The Role of SDN & NFV for Flexible Optical Networks: Current Status, Challenges and Opportunities

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***Abstract*—Today's optical transport domains are typically built using fixed grid technology. They are statically configured and operationally intensive to manage, lacking the capability for dynamic services and elastic bandwidth. Recent research has established the benefits of flexible grid technologies for optical switching allowing dynamic and elastic management of the available bandwidth resources. Combined with Software Defined Networks (SDN) control principles and Network Functions Virtualization (NFV) infrastructure, we have the potential to fundamentally change the way we build, deploy and control network applications built on top of flexible optical networks.**

This paper outlines the current Internet Engineering Task Force (IETF) developments for standardizing flexible grid optical technologies, and discusses how software-defined and function virtualisation principles have and will continue to provide the key capabilities to further enable flexible optical switching technologies to control and deliver NFV-based services and applications. It addition it describes the benefits for the virtual Content Distribution Network (vCDN) use case when combined with an IETF's SDN framework Application-Based Network Operations (ABNO). Finally, we highlight the research opportunities for furthering the application of SDN and NFV for control and orchestration of flexible optical networks using the IETF ABNO-based framework.

Keywords—flexible optical switching, Software Defined Networks, SDN, Network Function Virtualisation, NFV, Application-Based Network Operations, ABNO, network control, orchestration, flexi-grid, virtual Content Distribution Network, vCDN

I. INTRODUCTION

Optical transport networks are evolving rapidly from current static Dense Wavelength Division Multiplexing (DWDM) systems towards flexible and elastic optical switching, using flexible grid transmission schemes and dynamic switching technologies. In such an environment, a data plane connection is switched based on allocated, variable-sized frequency ranges within the optical spectrum creating what is known as a flexible grid (flexi-grid) [1]. This approach aims to utilise technology to increase both the scalability and agility of the optical network, allowing resource optimisation and scaling of bandwidth as demands change in bandwidth requirements.

The flexi-grid optical switching technology creates a need to develop innovative network control and orchestration mechanisms to reduce deployment and operational complexity, and maximize benefits of flexi-grid capabilities. While control plane approaches based on Generalized Multiprotocol Label Switching (GMPLS) are being developed [2], Network Management System (NMS) control remains popular within the transport network community. Traditional NMS platforms lack the flexibility to fully enable flexi-grid so we needed to look towards the architecture and principles defined by the Software Defined Networking (SDN) architecture developed and ratified by the Open Networking Foundation (ONF) [3]. These core SDN architectural principles offer a variety of possibilities when looking to plan, control, and manage flexible network resources both centrally and dynamically. Solutions exist that encompass direct control of switching resources from a central orchestrator, distributed control through a set of controllers, or devolved control through a hybrids with an active control plane.

The advent of Network Functions Virtualisation (NFV) [4] will provide the ability to deploy network functions on virtualised infrastructure hosted on commodity hardware, decoupling dedicated network function from proprietary hardware infrastructure. Consequently this allows network function to be instantiated from a common resource pool and to exploit performance predictability where dimensioning remains stable whatever the use of virtualised hardware resources. Emboldened with the suitable control and orchestration tools, these virtual and on-demand capabilities could have a significant impact on how telecom infrastructure is managed.

Most recently (March 2015), the Internet Engineering Task Force (IETF) published the Application-Based Network Operations (ABNO) framework as RFC7491 [5]. The ABNO framework provides a generic toolkit for a variety of network technologies and use cases. In its most basic form it describes how specific, well-defined functional components may be brought together within a single architecture to provide the capability to control a range of forwarding technologies in order to set-up and tear-down end-to-end services. However, it also provides a variety of deployment options to support a range of architectural principles including: programmatic control of optical and packet-optical transport elements; centralised or distributed deployment models; and northbound and southbound interfaces.

When we combine the elements described previously (flexi-grid, SDN, and NFV), we are able to consider a range of capabilities and functions that may be achieved using a unified framework.

In this paper we discuss the key design objectives necessary to build a unified framework underpinned by the flexible optical network platform for providing NFV-based use cases, these are derived from state-of-the-art developments across Standard Development Organisations (SDOs) combined with considerations of emerging technologies. As a result of this analysis we are able to highlight gaps and discuss the current challenges and opportunities for using SDN (ABNO) and NFV, to further empower the development and deployment of flexible optical networks. We also demonstrate the applicability of this unified architecture based on a virtual Content Distribution Network (vCDN) use case. Finally, we describe the state of the art, open source contributions and framework research gaps.

II. NEXT GENETATION FLEXIBLE TRANSPORT NETWORKS

In the current etymology of transport networks, dynamic and flexible optical resources are increasingly seen as a method to provide bespoke bandwidth, scale, distribution, and flexibility to match user demands. However, these are rarely real-time capabilities as they require significant engineering resources, and often lack the flexibility for dynamic scenarios. With the combination of flexi-grid, SDN, NFV, and ABNO, the capability to programmatically control resources and scale with given user bandwidth demand becomes feasible, providing resilient and elastic network capability in response to both real-time and predicted demands. This section outlines the core requirements, design principles, and enabling architecture for achieving use case requirements and design goals, and sets out the interfaces and protocols that facilitate deployment of infrastructure to meet these objectives.

A. Flexible Optical Switching

Flexible optical switching was defined by the International Telecommunications Union Telecommunications Standardization Sector (ITU-T) Study Group 15 [6] and refers to the updated set of nominal central frequencies (a frequency grid), channel spacing and optical spectrum management/allocation. A principle of flexi-grid is the "frequency slot"; a variable-sized optical frequency range that can be allocated to a data connection. Compared to a traditional fixed grid network, which uses fixed size optical spectrum frequency ranges or frequency slots with various channel separations, a flexible grid network can select its media channels with a more flexible choice of slot widths, allocating optical spectrum as required and available.

A flexible optical network will be constructed from DWDM subsystems that include links, tunable transmitters/receivers, and electro-optical network elements. It is assumed that, for our unified framework, we will require control of the media layer within the DWDM network, and of the adaptations at the signal layer: specifically defining the resource as a Spectrum-Switched Optical Network (SSON) and managing them using a distributed signaling mechanism from a centralized control architecture.

1) Control Plane Resource Modeling

Flexible optical resources (transmitters and receivers) may have different tunability constraints, and media channel matrixes may have switching restrictions. A set of common constraints have been defined in [1], these are described below:

- Slot widths: The minimum and maximum slot width.
- Granularity: The optical hardware may not be able to select parameters with the lowest granularity (e.g., 6.25 GHz for nominal central frequencies, or 12.5 GHz for slot width granularity)
- Available frequency ranges: The set or union of frequency ranges that have not been allocated (i.e., are available). The relative grouping and distribution of available frequency ranges in a fiber is usually referred to as "fragmentation"
- Available slot width ranges: The set or union of slot width ranges supported by media matrices. It includes the following information:
    - Slot width threshold: The minimum and maximum Slot Width supported by the media matrix. For example, the slot width could be from 50GHz to 200GHz
    - Step granularity: The minimum step by which the optical filter bandwidth of the media matrix can be increased or decreased. This parameter is typically equal to slot width granularity (i.e., 12.5GHz) or integer multiples of 12.5GHz

2) End to End Service

An "end-to-end service" may be characterized by one or a set of required effective frequency slot widths. This does not preclude that the request may add additional constraints such as imposing the nominal central frequency. A given effective frequency slot may be requested for the media channel in the control plane setup messages, and a specific frequency slot can be requested on any specific hop of the service setup. We will use the Label Switch Path (LSP) construct as the representation of a media channel and therefore “service”, and the LSP is assumed to be comprised of a nominal frequency and connects the endpoints (transceivers) including the cross-connects at the ingress and egress nodes.

B. Software Defined Networks

The key principles of Software Defined Networking (SDN) include:

- Programmatic and abstracted interaction with the network. These interactions include: control, provisioning, configuration, management, and monitoring.

- Use of an SDN Controller to exercise the aforementioned programmatic direct control of forwarding behavior.

Use for an SDN Controller and Programmable control facilitates network behaviour to be implemented and modified quickly and cohesively: automation techniques may be used to set up end-to-end services, with flexibility beyond the initial deployment, and with the capability to modify paths and network function nodes to be modified (torn down, resized, relocated) at any time particularly in response to rapid changes in the operational environment. This includes revised network conditions, fluctuations in the resource location or availability, and in the event of partial or catastrophic failure.

1) *Application-Based Network Operations (ABNO)*

The ABNO framework document [5] outlines the architecture and use cases for ABNO, and shows how the ABNO architecture can be used for coordinating control system and application requests to compute paths, enforce policies, and manage network resources for the benefit of the applications that use the network.

Within the framework resides the ABNO Controller which represents the main component of the architecture and is responsible for orchestrating the workflows and invokes the necessary components in the right order. ABNO is able store the workflows in a repository, and then execute the network operations, such as setting up or tearing down services, via the GMPLS provisioning plane for flexi-grid resources.

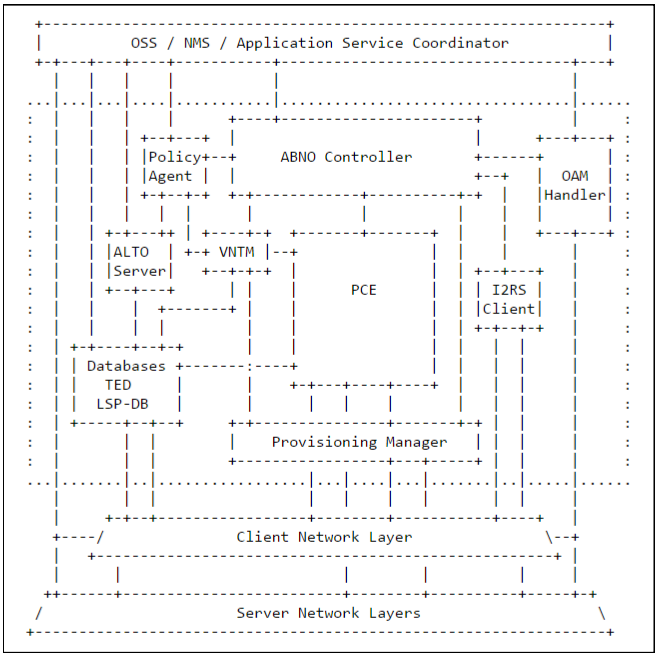

Figure 1: Generic ABNO Architecture

C. *Network Functions Virtualisation*

Network functions virtualisation (NFV) is used to leverage Information Technology (IT) virtualisation techniques to migrate entire classes of network functions typically hosted on proprietary hardware onto virtual platforms based on general compute and storage servers [7]. Each virtual function node is known as a Virtualised Network Function (VNF), which may run on a single or set of Virtual Machines (VMs), instead of having custom hardware appliances for the proposed network function.

Content delivery, especially of video, is one of the major challenges of all operator networks due to massive growing amount of traffic. Delivery of terrestrial transmissions over fixed networks is proving to be a huge consumer of bandwidth, the table below illustrates the Serial Digital Interface (SDI) bandwidth requirements for a variety of uncompressed interfaces and stream types:

Interface Type	**Video Stream**	**Bitrate**
SD-SDI	480i/576i	270 Mbit/s
HD-SDI	720p/1080i	1.5 Gbit/s
3G-SDI	1080p	3 Gbit/s
6G UHD-SDI	4K 30fps	6 Gbit/s
12G UHD-SDI	4K 60fps	12 Gbit/s
24G UHD-SDI	4K 120fps	24 Gbit/s

Table 1: SDI Bandwidth Requirements

1) *Content Delivery Requirements*

A Content Delivery Network (CDN) is a generic term describing a set of common components, such as: Cache Controller, Cache Nodes, Surrogate Server, Load Balancer, Proxy, and Peering Gateway. Normally the Cache Controller will select a Cache Node (or a pool of Cache Nodes) for answering to the end-user request, and then redirect the end-user to the selected Cache Node. The Cache Node shall answer to the end-user request and deliver the requested content to the end user. The CDN Controller is a centralized component, and CDN Cache Nodes are distributed within the network or situated within a Data Centre [8].

For industry, core requirements when designing and deploying a CDN include: capital cost-efficiency, flexibility of content fulfilment, performance predictability, and bandwidth or latency guarantees. These requirements would be well serviced with a server-layer comprised of flexible optical network technology.

2) *OpenCache: Content Caching Platform*

OpenCache [9] has been identified as a candidate open source vCDN platform, leveraging existing SDN research and embracing industrial demand for virtualising network functions. These principles directly impacted the OpenCache architecture, and enabled its use and manipulation within virtualised environments. A key facet of this architecture is the API-based control of caching function (instantiation, resize, and tear-down).

The following figure represents a virtualised Contend Distribution Network (vCDN) running on commodity hardware over a flexible optical network.

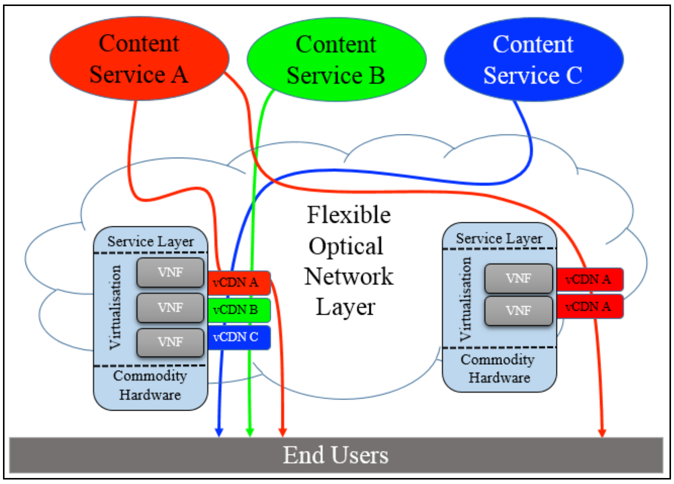

Figure 2: vCDN Application Running over Flexible Optical Network

Furthermore, this virtualisation allows multiple isolated VNFs or unused resources to be allocated to other VNF-based applications during weekdays and business hours, facilitating overall IT capacity to be shared by all content delivery components, or even other network function appliances. Industry, via the European Telecommunications Standards Institute (ETSI), has defined a suitable architectural framework [7], and has also documented a number resiliency requirements [10] and specific objectives for virtualised CDN infrastructure [11].

A final fundamental requirement is the need for the CDN to be resilient and reliable, beyond the capability to cope with a Distributed Denial of Service (DDOS) attack, the CDN must be capable of recovering from catastrophic failure that may affect the aforementioned CDN components [12].

Clearly, there is a need for an experimental platform to drive and develop the next-generation of CDN infrastructure for delivering future SDI steams up to 24 Gbit/s, led by both academia and industry, over a flexible optical network. The rest of this paper outlines a converged SDN and NFV architecture in support of programmable elastic optical networks to support NFV-based applications, based on the vCDN use case described previously.

III. CONVERGED SDN AND NFV ARCHITECTURE

The following figure (Blending Network Control & NFV Management based on ETSI NFV Reference Architectural Framework). It demonstrates a proposed converged SDN and NFV architecture facilitating programmable control of flexible optical network resources, for the NFV-based vCDN use case

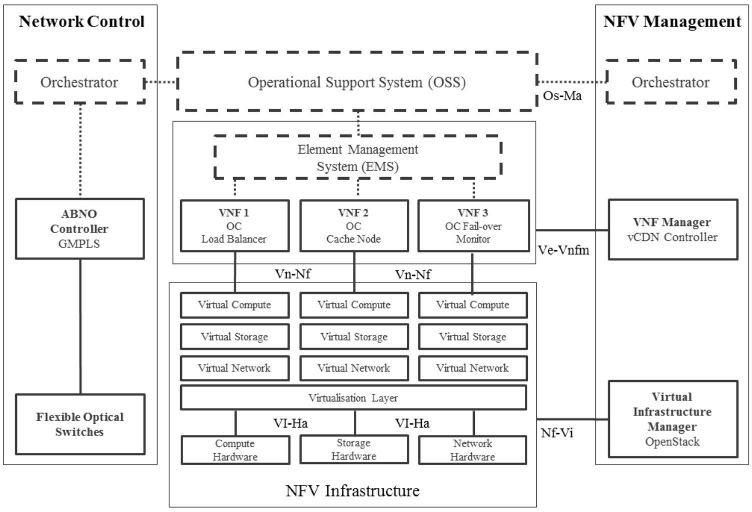

Figure 3: Blending Network Control & NFV Management based on ETSI NFV Reference Architectural Framework

The combined SDN & NFV architecture is comprised of two elements: Network Control & NFV Management. The Network Control element is underpinned with the ABNO Controller for programmable control of the optical network. The NFV Management is split into VNF Manager (vCDN Controller) and Virtual Infrastructure Manager (OpenStack) providing the hypervisor and virtualisation layer.

The central component is the NFV Infrastructure itself and these functional components and functions are mapped into interfaces within the unified SDN and NFV framework:

- Os-Ma: interface to OSS and handles network service lifecycle management and other functions
- Vn-Nf: represents the execution environment provided by the Vim to a VNF (e.g. a single VNF could have multiple VMs)
- Nf-Vi: interface to the Vim and used for VM lifecycle management
- Ve-Vnfm: interface between VNF and Vnfm and handles VNF set-up and tear-down
- Vi-Ha: an interface between the virtualisation layer (e.g. hypervisor for hardware compute servers) and hardware resources

The dotted lines in figure 3 represent missing functional components and interfaces, and represent a research opportunity for orchestration between the SDN to NFV domains.

IV. IN SUMMARY

The opportunity exists to combine SDN principles with an NFV-based architecture, providing the capability to deploy a vCDN and scale bandwidth for given user demand. Using an ABNO Controller to manage the flexible optical network, coupled with the required NFV infrastructure components, and OpenCache platform to deliver a resilient and elastic vCDN capability in response to high bandwidth real-time and predicted video stream demands for terrestrial TV services.

A. CURRENT STATUS

ABNO has been successfully demonstrated for a variety of flexi-grid network operations, including but not limited to:

- In-Operation Network Planning [13]
- ABNO: a feasible SDN approach for multi-vendor IP and optical networks [14]
- ABNO-based Network Orchestration of end-to-end Multi-layer (OPS/OCS) Provisioning across SDN/OpenFlow and GMPLS/PCE Control Domains [15]
- Adaptive Network Manager: Coordinating Operations in Flex-grid Networks [16]

1) ROLE OF STANDARDISATION

In order to facilitate industry adoption of the flexi-grid architecture and components outlined in this paper continued development of required flexi-grid standard proposal will be critical, these proposals include:

- Framework for GMPLS based control of Flexi-grid DWDM networks
- Generalized Labels for the Flexi-Grid in LSC Label Switching Routers
- GMPLS OSPF-TE Extensions in for Flexible Grid DWDM Networks
- RSVP-TE Signaling Extensions in support of Flexible Grid
- Extensions to PCEP for Hierarchical Path Computation Elements (H-PCE)
- A YANG data model for FlexGrid Optical Networks

2) AVAILIBILITY OF OPEN SOURCE

a) ABNO Interfaces and Controller

Where possible, the interfaces of the ABNO Framework and ABNO Controller itself, described in figure 1, have been implemented in Java and are available via the IDEALIST GitHub source code repository [17].

b) Experimental Caching Platform

An Open-Cache implementation is available at [9].

V. FUTURE WORK

Using a prototype implementation of the ABNO Controller with an NFV-based infrastructure, we plan to use OpenCache as the vCDN platform to prove the architecture described in figure 3 (Blending Network Control & NFV Management based on ETSI NFV Reference Architectural Framework). However, orchestration between the SDN and NFV domains remains an outstanding technical gap.

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