12-09-2014

MS103 (MJ1.1.1) White Paper Future Network Architectures

Contractual Date:	12-09-2014
Actual Date:	12-09-2014
Grant Agreement No.:	605243
Activity:	X/JRA1
Task Item:	T1
Nature of Deliverable:	R (Report)
Dissemination Level:	PP (Programme Participants)
Lead Partner:	NORDUnet
Document Code:	GN3PLUS14-976-35

Authors:	Henrik Wessing,DTU (editor)
	Kurosh Bozorgebrahimi, UNINETT
	Anna Tzanakaki, Bristol
	Bartosz Belter, PSNC
	Susanne Naegele-Jackson, FAU
	Andreas Metz, IRT
	Pavel Skoda, CESNET
	Josef Vojtech, CESNET
	Victor Olifer, JANET

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7 2007–2013) under Grant Agreement No. 605243 (GN3plus).

Abstract

This White Paper analyses the growing network capacity needs of NRENs and GÉANT, focusing on the predicted technological advances beyond 100G both from the vendor and research community perspective, and proposes possible network architecture models to meet these future requirements. Key areas are future high capacity transport network, architectures for fixed and mobile cloud services and the inherent need for alternative time synchronisation.

Table of Contents

Table of Figures

Table of Tables

Executive Summary

Today, a typical large central office in a national core network, e.g. a GÉANT or large NREN's node, might have a capacity of 8-10 Tbps in each of four directions. Given current estimated growth rates in capacity requirements of between 40% and 60% per year, such node capacity will be exhausted by 2015-2016 [GRI-2012]. Higher speed optical channels are therefore urgently needed, and nodes with 400 Gbps or 1 Tbps channels be installed within a 3-5 year time frame.

Some of the technologies that will be used to perform the next leap in optical transmission rate are further enhancements of the technologies used in 100G equipment (e.g. advanced modulation formats, coherent detection, FEC, etc.) while others are new and innovative (e.g. the flexgrid, super channels, new multiplexing schemes, etc.).These enabling technologies are currently being researched by various R&D centres of telecom vendors and universities' research centres, and feedback has been collected concerning vendors' planned uptake of 100+ equipment.

Many NRENs have just upgraded their optical backbones to 100G rates, hence do not need to immediately upgrade to 100G+ bit rates. However, some directions of backbone might experience bandwidth shortage in the short-term. A good solution for this for shorter reaches could be provided by 200 Gbps transponders working within the existing 50GHz grid.

Wavelength Selective Switches (WSSs) are now becoming the established standard flexibility enablers used in optical networks (DWDM networks). Using WSSs as a basic building block together with optical splitters enables the use of a split-and-select architecture, that supports the demands of present networks and whose features allow totally remote operation.

Software Defined Networking (SDN) is becoming a trend in the operation and management of today's networks, and a promising solution to network operators and Data Centre providers for reducing the complexity and costs of deploying and managing their heterogeneous networks and services. The advancements achieved recently, through Flexible Optical Networking and the introduction of flexibility in the optical domain, are expected to introduce the required functionalities to enable Transport SDN, e.g. utilising the SDN concepts for future core transport networks.

In order to investigate the different possible alternative "transport network architecture" scenarios, eight different transport network vendors were interviewed and about their views on transport network architecture were discussed with them. In terms of layering, three different models that could meet the need that was identified for a "packet and routing layer" (L3) and for a flexible photonic/optical transport layer are examined: the "IP over Optical", "IP over Ethernet over Optics" and "Dynamic transport network".

It is predicted that cloud computing services will emerge as one of the fastest growing business opportunities for Internet service providers and telecom operators. New demanding applications, distributed in nature, clearly mark a need for next generation networks to interconnect computing facilities (data centres) with end consumers and their home and mobile devices. The research community understands these needs and identifies opportunities and challenges to be addressed in the near future.

The White Paper summarises the requirements identified by the project and sets out the conclusions drawn by JRA1 Tasks 2 and 3 as to the features that should be provided by a suitable solution/framework to effectively support QoS-guaranteed cloud services from Cloud Service Providers (CSPs) to the NRENs' customers.

There are several efforts undertaken by major industrial cloud providers to improve processes of seamless provisioning of cloud and network services. Similarly, research communities in Europe have undertaken efforts to introduce network programmability and dynamicity to clouds. One such community is BonFIRE [BONFIRE], whereas one of the flagship EU-funded FP7 project, GEYSERS [TZA-2014], has identified and worked on a number of challenges enabling the provisioning of converged network + IT resources for cloud computing applications.

JRA1 Task 2 proposes a new solution for the GÉANT & NREN community in the GÉANT Open Cloud eXchange (gOCX), which provides a framework and facilities for QoS cloud services delivery from Cloud Service Providers to the NRENs' customers. JRA1 Task 3 performed a detailed analysis on the implementation of Wi-Fi and mobile services in NRENs and GÉANT, the output of which is reported in [GN3p-JRA1-T3]

To address the requirements of cloud and mobile cloud services, the EU FP7 STREP project CONTENT [CONTENT] has proposed a next generation ubiquitous converged infrastructure. The details of the CONTENT solution can be found at [CONTENT] and [ANA-2013].

Finally, as customers are increasingly interested in high speed packet access for mobile Internet, video on demand (VoD) and broadcast television services, network providers are looking to next-generation IP/MPLS (Multi-Protocol Label Switching) networks, with Ethernet as a carrier-grade technology in wide area networks (WANs), so that synchronisation information has become a critical factor next generation networks to include. One mechanism identified to provide such a service is distributed clock synchronisation with IEEE 1588 Precision Time Protocol (PTP), which offers frequency, phase and time synchronisation over a network. Experiments have been planned and designed to verify how well suited PTP is for synchronisation in transport networks.

1 Introduction

NREN end users are increasingly used to accessing data wherever they are and wherever the data is located. Such mobility, combined with increased data volumes, has significant repercussions in terms of the ways data is stored and accessed. This means that transport networks have to be upgraded and operated according to emerging usage patterns, and especially that network requirements from Mobile Aggregation, Cloud services and emerging services will have to be satisfied by the NRENs and GÉANT in the future.

The main objective of JRA1 Task 1 is to provide guidelines for the NRENs and determine whether the current architecture can support these services or new paradigms and technological solutions should be used. The findings of JRA1 tasks 2 and 3 are also considered in order to provide a consistent view. In addition, results from the Open Calls will be included to highlight trends and roadmaps from the research labs.

This White Paper covers the following topics:

Firstly, in Section 2, technological drivers and trends are described as seen from the research and vendor perspectives, and it is briefly discussed how these advances will find their way into the NREN infrastructures. Focus is on the technological advances beyond 100G and how such technologies can find their way into the NREN infrastructures including the need for controlling and subdividing “big fat pipes”[1]

As the availability of high-speed Internet access is increasing at a rapid pace, distributed computing systems are gaining greater popularity. This, coupled with increased user mobility, is changing the way data is accessed, so that it is necessary to gain an integrated view of the networking and IT resources available. This is discussed in Section 3, which also details the impact of emerging usage patterns on future network architectures in terms of capacity need, granularity of transport network, etc.

The necessary migration and upgrade of the network infrastructures from synchronous SONET/SDH circuit networks to more cost-efficient, asynchronous Ethernet-based networks poses a big challenge, as the timing reference that was intrinsically available for circuit networks is no longer present. As a number of the applications and services considered depend on timing references, Section 4 addresses this issue and discusses candidates for providing exact timing reference in current and emerging network technologies.

[1] The term Big Fat Pipe is commonly used to name high capacity connections.

2 Future Transport Network Architectures

This section outlines the trends in capacity and control for the future transport networks, from the research and vendor perspectives. The preliminary results from selected GN3plus Open Calls are also included.

Firstly, the capacity increase trends for the physical layer are identified from a short-, medium-, and long-term perspective (2.1). These technological advances are compared with vendor roadmaps and perspectives (2.2), and their direct impact on NRENs is described (2.3). Physical techniques for controlling the new high-capacity, “fat pipes” are discussed (2.4) and it is further elaborated (2.5) how upcoming concepts such as Software Defined Networks can be used in a transport network context. Finally, different models for providing the right bandwidth to the right service through appropriate layering are addressed (2.6).

2.1 Beyond 100G in the physical layer

A typical large central office in a national core network, e.g., a GÉANT or large NREN’s node might have a current capacity of 8-10 Tbps in each of four directions. With the current growth rates in capacity requirements of between 40% and 60% per year, given both a conservative and an aggressive estimate respectively, such node capacity will be exhausted by 2015-2016 [GRI-2012]. Higher speed optical channels are therefore urgently needed, and nodes with 400 Gbps or 1 Tbps channels will need to be installed within a 3-5 year time frame. The trends in the physical layer beyond 100G and research directions compared to vendor roadmaps in order to show the high-bit rate architectures that are possible in the short-, medium- and long-term are examined below.

2.1.1 Enabling techniques

Some of the technologies that will be used to perform the next leap in optical transmission rate are further enhancements of the technologies used in 100G equipment (e.g. advanced modulation formats, coherent detection, FEC, etc.) while others are new and innovative (e.g. the flexgrid, super channels, new multiplexing schemes, etc.).

2.1.2 Enhanced modulation formats

The need for 100G+ transmission in new modulation formats originates from the limitations of the modern electronic base. The next step in transmission speed to 1T with the 100G modulation formats (for example, PM-

QPSK) would require the use of 320 Gbaud systems with an electronics interface capable of laser modulation with 320 GHz frequency. This is highly challenging and currently only possible in practice in experimental demonstrations with the prospect of it coming into production with a time frame of 10 years.

Hence, to extend this approach to higher channel rates it is possible to use more powerful modulation formats such as PM-8QAM (2 x 3 bits per symbol), PM-16QAM (2 x 4 bits per symbol), PM-32QAM (2 x 5 bits per symbol) or PM-64QAM (2 x 6 bits per symbol) in conjunction with coherent detection. **Adding DSP and DAC (Digital Analog Converter) to a transmitter** allows the generation of these complex signals. Figure 2.1 shows **PM-QPSK** modulation using 2 modes of light polarization (PM) and 4 phase values (QPSK), so each symbol carries 2 bits in each polarization.

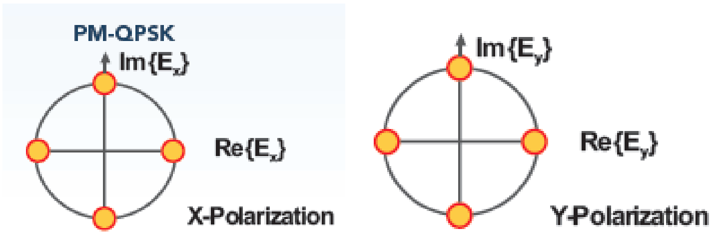

Figure 2.1: PM-QPSK modulation

This approach is very efficient as the baud rate is low while the information rate increases, however, a significant factor limits its efficiency, that is, the need to increase optical signal to noise ratio at the receiver side. This can be ensured by increasing the transmitting power, but is significantly limited by non-linear impairments of fibres. As a result, transmitters with the same power have a shorter reach when using modulation techniques with a higher bit-per-symbol value.

2.1.3 Super-channels (multi-carrier transmission)

The use of multiple carriers routed as a group (a super-channel definition) is a well-known way of increasing transmission capacity. In the case of optical networks, the limitations inherent in directly increasing the symbol rate and bit-per-symbol value mentioned above make super-channels the main candidates in the short- and mid-term perspective for increasing the total node capacity supported from the current 6-10 Tbps to 70 – 150 Tbps.

Tight spacing of sub-carriers is one of the main requirements for building an effective super-channel. Such a super-channel could use the benefits of flexgrid[2] in full by **improving spectrum efficiency beyond the current 2.0 b/s/Hz** (100 Gbps/50 GHz) [GRI-2012]

The fact that all sub-carriers travel over the same path, and therefore do not need to be added or dropped by ROADM like normal channels, allows the use of more sophisticated and efficient ways to pre-process and multiplex them into a combined super-channel signal by using a transmitter with robust detection by a receiver at the far end.

[2] Flexible grid spacing between wavelengths for improved utilization of spectrum.

Because super-channels could have different bandwidths, they require flexgrid to be effectively deployed. Recently ITU-T in G.694 has reached agreement on a centre frequency granularity of 6.25 GHz and full slot width as a multiple of 12.5 GHz. Any combination of frequency slots is allowed as long as no two slots overlap [GRI-2012].

2.1.4 Enhanced multiplexing techniques

Multiplexing of a number of carriers or sub-carriers is needed to form a channel or super-channel. Along with DWDM a number of other multiplexing techniques capable of tightly packing carriers or sub-carriers into a channel are under investigation.

- **Coherent optical OFDM** (**CO-OFDM**) has been introduced into optical channel design. Each CO-OFDM channel can be constructed with several optical subcarriers as long as the frequency spacing between any two subcarriers is a multiple of the symbol rate (i.e. sub-carriers are orthogonal) [GRI-2012].
- **Electrical-optical OFDM**. It is also possible to generate the orthogonal subcarriers in the electrical domain and use DAC and modulators to generate the optical subcarrier [GRI-2012].
- **Nyquist WDM.** This technique uses a signal specifically prepared in the electrical domain which includes only the minimum spectrum frequencies (wavelengths) sufficient for signal reconstruction on the receiver side according to the Nyquist rate rule.
- **OTDM** (Optical Time Division Multiplexing). Sub-carriers in OTDM occupy different time-slots which are created by sharp impulses of ultra-short duration of about picoseconds and repetition in the 5 – tens of Ghz range [TUC-1988].
- **SDM** (Space-division multiplexing) is a new technology that uses multicore fiber (MCF) or few-mode fiber (FMF) to increase fibre capacity [RYF-2011, CHA-2011].
- **OAM Multiplexing**. The most recent multiplexing technique being studied uses the Orbital Angular Momentum (OAM) of light [BOZ-2013].
- **TFP** (Time-Frequency Packing). In TFN signalling, pulses can be packed closer than the Nyquist limit without performance degradation [MAZ-1975]. This technology will be field-trialled by CNIT over the live GÉANT network within the framework of the GN3plus Project.

2.2 Vendors' developments

The enhanced and emerging techniques described in section 2.1 are currently being researched by various R&D centres of telecom vendors and universities' research centres. Feedback from different vendors indicates that their next steps in the planned uptake of emerging 100G+ equipment are likely to be the following:

- 16-QAM (200G) transponders for fixed 50 GHz grid. This is expected to be the natural first step towards 100G+ transmission as the 16-QAM modulation format can be fitted into the existing 50GHz grid and therefore won't require upgrading other than for the transponder parts of network gear. This feature is expected to be in general availability in 2014, so that NRENs could double the speed of their new 100G backbones starting from 2015.

- Transmitters with DSP and DAC capable to shape spectrum. Such transmitters are already available in the 100G equipment of some vendors and this is expected to become a common feature soon. This functionality is required to support sophisticated modulation formats and shape spectrum for creation of spectrum-efficient super-channels.
- Flex transponders – flexible in modulation format and bandwidth of signals
- Flexgrid Colourless/Directionless Multiplexors
- Support of 400G, 500G, 800G and 1T super-channels with narrower than 50 GHz space (38-40 GHz) between sub-carriers, therefore flexgrid ready. Nyquist WDM and OFDM are multiplexing techniques of the first choice.

The new 100G+ features for optical equipment have been demonstrated by vendors in a number of field trials, e.g. in the Ciena 800 Gbps trial over the live BT optical network [BT-800G], and the Ciena 1 Tbps trial over Comcast network [CIE-1T].

Tunable pluggable transceivers are already on the market for speeds typically up to 10 Gbps (e.g. XFP, SFP+). For higher speeds (100Gbps), tunable CFP and CFP2 modules have already been announced as becoming available in late 2014.

Colourless, omni-directional and contention-less features are typically already implemented in transmission systems. Vendors have also already introduced variable processing of spectrum, or are currently implementing it, typically with granularity of 50GHz for terrestrial systems. The reason for this is that planned channels/super-channels can allocate 100GHz, 150GHz or even 250GHz of optical spectrum.

Transceivers are also being developed to support variable bandwidth, e.g. 100, 200, 400Gbps or 50, 100, 200Gbps. As some reconfiguration of hardware is necessary, no vendor is promising to achieve this “on the fly” and without loss of a single bit.

Huawei launched the world's first 1Tbit/s WDM line card in June 2014, and other vendors are expected to follow in 2015 [HUA-2014] .

2.3 NREN impact

Many NRENs have just upgraded their optical backbones to 100G rates, hence do not need to immediately upgrade to 100G+ bit rates.

However, some directions of backbone might experience bandwidth shortage in the short-term. A good solution for this could be provided by 200 Gbps transponders working within the existing 50GHz grid, which would likely require only replacing the transponders but not the mux and WSS modules and vendors already announced availability.

A further increase of the speed of NRENs’ optical infrastructure to 400 Gbps and 1 Tbps super-channels would involve more changes in the network equipment as such an upgrade requires that multiplexers and WSS cards support flexgrid. Such 400 Gbps and 1Tbps optical modems are becoming generally available now.

2.4 Flexibility enablers in the Transport Network

In very early days of fibre optic networking, any change in the network meant a lot of manual work e.g. change of filters, removing and installation of patch cables, etc. The topology of DWDM systems evolved from point-to-point to rings due to the need for resiliency. In these topologies static Optic Add/Drop Multiplexers (OADM) have been replaced by Reconfigurable OADM (ROADM) with east and west line sides. These devices allow the dynamic addition or removal of a particular channel or channels to or from the transmission link. The equalization of optical powers (passed and added channels) is also possible. Obviously the deployment of ROADMs in realistic topologies (mesh, ring of rings, etc.) needs some manual patching. Further evolution brought usage of semiconductor tunable (non-mechanical) lasers within transceivers including pluggable transceivers. The advantage of this solution is in the significant reduction of the needed spare parts stock. However, in deployment with the above-mentioned ROADMs it has shown the drawback that after a change of wavelength manual re-patching has been necessary. Wavelength Selective Switches (WSSs) are now becoming the established standard used in optical networks (DWDM networks). More details regarding possible WSS architectures can be found here [JDSU-WSS].

Using WSSs as a basic building block together with optical splitters enables the use of a split-and-select architecture, where input signal from line is at first splitted and guided into the WSSs of all output lines. This architecture supports the demands of present networks:

- **Multi-degree approach** - In a multi-degree scenario the degree of node (number of line sides) can be easily increased over traditional value of two.
- **Omni-directionality** - Omni-directionality means that local lambdas can be routed without limits into any direction, i.e. line.
- "**Colourless" local ports -** In a colourless scenario, local ADD/DROP port can accept or provide any wavelength or group of wavelengths contrary to fixed wavelength in a traditional coloured scenario
- **Internal "contention-less" structure**. - "Contention-less" internal structure means that from local ports more lambdas with the same wavelength can be routed into different output links.

All these features allow totally remote operation, after initial installation, as everything can be configured without physical contact with equipment [HEAVY_ROADM]. The generation of WSSs currently being introduced can also offer dynamic processing of operational band, referred to as flexgrid in previous chapters.

This means that, as well as traditional fixed wavelength grids with a 50 or 100GHz spacing, it is possible to process channels with variable bandwidth at the same time. As ITU-T standardized flexgrid in G.694 the present WSS offer some non-standard approaches regarding channel bandwidth granularity, some offering fine-grained using multipliers of 12.GHz, and other coarser granularity with multipliers of 50GHz.

The latest flexibility enablers consist of transponders or transceivers directly attached into photonic networks. The boom of coherent transmission introduced Analogue to Digital Converters (ADC) into optical receiver and a foreseeable evolution (from QPSK modulation format to QAM) will bring Digital to Analogue Converters (DAC) into the transmitter side. Presence of the ADCs and DACs in transponder/transceivers allows flexibility in the transceivers so that they can change transmission modulation format (e.g. BPSK, QPSK, 8QAM, 16QAM) and speed. These changes obviously influence bandwidth, reach and power consumption in such way that bandwidth and reach can be tuned to the specific line, and bandwidth can be decreased during off-peak and power saved in these periods. Coherent detection in receivers furthermore allows some complexity reduction of modern ROADMs. It is not necessary to perform full optical filtering in the DROP process, as the input signal can be easily split and filtering done simply by tuning the local oscillator.

2.5 Dynamic control in transport network

Software Defined Networking (SDN) is becoming an established trend in the operation and management of today's networks, from Data Centres to the infrastructures of telecom operators. This trend has recently been reinforced by the evolution of network services through Network Functions Virtualisation (NFV) and the consolidation of SDN protocols such as OpenFlow that support decoupling of network control and the data plane. SDN brings a promising solution to network operators and Data Centre providers for reducing the complexity and costs of deploying and managing their heterogeneous networks and services.

While this section is in no way intended to provide solutions and developments to the existing work on SDN, it is however included to illustrate how the transport network can adapt to SDN concepts and to understand how the dynamic control of different layers can or cannot be applied.

Most of the early SDN developments were led by the US. However, over the past few years Europe has played a leading role in the development of layer 1 and layer 2 Transport SDN with the aim of supporting the operation and management of a variety of infrastructures with increasing need of convergence spanning from Data Centre to telecom operator networks in order to make a seamless and automated connection controlled by users within an agreed SLA framework. Transport SDN grows out of recent developments in SDN and is introducing new opportunities and challenges for equipment vendors and service providers. SDN is a control framework that enables migration from the traditional architectural model of vertically-integrated data and control planes and allows their decoupling supporting programmability of network functions and protocols [OIF-2013]. In this way SDN redefines the relationship between network devices and their control software and allows opening up of the interfaces to facilitate direct programming of the network hardware. This enables more flexible and predictable network control, and enhanced network functionality. SDN allows the underlying infrastructure to be abstracted and accessed directly by applications and network services making it a suitable candidate for use in an integrated network control and management platform, supporting convergence of multiple underlying transport technologies, open programmability and multilayer network integration. Currently several commercially available products include development kits for programming the relevant devices, while deployments of software-defined networks in experimental and production environments have been reported. However, a number of open issues need to be addressed, including architectural choices, network operating systems for control and management of optical network for telecom network operators and Data Centre providers, software platforms and implementation, transition of existing network solutions, optimal exploitation of SDN capabilities, interoperability issues etc.

Currently SDN is mainly applied to layer 2 packet switched networks and data centre infrastructures, but as an architectural concept it is not limited to a specific networking technology (packet or circuit), hardware realisation (specialized box vs. x86 server / Network Function Virtualization concept) or control protocol (Open Flow -OF), Border Gateway Protocol (BGP), etc.. In this context, SDN is becoming an established trend in the operation and management of today's networks in Data Centre and local networks which require a high degree of dynamicity. SDN has the potential to simplify the network operation at the IP and Ethernet layers. Many vendors offer layer 2/3 equipment supporting SDN today, but enabling SDN in a multi-layer, multi-vendor and multi-domain network introduces much bigger challenges. The main question that arises is how deep in the layers SDN should be enabled. In transport networks (TNs), this involves the MPLS-TP, the OTN (Optical Transport Network) and the photonic layer. The MPLS-TP and OTN include some necessary functions, which allow SDN to control the network, but for the photonic layer further advancements that will allow a higher degree of flexibility are required in order to benefit from the SDN features. The advancements achieved recently, through Flexible Optical Networking and the introduction of flexibility in the optical domain, are expected to introduce the required functionalities to enable transport SDN.

Transport SDN is a subset of the SDN architecture functions comprising the TN relevant SDN architecture components – Data Plane, Control and Management Plane and the TN relevant part of the Orchestrator [OIF-2013].

OIF published the "OIF Carrier WG Requirements on Transport Networks in SDN Architectures Transport SDN" in September 2013. This document describes the requirements on TN to support SDN features, services and applications based on the OIF SDN reference architecture. These requirements are generic and do not dictate any specific implementations. The OIF document gives a basic idea of how SDN could be used in an operator's network. Regarding the technical implantations of SDN, there are two different competing models the OpenFlow-based SDN model and the GMPLS/PCE (Generalized Multi-Protocol Label Switching / Path Computation Element)-based SDN model. Different approaches adopting one or the other or even a mixture of the two are proposed. Regardless of the choice of SDN model and the level of maturity of SDN suitability for the transport network the big question is whether the transport network including the photonic part is SDN ready. In order to have an SDN enabled TN, a TN that could be programmable and flexible in terms of rapid change of attributes is required. To make the TN programmable, operators need to deploy new HW platforms in addition to change their operational process which may delay the deployment of Transport SDN solutions (3 years horizon). The initial cost will also be a challenge for operators in order to make the next step towards an SDN-enabled transport network.

2.6 Service layering in Transport Networks

The aim of this section is to set out the different options for Transport Network Architecture in terms of layering. The definition of "Layering" used in this work is switching, multiplexing or/and routing technologies, which reside at the photonic layer, and/or in different layers in the digital domain (ODU-switching, packet switching and/or routing). In the digital domain the OTN switching (layer 1), Ethernet and carrier Ethernet switching (layer 2), and routing at layer 3 are considered as candidate technologies.

In order to investigate the different possible alternative "transport network architecture" scenarios, eight different transport network vendors were interviewed and about their views on transport network architecture were discussed with them.

The common building blocks which all vendors agreed on is the need for a "packet and routing layer" (L3), and for a flexible photonic/optical transport layer. Almost all sources of all services are somehow packet related and, in fact, all services could be delivered through a packet-based layer 3 IP network. The main question is whether it is economical and technically feasible to deliver all services through routers, or if another aggregation, grooming and switching level is needed. Three different transport network architecture models are defined here in the following sections.

2.6.1 IP over optical

The first model is the “IP over optical” approach. The concept is based on coloured router interface implementation only over DWDM and photonic layer. This view proposes that there is no need for an additional intermediate layer in order to support all services regardless of whether the service is circuit-based or not. Packet over optics models have been discussed for several years, but it seems that nowadays they are no longer as strongly favoured as they were a couple of years ago.

This is because the capacity of optical channels has increased from 10Gbit/s to 100Gbit/s, and commercial DWDM equipment beyond 400G is commercially available today. According to this model, increasing optical wavelength capacity will push implementation of higher link interfaces at router level, and will require routers with much higher routing capacity for aggregation and forwarding purposes. This will not only increase the cost significantly but also make it difficult to maintain the same level of capacity at the router level as well as at the photonic level.

2.6.2 IP over Ethernet over Optics

The second model is based on IP over Ethernet over optics. Layer 2 aggregation can perform statistical multiplexing of data traffic, and the WDM channels of the underlying optical network can be used much more efficiently than if only Layer 1 aggregation was used. Statistical multiplexing allows the bandwidth to be divided arbitrarily among a variable number of users in contrast to Layer 1 aggregation (time or frequency multiplexing), where the number of users and their data rates are fixed. Statistical multiplexing makes use of the fact that the information rate from each source varies over time and that bandwidth of the optical path only needs to be consumed when there is actual information to send. Since the traffic is concentrated at Layer 2 in the aggregation network it can be handed over to the IP core routers via a few high speed interfaces rather than over many lower speed interfaces. This simplifies administration and contributes to a lower cost per handled bit. As an additional benefit, the aggregation network itself can be used to offer services within the metro/regional area. For example, point to point Ethernet connections can be provided between offices in a city centre without loading any central router nodes. Such direct connectivity gives more rational traffic handling and reduced forwarding delay compared to using the central IP routers [TRANSMODE]. This model will keep the nature of incoming traffic as packet and perform grooming, aggregation and switching at layer two either with native Ethernet or with MPLS-TP [TRANSMODE].

2.6.3 Dynamic Transport Network

The third model uses OTN not only as a framing tool but also as a multiplexing and switching technique. The major driving factors for OTN switching are high utilization of DWDM pipes, easy and fast deployments, diversity of paths, and restoration potential [ROY-2014]. With emerging superchannel techniques that drive DWDM pipes to higher capacity, (500Gbit/s products are available today) there is a need for multiplexing and switching techniques in the digital domain in order to better utilise the DWDM pipes.

A great number of core routers in an IP/DWDM model are used to forward services rather than process local add/drop services on the nodes. This is where the OTN comes into play. The OTN layer, as a middle layer, separates the logical transport from the physical topologies. IP/MPLS routers will be connected based on the logical topology while the OTN/DWDM provides connections based on the physical topology. As a result, a demand that requires more than one logical link at the IP/MPLS layer can be accommodated in a fewer number of links at the OTN/DWDM layer, and thus significantly reduces the forwarding services that the core routers perform. [KAT-2009]

Figure 2.2 shows the three models for Transport network Architecture. The choice of model depends on the size of network and NREN´s (or service providers) service portfolio

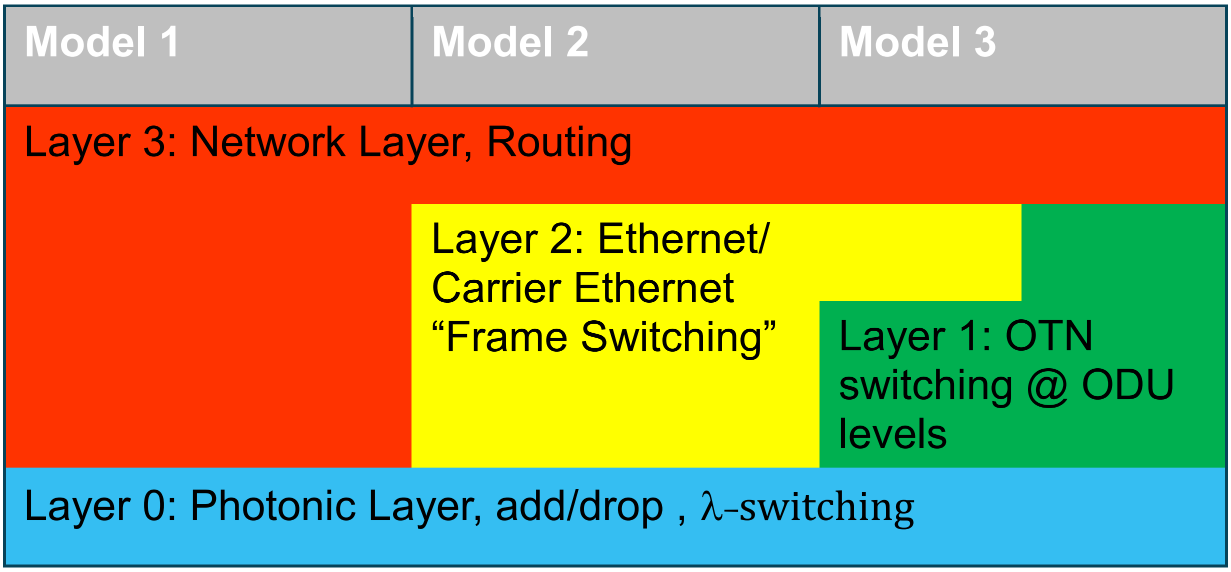

Figure 2.2: Transport Network Architecture Models

.

3 Fixed and Mobile Cloud Services

As the availability of high-speed Internet access is increasing at a rapid pace and new demanding applications are emerging, distributed computing systems are gaining increased popularity. The trend of using cloud services for storage and processing (the cloud paradigm) has, over the past decade, resulted in extensive deployment of large scale computer networks and processing power

Cloud computing facilitates access to computing resources on an on-demand basis, enabling end users to access remote computing resources not necessarily owned by them. This introduces a new business model and facilitates new opportunities for a variety of sectors. At the same time it increases sustainability and efficiency in the utilisation of available resources reducing the associated capital and operational expenditures as well as overall energy consumption and CO2 footprint.

Cloud computing architectures comprise a variety of hardware and software components that communicate with each other via a high-performance network infrastructure. On the other hand, cloud computing services need to be supported by specific IT resources, and these may be remote and geographically distributed with respect to where the end users are located, thereby requiring very high capacity connectivity and increased network flexibility and dynamicity. A strong candidate to support these needs is optical networking due to its carrier-grade attributes, its abundant capacity, its energy efficiency and recent technology advancements including dynamic control planes etc.

Also recently the concept of mobile computing is gaining increased attention, as it aims to support the additional requirement for ubiquitous access of mobile end users to computing resources. Mobile computing imposes the requirement that portable devices run stand-alone applications and/or access remote applications via wireless networks, moving computing power and data storage away from mobile devices to remote computing resources, in accordance with the mobile Cloud computing (MCC) paradigm [12-09-2014DINH-2011].

It is predicted that cloud computing services will emerge as one of the fastest growing business opportunities for Internet service providers and telecom operators [CISCO-2013, MUN-TECH]. In addition, as indicated in the forecast update for the period 2012–2017, mobile internet users are expected to experience an enormous growth, introducing a huge increase in mobile data, a big part of which will come from Cloud computing applications [CISCO-2013CISCO-2013].

At the same time the current best-effort Internet architecture poses significant constraints on the continuously growing deployments of cloud-based services. New demanding applications, distributed in nature, clearly mark a need for next generation networks to interconnect computing facilities (data centres) with end consumers and their home and mobile devices. The research community understands these needs and identifies opportunities and challenges to be addressed in the near future to enable closer cooperation of the two worlds − distinct so far− of networking and cloud computing.

3.1 Requirements of cloud and mobile cloud services

This section summarises the requirements identified by the project also taking into account the conclusions drawn by JRA1 Task 2 and JRA1 Task 3.

JRA1 Task 2: Requirements from Cloud Services

JRA1 Task 2 [GN3p-JRA1-TGN3p-JRA1-T2] has identified several current challenges in delivering guaranteed QoS cloud services to organisational/enterprise customers and end users generating large quantities of network traffic. In addition, there is a gap between two major components of the cloud services provisioning infrastructure. Namely the cloud service providers (CSPs) infrastructure that either has a global footprint or is intended to serve the global customer community, and the cloud service delivery infrastructure, which in many cases requires dedicated local network infrastructure.

An emerging need for joining/combining the CSP infrastructure and the local access network infrastructure has also been identified. This is especially the case when facing the "last mile" problem in delivering guaranteed QoS for cloud services to customer locations and end users.

To effectively support QoS-guaranteed cloud services from the Cloud Service Providers (CSPs) to the NRENs' customers (universities, research institutes and other organisations) and to end-users, and overcome the limitations of current solutions, JRA1 Task 3 has identified a set of requirements that need to be supported by a suitable solution/framework:

- In general, it should follow and leverage the Internet eXchange (IX) design and operational principle, adopted in such a way that it supports the specifics of cloud service provisioning.

- It should support a flexible operational scenario. This can be achieved through a hierarchical architecture and can be operated by both the NRENs and GÉANT.

- It would be beneficial to provide Layer 0 to Layer 2 network services to interconnect CSP Points of Presence (PoP) as this will make the solution fully transparent to current cloud service models. However, this may introduce further performance optimisation of the cloud infrastructure through Layer 2 network virtualisation.

- Support of secure topology information exchange between its peering members is needed to ensure effective interconnection services at different networking layers.

- The interconnection network infrastructure must guarantee high QoS parameters (e.g. bandwidth, latency, and jitter) in accordance to the cloud service SLAs.

- Smooth service delivery and integration between CSPs and customers is needed. Besides network connectivity, this implies support for the integration and operation of federated services.

JRA1 Task 3: Requirements from aggregating high-speed mobile networking

The white paper produced by JRA1 Task 3 [GN3p-JRA1-T3], outlines the following set of basic recommendations that core networks should support to offer efficient aggregation of high-speed mobile data, taking into consideration the specifics of the R&E networking environment:

- The core network capacity dimensioning must take into consideration that the additive traffic load generated by high-speed mobile data backhauling, during peak periods, may scale to multi-Gbps and it may be best for an NREN to handle this at a low layer instead of the IP layer.

- Investigate the economics of sustaining peering with the commercial Internet close to the interconnection point of the aggregation network and the NREN network to evaluate whether NRENs can be benefited by offloading large amounts of data in terms of capital expenditure for core optical network equipment CAPEX (by requiring e.g. reduced number of DWDM transponders, router linecards).

- Establishing direct tunnels to the closest Internet peering with the aim of minimising packet processing and achieving improved delay performance is an alternative option. This can be performed by installing either dedicated wavelength or higher granularity OTN circuits connecting NREN routers that are directly interconnected with the aggregation network with NREN routers peering with the Internet.

- In all cases and independently of choices in technology, mobile services need to be supported in an end-to-end fashion with guaranteed QoS as specified by the associated SLAs, including delay and any other requirements such as service availability determined through suitable resilience mechanisms.

3.2 Supporting dynamic network services for the cloud

Transport networks have been treated by cloud computing service providers as a vital commodity. However, most cloud management systems treat network services as granted and always on. The dynamicity of cloud applications is mostly exposed with dynamically provisioned IT services (computer and/or storage) on top of a distributed infrastructure, while the network layer is assumed to be statically provisioned. This assumption leads to an inefficient use of network resources and does not scale for large-scale cloud deployments. A continuously increasing number of cloud applications running in a distributed networked/computing environment introduce new requirements for dynamicity in network resource control and seamless coordinated provisioning of joint network/computation services to infrastructure users.

There are several efforts undertaken by major industrial cloud providers to improve processes of seamless provisioning of cloud and network services. For example, Vint Cert, an Internet pioneer and Google's chief Internet evangelist, explained at the third annual Open Networking Summit (2013) that Google runs OpenFlow in all data centre networks [TECHTARGET]. Additionally, Google applies the paradigm of SDN to WAN, by deploying SDN-based stack to allow control of interconnectivity services between data centres [EETIMES]. A more detailed discussion on how SDN can be applied on transport networks is provided in Section 2.5 of this document.

3.2.1 The BonFire Approach

Similarly, research communities in Europe have undertaken efforts to introduce network programmability and dynamicity to clouds. One such community, BonFIRE [BONFIRE], addressed the practical problem of introducing a cloud-to-network interface, which exposes new network capabilities to cloud service providers and its users to enable triggering of network operations dynamically, when specific needs arise. In BonFIRE the following requirements have been identified and further elaborated:

- Shared site-to-site Bandwidth on Demand (BoD) and application flow mapping
- Per application Bandwidth on Demand

The first group of requirements describes the dynamic on-demand setup of network connectivity between two cloud sites with QoS guarantees. A new network service between sites is described as a logical link aggregating specific flows from different cloud applications running in the two sites. Figure 3.1describes the concept of the shared site-to-site BoD implementation for BonFIRE using GÉANT and the corresponding NRENs' infrastructures.

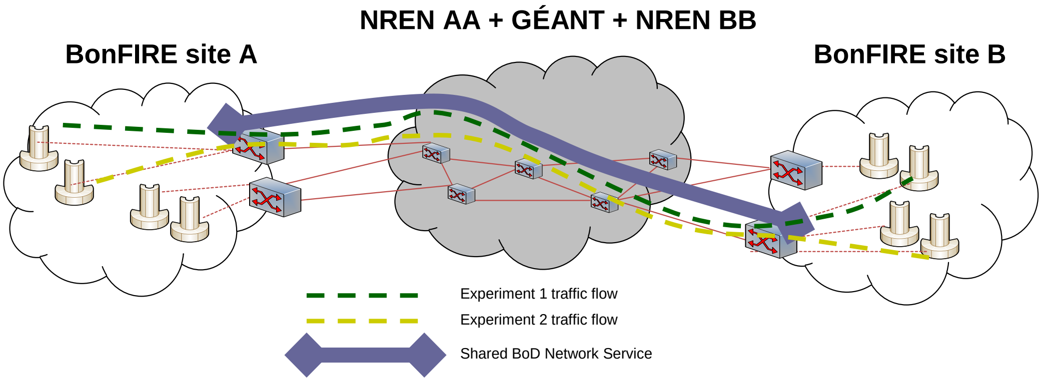

Figure 3.1 Shared site-to-site BoD implementation in BonFIRE

The second group of requirements describes the dynamic on-demand setup of network connectivity between two cloud sites with QoS guarantees strictly reserved for a specific application running in the infrastructure. Figure 3.2 presents the per-application BoD implementation for BonFIRE using GÉANT and the corresponding NRENs' infrastructures.

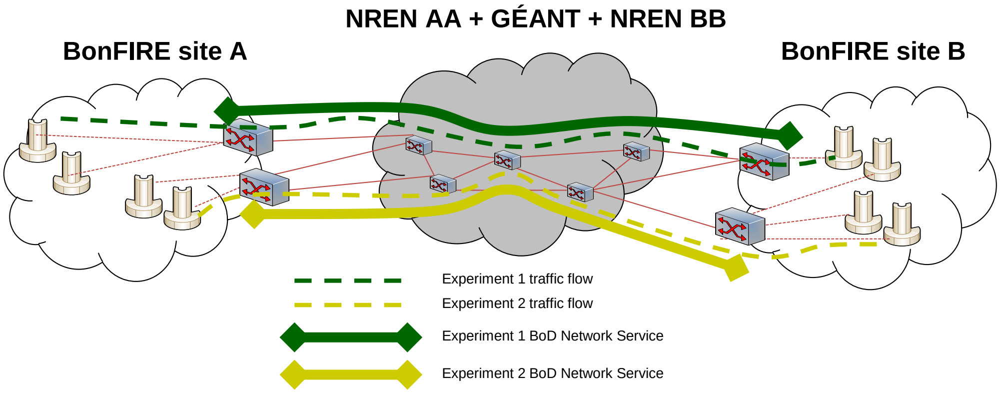

Figure 3.2: Per application BoD in BonFIRE

When implementing the controllable network environment for BonFIRE, several constraints were taken into account. Most of these constraints concerned the availability of the mature BoD service implementation in corresponding NRENs providing connectivity for BonFIRE partners. The lack of production BoD service deployment in these NRENs caused a limited usage of the research network infrastructure in the BonFIRE cloud computing service offering. As a result of the analysis performed during the project, just two BonFIRE sites (out of 7) supported the implementation of controlled network scenarios for cloud applications: EPCC (interconnected through JANET) and PSNC (the Polish NREN). These sites served as pilot sites in the BonFIRE infrastructure for the offering of integrated cloud and network resources to the experimenters.

3.2.2 The GEYSERS Approach

Figure 3.3 presents the architecture of one of the flagship EU-funded FP7 project, GEYSERS, targeting new solutions for end-to-end cloud services delivery over all-optical networks [TZA-2014]. The GEYSERS project has identified and worked on a number of challenges enabling the provisioning of converged network + IT resources for cloud computing applications: 1) network and IT resource abstraction and virtualization; 2) virtual IT and network infrastructure composition; 3) integrated IT and network service provisioning; 4) energy efficiency of the physical infrastructure (network + IT physical resources) and 5) scalability and dynamic re-configurability. These challenges also formulate strategic research directions for GÉANT, in order to enable the GÉANT network for provisioning of high-quality cloud services to its users.

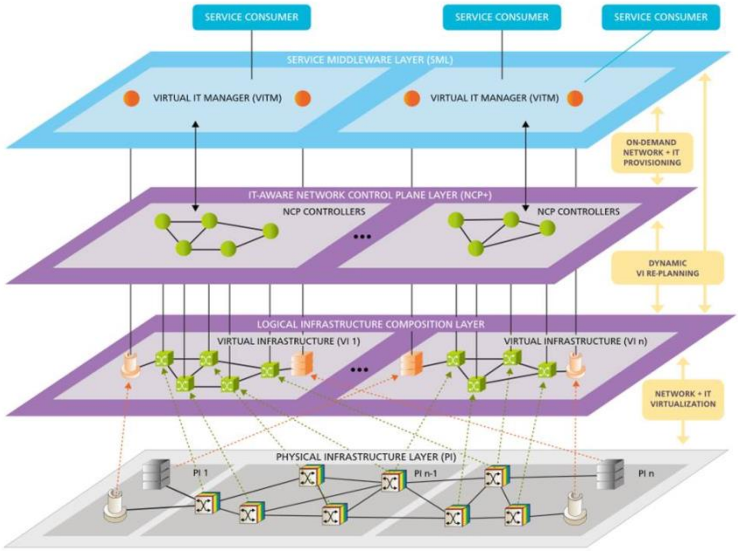

Figure 3.3: The GEYSERS architecture enabling end-to-end cloud service delivery

3.2.3 The GÉANT Open Cloud eXchange proposal

JRA1 Task 2 proposes a new solution for the GÉANT & NREN community in the GÉANT Open Cloud eXchange (gOCX), which provides a framework and facilities for QoS cloud services delivery from Cloud Service Providers to the NRENs' customers (including universities and research institutes) [GN3p-JRA1-T2]. As stated in the JRA1 T2 white paper [GN3p-JRA1-T2], the typical usage of cloud services by the NREN community covers email, storage and application on-demand services. It is noted however, that there are new emerging applications, which can be deployed and run on top of the distributed and large-scale infrastructures, to deal with Big Data tasks.

The proposed gOCX architecture leverages on and extends the concept of the Internet eXchange and Optical eXchange models with additional functionalities to enable the establishment of ad-hoc dynamic InterCloud federation and unrestricted cloud provider and customer peering.

Figure 3.4 presents how gOCX services can be provided by the Cloud Carrier or Network Provider (e.g. an NREN or GÉANT). For more details the interested reader is referred to [GN3p-JRA1-TGN3p-JRA1-T2].

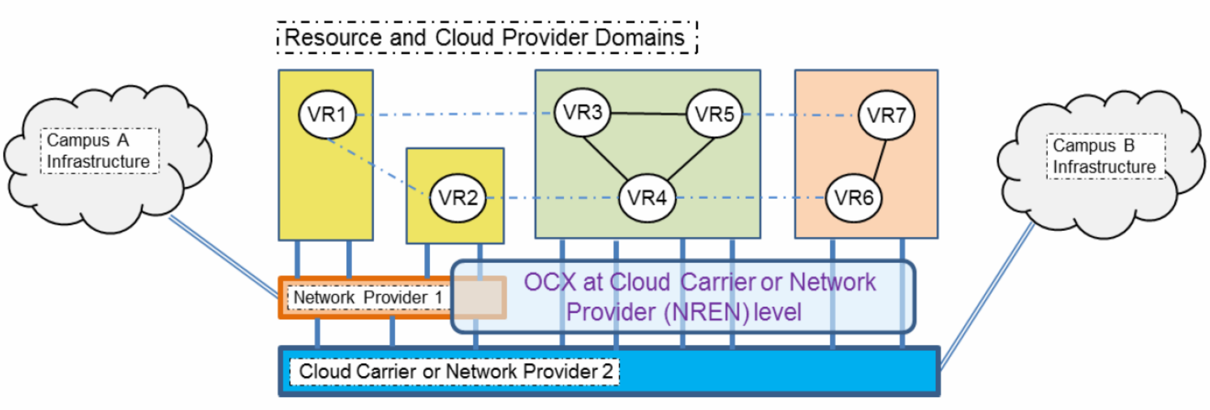

Figure 3.4: gOCX on the Cloud Carrier or Network Provider level

3.3 Heterogeneous Wireless-Optical Network infrastructures in support of Mobile Cloud Services

Recognizing that wireless and mobile communications have become an integral part of everyday life in the R&E community, JRA1 Task 3 performed a detailed analysis on the implementation of Wi-Fi and mobile services in NRENs and GÉANT, the output of which is reported in [GN3p-JRA1-T3]. As discussed in [GN3p-JRA1-T3], the 2013 GÉANT mobile connectivity business case study shows that only 9 out of 38 GÉANT partners are providing mobile services to the community in one way or the other. The white paper also addresses the network architectures that enable the improvement of the quality of wireless services provided to clients within universities, NRENs and GÉANT, and identifies the main difficulties NRENs face in integrating mobile data plane technologies with their core infrastructures.

In addition to traditional mobile services, it is predicted that mobile cloud computing services will experience a noticeable growth. Currently mobile cloud computing solutions allow mobile devices to access the required resources by accessing a nearby resource-rich cloudlet (micro data centres (DCs), rather than relying on a distant "cloud" [SAT-2009]. In order to satisfy the low-latency requirements of several content-rich mobile cloud computing services, such as high definition video streaming, online gaming and real time language translation [MUN-TECH], one-hop, high-bandwidth wireless access to the cloudlet is required. In the case where no cloudlet is available nearby, traffic is offloaded to a distant cloud such as Amazon's Private Cloud, GoGrid [GOGRID] or Flexigrid [FLEXISCALE]. However, the lack of service differentiation mechanisms for mobile and fixed cloud traffic across the various network segments involved, the varying degrees of latency at each technology domain and the lack of global optimisation tools in infrastructure management and service provisioning mean that current solutions are inefficient.

To effectively enable this emerging opportunity to be seized, there is a need for a converged infrastructure that supports integrated wireless and wired high-capacity optical networks interconnecting IT resources, allowing seamless orchestrated on-demand service provisioning across heterogeneous technology domains. Implementing such a converged infrastructure will result in a reduction of capital and operational expenditures, increase efficiency and network performance, migrate risks, support guaranteed QoS and meet the quality of experience (QoE) requirements of Cloud and mobile Cloud services.

3.3.1 The CONTENT approach

To address the requirements of cloud and mobile cloud services the EU FP7 STREP project CONTENT [CONTENT] has proposed a next generation ubiquitous converged infrastructure. This infrastructure (Figure 3.6) facilitates the interconnection of DCs with fixed and mobile end users through a heterogeneous network integrating optical metro and wireless access network technologies. The proposed architecture addresses the diverse bandwidth requirements of future cloud services by integrating advanced optical network technologies offering fine (sub-wavelength) switching granularity with hybrid wireless Long Term Evolution (LTE) and Wi-Fi access network technology supporting end-user mobility. The details of the CONTENT solution can be found at [CONTENT] and [ANA-2013].

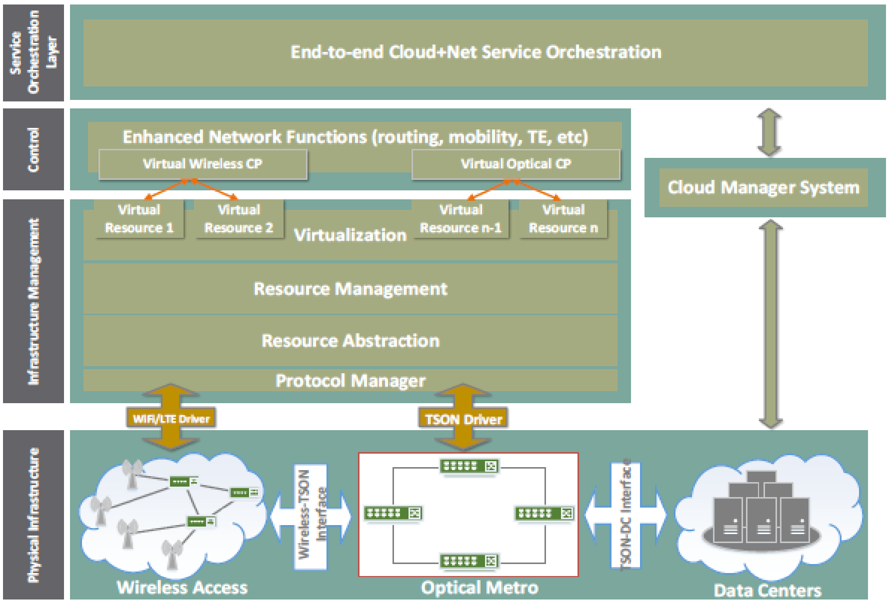

Figure 3.5: CONTENT layered architecture

3.4 Requirements of cloud and mobile clouds services on network architectures

It is clear that the details and specific characteristics of cloud and mobile cloud services have a direct impact on the requirements that the infrastructure needs to support. By taking service requirements into consideration, the functionality, performance and efficiency of the infrastructure can be optimised through suitable architectural, operational and technological choices. These infrastructure requirements can be summarised as follows:

- Suitable capacity allocation to support the volume and granularity of requests.

- QoS guaranteed end-to-end service provisioning to support service characteristics as specified by the associated SLAs e.g. acceptable latency, availability etc.
- Dynamic allocation of resources, flexibility and fast reconfiguration capability to address the dynamicity and uncertainty of service requests.
- Sharing of resources for cost and energy efficiency purposes.
- Resilience mechanisms to enable recovery from failures and disasters and support service availability requirements.
- Flexible and dynamic management of resources and orchestrated guaranteed QoS service provisioning to support mobility of end users.

Based on these requirements the new network architecture supporting cloud and mobile cloud services must provide the functions shown in Table 3.1 below.

Requirement	Description
Shared site-to-site Bandwidth on Demand	Dynamic on-demand setup of network connectivity between cloud sites with QoS guarantees. A new network service is aggregating particular flows from applications run in the different sites.
Per application Bandwidth on Demand between cloud sites	Dynamic and flexible on-demand setup of network connectivity between different cloud sites with QoS guarantees strictly reserved for a specific application running in the infrastructure.
Sharing of resources for cost and energy efficiency purposes	Abstraction and virtualisation of the infrastructure through suitable management/control solutions such as SDN.
Converged infrastructure supporting integrated wireless and wired high-capacity optical networks	The new architecture must support integration of heterogeneous network technologies, in particular it must address the issue of convergence of optical and wireless network infrastructures.
Integrated network and computation infrastructures	The new architecture must support integration of network and computer technologies to provide unified services to end users
Seamless, QoS-guaranteed, orchestrated on-demand service provisioning across heterogeneous technology domains	Service orchestration across multiple technology domains (mobile, optical, computation) is necessary to enable provisioning of new services to users seamlessly and on demand.
Dynamic InterCloud federation	New exchange points, extending the concept of Internet eXchange, should be designed to enable the establishment of an ad-hoc InterCloud federation between cloud and network providers

Table 3.1: Requirements from fixed and mobile cloud services

3.5 Future network architecture proposal in support of cloud and mobile cloud services

Based on what has been previously outlined, a layered architecture with the aim to support QoS-guaranteed, seamless and coordinated cloud and mobile cloud service across heterogeneous domains addressing the needs of the NRENs is proposed.

Physical Infrastructure Layer: To support the required services the physical infrastructure interconnects end users with computational resources hosted by geographically distributed data centres through a heterogeneous network comprising optical and wireless network domains.

Physical Infrastructure Management Layer: The infrastructure management layer is responsible for providing management of physical resources and enabling capabilities such as sharing resources. In view of this, it could support converged management functions (e.g. monitoring, abstraction, discovery, or lifecycle management) of physical resources as well as functions such as the creation of isolated virtual infrastructures composed of resources belonging to different technology domains. Additionally, the management layer, which lies directly over the physical infrastructure, should be capable of facilitating the management of computational resources.

Control Layer: The converged virtual infrastructures delivered through the infrastructure management layer described in the previous section can be jointly operated through a unified control layer based on the Software Defined Networking (SDN) paradigm (see section 0). This layer should implement converged control and management procedures for dynamic and automated provisioning of end-to-end connectivity in support of QoS-guaranteed cloud services for mobile users.

Service Orchestration Layer: The service orchestration layer is in charge of composing and delivering cloud services to the end-users. This layer should combine network and cloud resources and provide a complete and converged cloud service that matches the user’s requirements as specified by the respective SLAs.

An overview of the proposed architecture is shown in Figure 3.6.

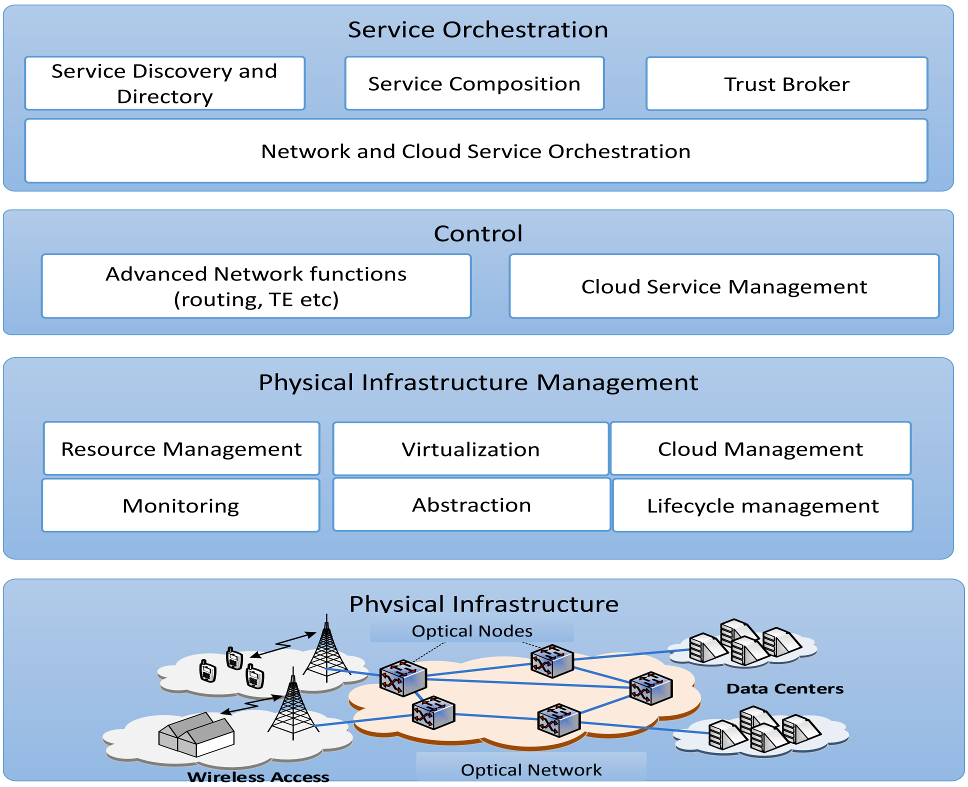

Figure 3.6: Proposed Architecture

4 Distribution of time synchronization

As customers are increasingly interested in high speed packet access for mobile Internet, video on demand (VoD) and broadcast television services, network providers are looking to next-generation IP/MPLS (Multi-Protocol Label Switching) networks, with Ethernet as a carrier-grade technology in wide area networks (WANs), to replace the traditional higher cost-per-bit time-division multiplexed (TDM) transport technologies, such as SONET/SDH/PDH (Synchronous Optical Network/Synchronous Digital Hierarchy/Plesiochronous Digital Hierarchy) services. The migration from circuit-based technologies to packet-switched networks (PSN) suffers from a severe drawback, however: The timing reference that was intrinsically available in synchronous SONET/SDH/PDH circuit networks is not present over asynchronous networks [TRANS-2011, JDSU-2012]. The synchronicity in TDM networks stems from its deterministic timeslot switching that is controlled by electronic circuits and PLL (Phased Locked Loops) [SEM-2008]. In Ethernet-based packet switched networks there is no such layer 1 framing reference information and frames are forwarded independently from one another [MEF-2012]. As many applications have strong requirements for frequency and time distribution, however, the ability to carry synchronisation information has become a critical factor for Ethernet amid its migration towards a carrier-class WAN-technology [CIS-2008, KUM-2013]. It is therefore very important next generation networks to include synchronisation information as a service.

The mobile telecommunications industry is one major area in which synchronisation is required. Cellular base stations depend on highly accurate Primary Reference Clocks (PRCs) for their radio carrier frequencies; without such accuracy, interferences can occur not only between channels at the local base station, but also between base stations at the same vicinity leading to call drops and a diminished call quality. Other applications benefiting highly from time synchronisation are eLearning, teleteaching and telemedical applications where multiple multimedia channels are merged and where it is possible to blend audio and video content interactively from rich media data centers [YOA-2014]. In any such delivery or production chain of audio and video over the network it is important to provide synchronisation, as otherwise either the audio and video content will be damaged by clicks, dropouts or digital noise, or lip-sync (audio-video synchronization) will not be guaranteed. Real-time multi-player computer games and simulations also have a requirement for clock synchronization throughout their network environment as all state changes should take immediate effect for all online players to see, regardless of the noticeable lag that is introduced by high latency [SIM-2000]. A common time reference is also beneficial for network measurements and monitoring where a sudden change of delay measurements, for instance, could indicate that a component failure may have occurred that led to route changes. With precise time references network administrators are also capable of troubleshooting and pinpointing failures and outages from log files more easily as events from different hosts can be accurately correlated and put into the precise order of occurrence [SYM-2007]. As network monitoring also serves as a basis for assurance of service level agreements (SLAs), the compliance with such SLAs can also be effortlessly tracked with a common time reference throughout the network.

Mechanisms offering synchronization over Ethernet are Synchronous Ethernet (SyncE) and the Precision Time Protocol (PTP IEEE 1588). SyncE is an ITU-T defined standard [ITUT-G8261] for the transport of clock frequency information over the Ethernet physical layer, but is only capable of providing clock pulse (frequency) information and does not deliver time (phase) synchronization. The Precision Time Protocol (PTP) of IEEE 1588TM Standard for A Precision Clock Synchronization Protocol for Networked Measurement and Control Systems [IEEE-1588] has the advantage that all three types of synchronization information (frequency, phase and time) are carried; in addition, PTP has the benefit that not all network components must adopt PTP [SIL-2013], as in the case of SyncE deployments where special hardware is required.

Distributed clock synchronization with PTP over a network typically involves one GPS-based grandmaster clock as the highest quality clock, with slave clocks spread throughout the network that synchronise to the grandmaster clock. Several factors can affect synchronisation levels [NAT-2013]: variations in network delay due to jitter at network components, for example, adversely influence the degree of synchronisation that can be obtained. Each clock is also affected by frequency changes in its local timing source. It is therefore important to investigate quality levels obtainable through PTP-based synchronization over wide area networks.

An example for such an experiment can be based on the synchronisation of high-quality video nodes as shown in Figure 4.1, where the reference video signal is synchronised directly via a GPS-driven video clock generator and a test signal is indirectly synchronised over the packet-switched network. A reduced accuracy of PTP (due to network interference) will influence the timing behavior of the video signal, which is synchronised via a PTP slave.

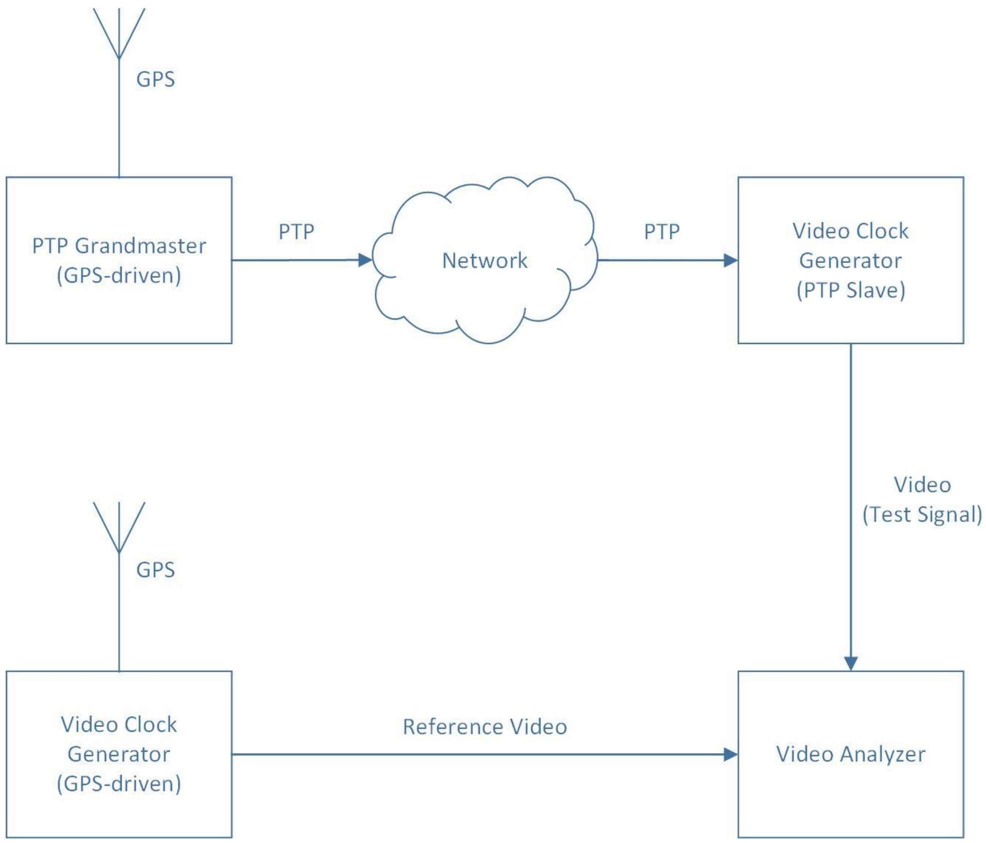

Figure 4.1: Experimental setup to investigate network influence on PTP accuracy

5 Conclusions

The different emerging physical technologies for increasing the bit rate beyond 100G have been investigated and specifically the modulation enhancements and the flexible use of the channel through flexible grids that have been aligned with vendor roadmaps. Interfaces for providing 200G are available from vendors within the original 50 GHz grid and super-channels of up to 1 Tbps have been demonstrated by vendors and will be commercially available presently or very soon according to press releases.

Advances in the physical layer will provide big fat bandwidth pipes which again will need control mechanisms for “slicing” to fit application bandwidth requirements. These control mechanisms were investigated and it was found that flexibility and dynamics in the Transport Network require the introduction of programmable and flexible optical network elements. In order to make the TN programmable, operators need to deploy new HW platforms in addition to changing their operational process, which may delay the deployment of Transport SDN solutions (3 years horizon). The initial cost will also be a challenge for operators in order to take the next step towards an SDN-enabled transport network.

In terms of layering, three different models are examined for Transport Network Architecture. The "IP over Optical", "IP over Ethernet over Optics" and "Dynamic transport network" models show possible options to meet the need that was identified for a “packet and routing layer” (L3) and for a flexible photonic/optical transport layer. The main question that arises is whether it is economical and technically feasible to deliver all services through routers, or if another aggregation, grooming and switching level is needed. The choice of Transport Network Architecture model for operators/NRENs much depends on the size of network they are running and the service portfolio they are supporting.

The typical NREN user in the future is likely to be even more mobile than today and expect access at all times. This requires access with QoS to the “closest’ data storage and an integrated view of the IT and network resources available is necessary. Therefore, the requirements of fixed and mobile cloud services from future network architectures have been identified, and a state of the art analysis of the existing approaches towards dynamic network services for clouds and mobile clouds has been carried out utilising the results from several European research projects (BonFire, CONTENT, GEYSERS). Based on the identified requirements (including key messages from GN3plus JRA1 Task 2 and Task 3), it has been possible to sketch an initial draft of the future network architecture.

Network providers are replacing traditional higher cost-per-bit time-division multiplexed (TDM) transport technologies with next-generation IP/MPLS networks with Ethernet in WANs. This migration to packet-switched networks has the drawback that the intrinsic timing reference in synchronous SONET/SDH/PDH circuit networks is lost. This influences major applications such as mobile telecommunications, video and audio, or real-time games, simulations and monitoring solutions, which require synchronisation. In order to be able to adequately support these applications time reference services must be added to next generation networks.

One mechanism to provide such a service is distributed clock synchronisation with IEEE 1588 Precision Time Protocol (PTP), which offers frequency, phase and time synchronisation over a network. As currently this technology is mostly used in small local environments, it will be important to investigate the quality levels obtainable through PTP-based synchronisation over wide area networks.

References

[ANA-2013] M. P. Anastasopoulos, A. Tzanakaki, G. S. Zervas, B. R. Rofoee, R. Nejabati, D. Simeonidou, G. Landi, N. Ciulli, J. F. Riera, J. A. García-Espín, “Convergence of Heterogeneous Network and IT infrastructures in Support of Fixed and Mobile Cloud Services”, FuNeMS 2013, Lisbon, Portugal

[BONFIRE] http://www.bonfire-project.eu/

[BOZ-2013] N. Bozinovic et. al. Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers. *Science* 28 June 2013: Vol. 340 no. 6140 pp. 1545-1548

[BT-800G] BT and Ciena Light World’s First 800G Super-Channel, http://www.ciena.com/about/newsroom/press-releases/BT-and-Ciena-Light-Worlds-First-800G-Super-Channel.html?campaign=X379513&src=blog

[CHA-2011] S. Chandrasekhar et al., “WDM/SDM Transmission of 10 Å~ 128-Gb/s PDM-QPSK over 2688-km 7-Core Fiber with A Per-Fiber Net aggregate Spectral-Efficiency Distance Product of 40,320 km.b/s/Hz,” ECOC ’11 Postdeadline Paper Th13.C4.

[CIE-1T] Comcast Conducts Industry’s First Live 1Terabit Network Trial with Ciena’s 6500 Converged Packet Optical Solution, http://www.ciena.com/about/newsroom/press-releases/Comcast-Conducts-Industrys-First-Live-1Terabit-Network-Trial-with-Cienas-6500-Converged-Packet-Optical-Solution.html?campaign=X414013&src=blog

[HUA-2014] “Huawei Launches The (Huawai)World's First 1T WDM Line Card”, Press Release: http://pr.huawei.com/en/news/hw-346706-1twdm.htm#.U-4BYfmSxsw

[CIS-2008] Cisco Systems, Synchronous Ethernet: Achieving High-Quality Frequency Distribution in Ethernet NGNs, Cisco white paper, 2008, available from http://www.cisco.com/en/US/prod/collateral/routers/ps9853/white_paper_c11-500360.pdf.

[CISCO-2013] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012–2017”, White Paper, 2013

[CONTENT] http://content-fp7.eu/

[DINH-2011] H. Dinh, C. Lee, D. Niyato, P. Wang, "A survey of mobile cloud computing: architecture, applications, and approaches," *Wirel. Commun. Mob. Comput*. Oct. 2011

[EETIMES] http://www.eetimes.com/document.asp?doc_id=1261562

[FLEXISCALE] http://www.flexiscale.com/

[GN3p-JRA1-T2] D. Regvart, Y. Demchenko, S. Filiposka, M. de Vos, T. Karaliotas, K. Baumann, D. Arbel, "Network Architectures for Cloud Services White Paper", MS101 (MJ1.2.1), GÉANT, March 2014

[GN3p-JRA1-T3] R. Tuminauskas, C. Tziouvaras, F. Panken, H. Yu, M. Garstka, Nicholas Garnier, Zbigniew Ołtuszyk, "Network architecture for aggregating high-speed mobile networking", MS102 (MJ1.3.1) White Paper, GÉANT, March 2014

[GOGRID] http://www.gogrid.com/

[GRI-2012] Steven Gringeri, E. Bert Basch, and Tiejun J. Xia. "Technical Considerations for Supporting data Rates Beyond 100 Gb/s", IEEE Comm. Magazine, February 2012, pp.S21-S30

[HEAVY-ROADM] The Need for Next-GenerationROADM Networks, http://www.jdsu.com/productliterature/NG_ROADM_WP_Final2.pdf

[IEEE-1588] Standard for A Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, http://www.nist.gov/el/isd/ieee/ieee1588.cfm.

[ITUT-G8261] Synchronous Ethernet, http://www.itu.int/rec/T-REC-G.8262-201007-I/en].

[JDSU-2012] R. Vaez-Ghaemi, Timing and Synchronization in Packet Networks, White Paper, July 2012, available from http://www.jdsu.com/productliterature/timesync_wp_tfs_tm_ae.pdf.

[JDSU-WSS] A Performance Comparison of WSS Switch Engine Technologies, http://www.jdsu.com/productliterature/wsscomp_wp_cms_ae.pdf

[KAT-2009] Katib, I., & Medhi, D. (2009). A Network Optimization Model for Multi-layer IP/MPLS over OTN/DWDM Networks. IP OPERATIONS AND MANAGEMENT, PROCEEDINGS, 5843, 180-185.

[KUM-2013] S. Kumar, V. Kumar, Synchronization in Packet-Switched networks: A Survey of Existing Techniques, White Paper, Tejas Networks, available from http://www.tejasnetworks.com/images/White%20Paper/Synchronization%20In%20Packet%20Switched%20Networks.pdf.

[MAZ-1975] J. E. Mazo et al., Faster-Than-Nyquist Signaling. Bell System Tech. J., vol. 54, pp. 1450–1462, Oct. 1975.

[MEF-2012] Metro Ethernet Forum 2012, Packet Synchronization over Carrier Ethernet Networks for Mobile Backhaul, MEF Positioning Paper, Version 1.0, January 2012, available from http://metroethernetforum.org/Assets/White_Papers/Packet_Synchronization_over_Carrier_Ethernet_Networks_for_MBH_2012021.pdf.

[MUN-TECH] K. Mun, "Mobile Cloud Computing Challenges", TechZine Magazine, http://www2.alcatel-lucent.com/techzine/mobile-cloud-computing-challenges/

[NAT-2013] National Instruments, Introduction to Distributed Clock Synchronization and the IEEE 1588 Precision Time Protocol, White Paper, Oct. 29, 2013, available from http://www.ni.com/white-paper/2822/en/.

[OIF-2013] OIF Carrier WG Requirements on Transport Networks in SDN Architectures Transport SDN, Date Approved: September 18, 2013

[ROY-2014] Variation of OTN Switching Benefits in Real-World Networks Based on Network and Traffic Connectivity, Soumya Roy, OFC 2014

[RYF-2011] R. Ryf et al., "Coherent 1200-km 6 x 6 MIMO Mode-Multiplexed Transmission over 3-Core Microstructured Fiber," ECOC '11, Th.13.C.1.

[SAT-2009] M. Satyanarayanan, P. Bahl, R.Caceres and N. Davies, "The Case for VM-Based Cloudlets in Mobile Computing." *IEEE Pervasive Comp*. 8 (4), pp.14-23, Oct. 2009

[SEM-2008] P. Diamond, Packet Synchronization in Cellular Backhaul Networks, Semtech White Paper October 2008, available from http://www.semtech.com/images/datasheet/advanced-communications/Packet-Synchronization-in-Cellular-Backhaul-Networks.pdf.

[SIL-2013] Silicon Labs, SyncE and IEEE 1588: Sync Distribution for a Unified Network, AN420, Silicon Laboratories, 2013, Rev. 0.3 7/13, available from http://www.silabs.com/Support%20Documents/TechnicalDocs/AN420.pdf.

[SIM-2000] Z. Booth Simpson, A Stream-Based Time Synchronization Technique for networked Computer Games, March 1, 2000, available from http://www.mine-control.com/zack/timesync/timesync.html.

[SYM-2007] Symmetricom, Timing and Synchronization in Next-Generation Networks, Application Brief, February 2007, available from http://www.scientific-devices.com.au/pdfs/WeTransfer-NZvJB6Cw/Telecommunication%20Synchronization/Timing%20&%20Synchronisation%20in%20Next%20Generation%20Networks.pdf.

[TECHTARGET] http://searchsdn.techtarget.com/news/2240181909/Vint-Cerf-At-Google-OpenFlow-now-runs-in-all-data-center-networks

[TRANS-2011] Transpacket, Synchronization and Precise Timing in Packet Networks, white paper, June 26, 2011, available from http://www.transpacket.com/wp-content/uploads/2012/06/white_paper_ packet_Synch_100612.pdf.

[TRANSMODE] Packet optical the TransMode way, TransMode

[TUC-1988] R. S. Tucker *et al.*, "Optical time-division multiplexing for very high bit-rate transmission", J. Lightwave Technol. 6 (11), 1737 (1988)

[TZA-2013] A. Tzanakaki, M. P. Anastasopoulos, G. S. Zervas, B. R. Rofoee, R. Nejabati, D. Simeonidou, "Virtualization of Heterogeneous Wireless-Optical Network and IT infrastructures in support of Cloud and Mobile Cloud Services, IEEE Communications Magazine, August 2013

[TZA-2014] A. Tzanakaki et al, "GEYSERS Planning of Dynamic Virtual Optical Cloud Infrastructures: The GEYSERS Approach", IEEE Communications Magazine, January 2014

[YOA-2014] John Yoakum, Harvey Waxman, Alan Johnston, The Future is WebRTC, Mobile and Web, p. 90-93, Avaya, Inc. 2014, available from http://www.avaya.com/usa/campaign/2013-guide/mobile-and-web-the-future-is-webrtc.html.

Glossary

ADC	Analog to Digital Converter
BPSK	Binary Phase Shift Keying
DWDM	Dense Wavelength Division Multiplex
DAC	Digital to Analog Converter
EC	European Commission
IP	Internet Protocol
Flexgrid	Flexible Grid
ISO	International Standards Organisation
ISP	Internet Service Provider
NAC	Network Access Control
NOC	Network Operations Centre
NREN	National Research and Education Network
OADM	Optical Add Drop Multiplexer
OTN	Optical Transport Network
PoP	Point of Presence
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
ROADM	Recinfigurable Optical Add Drop Multiplexer
SDN	Software Defined Networking
BoD	Bandwidth on Demand
WAN	Wide Area Network
WSS	Wavelength Selective Switch
SA	GN3plus Service Activity