requested VON size (m=0 means that there is no backtracking, m=∞ means that backtracking attempt is unlimited). In Figure 4.d, we can see that the backtracking can improve the VON mapping performance in terms of the acceptance ratio of requests, especially when the VON is larger.

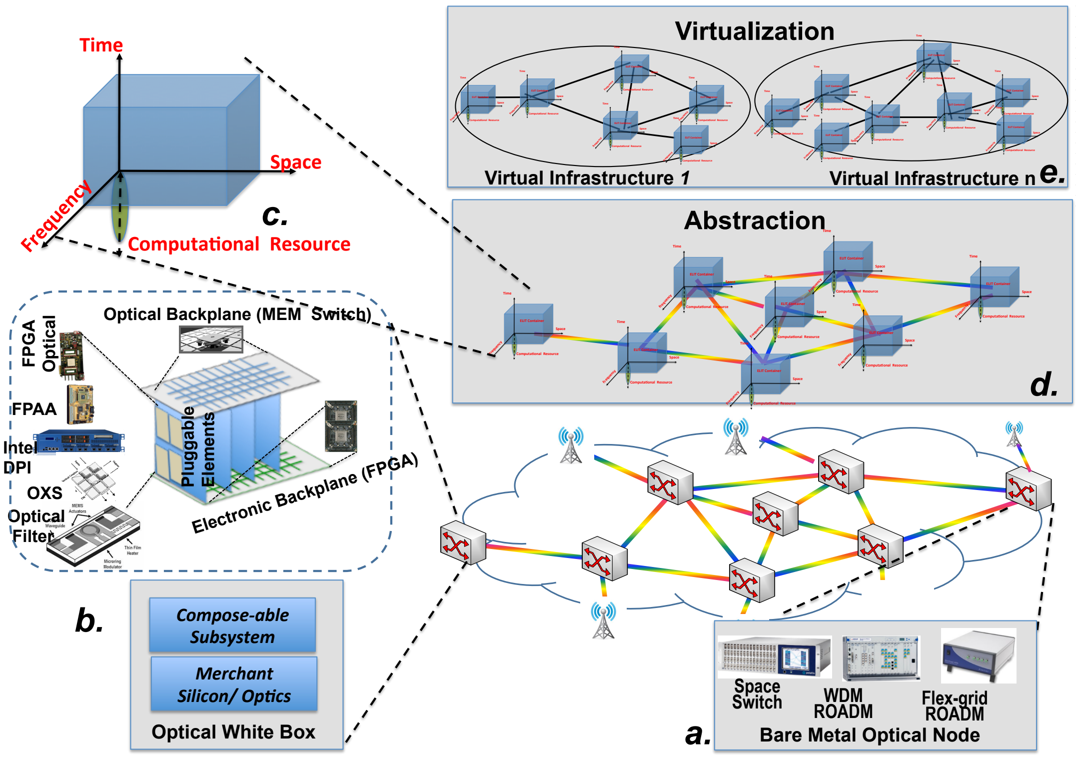

Figure 1. An architectural and technological view of a democratised optical network. **a:** bare metal optical switch, **b:** optical white box, **c:** multi-dimensional abstraction model, **d:** abstraction layer, **e:** virtualization layer

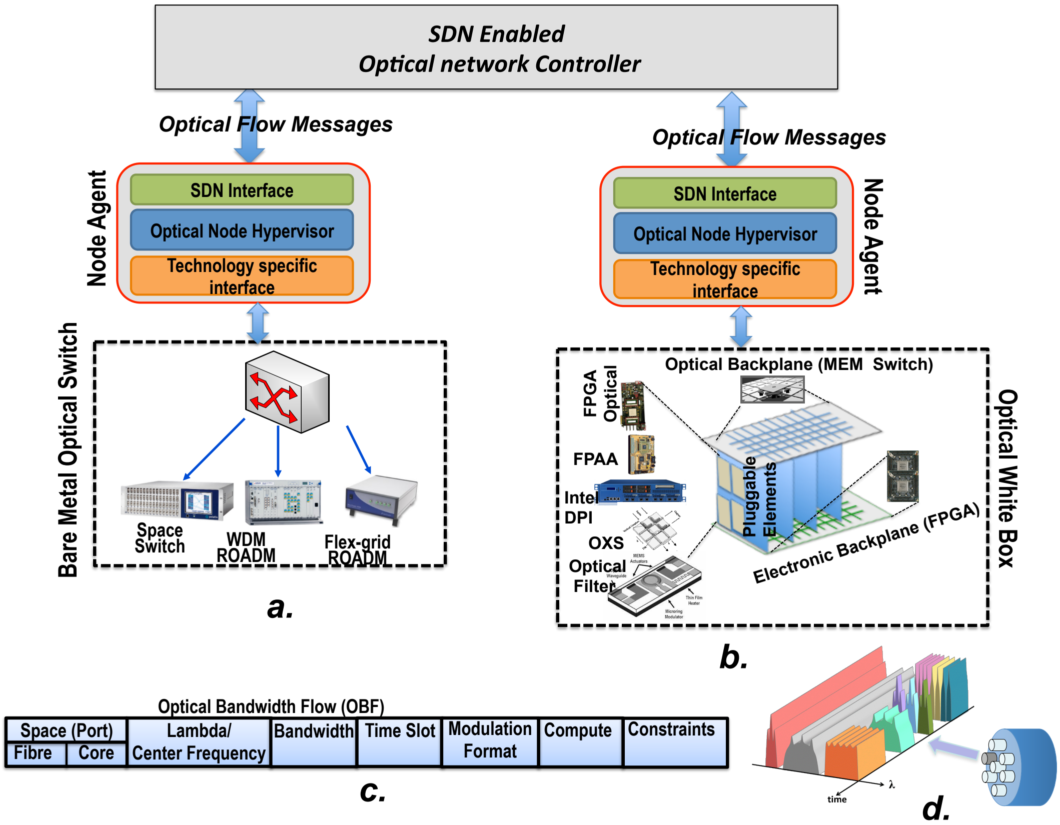

Figure 2. **a:** Optical agent on bare metal optical switch, **b:** Optical agent on optical white box, **c:**structure of optical bandwidth flow (OBF),**d:** optical network switching/connectivity dimensions

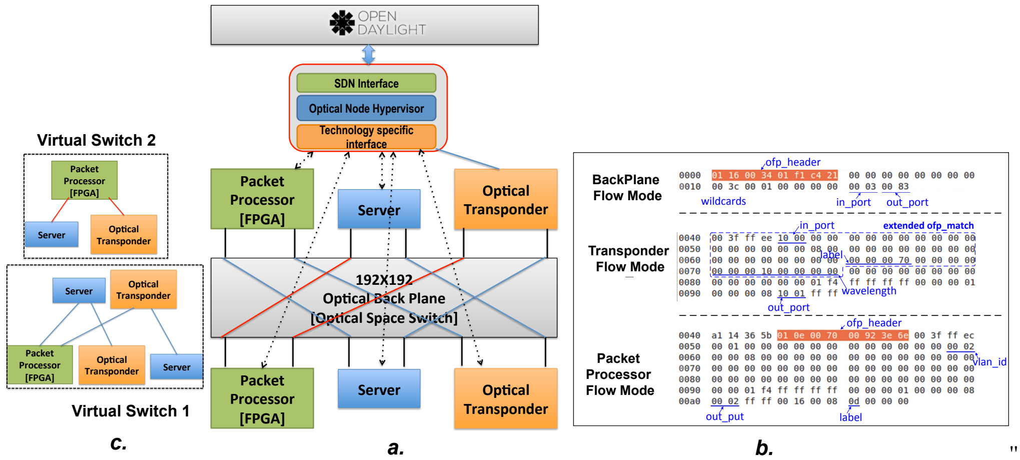

Figure 3. **a:** Experimental set up for an optical white box and an agent , **b:** SDN controller messages, **c:** Configuration of virtual optical switches

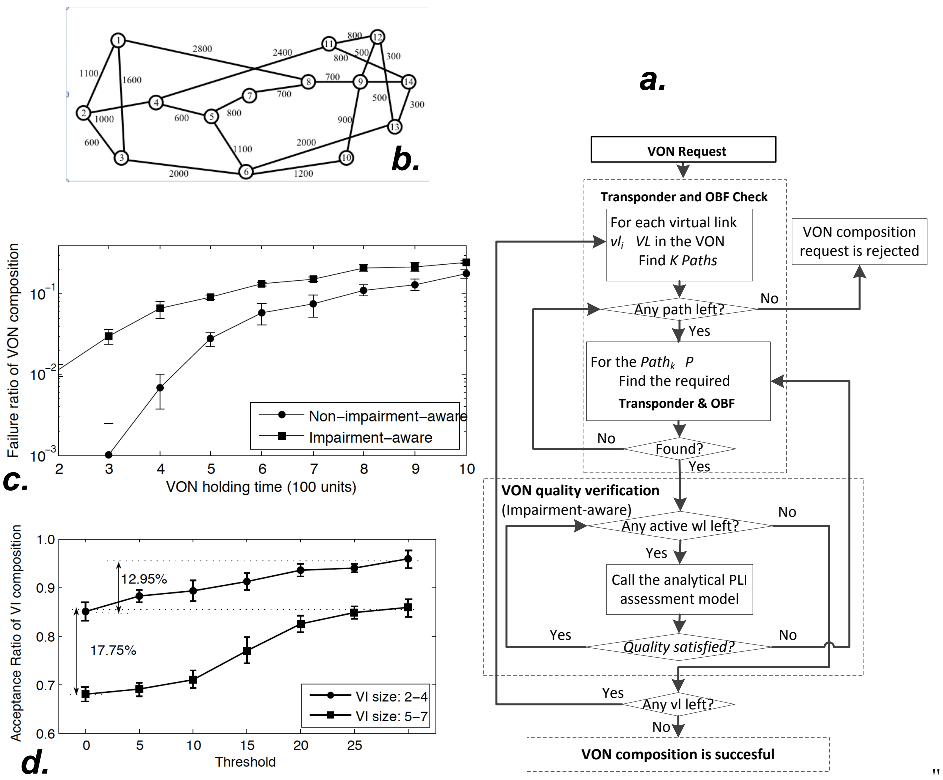

Figure 4. a: Impairment-aware virtualization algorithm, **b:** Simulation topology, **c:** impact of impairments on Resource-aware VON composition methods under NSF topology, **d:**The effect of backtracking on the compute-aware VON acceptance ratio

6. Conclusion

This paper for the first time introduced the concept of network infrastructure democratization and defined a set of key technological features required for creating such an infrastructure. In particular the paper focused on technology enablers for democratization of the optical network infrastructure. It proposed a new optical network architecture and its key technology enablers including open and programmable optical switches, abstraction and virtualization. The paper proposed the concept of bare metal optical switches and a novel design for an optical white box as fully programmable and open hardware solutions for optical networks. To eliminate their complexity, the paper proposed a novel SDN based and multi-dimensional abstraction mechanism supporting future optical transport technologies.

The optical white box will democratize the optical network infrastructure of an operator. When it is combined with virtualization and abstraction, it provides infrastructure owners and operators with new ways to efficiently monetize their infrastructure. This is achieved by creating new and innovative services that are enabled by infrastructure programmability and virtualization, network function virtualization as well as new and diverse network control and management software tools.

A proof of concept implementation of the proposed optical white box and the SDN agent was experimentally demonstrated. Finally, the paper proposed and evaluated via simulation a novel impairment-aware and compute-aware optical network virtualization supporting application specific slicing of the optical network.

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Authors’ contributions. Dr. Reza Nejabati carried out work on abstraction method as well as software defined network design and experimental implementation. He also contributed into design of virtualisation and optical white box. Dr. Shuping Peng carried out work on optical network virtualization. Prof. Dimitra Simeonidou carried out work on design of optical white box. She also contributed to design of abstraction method, software defined network control mechanism and virtualisation mechanism.

References

1. Veak, Tyler J., ed. *Democratizing technology: Andrew Feenberg's critical theory of technology*. Suny Press, 2012.
2. McKeown, Nick. *Software-defined networking*. INFOCOM keynote talk 17.2 (2009): 30-32.
3. Hammad, Ali, Reza Nejabati, and Dimitra Simeonidou. *Novel methods for virtual network composition*. Computer Networks 67 (2014): 14-25.
4. Yuval Bachar, *Introducing 6-pack: the first open hardware modular switch*, Facebook code, Feb. 2015
5. Morita, Hironobu, and Minoru Watanabe. "Mems optically reconfigurable gate array." Field Programmable Logic and Applications, 2009. FPL 2009. International Conference on. IEEE, 2009.
6. Hoppe, L., D. Fey, and W. Erhard. *Reconfigurable opto-electronic board-to-board interconnects based on fibre arrays and FPGAs*. Proceedings 7th German Workshop on Optics in Computing Technology. 2002.
7. Sambo, Nicola, et al. *Next generation sliceable bandwidth variable transponders*. Communications Magazine, IEEE 53.2 (2015): 163-171.
8. Sheng-Chyan Lee; Varrazza, R.; Ansell, O.; Siyuan Yu, *Highly flexible 4ÃŮ4 optical crosspoint packet switch matrix for optical multicast operations*. Photonics Technology Letters, IEEE , vol.17, no.4, pp.911,913, April 2005
9. Kim, Joongi, et al. *NBA (network balancing act): a high-performance packet processing framework for heterogeneous processors*. Proceedings of the Tenth European Conference on Computer Systems. ACM, 2015.
10. Roberto Selow, Heitor S. Lopes, Carlos R. Erig Lima, *A COMPARISON OF FPGA AND FPAA TECHNOLOGIES FOR A SIGNAL PROCESSING APPLICATION*. in Proceedings of the International Conference on Field Programmable Logic and Applications, 2009, pp. 230-235.
11. D. Simeonidou, N. Amaya, G. Zervas, *Infrastructure and architectures on demand for flexible and elastic optical network*., Optical Communications (ECOC), 2012 38th European Conference , vol1, no2, pp. 16-20 Sept. 2012
12. K. I. Kitayama, A. Hiramatsu, M. Fukui, T. Tsuritani, N. Yamanaka, S. Okamoto, M. Jinno, M. Koga, *Photonic Network Vision 2020 Toward Smart Photonic Cloud (Invited Tutorial)*. J. Lightwave Technol., Vol.32, No.16, pp.2760-2770, 2014.
13. McKeown, Nick, et al. *enabling innovation in campus networks*. ACM SIGCOMM Computer Communication Review 38.2 (2008): 69-74.
14. S. Peng, R. Nejabati, S. Azodolmolky, E. Escalona, D. Simeonidou, *An Impairment-aware Virtual Optical Network Composition Mechanism for Future Internet*. OSA Optics Express, vol. 19, no. 26, pp. B251âĂŞB259, Dec. 2011.
15. N. Sambo, M. Secondini, F. Cugini, G. Bottari, P. Iovanna, F. Cavaliere, and P. Castoldi, *Modeling and distributed provisioning in 10-40-100 Gb/s multi-rate wavelength switched optical networks*. IEEE/OSA J. Lightw. Technol., vol. 29, no. 9, May 2011
16. S. Peng, R. Nejabati, and D. Simeonidou, *Impairment-aware Optical Network Virtualization in Single-Line-Rate and Mixed-Line-Rate WDM Networks*. OSA Journal of Optical Communications and Networking, vol. 5, no. 3, March 2013